



Three-phase UPS Topology and Efficiency Enhancement

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Abstract

The development of Taiwan's electronic science & technology and semiconductor industry witnesses increasingly higher requirements on the quality of power supply to precision instruments and equipment necessary for manufacturing processes, thus driving the demand for large capacity three-phase UPS systems. In the context of energy crisis and greenhouse effect, how to raise UPS operating efficiency and reduce energy consumption and operation costs has become an important issue faced by UPS vendors. Therefore, this paper, starting from introducing topologies of three-phase UPS systems, describes the method for improvement of UPS efficiency based on comparison of PFC and inverter topologies, optimization of control methods, selection of key components & assemblies, and operation of highly efficient ECO mode. Meanwhile, it also makes a brief introduction about the current international regulations on UPS efficiency.

I. Introduction

Uninterrupted Power Supply (UPS) systems are mainly used to provide a stable power supply for critical loads so as to prevent any loss of important data due to poor power supply. Factors affecting electric power quality include over-high or over-low voltage, voltage surge and noise, voltage flicker, three-phase unbalance, harmonic distortion, frequency abnormality and mains supply outage. Against the backdrop of energy crisis and greenhouse effect, it is expected that UPS may also improve its conversion efficiency without affecting its reliability, in addition to providing a stable output power supply, which is its main function. Apart from environmental protection, such efficiency improvement will also reduce power costs and operation costs. Take a 200kW UPS as example, supposed its efficiency is raised from 92% to 96%, when running at full load, it can save annually about 80,000 kWh electricity.



Meanwhile, reduction of heat due to the UPS efficiency improvement may bring down the costs of installing air conditioners in datacenters as well as their power consumption. As a result, how to improve UPS efficiency has become a very important subject.

In this paper, Section Two discusses the basic topologies of three-phase UPS systems and makes a brief introduction to UPS composition and operation modes; Section Three is an overview of current international UPS efficiency-related regulations; Section Four describes PFC topologies in UPS double conversion, analyzes their characteristics and compares their advantages and disadvantages; Section Five introduces inverter circuit topologies commonly used in UPSs and their characteristics, and compares their advantages and disadvantages; Section Six discusses the relation between UPS control methods and efficiency; Section Seven explores and compares power switch and magnetic component, key components in UPS; Section Eight introduces high efficiency ECO mode operation; and Section Nine draws conclusions.

II. Basic Topologies of UPS Systems

By topology, UPS systems can be classified into online UPS, line-interactive UPS and offline UPS. When an offline UPS is used, the load receives power directly from mains supply in normal case and by UPS battery via inverter in case of mains outage. A line-interactive UPS is mainly different from an offline UPS in that, if the input voltage of mains supply is instable, it will provide a stable output to the load via voltage regulation and if there is mains outage or frequency abnormality, it will supply power via its battery. An online UPS with double conversion prevents the UPS output from being affected by input voltage quality and steadily provides the load with pure power supply. If the mains supply is interrupted, an online UPS will also supply power to the load via its battery. By efficiency, the three types of UPS systems are in the sequence of offline UPS > line-interactive UPS > online UPS; by power quality supplied to the load, the sequence is online UPS > line-interactive UPS > offline UPS.

The three-phase UPS systems currently available on market are mainly of online type, and therefore, the basic topologies of three-phase online UPS systems will be briefly introduced as follows. The basic topology of a three-phase UPS mainly comprises a bypass static switch (Bypass STS), a power factor correction circuit (PFC), an inverter (INV), an inverter static switch (INV STS) and a charger, as shown in Fig. 1. In normal cases, a UPS mainly outputs power by following the route of mains supply → PFC circuit → inverter → load to guarantee the quality of power supply and at the same time, to charge the battery. In case of mains supply outage, the UPS will supply power via its battery, and the inverter will convert DC voltage to pure AC sine-wave voltage and supply the load. If the mains supply is recovered, the UPS will be supplied again by the mains supply. If any abnormality found in the inverter, the UPS will be supplied by the bypass power supply. Therefore, a UPS is a stable, uninterrupted power supply to client's critical loads that may help prevent the client from huge loss caused by mains supply outage. UPS mainly functions as a bridge for electricity conversion between the mains supply and the load, and during the conversion from AC to DC and again back to AC power supply, the power loss and conversion electricity loss will naturally occur. In connection with this, many countries have released relevant regulations to standardize the UPS conversion efficiency. The next section will introduce international regulations related to UPS efficiency.

