Data Center Energy White Paper 03 — How to Increase UPS Efficiency

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Preface

Besides reliability, high efficiency is always pursued after the first UPS was borne. What efforts industry experts have made to increase UPS efficiency from 80% to 95%? What can be further improved in the future to further increase UPS efficiency? I tried giving some answers to these questions in this document.

1. Why High Efficiency Is Pursued?

1.1 Needed for Ensuring Reliability

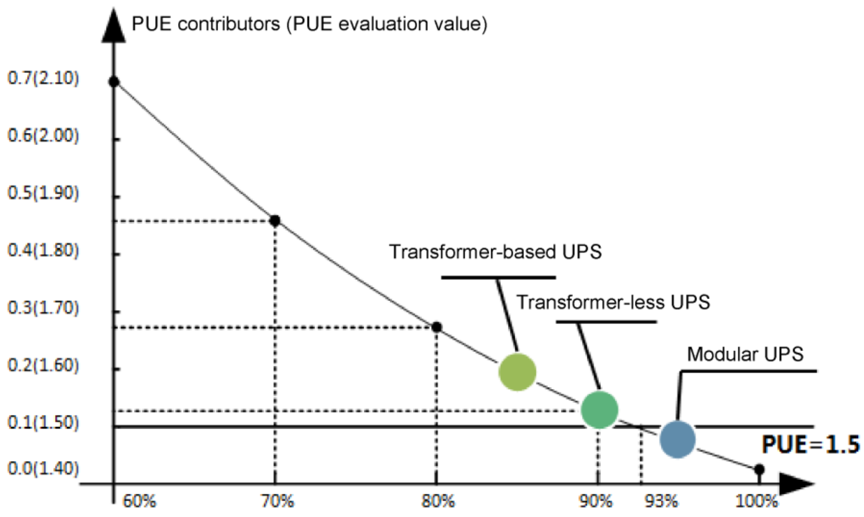
When selecting UPSs, customers are most concerned about reliability. For UPSs, higher efficiency means lower heat value. According to the Arrhenius theory, the service life of electronic products, such as capacitors and semiconductor devices, is reduced by half with every increase of temperature by 10°C. With the decrease of the heat value, temperature in products drops, which helps prolong the service life of products.

Of course, efficiency is only one of main factors that influence the temperature in UPSs. The heat dissipation design of UPSs shall also be taken into consideration. Lower efficiency means higher costs, as better heat dissipation components need to be used or a larger heat dissipation space is required, lower reliability, as fault sources increase, or lower working temperature, as continuous work is not allowed when the temperature is lower than 40°C. All these are to ensure that the temperature in UPSs is within the allowed scope.

1.2 Respond to the State's Policy of Energy Saving and Emission Reduction

At the beginning of 2013, the Ministry of Industry and Information Technology issued the *Directive Opinions for Building and Layout of Data Centers* (MIIT Joint Doc. No. (2013) 13) with five ministries, requiring that the PUE value of new-built data centers should be lower 1.5 and the PUE value of original reconstructed data centers should be reduced to lower than 2. The energy loss of UPSs is the main part of the energy loss of data centers, accounting for 6% to 10%. Therefore, to ensure a low PUE value, data centers must select UPSs with higher operating efficiency.

Figure 1 The difference in contributions of different types of UPSs to PUE can reach above 0.1



1.3 Customer Requirements of Reducing Electricity Expenses

Take a medium-scale data center as an example. Assumptions are as follows: The IT load is 500 kW. Efficiency of A series of UPSs is 93%, and that of B series of UPSs is 96%. The energy efficiency ratio (EER) of air conditioners is 3:1. See the following table for loss comparison of two series of UPSs.

Table 1 Loss comparison of two series of UPSs

	A Series of UPSs	B Series of UPSs
Electric energy loss (yearly)	329677 kW·h	182500 kW·h
Energy loss due to cooling (yearly)	109892 kW·h	60833 kW·h
Total loss	439569 kW·h	243333 kW·h

According to the table, we can see that B series of UPSs save 196,236 kW·h electricity every year. According to China's industrial electricity expense rates, not lower than CNY0.5 needs to be paid per kilowatt hour. A series of UPSs can help save about

CNY90,000. The service life of data centers is usually 10 years. Using B series of UPSs can save CNY900,000 in total, which is far higher than the expense paid for purchasing a 500 kVA UPS. In general, 10% to 20% electricity expenses can be reduced by each 1% increase of UPS efficiency. UPSs with high efficiency can create high benefits to enterprises.

