DC-modulated AC/AC converters

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Abstract— **Traditional methods of AC/AC converters have general drawbacks: output voltage is lower than input voltage, the input side THD is poor and output voltage frequency is lower than input voltage frequency by using voltage regulation method and cycloconverters. We introduce the novel approach - DC-modulated AC/AC converters in this paper, which successfully overcomes the drawbacks. Simulation and experimental results of the DC-modulated AC/AC converter are the evidences to verify our design. These methods will be very widely used in industrial applications.**

Keywords-component; *DC-modulated AC/AC convertes, total harmonic distortion (THD), power factor (PF), power transfer efficiency (η), .*

I. INTRODUCTION

Traditional methods of AC/AC converters have general drawbacks: output voltage is lower than input voltage, the input side THD is poor and output voltage frequency is lower than input voltage frequency by using voltage regulation method and cycloconverters. We introduce the novel approach - DC-modulated AC/AC converters in this paper, which successfully overcomes the drawbacks.

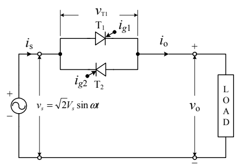
For example, Single-stage AC/AC converters are the most popular structure widely applied in various industrial applications [1-4]. These AC/AC converters are traditionally implemented by voltage regulation technique, cycloconverters and matrix converters. However, they have high total harmonic distortion (THD), low power factor (PF) and poor power transfer efficiency (η). A typical single-stage AC/AC converter with voltage regulation technique and the corresponding waveforms are shown in Figure 1. The devices can be thyristors, IGBT and MOSFET. For a clear example, MOSFETs are applied in the circuit with a pure resistive load R [5]. The input voltage is

$$v_S(t) = \sqrt{2}V_S \sin \omega t$$

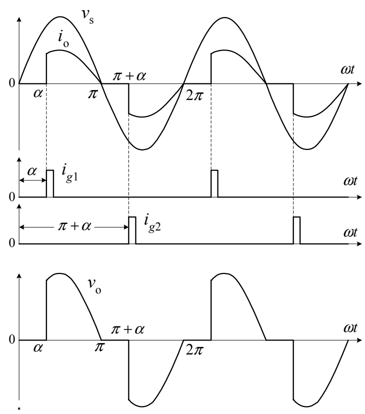
where V_S is the rms value, ω is the input voltage frequency ω = 2πf = 100π. The power factor is calculated by the formula [6],

$$PF = \frac{DPF}{\sqrt{1+THD^2}}$$

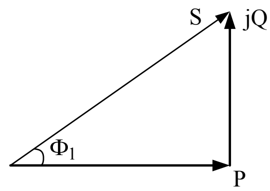
where DPF = cos Φ_1 is the displacement power factor, THD is the total harmonic distortion, the delay angle Φ_1 is the phase delay angle of the fundamental harmonic component.



(a) Circuit diagram



(b) Waveforms



(c) Power vectors

Figure 1. A typical single-stage AC/AC converter with voltage regulation technique

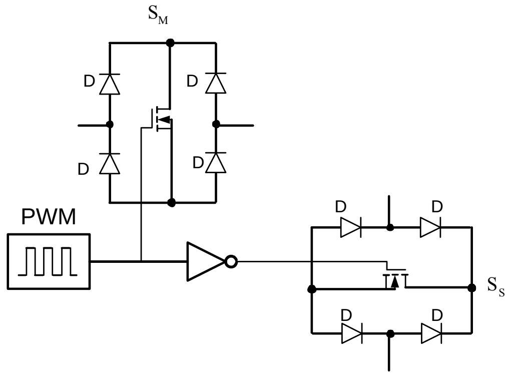
For example, if the faring angle α is 30^O (i.e. fundamental harmonic phase angle Φ_1 is 30^O), the typical values are that DPF = cos 30^O = 0.866 and THD is 0.15 (or 15 %). therefore, PF = 0.856. It is a low PF. The power vector diagram is shown in Figure 1 (c) where **P** is the real power, j**Q** the reactive power and **S** apparent power. **S = P +** j**Q**.

