Marine Generator Test

And the application of (marine) diesel powered generators in small hybrid power systems

Marine Generator Test

And the application of (marine) diesel powered generators in small hybrid power systems

1. Introduction

1.1. Why a marine generator test?

In 2003, Victron Energy introduced the first paralleling inverters for the marine marketplace – our MultiPlus. These have the capability to synchronize with a shore power supply, or an onboard AC generator, boosting the power available from either source, and also switching into battery charging mode when the AC demand is less than what the shore power cord or generator can handle.

The waveform from shore power is a true sine wave, and does not deviate under load. That from generators, especially small generators, is more erratic and changes under load. We wanted to learn more about the operation of our MultiPlus, and our new 5kVA Quattro inverter/chargers, in parallel with a wide range of generators under a wide range of operating conditions. Comparative testing on a number of generators would enable us to gather valuable information for the improvement of existing products as well as for future designs. In the text below, instead of systematically mentioning both the MultiPlus and the Quattro, only the MultiPlus is mentioned in order to keep the text as readable as possible.

We wanted to answer such questions as:

- Does the MultiPlus work with any generator?
- How many MultiPlus units can be paralleled to a generator?
- How does the MultiPlus influence the output waveform of a generator?
- What are the potential savings of the MultiPlus/battery /generator hybrid power system (in terms of reduced pollution, fuel consumption, and maintenance, and extended amortization schedule) when compared to stand alone generator use?

We also wanted to create a database of generator characteristics and corresponding MultiPlus set-up parameters for our customer support, and our distributors and dealers.

And having tested a number of generators for this purpose, we naturally looked at comparative generator characteristics such as fuel consumption, emissions, noise levels and more.

While our primary focus was on the use of marine generators together with our MultiPlus or Quattro inverter/chargers on boats, the results of our tests can also be applied to other small hybrid power systems for mobile homes, off-grid houses, farms or villages, remote telecommunication sites and more.

1.2. Where we tested

The test was carried out at the premises of BW Generator Techniek in Waterhuizen, near Groningen, in the North–East of the Netherlands. BW Generator Techniek is housed in the buildings of a former shipyard, and had the spare space available to carry out the tests. Jan Birza, the owner of BW Generator Techniek, has assisted us where he could with equipment, materials and advice. BW builds BW branded marine generators for professional boating, and also assembles generators for VETUS, a well known brand in the yachting industry. VETUS did not want to participate. We were however able to convince Jan Birza to delay delivery of one of his professional line of gensets for a few hours and allow us to test it. The results are part of this report.

1.3. Which generators were tested?

Time and resources were limited. We therefore had to make choices. We limited our tests to single phase, 230-volt, 50 Hz, marine generators ranging from 3kW to 11kW. Of course, higher power marine generators are also of interest, as well as 120-volt, 60 Hz generators, generators intended for land-based use, and lower power models. We hope to have the opportunity to do more testing in the coming years.

We asked the manufacturers or distributors of the major marine brands to put at our disposal free of charge a maximum of three units in the 3kW to 11kW range. Mastervolt declined to supply products. As Mastervolt is the major Dutch marine generator manufacturer, we felt that the test would be incomplete without Mastervolt products. We therefore bought three Mastervolt generators from different Mastervolt dealers in the Netherlands.

Table 1: the list of generators tested:

