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Comparison of the AC UPS and the DC UPS solutions for critical loads

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***Abstract*—The paper presents a conceptual comparison of the inherent properties of the DC UPS and the AC UPS system solutions for uninterruptible operation of data centers and other critical and sensitive loads. Compared parameters are efficiency, reliability, power quality and economy, among others. It is shown that the direct current UPS system offers a number of significant advantages.**

It is further reported that analysis and tests prove that many existing ac units can operate from dc without modifications. This makes it possible to apply DC UPS for existing computer plants as an intermediate step until the full range of servers and computers specially designed for dc operation will be available.

***Index Terms*— Uninterruptible power systems, DC power systems, DC-DC power conversion, DC-AC power conversion, Power system harmonics, Power system reliability, Power system economy, Energy conservation, Computer power supplies.**

I. Introduction

In the beginning electricity meant direct current, dc.

Soon it was found that alternating current, ac, had some important advantages – ease of changing the voltage level by means of transformers, less wear and tear of switches (caused by arcing) and so on.

Electric light bulbs worked fine on ac and so did electrical machines, at least as long you had no need to change the speed of rotation. And there wasn’t really much need for a totally uninterrupted energy supply. Who cared about transients and voltage outages, as long as they didn’t last too long?

With the advent of computers the loads became less forgiving of interruptions. The immediate solution was to include battery-backed inverters to feed them. That was the birth of the alternating current uninterruptible power supply, the AC UPS.

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For computers and other critical equipment this has more or less been the state of the art for a long time. System designers have tried to offset problems like single-unit fault mode and mediocre reliability of inverters by more and more sophisticated ac switching devices and system solutions.

In comparison the direct current uninterruptible power supply, the DC UPS, offers the unsurpassed opportunity of simple parallel redundancy and direct contact between the load and the backup battery. Besides the obvious advantages of vastly increased reliability the DC UPS also excels in energy conservation and economy, simply by being simple, straightforward and avoiding unnecessary conversion steps.

In this paper, even if it does not claim to be exhaustive on all points, the authors demonstrate that the DC UPS is already a fully realistic and advantageous solution for many existing types of equipment, computer- and server centers as well as office applications.

II. UPS systems

A. The DC UPS

The DC UPS is very simple in implementation and operation. The only parameter which requires management and supervision, is the voltage. This concept provides direct connection of the battery to the load, Fig 1, which is a great advantage for reliable service.

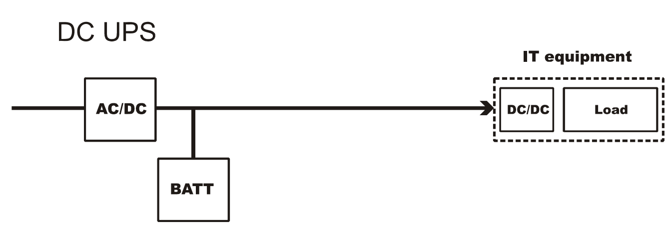

Fig 1. Structure of the DC UPS and load

B. The AC UPS

In comparison, the AC UPS [2] is far more complex and intricate to operate. All of the parameters: voltage, frequency, phase, and waveform require management, control and supervision, at a minimum. An ac bypass switch adds to the complexity.

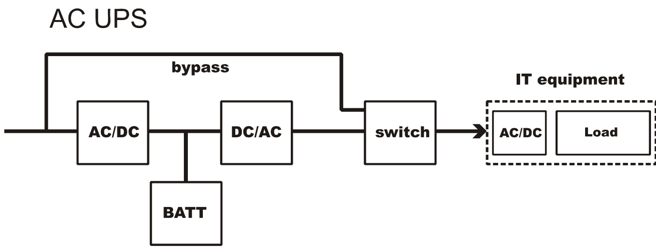

Fig 2. Structure of the AC UPS and load

III. Alternative energy sources

Even though normal operation will be to supply the equipment with energy from the commercial ac grid there are cases when there is a wish to be able to include alternative energy sources in a system. Photovoltaics and fuel cells give dc output which may easily be introduced in a DC UPS system, without the need for conversion to ac. This saves valuable energy and makes alternative energy an attractive supplementary energy source with a DC UPS.

IV. The equipment powered by the UPS

To evaluate the DC UPS and the AC UPS concepts in the fields of energy efficiency, power quality, reliability and overall system economy the implementation and properties of the equipment to be powered by the UPS must also be taken into account. In other words: the **load** must be considered.