II. BIDIRECTIONAL EXCLUSIVE SWITCHES S_M-S_S

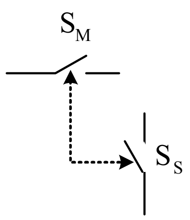
We need bidirectional exclusive switches for this technique. The switching devices for bidirectional exclusive switches can be MOSFETs and IGBTs. MOSFETs are selected for our design. The bidirectional exclusive switches S_M-S_S for the DC-modulation operation is designed and have following technical features:

1. The master switch S_M is controlled by a PWM pulse-train and it conducts the input current to forwardly flow in the positive input voltage. Vice versa, the S_M conducts the input current to reversely flow in the negative input voltage.
2. The slave switch S_S is conducted when the master switch S_M switched-off exclusively. It is the free-wheeling device to conduct the current to flow.

Figure 2 shows the circuit of the bidirectional exclusive switches S_M-S_S for the DC-modulation operation. The switching control signal is a PWM pulse-train that has adjustable frequency f_m and pulse-width. The repeating period T_m = $1/f_m$, the conduction duty cycle k = (pulse-width)/T_m.



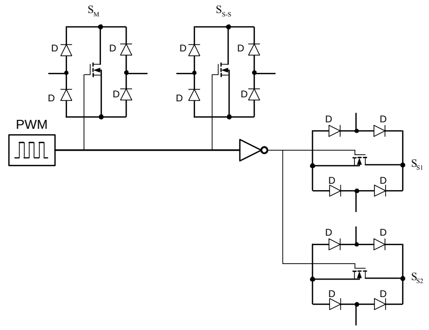
(a) Circuit of a bidirectional exclusive switches S_M-S_S



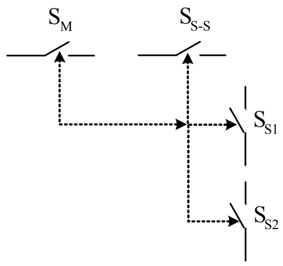
(b) Symbol of a bidirectional exclusive switches S_M-S_S

Figure 2. A bidirectional exclusive switches S_M-S_S for the DC-modulation operation

If some converters request more than one bidirectional exclusive slave switches, the construction of the further S_S just only need copy/repeat the existing one. If some converters request more than one bidirectional slave switches and one synchronously-bidirectional slave switch, the construction of the synchronously-bidirectional slave switch SS-S just only need copy/repeat the master switch SM. A group of a master switch SM with a synchronously-bidirectional slave switch SS-S plus two bidirectional exclusive slave switches SS1 and SS2 is shown in Figure 3.



(a) Circuit of a bidirectional switches S_M-$S_{S\text{-}S}$ plus exclusive switches S_{S1} and S_{S2}



(b) Symbol of a bidirectional switches S_M-$S_{S\text{-}S}$ plus exclusive switches S_{S1} and S_{S2}

Figure 3. A bidirectional switches S_M-$S_{S\text{-}S}$ plus exclusive switches S_{S1} and S_{S2}

III. DC-MODULATED SINGLE-STAGE AC/AC CONVERTERS

We can use various DC/DC converters to implement DC-modulated AC/AC converters. Some typical circuits will be introduced in this section.

A. Buck-type AC/AC Converter

The DC-modulated single-stage Buck-Type AC/AC Converter is shown in Figure 4. In order to keep the input current continuous, we have to apply an input filter before the Buck converter.