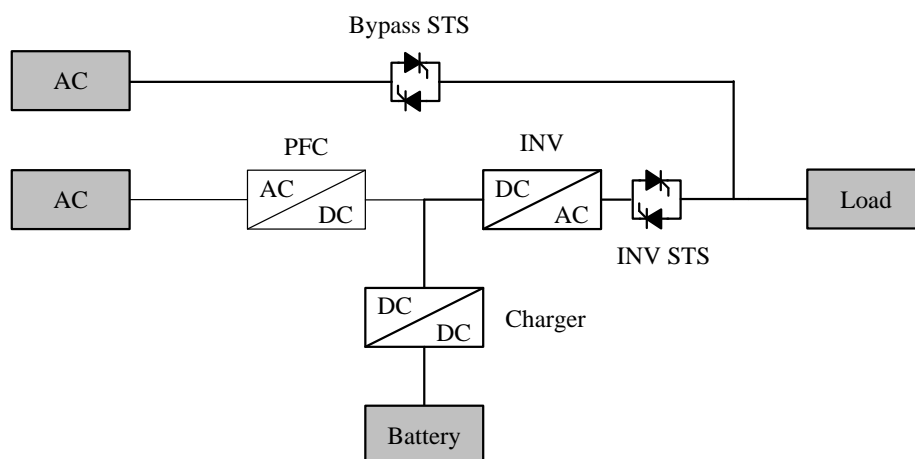


Fig. 1 Basic Topology of Three-phase Online UPS

III. International Regulations on UPS Efficiency

This section mainly introduces international regulations on UPS efficiency of China, Europe and USA Energy Star. Fig. 2 is UPS efficiency norms issued by the China Quality Certification Centre (CQC) in April 2011. It can be seen from the table that the specified normal efficiency for large online UPS systems (greater than 100 kVA) is 92%.

Fig. 3 is UPS efficiency norms set forth by Europe in March 2011. It can be seen from Fig. 3 that, in addition to regulations classified by power levels, European norms also include those classified by load sizes. For example, for a 200kVA UPS, the efficiency is required to be 90% at a 25% load, 92.5% at a 50% load and 93.5% at a 75% load and a 100% load.

Fig. 4 is the draft of UPS efficiency norms of US Energy Star, which are similar to Chinese CQC norms and classified mainly by operation mode and rated power. In Energy Star, VFD (Voltage Frequency Dependent) type is equivalent to the offline UPS mentioned above, VI (Voltage Independent) type is line-interactive UPS and VFI (Voltage Frequency Independent) is equivalent to online UPS. Take a 200kVA online UPS as example. According to Energy Star's norm, its efficiency should be greater than $0.0099 \times \ln(P) + 0.805$ or 92.58%.

To meet the requirements of international regulations on UPS efficiency as well as energy conservation & environment protection, UPS should be designed while optimizing PFC topology, INV topology, UPS control methods, and selection of power semiconductor components and magnetic component. Only in this way can UPS systems achieve high efficiency for customers. Next, this paper will analyze and compare in sequence PFC topology, INV topology, UPS control methods, selection of power semiconductor components and magnetic component, and the operation and control of ECO mode.



China Efficiency Requirement

分 类	微型在线式	小型在线式	中型在线式	大型在线式	ECO 状态 *
技术要求	≥84%	≥88%	≥90%	≥92%	≥97%
*10kVA 及以上者必须具备 ECO 功能					

微型：额定输出容量 < 3 kVA。

小型：额定输出容量 3~10 kVA，不含 10 kVA。

中型：额定输出容量 10 kVA~100 kVA，不含 100 kVA。

大型：额定输出容量 ≥ 100 kVA。

Fig. 1 CQC's UPS Efficiency Norms

Mode	from 1-1-2011 to 31-12-2012			
	UPS range: • 10 - < 20 kVA	UPS range: • 20 - < 40 kVA	UPS range: • 40 - < 200 kVA	UPS range: • 200 kVA
Normal mode Minimum efficiency measured according to EN 62040-3 Annex AA				
25 % of nominal power	85,5%	85,5 %	87,8 %	89,8 %
50 % of nominal power	89,8 %	90,3 %	91,3 %	92,3 %
75 % of nominal power	91,3 %	91,8 %	92,5 %	93,3%
100 % of nominal power	91,5 %	92 %	92,5%	93,3 %
Mode	from 1-1-2013 to 31-12-2014			
	UPS range: • 10 - < 20 kVA	UPS range: • 20 - < 40 kVA	UPS range: • 40 - < 200 kVA	UPS range: • 200 kVA
Normal mode Minimum efficiency measured according to EN 62040-3 Annex AA				
25 % of nominal power	86,5%	87,5 %	89,0 %	90,0 %
50 % of nominal power	91,0 %	91,5 %	92,0 %	92,5 %
75 % of nominal power	92,0 %	92,5 %	93,0 %	93,5%
100 % of nominal power	92,0 %	92,5%	93,0%	93,5 %

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2011-03-16

Fig. 3 European UPS Efficiency Norms

Minimum Average Efficiency Requirement ($Eff_{AVG MIN}$), Where:				
• P is the Output Power in watts (W), and				
• ln is the natural logarithm.				
UPS Class	Output Power	Input Dependency		
		VFD	VI	VFI
Consumer	$P \leq 1500 W$	0.97		
Commercial	$1500 W < P \leq 10,000 W$	0.97	0.96	$0.0099 \times \ln(P) + 0.805$
Data Center	$P > 10,000 W$	0.97	0.95	$0.0099 \times \ln(P) + 0.805$

Fig. 4 Energy Star's UPS Efficiency Norms

IV. Topology of PFC

The PFC circuit is mainly used to provide a stable DC power supply, reduce harmonic waves at mains supply input end and lower losses of reactive power. There are various types of PFC topologies in UPS systems. Each of them has their respective strengths and weaknesses in terms of their impacts on efficiency, and therefore, is suitable for different applications, which are to be detailed as follows.

