Sizing a diesel generator for a high power UPS - an art or a science?

Abstract

When UPS application engineers get into a technical discussion eventually the topic of conversation will turn to 'how big does a genset need to be for a UPS system'? When that happens many 'rules-of-thumb[1]' are expressed with very few, if any, caveats. Unlike many topics in the UPS world the subject of generator sizing has become more complicated with time as UPS topology has changed the nature of the rectifier-charger interface with the upstream power supply, be that mains or standby-generator - but the rules-of-thumb have persisted.

This paper will attempt to show that rules-of thumb are hardly ever right and are increasingly misguided. To understand the issues requires far less technical ability in the reader than that required selecting a genset in a real application - and so everyone can become an expert with a little careful consideration of the facts.

History

When all three-phase UPS were fitted with a thyristor-bridge converter as a rectifier the answer was easy: For 6-pulse rectifiers the genset had to be at least at 2.3 times the rating of the UPS and for 12-pulse rectifiers the factor reduced to 1.6. Then along came passive filters that reduced the harmonic distortion that the genset had to handle from the load and the rating numbers reduced again. What they reduced 'to' is of little consequence because, as we shall see, the number rarely helped in practice. However, the principle of lower distortion equates to less up-rating points the way to the heart of the question: How does a standby-generator set react to a non-linear load such as that presented by a UPS rectifier?

The reason that this topic has raised its head again is the advent of the UPS with a 'linear' input - a result of the application of transistors to the rectifier in place of the traditional thyristors. In both double-conversion and line-interactive topology it is now possible to have a near-sinusoidal input current (<3% THDi) without filters. This near-perfect genset load has brought yet another rule-of-thumb to the fore - factor 1.0, no re-rating at all. Though apparently very attractive it shall be shown that caution must be exercised with such sweeping generalisations.

Theory - Part 1:
A non-linear current load distorts the voltage

Without considering the mathematical details it is a straightforward matter to understand the relationship between an electronic load (a rectifier in a UPS) and a rotating machine (an alternator on a genset):

- The electronic load draws current from the supply in a 'non-linear' way - that is the current waveform does not resemble a sine-wave
- That non-linear load current distorts the voltage waveform of the alternator such that the voltage is no longer sinusoidal. The alternator has 'impedance' that dictates the level of distortion against a given load - the lower the impedance the lower the distortion
- The bigger the non-linear load is to the rating of the alternator the worse the voltage distortion gets, although one simple way of achieving a low impedance alternator design is simply to specify an oversized machine
- The principle design goal is to keep the generator voltage waveform within 'acceptable' limits so that other loads connected to it run, more or less, without problems - hence the higher the distortion in the load the larger the genset has to be. If the genset is run in parallel with the grid supply then the voltage fidelity must be better than 'acceptable'

Set against this simple set of relationships is the design (and cost) of the alternator: A low specification example will have the lowest amount of copper and iron in its construction and will have 'high' impedance - not good for a non-linear load. A 'better' design will have more active material, a larger frame size and lower impedance - with a resultant improved voltage output waveform.

So we could imagine a typical situation where, to keep the voltage distortion from the genset to around 5%, the genset feeding a UPS of 500 kVA with a 6-pulse rectifier and no filter should be rated at higher than 2.3x500 = 1150 kVA. **Figure 1** shows the effect.

Simple, easy to understand, but generally misguided. Why? Let us consider the real situation:

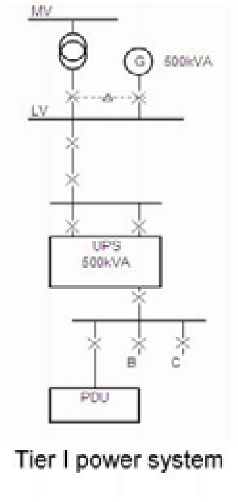
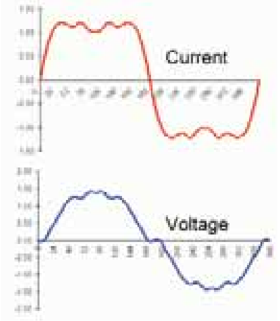


