A Single-Three Phase Inverter Adopting SLH Scheme*

Zhou Qianzhi**　　Zhang Handong　　Zhuang Kai

(School of Electrical Engineering & Information, Anhui University of Technology Anhui Maanshan 243002)

Abstract　A Novel Switch-Linearity Hybrid power conversion technique is introduced. Experiments and simulations show that the proposed system can operate in audio switch frequency range without audio noise from the motor load, meanwhile, EMI can be limited to low level. These are beneficial to human's health, extending the power devices' life, and also improving the quality of the processing matched to the motor's operation.

Key words　switch-linearity hybrid;　harmonic;　phase balance;　torque ripple

开关线性复合变换式单变三相逆变器*

周谦之**　　张捍东　　庄　凯

(安徽工业大学电气信息学院　安徽 马鞍山　243002)

【摘要】介绍了一种新颖的开关-线性复合功率变换技术SLH。实验与仿真结果表明：该系统采用音频开关而不导致电机负载的音频噪声，同时使EMI能被限制在低电平。这些均有利于人类健康和延长功率器件的寿命，也能提高电机的运行质量。

关　键　词　开关-线性复合;　谐波;　相平衡;　转矩脉动

中图分类号　TN43;　TM46　　**文献标识码**　A

In recent years, more and more single-three phase PWM ac inverters are used in small size power conversion system, so that a single phase ac supply can feed an inverter for driving three phase motor. In order to reduce power device numbers and auxiliary circuits, a normal configuration is adopted as shown in Fig.1[1]. Obviously, if the fundamental output-voltage of three phases is set as

$$v_a = V_m \sin wt \qquad v_b = 0 \qquad v_c = V_m \sin(wt - 60°) \tag{1}$$

the line voltage will be

$$\begin{cases} v_{ab} = v_a - v_b = V_m \sin wt \\ v_{bc} = v_b - v_c = V_m \sin(wt + 120°) \\ v_{ca} = v_c - v_a = V_m \sin(wt - 120°) \end{cases} \tag{2}$$

This is a balanced three phase system in theory with excellent performances, however, in the practical application, there are some problems with above single-three phase system.

The special one is that large voltage variations across the dc-link capacitors cause the phase currents

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** 女　57岁　教授　主要从事电力电子技术及应用方面的研究

unbalanced, and torque ripples during motor applications. One of the present improvements is adopting an Adaptive Space Vector Modulation (SVM) which compensates the dc-link voltage ripples by means of the complex algorithm and the controller[2].