1. Three-phase Two-switch Three-level Boost Converter

A Three-phase two-switch three-level boost converter is as shown in Fig. 5, wherein the three-phase power input is rectified into a stable DC power supply by a three-phase SCR first and then, inductor, IGBT and diode in sequence. As only two IGBTs are used in such topology, it boasts of low costs. However, it is unable to enlarge power levels due to the usage of only two IGBTs. The disadvantage of such topology lies in high harmonic wave distortion of its input current. The advantage of two-switch three-level topology is that its switch assembly is subject to bus voltage only and therefore, low withstand voltage switches can be used, thus enhancing its conversion efficiency.

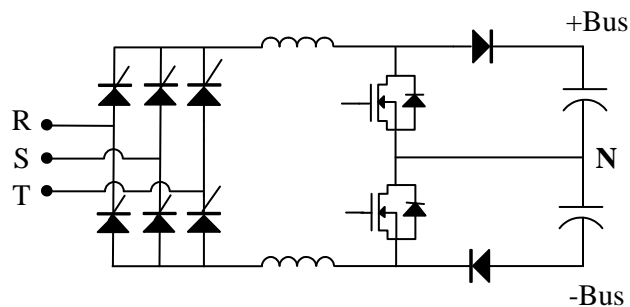


Fig. 5 Three-phase Two-switch Three-level Boost Converter

2. Three-phase Six-switch Boost Converter

A three-phase six-switch boost converter is of a common three-phase PFC topology consisting of six active switches and three inductors, as shown in

Fig. 6. They are suitable for high power level applications. The main disadvantage of a three-phase six-switch boost converter is that its switches must withstand a voltage more than twice of bus voltage, leading to a great increase of switching loss. As a result, three-phase six-switch boost converters generally have a relatively low switching frequency so as to reduce its switching loss.

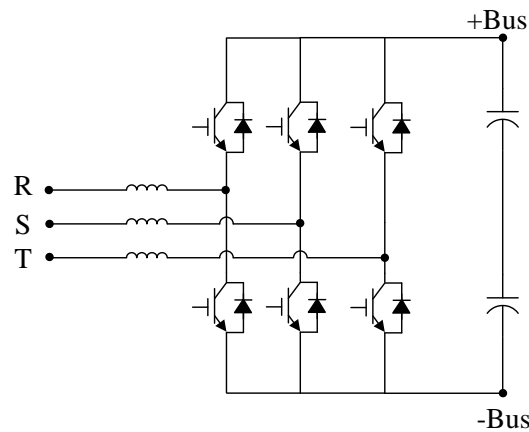


Fig. 6 Three-phase Six-switch Boost Converter

3. Three-level Boost Converter

The application of a three-level boost converter is as shown in Fig. 7. It comprises six switches, six fast diodes, six slow diodes and three inductors. The switch assembly of three-level boost converter is subject to bus voltage only and therefore, low withstand voltage switches can be used to effectively reduce the switching loss, thus enhancing its conversion efficiency.

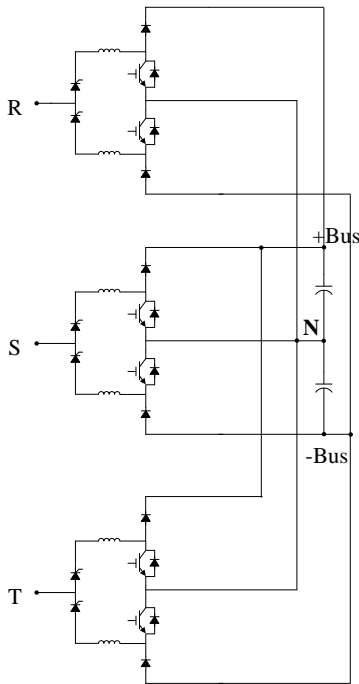


Fig. 7 Three-level Boost Converter

4. Three-phase Four-switch Boost Converter

The working principle of a three-phase four-switch boost converter is the same as that of a three-level boost converter, as shown in Fig. 8. It is mainly characterized in a simplified three-level boost converter which may realize the same effect as a three-level converter does with only a four-switch assembly. Therefore, it is more suitable for high power density applications. The three-phase four-switch boost converter is a patented topology of Delta Electronics, with which UPS products may achieve high efficiency and high power density.