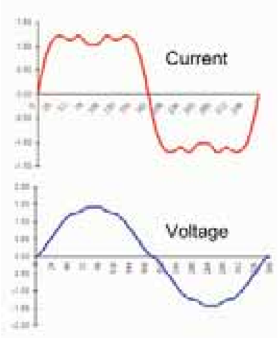
Fig. 1 - the classic view



The rule-of-thumb method

A typical 6-pulse rectifier has an input current distortion of around 33% and harmonic profile as shown left

Feeding 500 kVA of that load from a 500 kVA (17.5% impedance) genset results in an unacceptable voltage distortion of 12% (left)



Typical rule-of-thumb 2.3x

Increasing the genset rating to 1150 kVA (2.3x500) reduces the effective impedance and cuts the voltage distortion to a more acceptable 6% (left)

Reality - Step 1:
The spread of the electronic load

Very few installations have a single UPS fed by a single genset whose only load comprises the UPS itself.

In the classic computer-room UPS application the genset (even if only a single set) is there to support the whole critical load when the mains fails. That is typically made up of 40% UPS, 35% cooling load (fan and pump motors) and 25% 'other' that includes lighting etc. In this way our 500 kVA example above would have a genset feeding it of at least 1250 kVA before any 're-rating' could be applied. If being pedantic a consultant could take the suggested re-rating factor (e.g. 1.6) and apply it to the UPS load before adding the 'rest'. That would give our example a 1550 kVA minimum genset rating. Since gensets are built in standard power series the next larger available would be 1750kVA and that would be the unit specified. In the early days this was indeed the solution and the 'question' just faded away.

Unfortunately for the genset the situation changed drastically with the encroachment of variable-speed drives into the building services market. For better control and energy saving reasons the majority of the previously 'linear' loads (motors for fans, pumps, lifts and resistive heating and lighting) became non-linear with VSD's (rectifier front-end) and ballasted electronic lighting. Almost the entire load became non-linear. So now, how can we answer the 'how big' question? A UPS supplier can't be expected to.

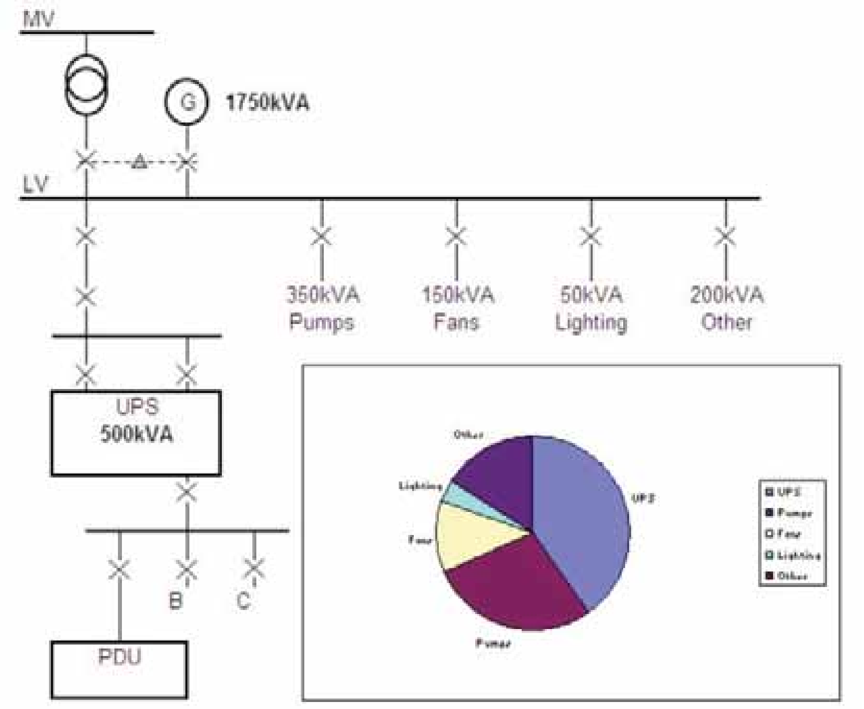


Fig. 2 - supplying other, linear, loads

Reality - Step 2: Redundancy reduces impedance

The question becomes more applicable when the system is larger and dedicated to a critical load, such as a data centre. As the systems get larger, and certainly beyond Tier I, we invariably meet the requirement for redundancy, both in UPS and in standby generation.