Model	**rpm**	**rating**	**engine**	**Cyl**	**governor**	**AC alternator**	**List price**
BW Generator Techniek 615 SIKSE	1500	5,2kW	Mitsubishi L3E	3	electronic	Synchr AVR	10.005 €
Fischer Panda 4000i	2800	3,5kW	Kubota EA300	1	electronic	Inverter	7.072 €
Fischer Panda 8000	3000	6,1kW	Kubota Z482	2	mech/servo	Asynchr	9.423 €
Fischer Panda 12000	3000	9,2kW	Kubota D722	3	mech/servo	Asynchr	11.523 €
Kohler 3.5 EFOZ	3000	3,2kW	Farymann 18W435	1	mechanical	Synchr cap	7.595 €
Kohler 7 EFOZD	1500	6.5kW	Yanmar 3TNV76	3	mechanical	Synchr AVR	10.290 €
Mastervolt Whisper 3.5	3000	3kW	Kubota OC60	1	mechanical	Synchr cap	6.292 €
Mastervolt Whisper 8	3000	6,4kW	Mitsubishi L2E	2	electronic	Synchr cap	9.802 €
Mastervolt Whisper 6 ULTRA	1500	5,7kW	Mitsubishi L3E	3	mechanical	Synchr cap	9.984 €
Northern Lights M673LD2	1500	4,5kW	Lugger L673L	3	mechanical	Synchr AVR	7.779 €
Northern Lights M773LW2	1500	7kW	Lugger L773L2	3	mechanical	Synchr AVR	10.010 €
Onan 4.0 MDKBH-50Hz	2400	4kW	Kubota Z402-ESO2	2	electronic	Synchr AVR	6.980 €
Onan 7.0 MDKBL	1500	7kW	Kubota D1105-BG-ESO1	3	electronic	Synchr AVR	9.500 €
Onan 11.0 MDKBN	1500	11kW	Kubota V1505-BG-ESO1	4	electronic	Synchr AVR	11.600 €
Paguro 4000	3000	3,5kW	Farymann 18W435	1	mechanical	Synchr cap	6.400€
Paguro 8500	1500	8kW	Lombardini LDW1404LG	4	mechanical	Synchr cap	11.400€
SAIM Dynamica Mini-60 MK2	3000	5,8kW	Perkins 402C-05	2	mechanical	Synchr cap	10.200€
Westerbeke 5.7EDT	1500	5,7kW	Mitsubishi L3E	3	electronic	Synchr AVR	9.785 €
Westerbeke 9.4EDT	1500	9,4kW	Mitsubishi S4L2	4	electronic	Synchr AVR	11.875 €

Synchr = synchronous; Asynchr = asynchronous; Synchr cap = synchronous capacitor; AVR = Automatic Voltage Regulator

Note1: The power rating given in the table is the **continuous power rating in kW** of the generator taken from the manufacturer's documentation.

Note2: The list prices of the European brands (BW Generator Techniek, Fischer Panda, Mastervolt, Paguro, SAIM) are the manufacturer's published end user list prices. The list prices of the North American brands (Kohler, Onan, Westerbeke and Northern Lights) are the published end user list prices of the distributor in the Netherlands, except for the list price of the Northern Lights generators, which is the published end user price of the UK distributor, converted to Euro at 1GBP = 1.43 Euro.

Addresses are available on request.
All prices are ex VAT
All prices are inclusive of a sound enclosure.

Photo 1: The tests could be followed on plasma screens

Table 2: Control panels

Model	Control panel on the unit	Remote panel included yes/no
BW Generator Techniek 615 SIKSE	yes	Yes
Fischer Panda 4000i	no	Yes
Fischer Panda 8000	no	Yes
Fischer Panda 12000	no	Yes
Kohler 3.5 EFOZ	no	Yes
Kohler 7 EFOZD	yes	Yes
Mastervolt Whisper 3.5	no	Yes
Mastervolt Whisper 8	no	Yes
Mastervolt Whisper 6 ULTRA	no	Yes
Northern Lights M673LD2	yes	Yes
Northern Lights M773LW2	yes	Yes
Onan 4.0 MDKBH-50Hz	yes	No
Onan 7.0 MDKBL	yes	No
Onan 11.0 MDKBN	yes	No
Paguro 4000	no	Yes
Paguro 8500	no	Yes
SAIM Dynamica Mini-60 MK2	no	Yes
Westerbeke 5.7EDT	yes	Yes
Westerbeke 9.4EDT	yes	Yes