1.4 Certification Requirements

To cope with the change of the global climate and the lifting of the technical threshold, authorities across the globe issued energy saving certification standards for various products, for example, China's CQC and USA's Energy Star. The two are mandatory certification standards of local government departments. Products that fail to pass required certification cannot be included in the procurement list of government departments. UK's ECA requires that efficiency of the UPS above 200 kVA shall reach 96% in full load. Customers who purchase products that are ECA certified can apply for 100% tax exemption in the first year of purchase. Energy saving certification greatly improves competitiveness of products with high efficiency and indicates that various countries attach great importance to high efficiency of products.

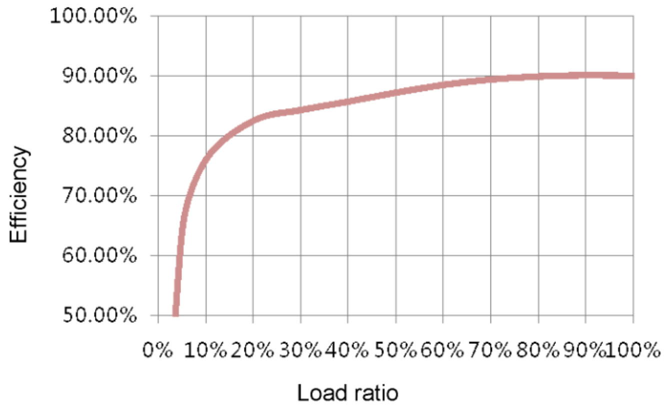
CQC Energy Star ECA

1.5 Low Efficiency of UPSs in Use By Customers

High efficiency is a consistent pursuit of UPSs. However, actually, when customers use UPSs, they cannot ensure a high operating efficiency of UPSs. Main reasons are as follows:

The load ratio greatly influences efficiency of UPSs. As shown in the following figure, in general, efficiency of UPSs raises with the increase of the load ratio and reaches the highest level when the load ratio reaches 70%.

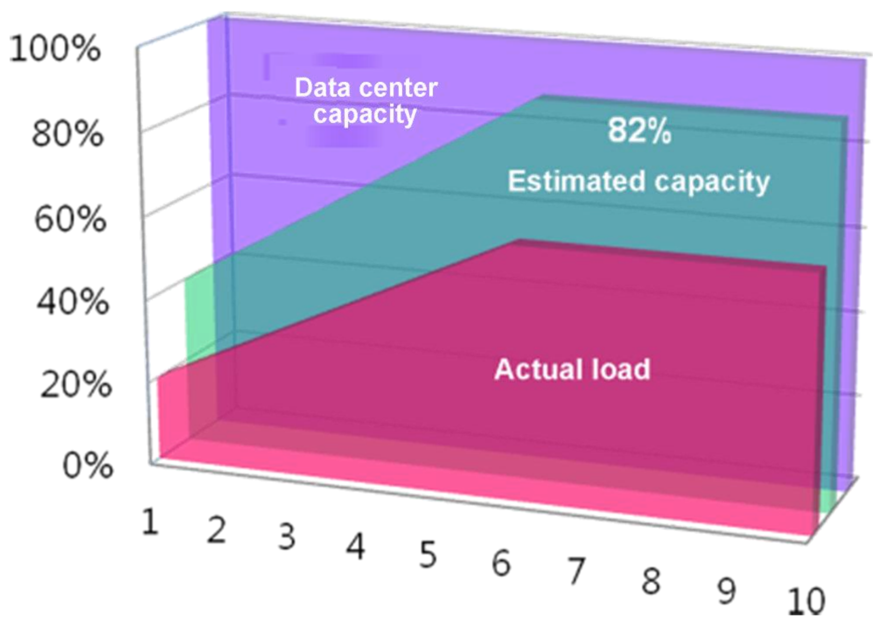
Figure 2 Curve about changes of UPS efficiency with changes of the load ratio



According to the curve, we can draw the following conclusion: It is a feasible means to allow UPSs to continuously work in a load range in which UPS efficiency is the highest to improve UPS efficiency. However, in the actual situation, due to the following factors, UPSs cannot work in the aforesaid range to improve their efficiency. Even worse, their load ratio is too low and therefore their efficiency is too low.