Now we have UPS modules running at partial load being fed by an oversized (via redundancy) multi-module genset installation. By the time we get to Tier IV and dual-bus systems the UPS modules are running at <30% and the gensets are hardly ever going to see more than 35% per set. The whole notion of further de-rating is a waste of capital and material resources. It also would lead to (even) lower operating efficiencies and high energy losses. So, as a rule-of-thumb Tier IV gensets can only justify a rating factor of 1.0.

Reality - Step 3: kVA versus kW

Not everyone in the industry gets to Step 3 so we are in good company as we now challenge any notion that went before in this paper of simply increasing the kVA rating of the diesel generator.

A genset comprises two major components, the engine and the alternator, coupled together and mounted on a common bed-plate. The engine only cares about kW (mechanical power as a product of torque and speed of its output shaft) but the alternator cares about electrical characteristics of the load (the distortion and kVA) and the true power (kW).

When we actually need to re-rate a genset to get lower impedance (and a better voltage waveform) actually what we really mean to do is to require a larger alternator - not a larger engine. The power remains the same and all we need to consider is step-load performance etc.

Now, gensets have become standardised and, in base format, commoditised, so it is feasible that just going to the next size up in the power series will prove a good solution but specifying a larger alternator onto a base set can prove technically advantageous. E.g. mounting a 2000 kVA alternator onto a 1200 kW engine that would normally feed a 1500 kVA set to produce a low-impedance 1500 kVA set.

Theory - Part 2: Gensets don't like leading Power Factors

A standard genset alternator is a simple synchronous electrical machine, often with a permanent magnet exciter and an analogue automatic voltage regulator (AVR). They are designed to deliver kVA at 0.8 lagging (inductive) Power Factor - as typified by an induction motor load. In this way they can deliver a maximum of either kVA or kW with Power Factor from unity to 0.8_{lag}. For example a 1000 kVA rated set can deliver 800 kW or real power from PF=1 to PF=0.8_{lag}.

What they can't do is to supply the same amount of power if the load is capacitive rather than inductive. For the machine the difference is between delivering reactive power (kVAr) into an inductive load and absorbing kVAr fed back from a capacitive load. A standard alternator is largely incapable of absorbing large amounts of reactive power. The result of capacitive load is a loss of voltage stability, particularly on load-steps. The voltage can no longer be controlled to within acceptable limits.

The solution is to limit the capacitive load and to mix it in with sufficient inductive load as to cancel out the overall 'leading load' problem. It is also important to get the genset loaded up 'first' with inductive load and then add the capacitive load once running and stabilised.

This limitation of genset application has only been a problem since the nature of IT loads changed during 2004-5 - to that of lower harmonic content but capacitive. Power Factors as low as $1.15_{leading}$ have been measured in large mono-load dual-bus redundant systems.

Reality - Step 4: The final step?

Having previously claimed that only a few pundits get to Step 3 it goes without saying that even fewer get to Step 4 in pursuit of the question 'how big should my genset be?'

All large UPS systems have an Automatic Bypass (to protect the load from instantaneous UPS failure and to provide a break-free path to the reserve power supply) and a Maintenance Bypass to enable the load to be run whilst essential maintenance work is carried out. Of course, this doesn't apply to Tier IV dual-bus systems but they still have the bypasses fitted.

When the UPS is in bypass the genset has to feed the raw load, not the UPS rectifier. However the load characteristics have changed from very highly distorted in 2000 to close to linear today, although a vast mix of legacy-new in the installed base complicates things.

Unfortunately the modern load, especially in its dual-corded format, has a leading power factor and certainly not the lagging nature that the genset needs for correct voltage control. So, if a modern load is transferred to a bypass and the genset is feeding that bypass (as is the case of most maintenance scenarios) then the genset needs to be rating to supply the capacitive load. This can be achieved by mixing the capacitive load with inductive load that has been accepted by the genset first although this requires careful load management via the BMS system. In addition there may be the need for a de-rating factor for the alternator.