1.4. What we tested

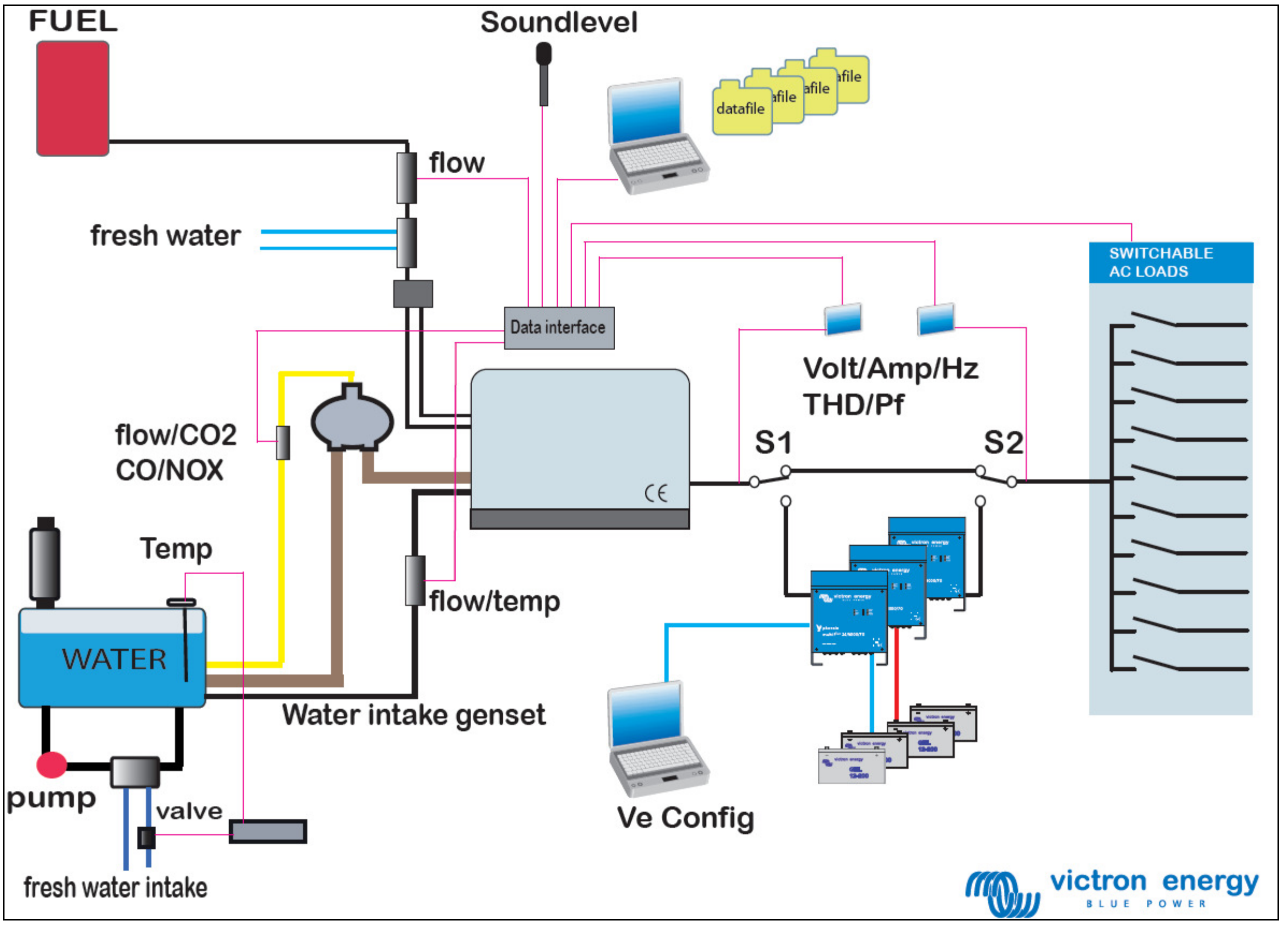


Figure 1: Overview of test set up

We went to some trouble to ensure consistency in our testing. The diesel fuel used is calibration fuel. It is passed through a heat exchanger to ensure a uniform supply temperature to the engines. The cooling water for the engines is likewise temperature-controlled to ensure consistent conditions. The engines were warmed up before testing. The test rig set-up, and the testing, was supervised by TNO-EPS[1)], an independent, outside testing agency.