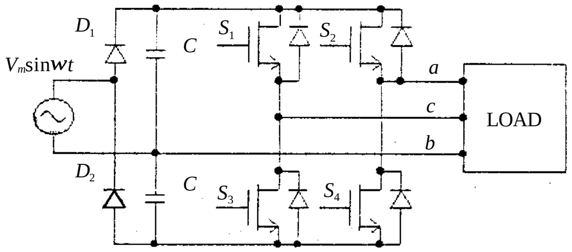


Fig.1 Conventional single-three phase PWM converter

Another one is that, like all the switch converters operating in high frequencies for home appliances, it is harmful to human's health. Normally for avoiding audio noise, the switch frequency is always selected at the ultrasonic range. Nobody can hear it, which is thought safe because that the band is under radio frequency range and above audio frequency. Practically the microwave spectrum is still strong during rise-time and fall-time of each switch pulse. The higher the switch frequency is, the stronger the effect of microwaves on human's body. It is well known that one's organism will be sterilized near the microwave-cooker. Like the same way human's memory might be weakened during working year by year in a power electronics laboratory. Therefore, it is not an optimal option for increasing the switch frequency for concentrating the size of a converter inside housework machine. Is there any way to reduce the switch frequency for keeping human's health without waveform distortion to the load? Yes, there is. A Switch-Linearity Hybrid (SLH) power conversion technique[3], whose past name is CTA, has been proved that it got better sinusoidal waveforms with low switch frequency than a SPWM conversion system with the same switch frequency did. At the same time, it shows very universal characteristics in matching to multi-kinds of load (R, RL, RC or their hybrid, even nonlinear one) with minimized waveform distortion, which has been proved by the test results from “95 key project” of science and technology of Anhui Province (see Tab.1). Fortunately SLHs' output waveforms just track the reference signal firmly in shapes, frequencies and phases, which don’ t depend on dc link voltages' variations. Why not take the SLH scheme in normal single-three phase inverter system (as shown in Fig.1)to cut off the complex control strategy and meanwhile obtained load adaptability? This is just what the present paper introduces. From the paper's proposed pattern, the result shows an excellent validity that the novel inverter exhibits good performances, for instance the output waveforms (both voltage and current) with minimized distortion, minimized torque ripples, three phases balanced, no audio noise, most weakened microwave's spectrum caused by rise-time and fall-time of switch pulses, operating in proper switch frequencies, so no harmful to human's health, etc.

Tab. 1 The comparison of THD between a 1KVA of SSLH-UPS and a SPWM-UPS

Load kind	SSLH	PWM+LC	Test condition
①R (460 W)	1.34	1.75	
②2×CRT of computer (180 W)	1.30	4.18	
③SCR Variable speed drill (500 W)	1.74	Failure	Braking
②+③ (680 W)	1.37	failure	

1 Operation Scheme

Inserting a LC network and two phases of NP-pairs of MOSFETS between a normal single-three phase system and a motor load in series, the novel SLH(CTA) single-three phase inverter can be obtained (as shown in Fig.2). As long as the synchronous reference signals with 60 phase shift excite the PN-pairs which operate as voltage followers, voltage v_{a_3} and v_{c_3} will follow v_{a_1} and v_{c_1} respectively. Then the regulation of (v_{a_3}, v_b, v_{c_3}) will be similar to Eq.(1), while the harmonic contents have been cut off. Thus the ($v_{a_3 b}, v_{bc_3}, v_{c_3 a_3}$) will be similar to Eq.(2). The harmonic voltages of various order across the PN-pairs of MOSFETs are only near to MOSFET's saturation voltage drop in magnitude during the MOSFETs' on-period, while the untiparallel diodes inside MOSFETs' packages clamping their voltages during MOSFETs' off-period, which allows PN-pairs of MOSFETs being chosen at very low voltage rating, so as to get low cost. This is a merit better than original basic SLH(CTA) topology[3].

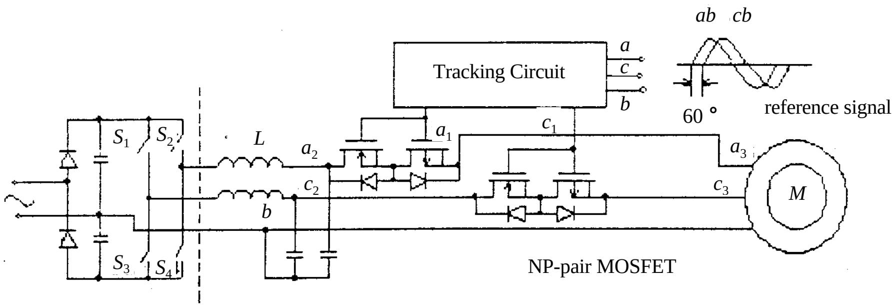


Fig.2　The proposed circuit

Fig.3 shows the basic SLH(CTA) circuit ,in which the PN-pairs of MOSFETs need high voltage rating. In Fig.3, v_0 follows v_0,

$$\begin{cases} v_{B1} - v_0 \approx v_{sat} & \text{positive half cycle} \\ v_{B2} - v_0 \approx v_{sat} & \text{negative half cycle} \end{cases} \tag{3}$$

where v_{B1} and v_{B2} are ripple voltage feeding the Amplifier of PN-pairs of MOSFETs, v_0 is output voltage on load, $v_{0'}$ is followed voltage signal, v_{sat} is saturation voltage of MOSFET.