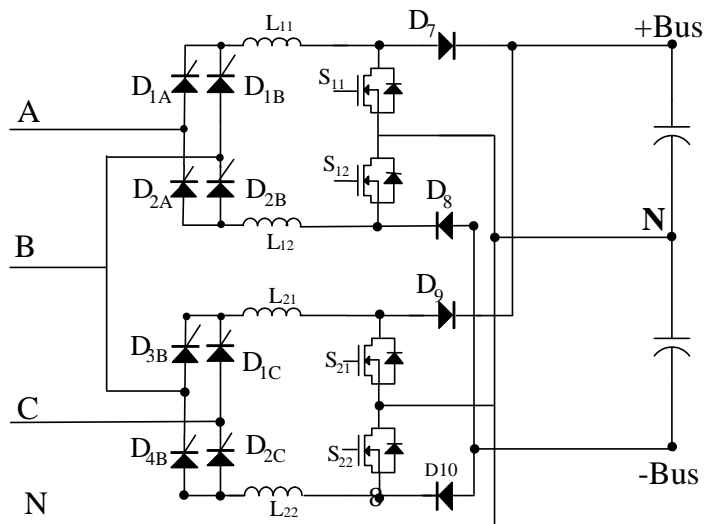


Fig. 8 Three-phase Four-switch Boost Converter

Table 1 compares the above-mentioned four PFC circuits in terms of current harmonic wave distortion, efficiency, magnetic component quantity, semiconductor assembly cost and availability of dual-direction current flow capacity.

It can be known from the table that these four topologies have pros and cons, and designers should select a suitable one in light of applications and product positioning.

Table 1 Comparison of PFC Circuit Topologies

Topology	Current harmonic wave distortion	Efficiency	Magnetic component quantity	Semiconductor component costs	Dual-direction current flow
Three-phase Two-switch Three-level Boost Converter	Poor	High	2	Low	No
Three-phase Six-switch Boost converter	Good	High	3	Medium	Yes
Three-level Boost Converter	Good	Relatively high	6	High	No
Three-phase Four-switch Boost Converter	Good	Relatively high	4	Medium	No

V. Topology of Inverters

1. Three-phase Isolated Full-Bridge Inverter

A three-phase isolated full-bridge inverter is as shown in Fig. 9. It has a relatively low bus voltage and mainly generates a boost and an N wire via an output isolated transformer to supply the load. As its output isolated transformer has both large size and weight and also a very high power loss, the efficiency of a three-phase isolated full-bridge inverter is relatively low.

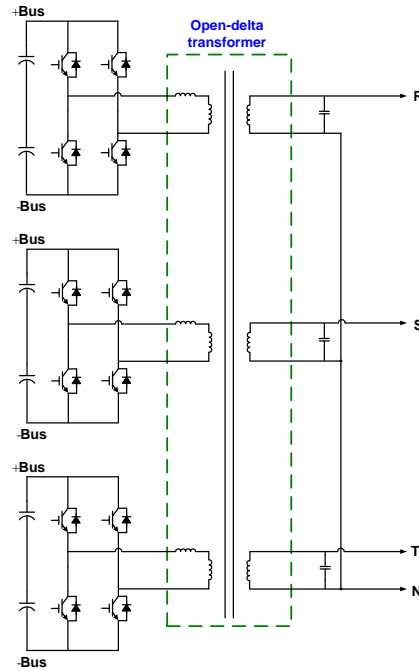


Fig. 9 Three-phase Isolated Full-Bridge Inverter

2. Three-phase Two-level Inverter

A three-phase two-level inverter is as shown in Fig. 10. Its main disadvantage is that the switch assembly must have a withstand voltage more than twice of the bus voltage, restricting its switching frequency. Therefore, how to select a switching frequency and change the control algorithm so as to enhance the conversion efficiency of two-level topology has become a main subject for designers.

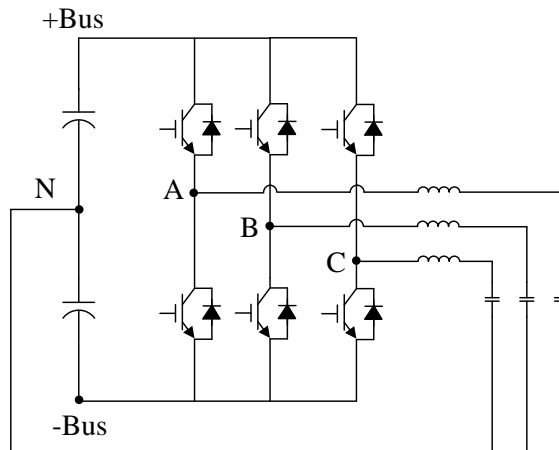


Fig. 10 Three-phase Two-level Inverter

3. Three-phase Three-level Inverter

A three-phase three-level inverter is as shown in Fig. 11. Similar to a three-level boost converter, its switch assembly is subject only to bus voltage, so it is highly efficient inherently. Though the three-phase three-level inverter topology requires many switch assemblies, its three-level topology has advantages of small inductor current ripples, small cross-voltage of switch assembly and low power loss, making it often seen in high efficiency UPS topology.

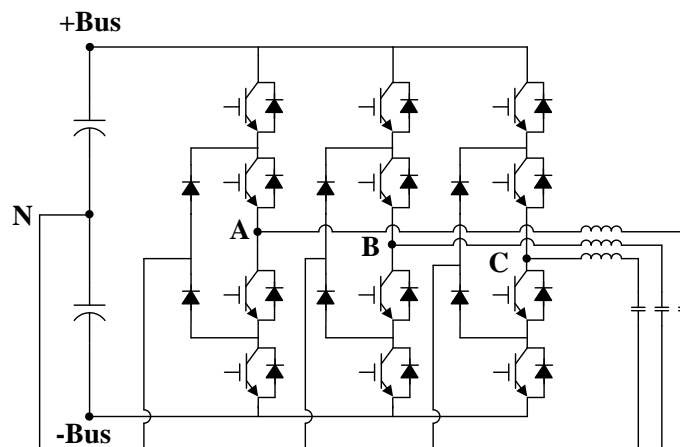


Fig. 11 Three-phase Three-level Inverter

Table 2 compares the abovementioned three inverter topologies in terms of harmonic wave distortion of output voltage, efficiency, magnetic component quantity, semiconductor assembly costs and availability of dual-direction current flow capacity. Currently, the main trend is to use a topology without transformers.