The electrical loads we used consisted of:

1. A bank of resistive loads that enabled us to vary the load from 500W to 12kW
2. A 4-hob induction cooker that enabled us to vary the load from 200W to 7kW
3. An air compressor driven by a 1.8 kW electric motor that enabled us to create high inrush loads

The tests can be divided into two parts:

1.4.1. A semi automated test of generator characteristics in stand alone operation and with resistive loads. All parameters tested were recorded in a data acquisition system. The only thing the operator had to do was to push a button to switch to the next load step. At each step we gave the generator time to stabilize. This part of the test was carefully monitored by TNO. This is the objective part of the test

Parameters measured:

- Fuel consumption
- Frequency stability
- Total Harmonic Distortion (THD)
- Voltage stability
- NOx emission
- CO emission
- Sound levels

1.4.2 Tests with different loads and with one or more MultiPlus 24/3000/70 modules in parallel. The second part of the test was manual and could therefore not be monitored by TNO-EPS to the fullest extent. It consisted of tests with:

- A 1,8kW (7,8A) air compressor. This compressor had an inrush current of about 23A (3x steady state). There are good solutions available to reduce the inrush current of electric motors (see http://www.victronenergy.com/upload/documents/Book-EN-EnergyUnlimited.pdf paragraph 6.7: The diving compressor). These solutions are not always available and therefore the inrush capacity of low power generators can be important in starting up air-conditioning, a water maker or a diving compressor.
- An induction cooker (http://en.wikipedia.org/wiki/Induction_cooker).
  Wikipedia: Induction cookers are faster and more energy-efficient than traditional hobs. Additionally, the risk of accidental burning is diminished since the hob itself only gets marginally hot (due to heat conduction down from cookware), allowing direct contact with a reduced chance of harm. Also, no heat is lost to the air directly from the hob, keeping the kitchen containing the cooker cooler.
  Induction cookers are installed more and more frequently on boats because it is the safest (no gas on board!) and most efficient solution. Cooking on battery power is a realistic alternative to starting the generator (see http://www.victronenergy.com/upload/documents/Book-EN-EnergyUnlimited.pdf paragraph 6.6).
  Induction cookers however are very sensitive to frequency. The four hob, maximum 7kW, cooker we used for our tests would stop whenever the frequency deviated more than 4Hz from the nominal 50Hz generator output.
- Parallel operation with our Multi's and Quattro's, with resistive loads as well as with the compressor and the induction cooker.

[1)] TNO Electronic Products & Services (EPS) B.V is an independent and internationally recognized organization for testing and certification.

1.5. What we did not test or evaluate

We are not generator specialists, and we were most interested in the electrical performance of generators. We therefore did not look at:

- Ease of installation
- Ease of service
- Quality of materials and components used
- Quality of owners and installation manual
- Expected service life (except for a very general remark in paragraph 2.1)
- Electrical efficiency in converting mechanical energy to electrical energy

1.6 The Case for small Hybrid Power Systems

For us, at Victron Energy, the results of the tests represented a quantum leap in our generator knowledge. The data provide compelling support for a Hybrid Power System as an alternative to stand alone generator operation, be it in a boat, mobile home or the myriad of land based off-grid applications.