(1) Planning in advance: As the power supply and distribution system is not easy to be reconstructed, future three to five years' capacity expansion is considered in planning of the data center. The power supply and distribution system is usually planned with consideration of capacity expansion.

Figure 3 Planning in advance reduces the load ratio of UPSs



(2) Redundant configuration: To ensure reliability, the power supply and distribution system needs the redundant configuration. Usually the configuration is N + 1. The configuration of some core loads is even 2N or 2 (N + 1), to ensure no power failure in failure of any lines of the power supply and distribution system.

Figure 4 The redundant configuration reduces the load ratio of UPSs

Configuration	Load ratio	Operating efficiency on the live network
2*(1+1)	15%-20%	85%-89%
2*(2+1)	20%-27%	88%-90%
2*(3+1)	22.5%-30%	88%-91%
1+1	30%-40%	89%-92%
2+1	40%-53%	91%-93%
3+1	45%-60%	91%-94%
1+0	60%-80%	92%-94%

Reliability Load ratio Efficiency

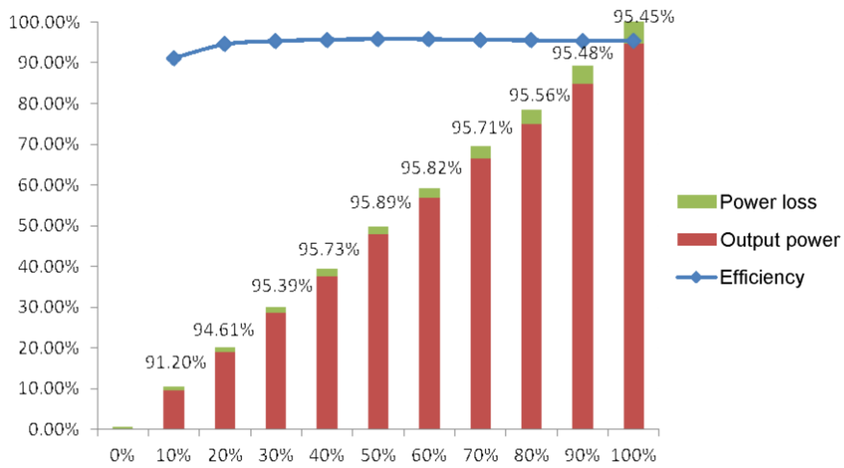
(3) In design of the data center, the load ratio cannot be 100%. Usually, the load ratio is not higher than 80%.

Due to aforesaid three reasons, in general, the actual load ratio of a UPS is usually lower than 40%. The higher the redundancy, the lower the load ratio is. (See figure 4.) Load ratios of UPSs of some data centers are as low as about 20%. With low load ratios, it is impossible that efficiency of UPSs is high. Actual operating efficiency of most of UPSs on the live network are lower than 90%, which causes high electric energy losses for customers.

2. Constitution of UPS Losses

How to increase UPS efficiency? First, let us see constitutions of UPS losses. Figure 5 shows the relationship between the power loss, output power, and efficiency of the UPS. In figure 5, red parts are the UPS final output power, that is, energy provided for loads. Green parts are losses of the UPS, which are finally converted to heat or radiation. The blue line chart shows the efficiency change trend of the UPS. According to the figure, we can see that losses of the UPS do not increase linearly. This is because that UPS losses consist of multiple parts. No-load and full-load losses of the UPS are analyzed separately in the following, to find basic rules on loss constitution of the UPS.

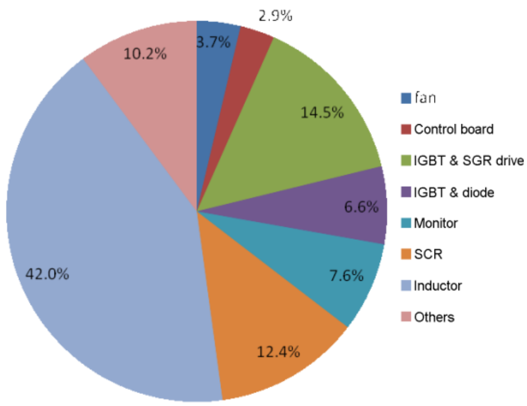
Figure 5 Relationship between the power loss, output power, and efficiency of the UPS