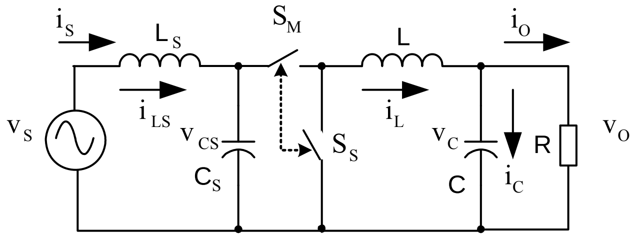
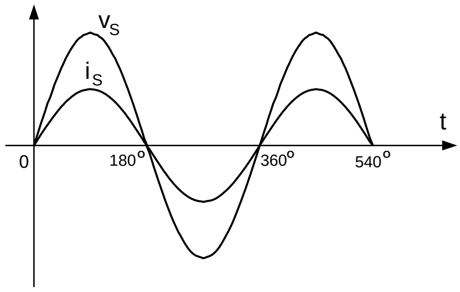


Figure 4. A DC-modulated single-stage Buck-Type AC/AC Converter

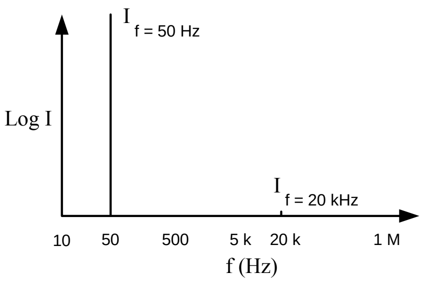
The output voltage is calculated by

$$v_O = -k \mid v_S \mid = k\sqrt{2}V_S \sin \omega t \qquad (1)$$

where **k** is the conduction duty cycle, V_S is the rms value of the input AC voltage, ω is the power supply radian frequency. The whole cycle input voltage and current waveforms are shown in Figure 5 (a). The spectrum of the input current is shown in Figure 5 (b). The spectrum is very clean and the little distortion from the harmonic component I_M at 20 kHz that is far away from the fundamental frequency component I_S at 50 Hz. Its vale is only 0.5 %, i.e. I_M/I_S = 0.005. Therefore, THD = 1.0000125. Considering the DPF = 0.9998, we obtain the final PF = 0.99979.



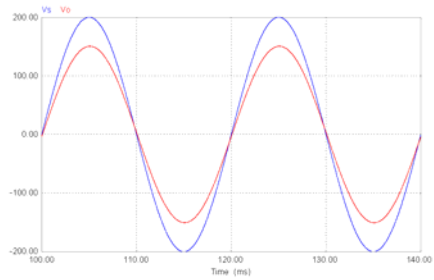
(a) The input voltage and current waveforms



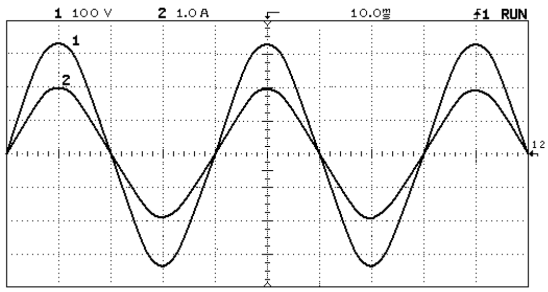
(b) The spectrum of input current

Figure 5. The input voltage/current waveforms of the DC-modulated Buck-Type AC/AC Converter

We choose the DC-modulated Buck-type AC/AC Converter has components: L_S =1mH, C_S = 10 μF, L = 10mH and C = 3μF, R = 150 Ω. The conduction duty cycle is selected as k = 0.75. The simulation results are shown in Figure 6(a). The output voltage V_O = 0.75 x V_S = 150 Vrms (peak value is *approximately 212 V) with the frequency f = 50 Hz. The tested waveforms of the input and output voltages vS (t) and vO (t) are shown as Channel 1 and Channel 2 in Figure 6 (b). It can be seen that there isn't any phase delay, although there may be about 3.374° phase angle delay from our analysis. The output current IO should be 1 Arms, and the output power PO = VO2 /R = 150 W. It can be seen that there nearly isn't any phase delay, although there may be about 3.374° phase angle delay from our analysis, and the THD = 0.015. The input power Pin = Vs x Is = 190 W. Although the theoretical analysis no power losses for idea condition (η = 1), but the particular test shows there are power losses, which are mainly caused by the switches power losses. From the test results we obtain the final PF = 0.9979 and the power transfer efficiency η = Po/Pin 190/200 = 0.95or 95 %.*