Table 2 Comparison of Inverter Topologies

Topology	Voltage harmonic wave distortion	Efficiency	Magnetic component quantity	Semiconductor component costs	Dual-direction current flow
Three-phase Two-level Inverter	Good	High	3	Low	Yes
Three-phase Three-level Inverter	Good	Highest	3	High	Yes
Three-phase Isolated Full-bridge Inverter	Good	Poor	3 (large)	High	Yes

VI. UPS Control Methods

For control methods of a UPS inverter, SPWM (sinusoidal pulse width modulation) is generally adopted for pulse width modulation, as shown in Fig. 12. The control signal (V_{ctrl}) is compared with triangle waves to generate a PWM signal for driving the switch assembly. The SPWM in inverter application has a bus voltage utilization rate of 0.866, i.e., the bus voltage in a 380Vac system should be at least greater than 620V. As this control method has a low utilization rate of bus voltage, a high bus voltage is needed, thus increasing the switching loss of switch component. Meanwhile, with a high bus voltage, the

voltage stress of switch component will increase accordingly, and some Snubber circuits have to be added for absorbing voltage surge, leading to more power loss. Therefore, if the utilization rate of bus voltage can be improved by changing control methods, the system efficiency will be increased accordingly.

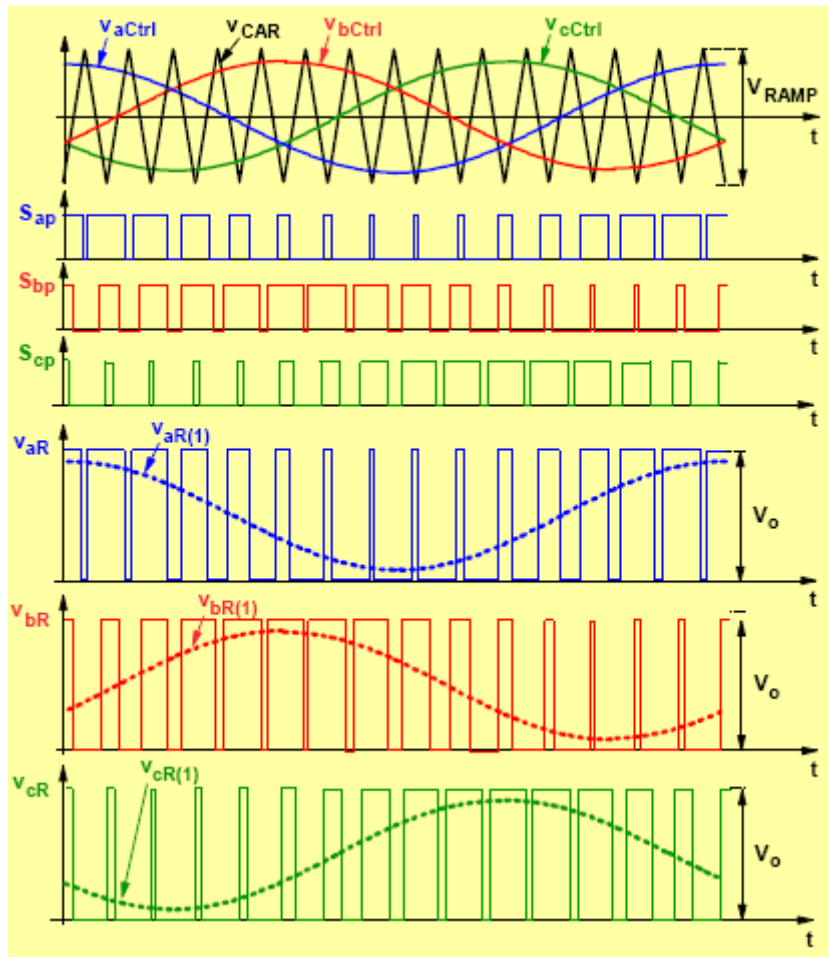


Fig. 12 Three-phase SPWM Control Method

As shown in Fig. 13, a third harmonic wave V_z is injected into the original control signal (V_{ctrl}) and the new control signal generated is then compared with the triangular wave to generate a PWM signal for driving the switch component. The harmonic injection method can effectively increase the utilization rate of bus voltage from 0.866 to 1. In other words, with the harmonic injection method, a system originally requiring a 620V bus voltage will now

need only 540V. What's the impact of a bus voltage reduction from 620V to 540V on the efficiency? For example, for a 200kW inverter with a switching frequency of 5 kHz, the switching loss of the switch component in a 540V bus voltage system will be reduced by 250W compared with that in a 620V bus voltage system.