Hence last stage operates in high efficiency near 98%[3]. In Fig.2's novel SLH topology, the situation is similar to the basic one. v_{a_2} and v_{c_2} are also ripple voltages feeding NP-pairs of MOSFETs, thus

$$\begin{cases} v_{a_2} - v_{a_3} \approx v_{sat} \\ v_{c_2} - v_{c_3} \approx v_{sat} \end{cases} \tag{4}$$

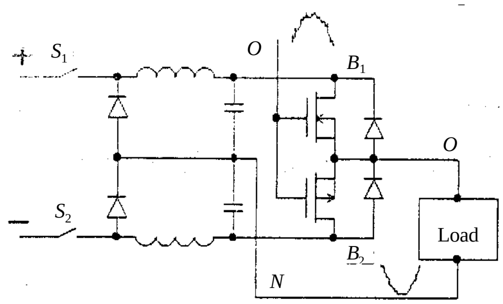


Fig.3　Basic SLH(CTA) circuit

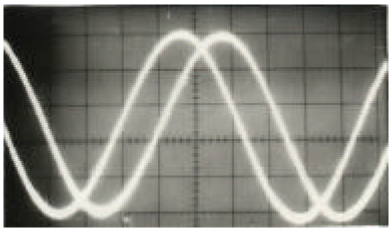
Here v_{a_3} tracks v_{a_1} during both positive and negative half cycle of phase voltage. So does v_{c_3} tracks v_{c_1}. Then, the efficiency of the novel SLH's last stage should be higher than that of the basic one in three phase system, because not only the number of power device have been reduced, but also the saturated voltage drop on MOSFET with low voltage rating is smaller than that with high voltage rating.

2　Simulations and Results

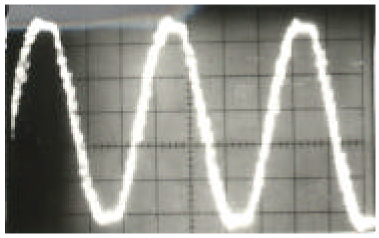
Fig.4 shows the experiment results. Fig.4a expresses the followed waveforms from the pre-voltage unit during the motor load operates at 26 Hz, Fig.4b expresses the feeding waveforms from the LC unit during the R load operates at 45 Hz, Fig.4c expresses the load phase voltage during the motor operates at 26 Hz, Fig4.d expresses the feeding waveforms and the load waveforms in the same coordinate, which just demonstrates that only a saturation voltage drops on the PN-pair MOSFET, and Fig.4e expresses the resistive load waveforms of line voltage operating at 26 Hz. All above illustrates that the present SLH can get good related waveforms for different loads similar to basic SLH(CTA)[3].

For an inductive load, there exists a commutating fold angle on the waveforms(as Fig.4c shows.), which is in normal operation conditions at about 2 kHz of switch frequency.

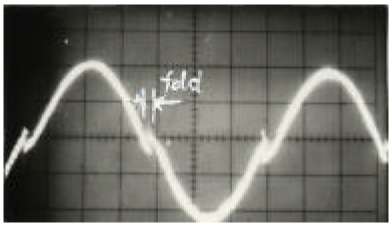
Fig.5 shows the comparison of simulation results between conventional single to three phase inverter and the presented one at about 2 kHz of switch frequency, where the motor load operates at 26 Hz.