(a) Simulation results of the input/output voltage waveforms



(b) The tested input voltage and current waveforms of the DC-modulated Buck-type AC/AC converter

Figure 6. The simulation and tested results of the DC-modulated Buck-type AC/AC converter

B. Boost-type AC/AC Converter

The DC-modulated single-stage Buck-Type AC/AC Converter can only convert an input voltage to a lower output voltage. For certain applications, the output voltage is requested to be higher than input voltage. For this purpose, the DC-modulated single-stage Boost-Type AC/AC Converter has been designed, and is shown in Figure 7. Since the input current is continuous current, it is no need set a low-pass filter. The output voltage is calculated by

$$v_O = \frac{v_S}{1-k} = \frac{\sqrt{2}}{1-k} V_S \sin \omega t \qquad (2)$$

where **k** is the conduction duty cycle, V_S is the rms value, ω is the power supply radian frequency. The whole cycle input and output voltage waveforms are shown in Figure 8 with the duty cycle k = 0.25. It is easy to obtain variable output voltage higher than the input voltage with very high PF and high efficiency.

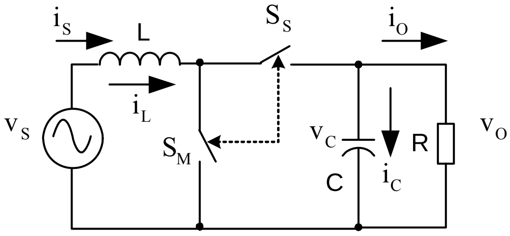


Figure 7. A DC-modulated single-stage Boost-Type AC/AC Converter

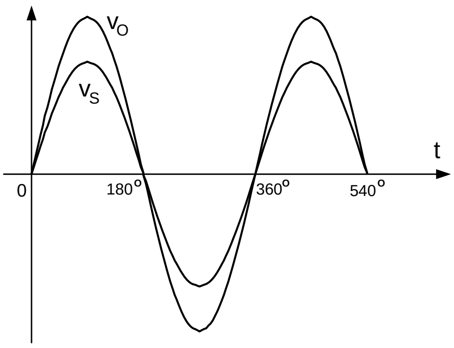


Figure 8. The input/output voltage waveforms of the DC-modulated Boost-Type AC/AC Converter

The simulation results of a DC-modulated Boost-type AC/AC Converter that has components: L = 10 mH, C = 3 μF and R = 150Ω, are shown in Figure 9. The conduction duty cycle is selected as k = 0.25. The experimental results are shown in Figure 10. The output voltage $V_o = V_s / (1\text{-}k)$ = 267 Vrms (peak value is approximately 377 V) with the frequency f = 50 Hz. The waveforms of the input and output voltages v_s (t) and v_o (t) are shown as Channel 1 and Channel 2 in Figure 10. From it we can see that there isn't any phase delay, although there may be about 3.374° phase angle delay from our analysis. The output current Io should be 1.8 Arms, and the output power $Po = V_o^2/R$ = 475 W.