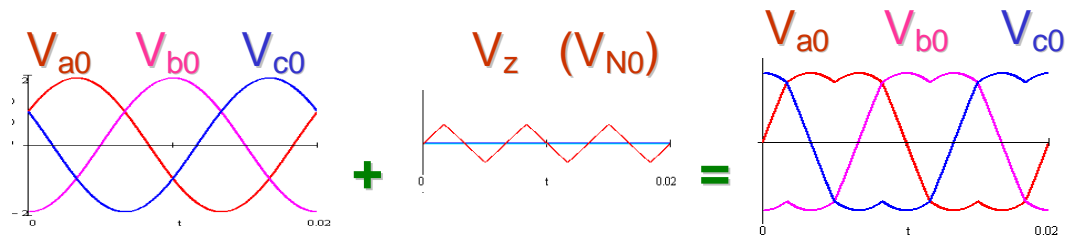


Fig. 13 Three-phase SPWM Control + Harmonic Injection

It can be known from the above example that the improvement of control methods will increase the UPS conversion efficiency and make it better conform to the requirement of high efficiency and energy conservation. In general UPS topologies, in addition to the topology selection and control methods, the key factors affecting the whole unit loss include the selection and design of power and magnetic components, which can have a major impact on the efficiency. This will be described in detail in the next section.

VII. Selection of Power Switch and Magnetic Components

1. Power Switch Component

Common power switch assemblies used in UPS systems include metal-oxide semiconductor field effect transistor (MOSFET) and insulated gate bipolar transistor (IGBT). Applications of the two types of components, to put it simple, are shown as follows: MOSFET is mainly used in applications where the withstand voltage and withstand current are relatively small while IGBT is suitable for applications where the withstand voltage and withstand current are large.

The current mainstream MOSFET used in UPS is CoolMOS, as CoolMOS has a low $R_{ds,on}$ and low conduction loss, enabling it to withstand a high current. Therefore, it is often used in small power UPS systems (lower than 20kVA). Though IGBT is inferior to MOSFET in both switching speed and switching loss, it has a higher power processing capacity. Therefore, IGBT plays a very important role in high power applications.

Let's take a 200kW UPS as example and make a comparison pertinent to IGBT loss. For comparison, the PFC adopts a three-phase six-switch boost transformer topology while the INV adopts a three-phase two-level inverter topology. On this basis, we will compare the IGBT losses at different switching frequencies and different bus voltages, and the losses of IGBT modules from different vendors.

Fig. 14 compares IGBT losses at different switching frequencies. It can be seen from the figure that the higher the switching frequency is, the higher the IGBT loss will be. The IGBT loss at a 2 kHz switching frequency is roughly one fifth that at a 20kHz switching frequency. Though the IGBT loss at a lower switching frequency is smaller, the corresponding cost is a larger magnetic component, leading to larger losses of magnetic component and a slower response speed and poor bandwidth. Selection of switching frequency has a direct impact on the UPS efficiency, but other conditions should also be cross-compared so as to find out a good switching frequency point favorable to the unit efficiency.

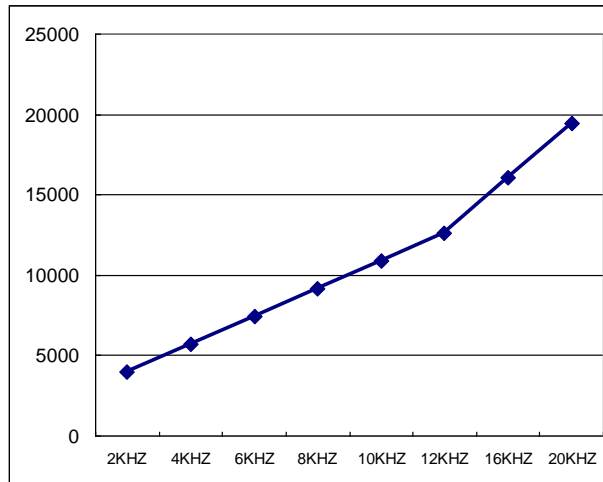


Fig. 14 Analysis of IGBT Losses at Various Switching Frequencies
(200kW UPS; input /output voltage: 380/220V; bus voltage: 800V)

Fig. 15 makes an analysis on IGBT losses at various bus voltages. It can be seen from the figure that the higher the bus voltage is, the larger the IGBT loss will be. The bus voltage mainly affects the switching loss of IGBT, but it has little influence on conduction loss. It can be known from the figure that how to realize a low bus voltage in UPS systems is also an important indicator for the UPSs' efficiency.