2.1 No-load Loss

Figure 6:

Figure 6 No-load loss

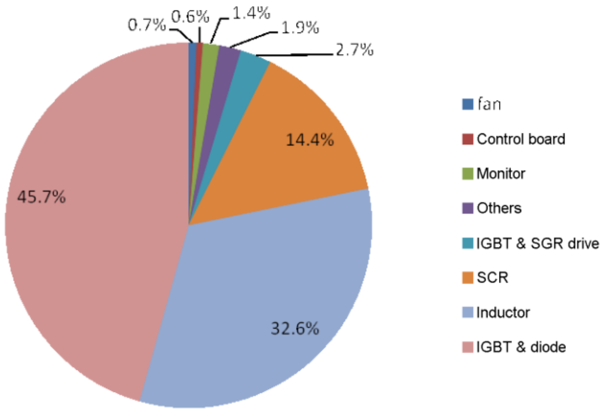


According to the figure, we can see that some components are always in the working state after the UPS powers on. Even when the UPS is in a state of no load, their losses are unavoidable. Among these components, losses of the inductor are the highest, accounting for 42%. Losses of the IGBT & SCR drive and SCR are the second highest, accounting for about 26%. Losses of other components, such as the dumping resistor and internal resistor of the capacitor, are low, usually accounting for 0.5% to 3% of the largest rated capacity of the UPS.

2.2 Full-Load Loss

Figure 7 shows the full-load loss. We can see that, compared with no load, losses of IGBT & diode increase greatly, from 6.6% to 45.7%. Losses of the inductor decrease slightly, accounting for 32.6%. Losses of SCR increase slightly, from 12.4% to 14.4%. Proportions of losses of other components, such as the fan, monitor, and control board, decrease.

Figure 7 Full-load loss



According to the aforesaid comparison, we can see that losses of the IGBT, diode, and inductor account for a large proportion. To improve UPS efficiency, we need to reduce losses of these components and select a better topology. In the following, details are introduced.

3. How to Reduce UPS Losses

3.1 Reduce Losses of Components

Semiconductors used in transformer-less UPSs are usually IGBT, diode, and MOSFET. Due to different structures and working characteristics, constitutions of losses of different components are different.

(1) IGBT

The conduct loss is the product of conduct current ICE and forward conduct voltage drop VCE-on.

$P_{conduct\ loss\text{-}IGBT} = V_{CE\text{-}on} \times I_{CE}$

Switching loss:

$P_{Turn\ on-\ loss-IGBT}$ = Eon x F_{sw}

$P_{Turn\ off-\ loss-IGBT}$ = Eoff x F_{sw}

IGBT switching loss includes the turn on loss and turn off loss. Multiply the loss of each switching (Eon or Eoff) by the switching frequency (Fsw) to get the turn on loss and turn off loss.

Figure 8 Photo of IGBT

To reduce losses, we need to select the IGBT with low conduct voltage drop and switching loss. Usually we cannot ensure low conduct voltage drop and low switching loss at the same time. Therefore, we need to judge which losses, conduct loss and switching loss, are higher in actual circuits and then select the IGBT that can ensure the best benefits.

With the development of semiconductor technologies, IGBT efficiency has been improved. Losses of the new generation of IGBTs are usually lower than losses of their earlier generation of IGBTs. It is a common method to select IGBTs manufactured with the latest technologies to reduce losses.

Huawei UPS U5000 uses different types of IGBTs for rectifiers and inverter lines based on actual working characteristics of these lines to reduce losses to the maximum extent.

Note: Anti-parallel connect diodes of IGBTs on some lines can also cause losses. Therefore, also pay attention to characteristics of diodes in selecting IGBTs.

(2) Diode

A UPS uses many power diodes. According to working frequency of circuits, diodes are classified into high-frequency diodes and rectifier (power-frequency) diodes. Losses of the two kinds of diodes are slightly different. In this document, losses of high-frequency diodes are introduced.

Losses of high-frequency diodes mainly consist of the conduct loss and switching loss.

The conduct loss is the product of conduct current IF and forward conduct voltage drop VF.

$P_{conduct\ loss\text{-}diode\text{-}REC} = V_F \times I_F$

The switching loss is mainly caused by reverse recovery currents of diodes.