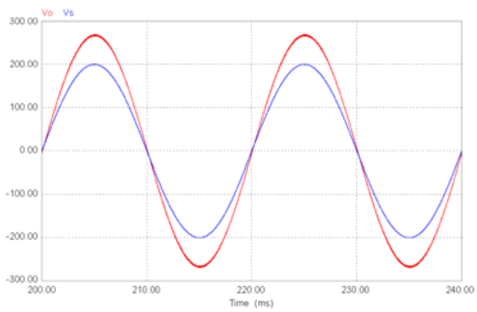


Figure 9. The simulation results of the DC-modulated Boost-type AC/AC converter

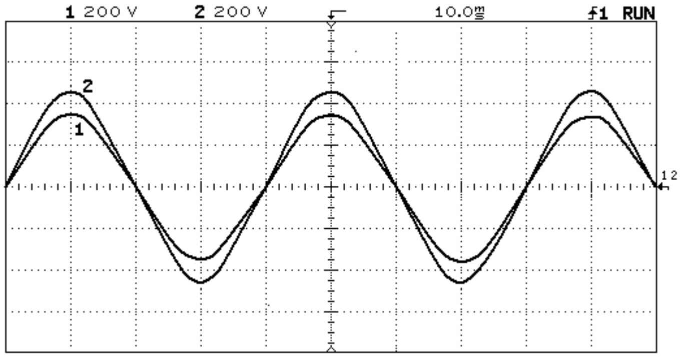


Figure 10. Test results of the DC-modulated Boost-type AC/AC converter

C. Buck-Boost-type AC/AC Converter

For certain applications, the output voltage is requested to be lower and higher than input voltage. For this purpose, the DC-modulated single-stage Buck-Boost-Type AC/AC Converter has been designed, and is shown in Figure 11. Since the input current is pulse-train with the repeating frequency fm, a low-pass filter L_S – C_S is requested. We have to investigate the operation during both positive and negative half-cycle of the input voltage.

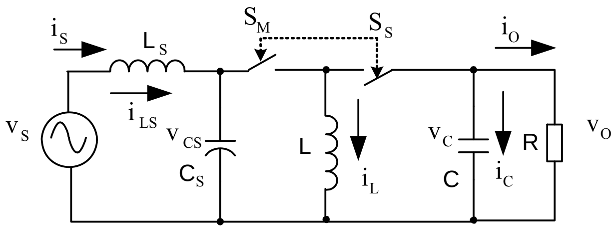


Figure 11. A DC-modulated single-stage Buck-Boost-Type AC/AC Converter

The output voltage is calculated by

$$v_O = kv_S = \frac{k\sqrt{2}}{1-k} V_S \sin \omega t \qquad (3)$$

where **k** is the conduction duty cycle, V_S is the rms value, ω is the power supply radian frequency.

The input and output voltage waveforms are shown in Figure 12 with the duty cycle k = 0.43. It is easy to obtain variable output voltage higher or lower than input voltage with very high PF and high efficiency. There is polarity reversion between input and output voltages, or phase angle shift 180^{O}. Usually, this phase angle shift does not affect most industrial applications. For harmonic analysis, its value is only 0.5 %, i.e. I_M/I_S = 0.005. Therefore, THD = 1.0000125. Considering the DPF = 0.9998, we obtain the final PF = 0.99979.

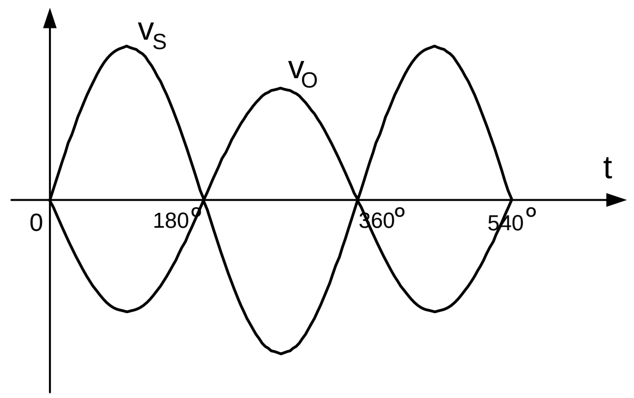


Figure 12. The input/output voltage waveforms of the DC-modulated Buck-Boost-Type AC/AC Converter

The simulation results of a DC-modulated Buck-Boost-type AC/AC Converter that has components: L_S =1mH, C_S = 10 μF, L =10mH and C = 3 μF, are shown in Figure 13. The conduction duty cycle is selected as k =0.45. The output voltage $V_O = k/(1-k) \times V_S = 0.818 \times V_S$ = 163.6 Vrms (peak value is approximately 231.4 V) with the frequency f = 50 Hz. The waveforms of the input and output voltages v_S (t) and v_O (t) (reversed the polarity) are shown as Channel 1 and Channel 2 in Figure 14. It can be seen that there isn't any phase delay, although there may be about 3.374° phase angle delay from our analysis in section 3. The output current I_O should be 1.1 Arms, and the output power $P_O = V_O^2/R$ = 178.5 W.