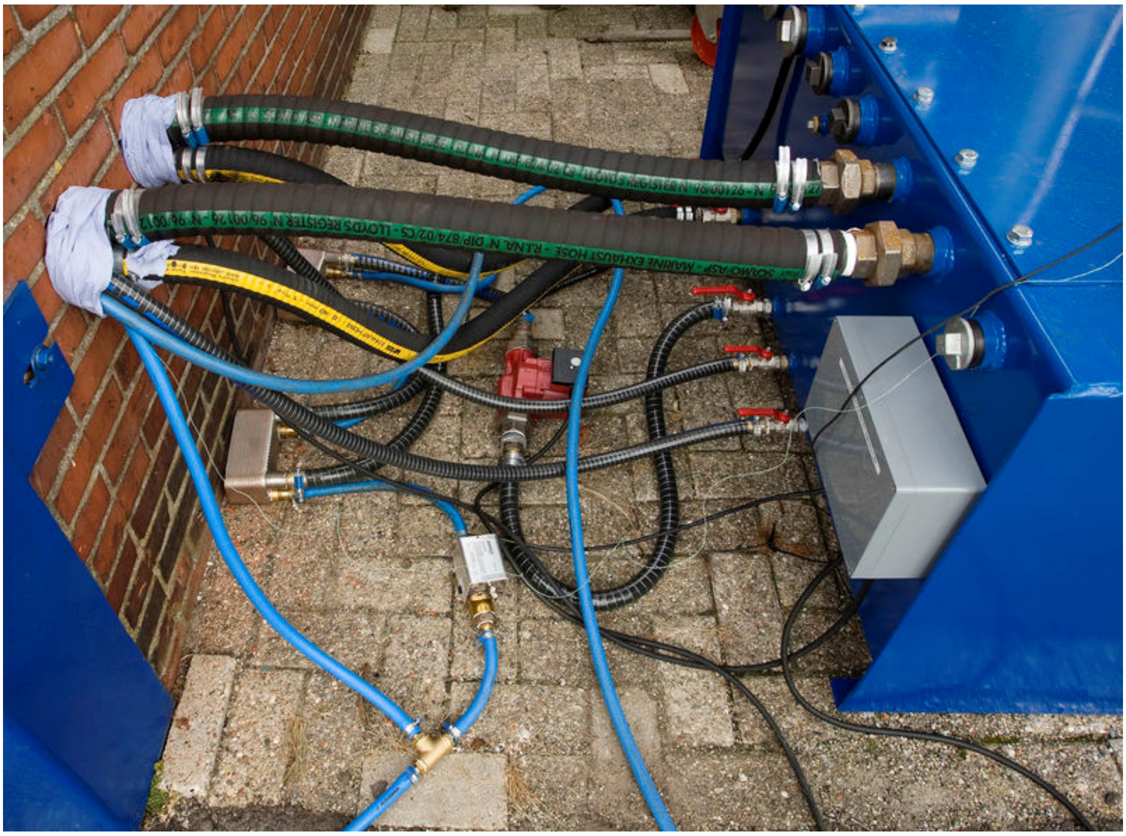


Photo 2: Temperature controlled cooling water tank as used for the tests.

2. Results Part 1:
The generators in stand alone operation with resistive load

The most important result is that all generators tested worked well! The only small problem we had was with the Mastervolt Whisper 3.5: the exhaust temperature sensor failed during the test. This problem was quickly solved.

Given the large amount of data collected, we felt that a graphical presentation would be the most informative. By plotting the data we have been able to quickly identify some 'families" of generators with similar characteristics, and relate these characteristics to certain design parameters.

We will briefly discuss these parameters in general terms:

2.1. Speed of rotation (rpm)

With rare exceptions, AC Gensets must run at a fixed speed in order to produce the required 50Hz or 60Hz output ('Hz' = cycles per second).

We tested 50Hz generators only, but one can safely assume that corresponding 60Hz models will show a very similar performance, with one exception: a 60Hz generator will run at a 20% higher rpm and therefore the engine and generator will deliver up to 20% more power.

For a 50Hz output, the engine of a direct drive genset with a 2 pole alternator must run at 3000rpm. With a 4 pole alternator, rotation speed is reduced to 1500rpm. More poles, and lower rpm, are not practical.

Gensets can therefore be split into two broad categories: those running at 3000rpm and those running at 1500rpm.

The main differences:
- Service life of a 1500rpm genset will be longer. 1500rpm gensets have a service life of up to 10.000hrs (2,5 years continuous use), whereas 3000rpm gensets will last up to 5000hrs (1,5 years continuous use). Small 3000rpm gensets with a one cylinder engine have a shorter service life.
  For comparison: A car diesel engine will do up to 500.000 km at an average speed of 75km/hour; this equates to 6.600hrs.
- Typically, a 1500rpm genset will be less noisy.
- For a given power output, fuel consumption of a 1500rpm genset will be slightly lower.
- For a given rated output, a 3000rpm genset will be smaller and lighter.
- On average, 3000rpm gensets have a lower purchase price.