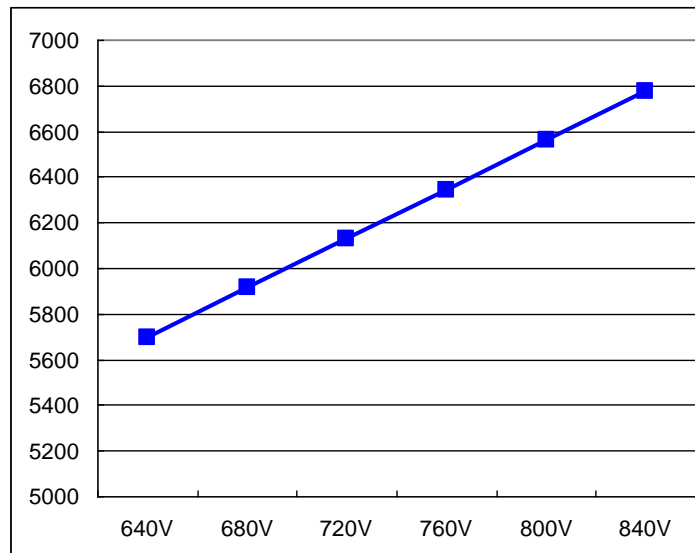


Fig. 15 Analysis of IGBT Losses at Various Bus Voltages
(200kW UPS; input/output voltage: 380/220V; switching frequency: 5 kHz)

Table 3 compares losses of different IGBT modules under the same testing conditions. It can be seen from the table that different IGBT modules, even with the same package and same size, may have different power losses, and such difference may be as large as 20%. Therefore, to improve UPS efficiency, special attention should also be paid to the characteristics difference and correct selection of IGBTs from different vendors.

Table 3 Loss Analysis of IGBTs from Various Vendors
(200kW UPS; input/output voltage: 380/220V; switching frequency: 5 kHz)

	A	B	C	D	E
PFC Conduction loss	1165	1290	1066	1020	1141
PFC Switching loss	2208	2542	2391	2479	1948
INV Conduction loss	1087	1105	1017	1022	1165
INV Switching loss	2133	2428	2294	2383	1857
Total loss	6593	7365	6768	6904	6111

2. Magnetic Component

The loss of magnetic component also accounts for a considerable proportion in the UPS unit loss. When selecting magnetic component, switching frequency and topology are two main determinants. Designing of magnetic component mainly depends on the ripple current in switching, which is subject to topology and switching frequency. For example, the inductance value required by a three-phase two-level inverter will be larger than that for a three-phase three-level inverter. The main reason is that the cross-voltage of the inductor of a three-phase two-level inverter is larger. The switching

frequency will also directly affect the ripple current of an inductor. Generally, the higher the switching frequency is, the smaller the required induction value of magnetic assembly will be, and also, the smaller the loss of magnetic assembly will be.

In addition to switching frequency and topology, another key factor affecting the loss of magnetic component is the materials it is made of. The common materials for magnetic component include silicon steel sheet, amorphous alloy, iron powder core, etc. Iron cores made of different materials have their respective applications. Therefore, selecting a proper kind of magnetic material also plays an important role in terms of UPS efficiency. Silicon steel sheets are generally used in applications with a low switching frequency. A high switching frequency will increase the iron loss of silicon steel sheet sharply, thus greatly reducing the UPS efficiency. Amorphous alloys and iron powder cores are widely used in UPS systems mainly because of their low iron loss. There are various types of iron powder cores, such as MPP, High Flux, Mage Flux and Sendust, and therefore, selecting an iron powder core right for your application is also critical for ensuring the UPS efficiency.

VIII. High Efficiency ECO Mode Operation

The ECO mode operates in the following manner: when the mains supply is normal, the load will receive power directly from the mains supply and the inverter is generally at a no-load status; and in case of a mains outage, the load will receive power from the inverter, as shown in Figs. 16 and 17. The main advantage of the ECO mode is high energy conservation. The UPS efficiency upon double conversion is generally about 92%~94%, and when operating in the ECO mode, its efficiency will be improved to above 98%. The main disadvantage of the ECO mode is that, in a mains supply outage, it needs a switching time for the bypass mode to transfer into the inverter mode. Especially, if the load is an inductive one such as a transformer, the phase

unlocking of mains supply and inverter voltage in such transfer may cause the risks of transfer failure and power interruption. The patented ECO mode transfer control method of Delta Electronics utilizes a rapid phase locking control and detection mechanism to greatly reduce the transfer time and eliminate the risk of transfer failure caused by unlocking, as shown in Fig. 18.