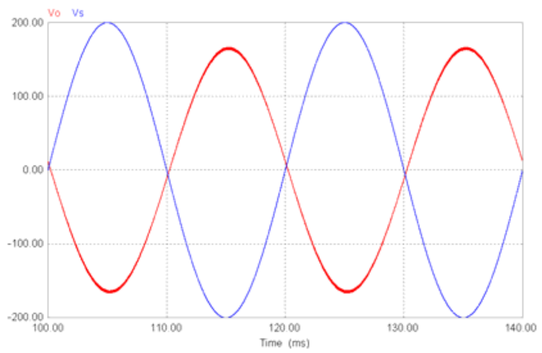


Figure 13. The simulation results of the DC-modulated Buck-Boost-type AC/AC converter

The input current is measured I_S = 0.9 Arms (peak value is approximately 1.27 A) with the frequency f = 50 Hz. The waveforms of the input voltage v_s (t) and current i_s (t) are shown as Channel 1 and Channel 2 in Figure 14. It can be seen that there nearly isn't any phase delay, although there may be about 3.374° phase angle delay from our analysis. The THD = 0.1357. The input power $P_{in} = V_s \times I_s$ = 180 W. Although the theoretical analysis no power losses for idea condition (η = 1), but the particular test shows there are power losses, which are mainly caused by the switches power losses. From the test results we obtain the final PF = 0.9939 and the power transfer efficiency $\eta = P_o/P_{in}$ = 178.5/180 = 0.9917 or 99.17 %.

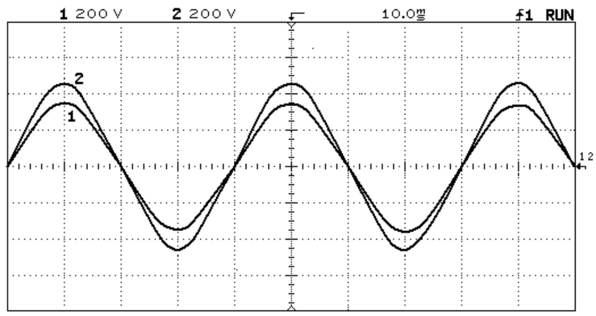


Figure 14. Test results of the DC-modulated Buck-Boost-type AC/AC converter

IV. DC-MODULATED OTHER-TYPE AC/AC CONVERTERS

Understanding the clue to design and construct DC-modulated single-stage AC/AC Converter, we can easily design and construct two-stage AC/AC Converters. Some converters have more complex structure such as Luo-Converters, Super-lift Luo-Converters and multistage Cascaded Boost converters [7, 8, 15-19]. In order to offer more information to readers, a DC-modulated positive output Luo-Converter and a two-stage Boost-Type AC/AC Converter have been designed.

A. P/O Luo-Converter-type AC/AC Converter

The DC-modulated Positive Output (P/O) Luo-Converter-type AC/AC converter is shown in Figure 15. Its output voltage has same polarity with input voltage. The simulation results are shown in Figure 16.

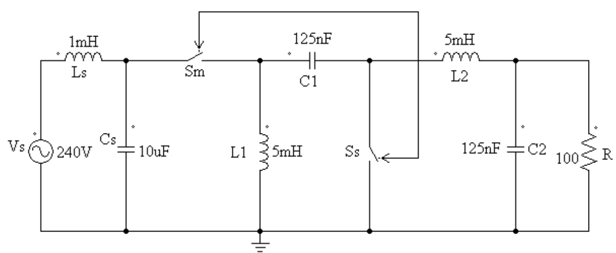


Figure 15. DC-modulated positive output Luo-converter-type AC/AC converter

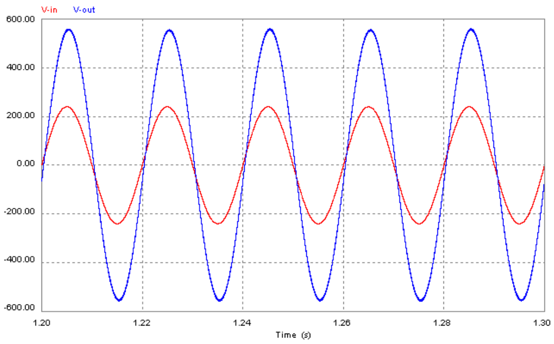


Figure 16. Simulation results of the DC-modulated P/O Luo-converter-type AC/AC converter