The Science, as opposed to the Art

Individual harmonics 'add' and 'subtract' (cancel out) from each other and so the correct method of sizing an alternator for genset duty in a harmonic-rich environment is to tabulate all of the loads in terms of their harmonic spectrum, sum the result at each harmonic frequency, add any linear load and then apply the total spectrum to the alternator impedance spectrum.

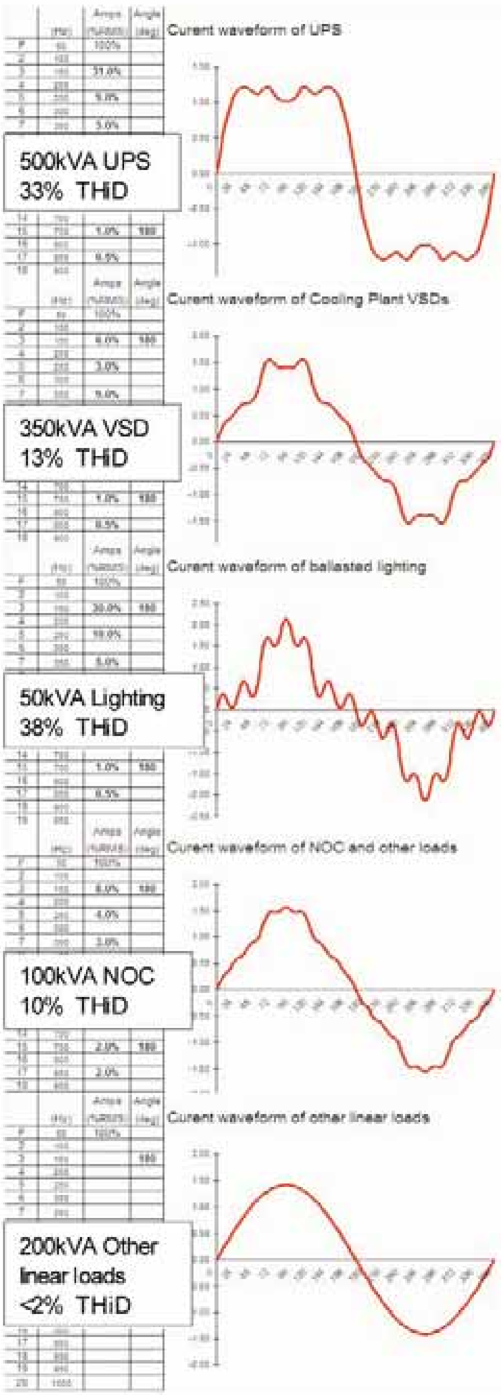
A low-voltage (e.g. 400V) alternator on a standard genset can have an impedance as high as 15%. Higher is possible but only on very low-specification machines. This means that it will have an impedance at each forward (+ve) and reverse (-ve) rotating harmonic of Nx15%, where N is the harmonic number. However, since most are wound with 2/3 pole-pitch, at the stationary (zero) harmonics (importantly including the third-order Triplens) the impedance will be lower at Nx2.5%. These figures are shown in the table overleaf.

If the alternator is arranged to feed at medium-voltage (e.g. 11 kV) then the pole-pitch used is 5/6 and a different situation with the harmonic phase rotation results.

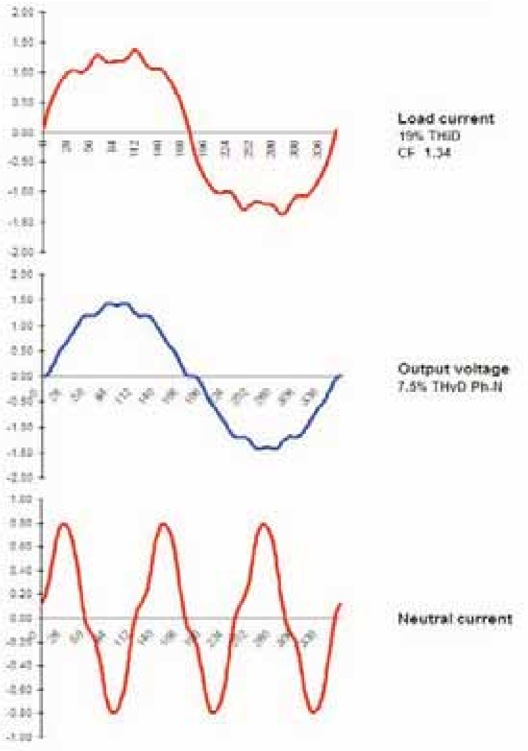
The example shown here is for a simple Tier I data centre with 500 kVA of UPS, 350 kVA of pumps and fans driven by VSDs, 200 kVA of linear, 50 kVA of ballasted lighting and 100 kVA of other high-tech office type non-linear load - fed by a single 1750 kVA genset. The 7.5% THvD result is probably slightly on the high-side but by selecting different alternator impedances the output voltage distortion can be optimised versus cost.