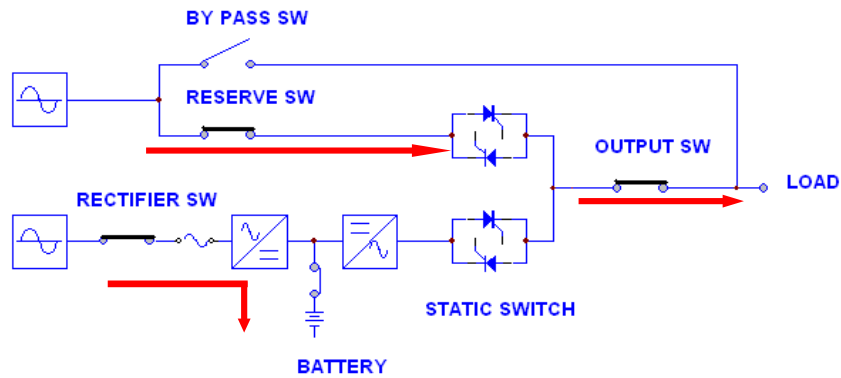


Fig. 16 ECO Mode in Normal Mains Supply

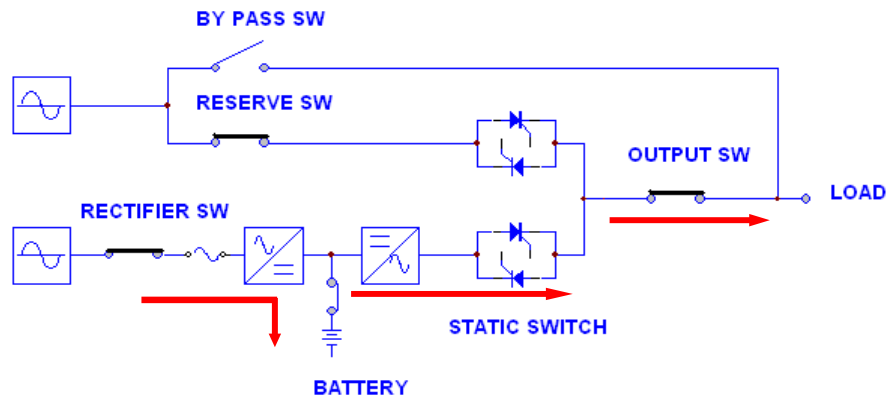
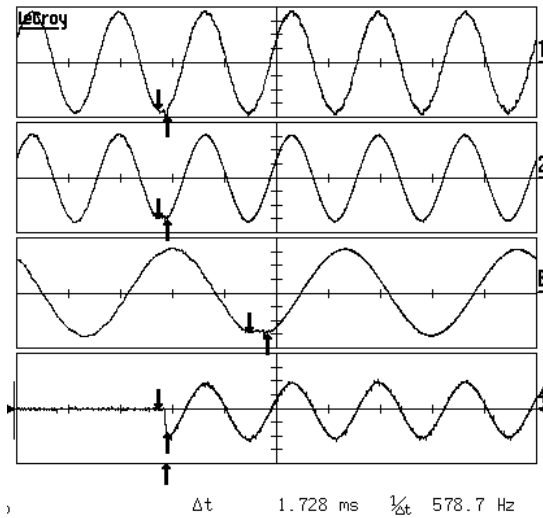


Fig. 17 ECO Mode in Abnormal Mains Supply



Test Condition:

BYPASS MODE → INV. MODE

CH1: R Phase Bypass Voltage (100V/DIV)

CH2: R Phase O/P Voltage (100V/DIV)

CH3: R Phase O/P Voltage ZOOM (100V/DIV)

CH4: R Phase INV. Current (100A/DIV)

Transfer time: 1.728ms

Fig. 18 ECO Mode Transfer Waveforms

IX. Conclusions

This paper mainly introduces three-phase UPS topologies and discusses how to improve the UPS conversion efficiency by optimizing circuit topology, control methods and combination of key components & assemblies. Delta Electronics' three-phase large power UPS system has successfully realized the objective of high efficiency and met the requirement of high performance by the abovementioned optimization of circuit topologies, control methods and power components and assemblies. Fig. 19 is the efficiency curves of a 200kVA UPS practically measured by a certification institute. Its top efficiency can reach 96.43% at a double conversion (on-line mode) power supply and 99.17% at an ECO mode power supply.

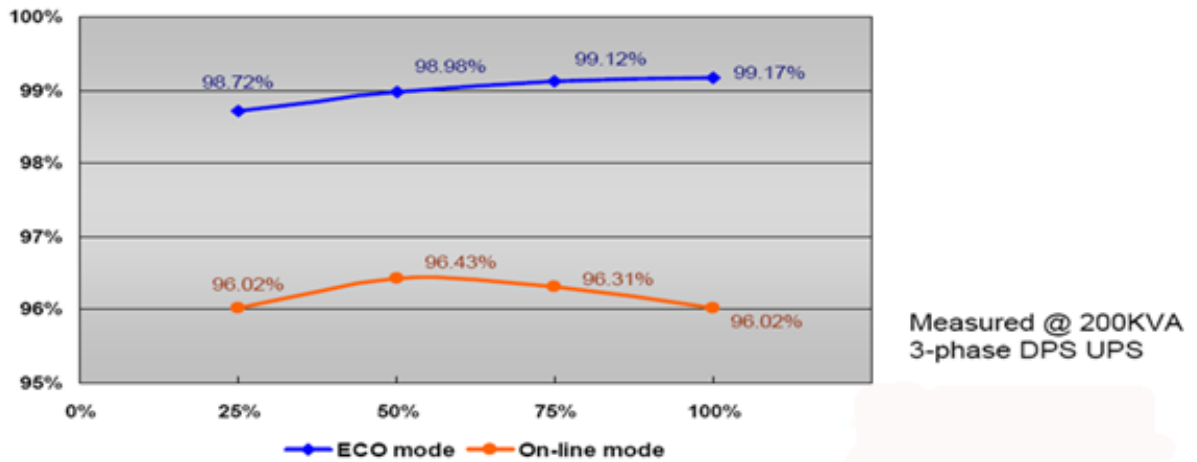


Fig. 19 Efficiency Curves of Delta Electronics UPS

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