The voltage transfer gain is,

$$v_O = kv_S = \frac{k\sqrt{2}}{1-k} V_S \sin \omega t \qquad (4)$$

B. DC-Modulated Two-Stage Boost-type AC/AC Converter

A DC-modulated two-stage Boost-type AC/AC converter is shown in Figure 17.

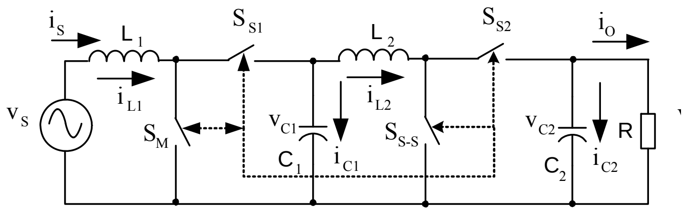


Figure 17. Circuit diagram of a DC-modulated Two-stage Boost-Type AC/AC Converter

The voltage transfer gain is,

$$v_O = (\frac{1}{1-k})^2 v_S = (\frac{1}{1-k})^2 \sqrt{2} V_S \sin \omega t \qquad (5)$$

V. DC-Modulated Multi-phase AC/AC Converters

Use same technique we can construct DC-modulated multi-phase AC/AC converters

A: DC-Modulated Three-Phase Buck-type AC/AC Converter

A DC-modulated three-phase Buck-type AC/AC converter is shown in Figure 18. The simulation results are shown in Figure 19.

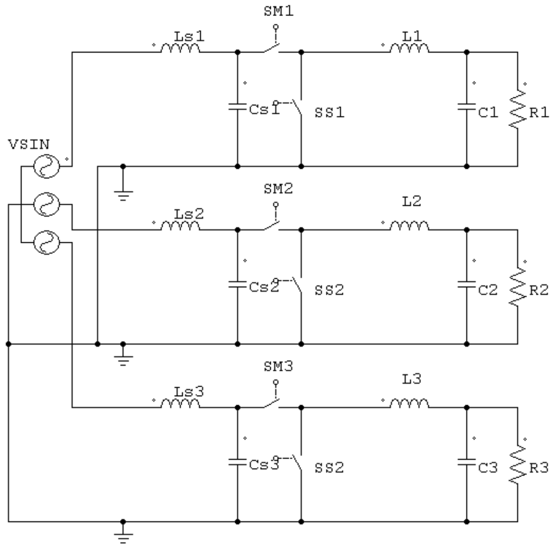


Figure 18. A DC-modulated three-phase Buck-Type AC/AC Converter

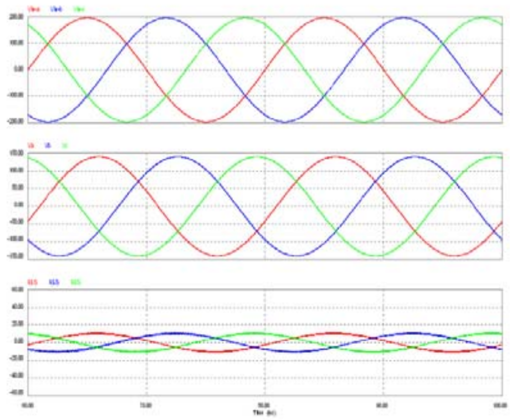


Figure 19. Simulation results of the DC-modulated 3-phase Buck-type AC/AC converter

B: DC-Modulated Three-Phase Boost-type AC/AC Converter

A DC-modulated three-phase Boost-type AC/AC converter is shown in Figure 20. The simulation results are shown in Figure 21.