The most common loads for UPS are computer centers, servers and peripheral equipment. Other loads for UPS may be life sustaining equipment in hospitals, office computers, emergency lighting and process industry. The applications are numerous and all of them are vital, sensitive and critical.

In the past many of these applications were powered from small rectifiers, including low frequency transformers, to be connected directly to the ac mains wall outlet. Those applications were not suitable for dc feeding.

Not so anymore. Many of the existing types of equipment occurring as UPS loads can today be supplied with dc without any modifications [1]. These loads are, based on their construction, divided into three main groups: resistive loads, electronic loads and rotating loads. The characteristics of each group will be further described in this section.

Resistive loads are mainly used for lighting and heating purpose. Examples of such loads are incandescent lamps, kettles and stoves. This type of load can be supplied with dc without any modification. However, it is important to consider the voltage level since it directly affects the power consumed by the load.

"Electronic loads**"** are today found in many different appliances. Common for these loads are that they internally use a different magnitude and frequency than the supplying voltage. In most cases the voltage is converted by a diode rectifier in series with a dc/dc converter as shown in Fig. 3. This construction makes it possible to operate the load with both ac and dc. However, the dc voltage level must equal the peak value of the ac voltage. Battery chargers and high frequency switch mode power supplies are example of such electronic loads.

"Rotating loads" include both ac machines and universal machines. Universal machines can, as the name indicates, be supplied with both ac and dc. This type is mostly used in simple appliancies. Ac machines cannot be supplied with dc since they need a time varying magnetic field. However, for reasons of energy saving ac motors, fans, pumps etc today are often interfaced by variable speed electronic drives. This power electronic device is nothing less than an inverter circuit, fed from dc, making it possible to control the speed of the machine by controlling voltage and frequency.

A. *The switch mode power supply unit fed from ac*

On a large scale, we nowadays use electronic equipment and illumination with built-in switch mode power supplies, SMPS, composed of three fundamental parts, Fig 3. (A similar configuration with the DC/DC converter replaced by a DC/AC low respective high frequency inverter is used in variable speed drives and eletronic ballasts for lighting.)

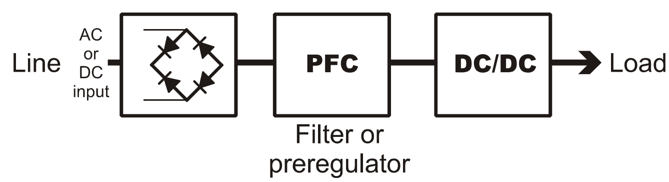

Fig 3. Structure of the switch mode power supply unit

The first step is a rectifier of varying complexity, followed by a DC/DC converter. The rectifier converts the ac voltage to dc voltage of approximately the peak value of the ac voltage. Such power supplies are not designed in an optimal way for the alternating current distribution system or for the AC UPS. In the present situation we are facing problems due to increasing losses from the power supplies and insufficient quality of electric power. The rectifier part of the power supply unit also tends to feed distortion back into the ac system in the form of current harmonics, see Fig. 4. This distortion may, if there are numerous powered units – as often is the case – cause problems in the AC mains and for the AC UPS inverters. As a remedy, the AC/DC part of the power supply is provided with an active or passive power factor correction circuit, PFC. Active PFC, the more effective solution, means introduction of an extra conversion step in the power supply. Despite the added complexity, the PFC types are seldom impressingly effective in performing their task for small units, for cost reasons. Active PFC in larger units may work well, though.

B. The switch mode power supply unit when fed from dc

From Fig. 3 it is obvious that it ought to be fully possible to feed most switch mode power supplies with dc. They can be connected to either 230 VAC or 350 VDC directly. (350 VDC is close to the peak value of the alternating voltage). This introduces an opportunity to reduce the unfavorable loading of the ac mains network and to eliminate the disturbances and problems in AC UPS systems. A DC/DC converter generates no harmful low frequency overtones back to the source, of course, see fig 4.

If exclusively direct current is to be distributed to the equipment, as from a DC UPS, the power supplies can consist of DC/DC-converters only. The rectifying part (with the preregulating PFC or filter) can be omitted. As a consequence the efficiency of the power unit will be increased by 2-5%. This may sound negligible but as there are billions of them it will have a great impact in the macro perspective.

Thus the DC UPS would give the best results if it is used with loads including switch mode converters specially designed for the uninterrupted DC voltage. That would allow the designers to fine tune performance to highest possible efficiency and reliability and also save some money in components since equipment designed exclusively for DC input is less complex and has a lower component count than SMPS AC/DC units.