$P_{leakage\text{-}diode\text{-}REC} = I_{leakage\text{-}diode\text{-}REC} \times V_{diode\text{-}REC}$

VR is the reverse voltage of diodes. Qrr is the reverse recovery charge of diodes. Fsw is the switching frequency of circuits.

Total losses of diodes:

$P_{loss\text{-}diode\text{-}REC} = P_{conduct\ loss\text{-}diode\text{-}REC} + P_{leakage\text{-}diode\text{-}REC}$

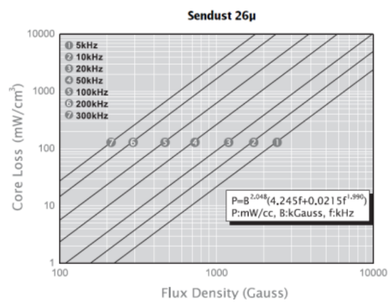
As shown by the aforesaid formula, to reduce losses, we need to select high-frequency diodes whose conduct voltage drop is low and whose reverse recovery is quick. If the working frequency is very high, consider using silicon carbide diodes (whose reverse recovery loss is very low) to reduce losses.

(3) Power Inductor

Losses of power inductors consist of magnetic core losses and coil losses. Magnetic core losses include magnetic hysteresis losses, eddy current losses, and residual losses. The working frequency of a UPS is usually not high, about 20 kHz. Magnetic core losses mainly consist of magnetic hysteresis losses and eddy current losses. Usually the fitting loss curve provided by magnetic core suppliers includes these losses. Take CSC sendust 26u magnetic core as an example. The following figure shows the fitting formula of losses. First work out B, and then substitute the working frequency into the formula to get the losses per unit volume. According to the formula, magnetic core losses can be effectively reduced by reducing B. In other words, magnetic core losses can be reduced by increasing the frequency or the cross-sectional area of the magnetic circuit or reducing the working voltage.

Take CSC iron-silicon-aluminum 26u magnetic core as an example. If we increase the cross-sectional area of the magnetic core by 25% and keep other conditions unchanged, B decreases by 25% and magnetic core losses decrease by 45%.

Figure 9 Line diagram of magnetic core losses



Coil losses are caused as currents flow through conducting wires. Circuits flowing through inductors include power-frequency currents or low-frequency DC and switching-frequency, high-frequency currents. Due to the skin effect, when the switching frequency is high, the AC impedance of a coil is higher than its DC impedance. Therefore, in design, if the switching frequency is high, consider parallel winding of multiple fine lines to reduce the influence of the skin effect.

(4) Fan

Main losses of fans are losses of motors. Usually, losses of motors are proportional to the third power of the rotational speed. Therefore, losses of fans in different load periods can be reduced by properly adjusting the rotational speed of fans.

3.2 Reduce Losses Caused by the Topology

Besides reducing losses of components, we can optimize the topology of the UPS to reduce losses.

In the UPS field, the multi-level topology is applied on a large scale. Compared with the inverter using the traditional two-level topology, the inverter using the diode-clamped three-level topology which is popular at present can ensure the smaller size and lower losses of filtering inductors. Loss analysis is as follows:

(1) Loss Analysis of Three-level Inverter

Figure 10 shows the topology of the diode-clamped three-level inverter. Main losses of circuits are the conduct loss and switching loss of switching devices and loss of output filter inductors. As losses of three bridge arms of the three-phase circuit are the same, to facilitate calculation, loss analysis is conducted based on the bridge arm of phase A.