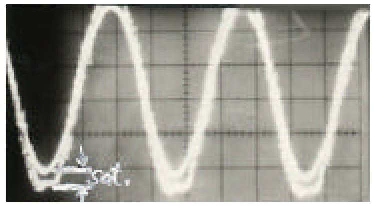
(a) Followed waveforms From
pre-voltage unit (10 V/div, 5 ms/div)



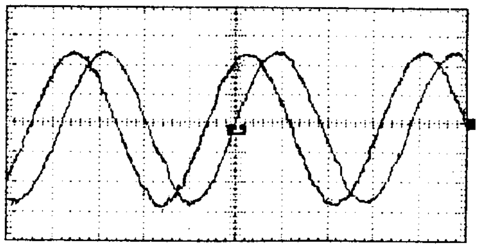
(b) Feeding waveforms from
LC unit for a R load, 45Hz (10 V/div, 2 ms/div)



(c) Load waveforms of phase voltage
from linear unit (10 V/div, 5 ms/div)

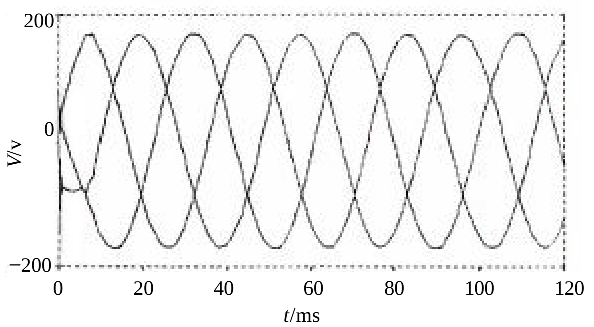


(d) Feeding waveforms and load waveforms in
the same coordinate (20 V/div, 2 ms/div)

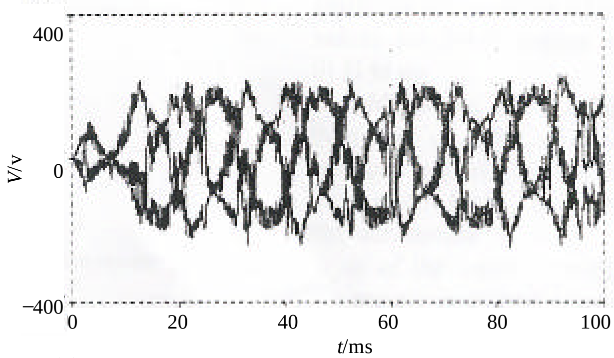


(e) Load wave forms of line voltage $v_{ab}\, v_{bc}$

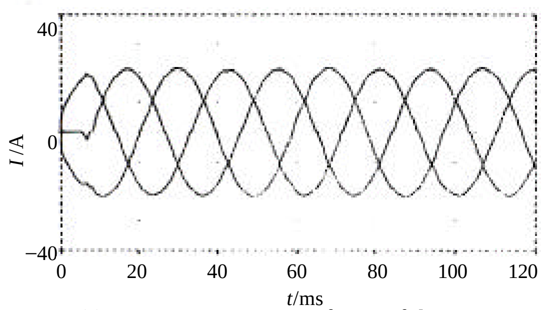
Fig.4 Followed waveforms, feeding waveforms and load waveforms



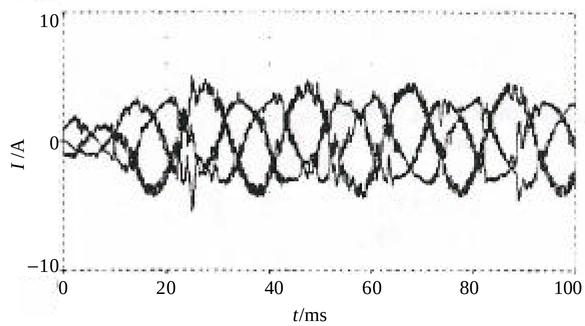
(a) Output voltage waveforms of the SLH



(b) Output voltage waveforms of the conventional one



(c) Output current waveforms of the SLH



(d) Output current waveforms of the conventional one

Fig.5 The comparison of simulation

The simulation results shows that SLH has sufficient ability to keep balance of three phases in a single-three phase system without complex controlling strategy, which is beneficial to eliminating torque ripples.