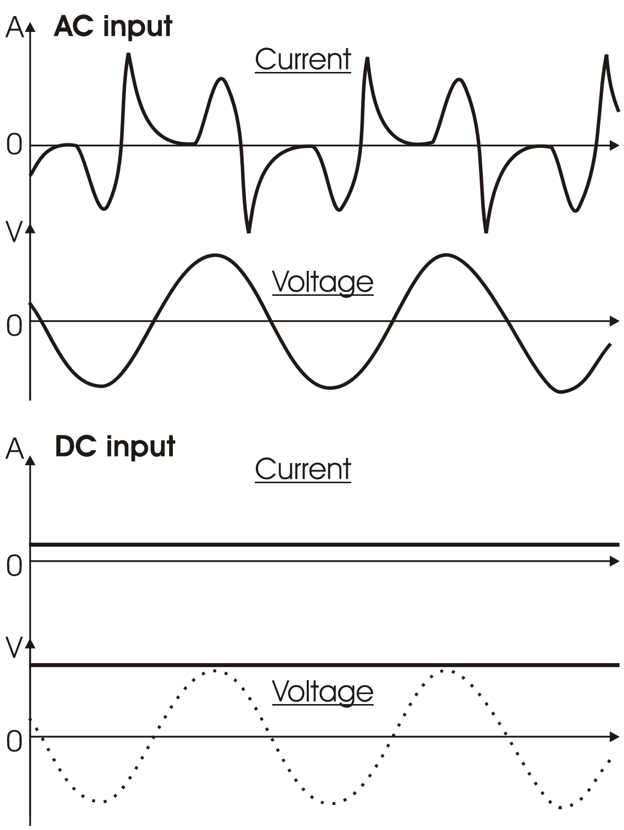

Fig 4. Input currents to SMPS with passive PFC, fed from ac and dc. (Same load, scale and power supply.)

C. Redesigned power units is the optimal solution when changing to DC UPS.

The limitation of applying DC UPS for loads exclusively designed for dc would affect the area of applications for such systems negatively because very few pieces of equipment, like servers, are today available dedicated for a dc supply.

An obvious solution would be to replace the AC/DC power supplies in existing equipment with compatible dc units. There is some interest from end unit manufacturers and OEM DC/DC manufacturers, so eventually there may be replacement units available for the more popular types of equipment.

However, provided one selects a suitable dc level to operate from, there is an intermediate solution: *a multitude of equipment, originally designed for 230 VAC operation, may already be operated directly from the dc system voltage equally.*

D. Testing proves that many existing ac units can operate from dc

Netpower Labs AB has tested a large number of loads to find out which of them would accept a dc input, with only minor external modifications or no modifications at all.

The analysis shows that there are principally four different categories of designs:

1. AC units with input rectifiers (with or without active PFC circuits) and straight forward switch mode DC/DC design in the conversion circuits.
2. Same as category 1, but where the designers for some reason have taken shortcuts in the design using capacitive couplings or mains frequency transformers to produce internal voltages (e.g. for starting the equipment or for signalling).
3. Same as category 1, but with alarm circuits to sense the ac input voltage zero crossings in order to indicate "mains problem". This somewhat overambitious alarm is sometimes used to block the power supply from operation, but more often it is just sent to the powered equipment for a decision of what action to take.
4. Pure ac designs with low frequency transformer input circuits.

The investigations show that category 1 units usually work excellently from 350 VDC, without any problem whatsoever.

Category 2 units are a bit more tricky. Very often they are dependent on the polarity of the applied dc voltage to operate. With the right polarity sometimes they have to be started by temporarily applying a series of pulses on the dc input voltage during start up. Once started these units operate fine off the uninterrupted dc voltage.

If units of category 3 start at all they seldom present any problems. The equipment driven from such units usually only makes a note of the alarm but takes no further actions. If it is a computer or a server unit one may even be able to turn off the alarm altogether in the BIOS setup.

Category 4 units are normally small external units. They may easily be replaced with standard switch mode converters which are readily available.

The investigations at Netpower Labs show that almost all PCs, displays and workstations with 230 VAC rated power supplies, both laptops and ATX form factor, work fine when supplied directly from a 350 VDC source.