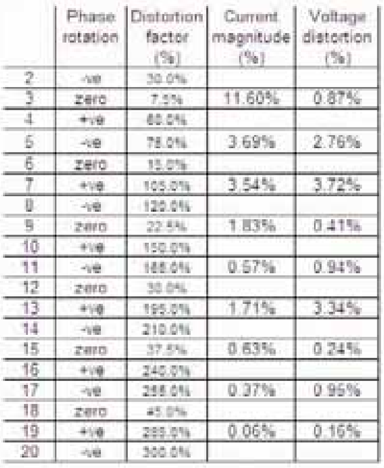
Conclusions

The old question of 'how big should my genset be' was related to the UPS rectifier topology and many rules-of-thumb were applied. Rarely did one genset feed just one UPS so the rest of the gensets' load really dictated the size required and the rules-of-thumb were rarely meaningful.



The aggregated load of 1200kVA applied to an alternator rated at 1750 kVA whose impedance is 15% at the 50Hz fundamental produces the resultant THvD shown below:





	Phase rotation	Distortion factor (%)	Current magnitude (%)	Voltage distortion (%)
2	-ve	30.0%		
3	zero	7.5%	11.60%	0.87%
4	+ve	60.0%		
5	-ve	75.0%	3.69%	2.76%
6	zero	15.0%		
7	+ve	105.0%	3.54%	3.72%
8	-ve	120.0%		
9	zero	22.5%	1.83%	0.41%
10	+ve	150.0%		
11	-ve	165.0%	0.57%	0.94%
12	zero	30.0%		
13	+ve	195.0%	1.71%	3.34%
14	-ve	210.0%		
15	zero	37.5%	0.63%	0.24%
16	+ve	240.0%		
17	-ve	255.0%	0.37%	0.95%
18	zero	45.0%		
19	+ve	285.0%	0.06%	0.16%
20	-ve	300.0%		

Fig. 3 - example of aggregated harmonic load

The expansion of VSD's into building services converted nearly the whole load to a non-linear electronic characteristics and the 'question' to the UPS provider could only be to one of many equipment suppliers. The non-UPS loads sum to larger than the UPS itself and so the question is best directed to the VSD's OEM.

Highly redundant systems often negate any re-rating requirements due to over-sizing leading to inherent low impedance. Any re-rating can lead to lower efficiency and wasted material resources.

A particular re-rating should be applied to the kVA rating of the alternator, not to the 'size' of the genset - since it rarely affects the kW rating of the engine. The result can be a 'special' arrangement with an oversized alternator.

The ability of the UPS to be placed in bypass has nearly always been ignored in genset selection and the capacitive nature of the modern loads makes the transfer highly undesirable unless the genset is rated to carry the critical load - again not a question for the UPS provider.

It is possible to select the genset using the expected data (rather than rules-of-thumb) but the computer-load remains the sticking point as very few IT organisations can (or will) predict the nature of their load - and it changes on a <3-year product life cycle. This makes the option of running the load on the gensets problematical and worthy of close inspection.

The specifying engineer who accepts the argument that an IGBT front-end UPS means that he can downsize his genset to the bare kW rating required should carefully consider what the other loads are comprised of and whether or not he ever intends for the load to be run from the genset for disaster-recovery or even essential maintenance.

Reference

(1) As it described the maximum diameter of birch that a man was legally entitled to use to beat his wife with. The wide dimensional variation in the man-thumb-wife triangle adapts perfectly to our UPS-genset question.

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