3 Discussion

3.1 Filter Parameter LC

Somebody wonder, the topology of switch circuit plus LC filter (S-LC unit) is sufficient for smoothing waveforms' needs, why need a linear amplifier with high efficiency to follow S-LC unit? The two stages of configuration must lead to total efficiency lower than that of one stage's S-LC. The answers can be obtained from the comparison between two groups of data. If the switch frequency has been set for a resistive load system, LC parameters may be calculated from the following equations[4,5]

$$\frac{\Delta V_0}{V_0} = \frac{1}{2} \eth^2 (1-D)(\frac{f_c}{f_s})^2 \tag{5}$$

$$R = (0.5 \sim 0.8) R_L \tag{6}$$

where R_L is load resistor, R is characteristics impedance, f_c is frequency of the filter, f_s is switch frequency, $\Delta V_0 = v_{rip}$ is ripple voltage, D is duty cycle.

Then, during switch frequency f_s=2 kHz, for the peak to peak value of ripple voltage margin v_{rip}=50 mV, get L=35 mH, C=19.5 μF; While v_{rip}=5 V, then get L=3.5 mH, C=1.95 μF

Above results mean that using the second group of data, followed a linear amplifier, can get a better validity than using first group of data without amplifier followed. In other words, it needs bigger LC values for S-LC system to smooth waveforms than SLH to do.

Moreover, SLH's adaptability to load is stronger than that of S-LC unit, and then why not adopts SLH? Also previous experiment results show excellent situation for a motor load. Then relating to efficiency problem, the conception of it should be considered the total value of the whole system, including load efficiency, not merely including converter efficiency. It is evident that the efficiency of S-LC is higher slightly than SLH's, however still lead to harmonic loss to the load during the LC values not big enough. Therefore, a balance situation in total system efficiency can be accepted between S-LC system and SLH system.

3.2 Spreading Significance

The difference in configurations between novel SLH and basic SLH(CTA) is that the basic one connect the MOSFET PN-pairs of linear amplifier S-LC unit in parallel, while the novel one does it in series. They are all Switch-Linearity Hybrid (SLH) power converters. For distinguishing them, the basic one is named after PSLH, while the novel one is named after SSLH.

The novel scheme of SSLH can just satisfy the requirement of "green feeding back" and "single to three phase conversion" in keeping three phases balanced. It means, facing human's environment of 21 century, in hybrid electricity network, the carbon burning electricity generator will be limited, while "green" new energy will be more and more developed[6]. SSLH will develop with the tendency, too.

Then an application for SSLH system in this paper can be spread out to electrical power feeding back system. For instance in hybrid network of the solar energy, wind energy and battery electricity station, if connecting to local network is needed, excellent waveforms feeding back to general network is necessary to keep clean. In this condition, the signal reference can be taken from the general network so that the phase synchronous problem must be treated much easier relying upon the back transmission-transformer.

Of course, some tests of the product need 24 hours of operation with load before coming to the market from manufacturing factory, the energy transmitting back to network can also use SSLH scheme. Particularly in large scale systems, during adopting Least Switch Times' PWM technique[7] for deducing switch losses in S-LC unit, SSLH mode still acquires optimal waveforms, but S-LC without linear unit followed can not, because in low switch frequency's situation, voltage ripples will be enlarged.

4 Conclusions

A novel Switch-Linearity Hybrid Conversion scheme SSLH can be used in single-three phase system and other conversion systems. Its special significance is, like the basic PSLH(CTA), SSLH possesses electricity-transmitting function (back to network or forward to load) with optimal waveforms regardless of switching frequency, good adaptability to multi-kinds of loads, no audio and radio noise harmful to humans health, but cheap and reliable than PSLH. PSLH(CTA) has Bi-Buck unit not caring about each LC parameter equal or unequal, so it requires the parameter coincidence not very strictly as in SSLH. Its (3 phases and 4 lines) configuration leads to better three phases' balance than in SSLH system. It can bare some phase shift between reference signals and output waveforms of LC filters without distortion. But people should think of SSLH and PSLH having their advantages and disadvantages respectively.

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