Figure 10 Three-level topology

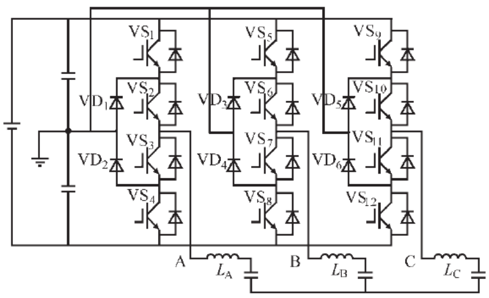


Figure 11 Relationship between drive signals and output voltage & current

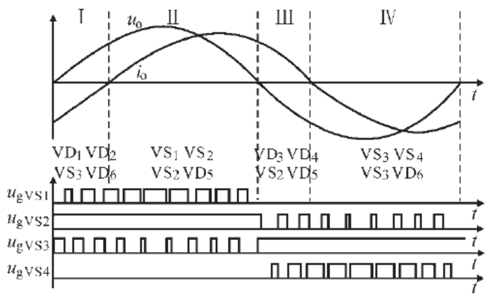


Figure 11 shows the relationship between drive signals ugVS1 to ugVS4 of switches VS1 to VS4 of the bridge arm of phase A and output voltage uo & current io. Four areas, I, II, III, and IV, are determined for switching behavior based on the direction of uo and io. In area I, the io direction is negative, that is, io flows into the inverter. When the output is of the high level, VD1 and VD2 conduct. When the output is of the zero level, VD5 and VS3 conduct. If we ignore changes of io in a switching period, the power loss of single-phase semiconductor devices of the inverter in area I is as follows:

$P_I = f\ (E_{swI} + E_{conI+} + E_{conI0})$

In the formula, EswI is total switching loss of devices in area I. EconI+ is the total conduct loss of devices in area I when the output is of the high level. EconI0 is the total conduct loss of devices in area I when the output is of the zero level. f is the frequency of the output voltage. In area II, the io direction is forward, that is, io flows out of the inverter.

When the output is of the high level, VS1 and VS2 conduct. When the output is of the zero level, VD6 and VS2 conduct. If we ignore changes of io in a switching period, the power loss of single-phase semiconductor devices of the inverter in area II is as follows:

$P_{II} = f\ (E_{swII} + E_{conII+} + E_{conII0})$

In the formula, Esw II is total switching loss of devices in area II. EconII+ is the total conduct loss of devices in area II when the output is of the high level. EconII0 is the total conduct loss of devices in area II when the output is of the zero level.

According to analysis results, we can see that area I & area III and area II & area IV have the duality relationship. Therefore, losses of devices in area I are the same as losses of devices in area III, while losses of devices in area II are the same as losses of devices in area IV. Therefore, the total power loss of three-phase semiconductor devices of the three-level inverter is as follows:

a. $P_{total} = 3\ (P_I + P_{II} + P_{III} + P_{IV}) = 6\ (P_I + P_{II})$

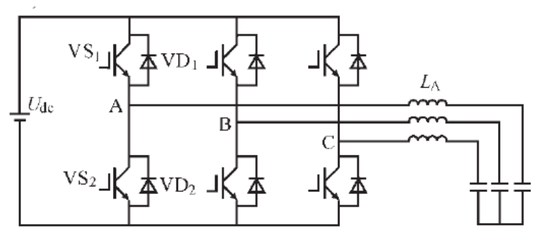
(2) Loss Analysis of Two-level Inverter

Four areas, I, II, III, and IV, are determined for switching behavior based on the direction of uo and io. The total power loss of three-phase semiconductor devices of the two-level inverter is as follows:

b. $P_{total*} = 3\ (P_{I*} + P_{II*} + P_{III*} + P_{IV*}) = 6\ (P_{I*} + P_{II*})$

Value calculation of various elements is the same as that in the three-level inverter part. However, loss parameters are modified.

Figure 12 Two-level inverter



According to formulas a and b, the loss and efficiency of the three-level inverter and the two-level inverter with the same given application conditions can be worked out by using Mathcad software.

Calculation based on the following given values: The three-level inverter uses the IGBT as the switching device, whose type is 2MBI300U2B-060(600 V/300 A) and diodes VD5 and VD6 whose type is 1FI150B-060(600 V/200 A). The two-level inverter uses the IGBT whose type is 2MBI300UC-120(1 200 V/300 A).

The drive resistance Rg of the two types of inverters with two kinds of topologies is 5 Ω and the working temperature Tj is 125°C.

Theoretically, when fs = 10 kHz, efficiency of the three-level inverter can be increased by 1.7%. When fs = 20 kHz, efficiency of the three-level inverter can be increased by 2.79%. We can see that efficiency can be improved prominently by selecting a better topology.

3.3 Reduce UPS Losses

To reduce UPS losses, we need to ensure that the UPS continuously works in a range in which its efficiency is the highest. With the consideration of initial investments on the UPS, we can select the modular UPS to achieve the target. The advantages of the modular UPS are as follows:

(1) Capacity Expansion on Demand

A great advantage of the modular UPS is that online capacity expansion is allowed. With such design, customers do not need to plan the capacity of the UPS in advance and select the capacity close to the load capacity in a proper range, to ensure the highest efficiency.