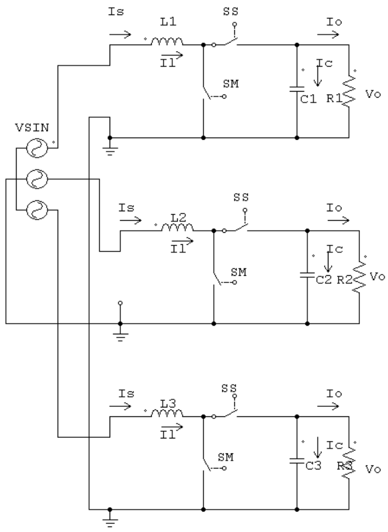


Figure 20. DC-modulated three-phase Boost-Type AC/AC Converter

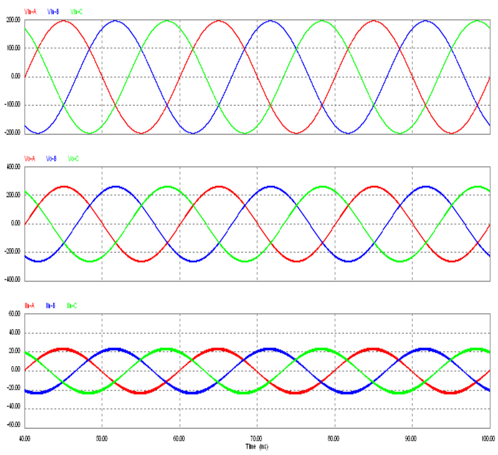


Figure 21. Simulation results of the DC-modulated 3-phase Boost-type AC/AC converter

C: *DC-Modulated Three-Phase Buck-Boost-type AC/AC Converter*

A DC-modulated three-phase Buck-Boost-type AC/AC converter is shown in Figure 22. The simulation results are shown in Figure 23.

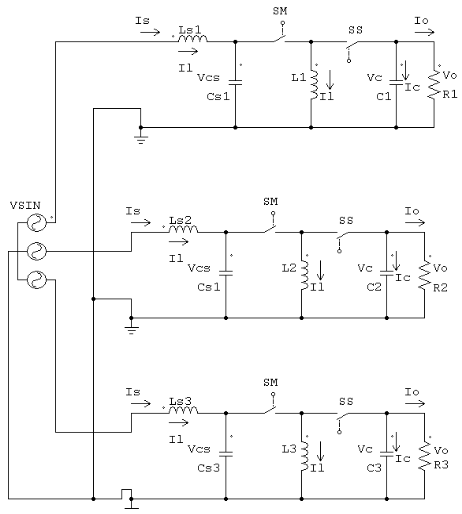


Figure 22. A DC-modulated three-phase Buck-Boost-Type AC/AC Converter

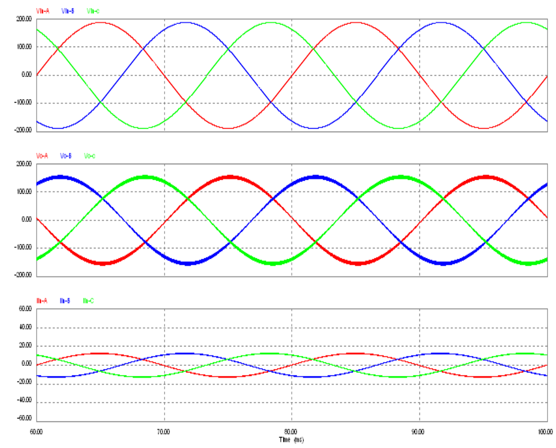


Figure 23. Simulation results of DC-modulated 3-phase Buck-Boost-type AC/AC converter

VI. CONCLUSION

Traditional methods of AC/AC converters have general drawbacks: output voltage is lower than input voltage, the input side THD is poor and output voltage frequency is lower than input voltage frequency by using voltage regulation method and cycloconverters. We introduce the novel approach - DC-modulated AC/AC converters in this paper, which successfully overcomes the drawbacks. Various circuits have been illustrated. Simulation and experimental results of the DC-modulated AC/AC converter are the evidences to verify our design. These methods will be very widely used in industrial applications.

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