Servers, on the other hand, tend to have slightly more complex power units. Many of them have facilities for dual redundancy and hot replacement. Several of the most popular server types have power supplies that go into categories 2 and 3. This is further complicated by the fact that there usually are several different types of power supplies going into the same server version - and all the power supply types do not react equally. If you are lucky you may find a type that works OK. However, by means of proprietary methods Netpower Labs AB has been able to overcome the problems and run most servers on dc.

When it comes to data switches and I/O equipment almost all of them fall into category 1 (or 4 for older types) and consequently present very few problems when run from dc.

As for fluorescent lighting - all tested types with HF ballasts work fine with dc input. This provides excellent means for emergency lighting. The same goes for many types of energy saving light bulbs. Old types of fluorescent lighting with inductor ballasts will of course not work – category 4!

E. No need to replace all existing equipment when changing to DC UPS.

This answers the question put by many owners of data centers, "I realize the advantages with DC UPS, but must I replace all my existing equipment?".

The answer is a firm "No!", because many existing units indeed work fine on dc. However, there is always a need to do a survey, and sometimes testing, before dc is introduced as a power source for an existing plant. Some equipment needs special measures to be taken, but in most cases problems are easy to solve.

Fuses or circuit breakers certified for dc **must** always be used for the equipment, either by replacing existing fuses or by introducing an additional external fuse.

Another question often put forward is if running off dc hurts the existing equipment, originally designed for ac. Analysis and affirmative testing shows that running from dc, far from being harmful, tends to increase lifetime of the equipment due to lower continuous stress and less exposure to transients and dangerous dips on the input.

F. Which is the best system voltage for the DC UPS?

The selection of dc voltage is a delicate issue.

If you are building a completely new plant from scratch any system voltage is fine as long as the equipment accepts it. There has been argumentation for 380 VDC as nominal voltage, because it maximizes performance of the DC/DC converters.

However, in most cases all equipment is not replaced at the same time, and some of the needed equipment will not be available in special dc versions.

By choosing a dc system voltage within the margins (including tolerance) of the rectified peak value of the 230 VAC mains all components in connected ac power units will still be operating within permissible design limits. Choosing a nominal dc voltage of 350 V will give some headroom without exceeding voltage margins of connected equipment nominally rated at 230 VAC.

It is anticipated that the advantages of being able to supply occasional equipment originally designed for ac from a 350 V DC UPS far exceeds the marginal gains of using an elevated system voltage, e.g. 380 V.

V. Comparison between AC and DC UPS

A. Energy efficiency comparison

The total efficiency of a direct current system can be made greater than in present ac systems owing to elimination of the extra conversion step of the inverters. The centralization of rectifiers and PFC circuits can be made more efficient than when each single device includes rectifying the ac to dc with (more or less effective) power factor correction. Moreover, all equipment connected to the mains network would be embraced by the PFC technique in contrast to now, when a lot of small, and indeed also large, equipment is not included. Use of dc will provide higher energy efficiency and reduced losses when DC/DC converters are used in electric equipment instead of AC/DC power supplies.

The efficiency of electric power distribution and equipment can become 5-20 % higher as compared to the present ac solutions. DC/DC converters can reach an efficiency of 85-90 % as compared to AC/DC power supplies which provide an efficiency of 65-75 %, typical values of PC power supplies [2].

Even if you compare best-in-class AC/DC to DC/DC you find a 2-5% advantage to the DC/DC, at a lower cost.

A number of factors contribute to the lower power losses. Such factors are fewer conversion steps and that continuously running inverters, used in AC UPS equipment, no longer are needed. The reduced losses in the power supplies also means less cooling requirements for the premises.

The buildings can be designed for an effective connection of alternative energy sources, for instance photovoltaic- or fuel cells. Connection of such cells to a direct current system is highly efficient as no losses for transformation to alternating current will occur.

Altogether, the efficiency of the use of electrical power is estimated to increase by 5-20 % for applications that could be supplied with direct current. This estimation also takes into account losses of a potentially needed transformer to isolate the dc plant from the incoming ac grid. If the better efficiency of the DC UPS means that otherwise necessary cooling equipment can be eliminated or reduced, a figure up to 30 % may be reached.

The most common class of AC UPS has 85 % efficiency, ref [2], but many UPS systems operate on lower efficiency. (See also comment 3 under C. Reliability Comparison). If connected directly to a high voltage line a best in class DC UPS can operate at 98 % efficiency.