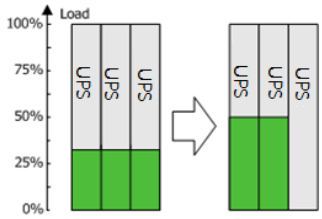
Figure 13 Huawei modular UPS

(2) Power Module Redundancy

The reliability of the UPS is an indicator to which customers attach great importance. In general, the N + 1 redundancy configuration of the UPS can meet reliability requirements in most of application scenarios and N + 1 is the most cost-efficient configuration. Usually, tower-mounted UPSs adopt the N + 1 configuration to ensure reliability. However, this will cause high initial investments and have the load ratio be lower than 50%. Such problems are not encountered when modular UPSs are used.

(3) Intelligent Hibernation Function

Figure 14 Intelligent hibernation



Modular UPSs usually have the intelligent hibernation function. With this function, low efficiency due to low load can be avoided. UPSs allow one to two power modules to enter into the hibernation state according to the load on the premise of ensuring redundancy, to increase the load ratio of other power modules in the working state. In this way, UPS efficiency is increased. The lower the load ratio of the UPS, the more prominent the energy saving effect is. Take the 3 + 1 power module redundant UPS whose load ratio is 20% as an example. With the intelligent hibernation function, the UPS allows two power modules to enter into the hibernation state. In this way, it enables the load ratio of remaining two power modules to reach 40%. In such a case, the UPS still ensure redundancy, that is, one power module can normally operate with the load when the other power module fails. Assume that the load is 500 kW and EER of air conditioners is 3:1. Energy saving comparison before and after hibernation is as follows.

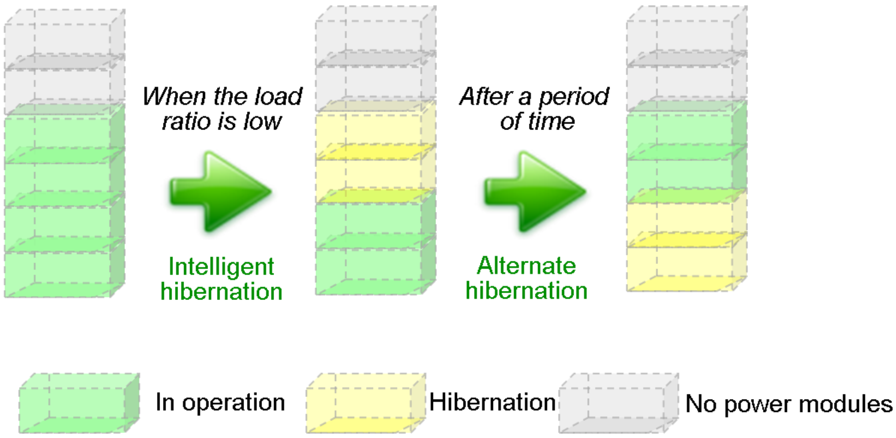
Table 2 Energy saving comparison before hibernation and after hibernation

	Load Ratio	Efficiency	Annual Electric Energy Loss (kW·h)	Annual Energy Loss Due to Cooling (kW·h)	Total Loss (kW·h)
Before hibernation	20%	91%	433187	144396	577582
After hibernation	40%	94%	279574	93191.5	372766

According to the preceding table, we can see that the total loss decreases by more than 33.33% after hibernation. After 10 years, 2,040,000 kW·h electricity can be saved, which can bring the benefit with the amount of CNY1 million.

In addition, Huawei UPS5000-E has the alternate hibernation function. It alternately allows working power modules to enter into the hibernation state, to ensure that all power modules work with the same time period to prolong the service life of power modules.

Figure 15 Alternate hibernation of UPS5000-E



4. Summary

At present, the highest efficiency of UPSs in the industry is usually 96% or higher. However, UPS efficiency improvement is still always pursued in the industry. Selecting high-quality components and a better topology is a reliable way. In addition, the Intelligent hibernation function of modular UPSs can have UPSs work in a range in which its efficiency is the highest.

Reference:

1. Efficiency Analysis and Comparison of Three-level and Tow-level Inverters; Boris L Corral Martinez, Ma Ke, Li Rui, and Xu Dehong; (Power Electronics; issue 07 of 2009)

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