B. Power quality comparison

The most important deficiencies of power quality in AC UPS systems are the current harmonics, Fig 5. They lead to very high currents in the neutral line causing risk of fire and disturbances in operation. The harmonics give rise to leakage currents, disturbing earth fault breakers and generating stray currents with undesirable magnetic fields which may disturb equipment and annoy people. Leakage currents may disturb operating function, reduce the lifetime of equipment and, if worst comes to worst, destroy it due to strongly increased wear of e.g. ball bearings of fans in ventilation systems etc.

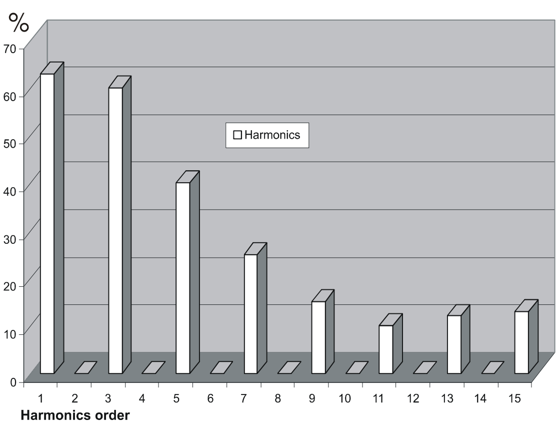

Fig 5. Harmonics spectrum of ac input current for a passive PFC SMPS.

C. Reliability comparison

Now, due to IT/telecom convergence, AC UPS is introduced on a large scale in telecommunication systems and other mission critical use, reliability has become more important for UPS technology than before. The requirements traditionally imposed by telecom systems on the power supply system and the portion of unavailability that may be allocated to the power supply system of a telecom installation is 5×10^{-7}, which is equivalent to 15 seconds of service disruption per year [3]. This requirement was derived from the service level needed for telephony service given in Bellcore standards to 5.3 min (5 nines – 99,999 %) telephony service down time per year as a target level.

In the INTELEC® white paper from 1998, "Powering the Internet, Datacom Equipment in Telecom Facilities" [3], a comparative calculus of unavailability was made comparing the AC UPS with the DC UPS as used in their respective standard configurations. See Fig 6 and Fig 7.

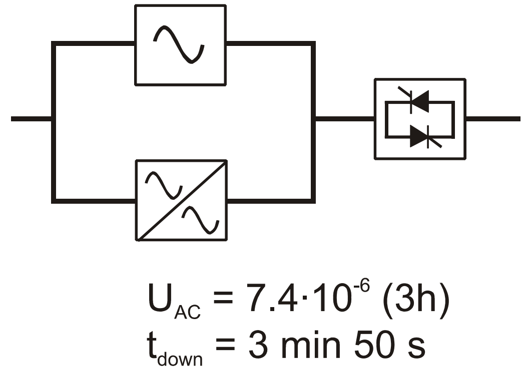

Fig 6 Reliability model AC UPS [3]. 3 hours battery reserve.
U = unavailability

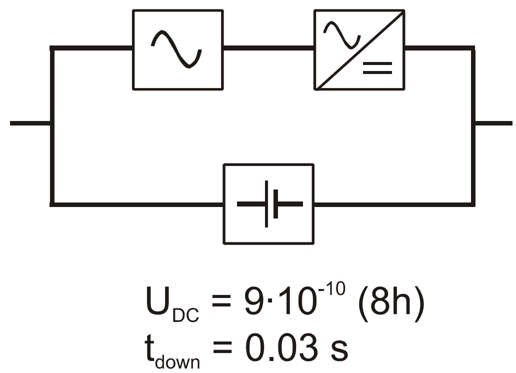

Fig 7 Reliability model DC UPS [3]. 8 hours battery reserve.
U = unavailability

The difference is found to be as large as 7600 times in advantage of the DC UPS. In large-scale operation and use, this difference will give a valuable contribution to overall performance and economy on system level for the operators and the public, when using internet.

Three comments to these calculations:

1. This comparison was done in 1998 and for 48 VDC. The same topology is valid for 350 VDC systems and gives the same results.
2. Present AC UPS reliability has been improved, but the UPS system that was analyzed is still delivered to new installations for cost reasons.
3. Battery reserve time does not improve the AC UPS system reliability as it does in DC UPS systems, since the by-pass switch is the bottle neck of the AC UPS system.

D. Economy

A major operator of server hotels in Sweden has reported that electricity stands for roughly one third of the total operating costs over a 5 year period for his server centres.

The economical aspects of operating a data centre is complex and involves many parameters. One dominant factor is cost for the total energy supply and system inclusive of cooling. Lowest possible heat dissipation i.e. highest possible efficiency in equipment is of course a key factor. But other aspects like the reliability of the power supply system and the power quality are important for a continuous low cost operation. Simplicity and good overview facilitates maintenance and low cost for service and trouble shooting.

Operators face a situation where the heat dissipation has become the limiting factor for expansion of data centres. Modern blade servers has become so compact, powerful and heat producing, that the data centre cooling system has become a bottle neck blocking expansion. Expensive data centre floor area can not be used unless the complete cooling system is upgraded. This leads to extreme marginal effects in cost. Conversely even small improvements in efficiency will have tremendous impact on cost.

It is beyond the scope of this paper to discuss all different system options and their pros and cons in the field of economy. A moderate number of combinations generate numerous efficiency numbers and figures to calculate and discuss, [2] and [4].

A qualitative estimation shows that there definitely is a potential for great savings in total cost of operation of data centres by using DC UPS. We judge the range to be of 10 to 30 % in savings versus the current ac concepts. The amount of electric energy used for data centres and data processing worldwide has now reached a magnitude where every percent saved in heat dissipation is extremely valuable, see [5].

VI. Personal Safety Considerations

Regarding personal safety, direct current has obvious advantages. No doubt alternating current at 50 - 60 Hz is a danger to the life of human beings and animals. Alternating current can cause cramps in the muscles and in the heart. Direct current does not cause cramps nor pose as high a risk of fibrillation as ac. The shock perceived in contact with a dc-cable is an electrostatic shock. The reaction is a reflex movement away from the conductor to break the contact. The possible resulting harm is secondary injuries from falling or bumping against other objects. Burns can occur with both of the current modes.

The influence from electric current on human beings has been described in [6], [7]:

“It is not the voltage itself that is injurious but the electric current that is propulsed through the body by the voltage. Alternating current at 50 Hz is particularly hazardous for humans. Already very low current (0.5 mA) may cause discomfort, and higher current level (10 mA) can give rise to cramp, making it impossible to leave hold of a live object. Should the current increase to about 40 – 50 mA there is a high risk of fibrillation and lethal influence already after about a second, and at higher current level even faster.”

VII. Conclusion

It is shown that in most fields studied the DC UPS compares advantageously over AC UPS. Because of the advances in electronics, a mains frequency inverter is seldom a necessary part of a UPS system. Such an inverter in the UPS system contributes negatively to efficiency, cost and reliability of the system. Various types of by-pass switches often included also make the system complicated and vulnerable.

The 350 V DC UPS system offers a possibility to implement substantial energy savings in two steps:

1. Successive implementation of DC UPS in plants also including existing (AC/DC) SMPS units rendering up to 20% efficiency increase.
2. Using 350-380 V DC/DC power units in the powered equipment instead of the present AC/DC. That will give an additional efficiency increase by up to 5 %.

The annual energy consumption in the world for computer and server equipment apt for back up has been estimated to the magnitude of 100 TWh (10^{11} = hundred billion kWh) and doubling every third to fourth year. Even few percents of efficiency increase will give substantial benefits for energy conservation.

The simple implementation of DC UPS systems makes better use of energy and other resources which in the end will contribute to meeting the challenge of global warming as well as it gives clear advantages in security and operation of advanced technology equipment.

Acknowledgment

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References

[1] D. Nilsson and A. Sannino, Load modelling for steady-state and transient analysis of low-voltage dc systems. In Conf. Rec. IEEE-IAS Annu. Meeting, vol. 2, Seattle, WA, Oct. 3.8 2003, pp. 774.780.
[2] My Ton, Ecos Consulting, Brian Fortenbery, EPRI, William Tschudi, Lawrence Berkeley National Laboratory, DC Power for Improved Data Center Efficiency, January 2007
[3] Intelec Adhoc group, the INTELEC® white paper, “Powering the Internet, Datacom Equipment in Telecom Facilities”, INTELEC® 1998.
[4] My Ton, Ecos Consulting, Brian Fortenbury. EPRI, High Performance Buildings: Data Centers Uninterruptible Power Supplies (UPS) December, 2005.
[5] Jonathan G. Koomey, Ph.D. Staff Scientist, Lawrence Berkeley National Laboratory and Consulting Professor, Stanford University, Estimating Total Power Consumption by Servers in the U.S. and the World
[6] IEC TS 60479-1
[7] Swedish Electrotechnical Commission Manual No 413