Exception 1: the Onan MDKBH-50Hz (4kW)
This is an indirect drive genset, with the engine running at 2400rpm and the AC generator at 3000rpm

Exception 2: the Panda 4000i (4kW)
The Panda 4000i is a so called "inverter generator". An engine driven permanent magnet generator produces relatively high frequency AC at 400-500V. This is rectified and then fed to a static transformerless DC to AC inverter.
The advantages are:
- Output frequency is independent of engine rpm.
- Excellent frequency and voltage stability because of static inverter technology.
- Excellent overload capacity.
- The permanent magnet DC generator is smaller and lighter than a traditional AC generator.

The “inverter generator” is a recent development that will probably find wider adoption. (The small portables from Honda and Mitsubishi, for example, are also inverter generators, and Paguro also sells a diesel fuel powered inverter generator)

2.2. The governor

The governor controls the speed of the engine. The main difference is between mechanically- and electronically-controlled governors. In general electronic governors will regulate frequency more accurately and respond faster (a frequency deviation due to a sudden load variation will be corrected faster).

The Fisher Panda 8000 and 12000 have yet another speed control mechanism - a servo motor that is used to increase the speed of the engine when the load increases. This is to stabilize the output voltage.

2.3. The AC generator or alternator[2)]

Aside from categorizing by speed of rotation and governor type, the generators that we tested can be divided into three groups:

2.3.1. Generators with brushless, self excited, externally voltage regulated, synchronous alternators (“synchronous AVR” alternator). This is the most common topology for alternators rated at more than 5kW. The output voltage is relatively easy to control and Total Harmonic Distortion[3)] (THD) is low. These alternators have low output impedance which results in a high peak power capacity. The output voltage can be accurately controlled. The output voltage of the AVR alternator is not very sensitive to the power factor of the load[4)].

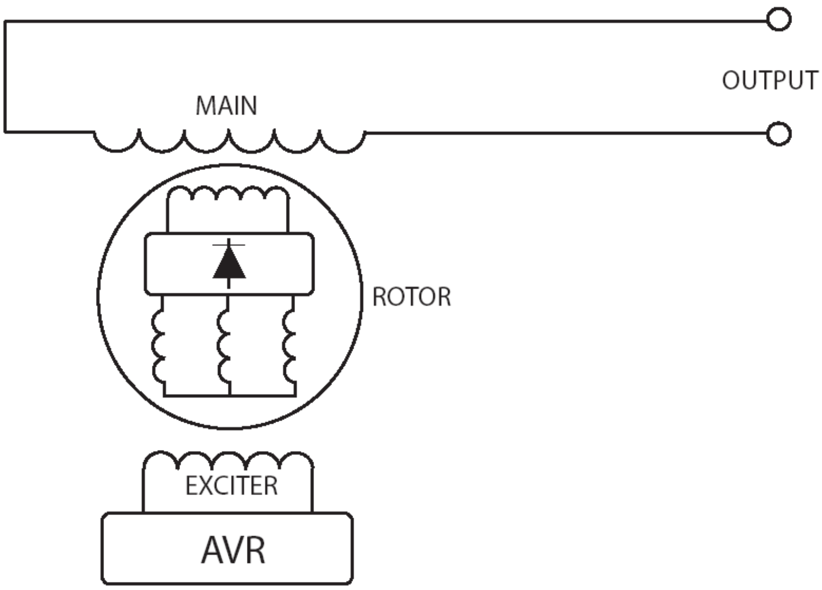


Figure 2: Synchronous AVR alternator

[2)]Different names are used for the electrical end of a generator. Our choice was ‘alternator’, not to be confused with the small alternators used to recharge the starter battery.

[3)] For an explanation of THD, see http://en.wikipedia.org/wiki/Total_harmonic_distortion

[4)] For an explanation of power factor, see http://en.wikipedia.org/wiki/Power_factor

2.3.2. Generators with brushless, self excited, capacitor regulated, synchronous AC alternators ("synchronous capacitor" alternator). The synchronous capacitor topology is a simple, robust and low cost solution for low power generators. It is, however, not easy to keep output voltage within a tight range. Output power is auto-limited. The synchronous capacitor topology is therefore not capable of supplying high peak power.

The output voltage of a synchronous capacitor alternator is very sensitive to the power factor of the load. During start-up an electric motor draws a lot of current and at the same time has a very low (lagging) power factor. This can result in a large voltage drop when starting an electric motor with a synchronous capacitor alternator.

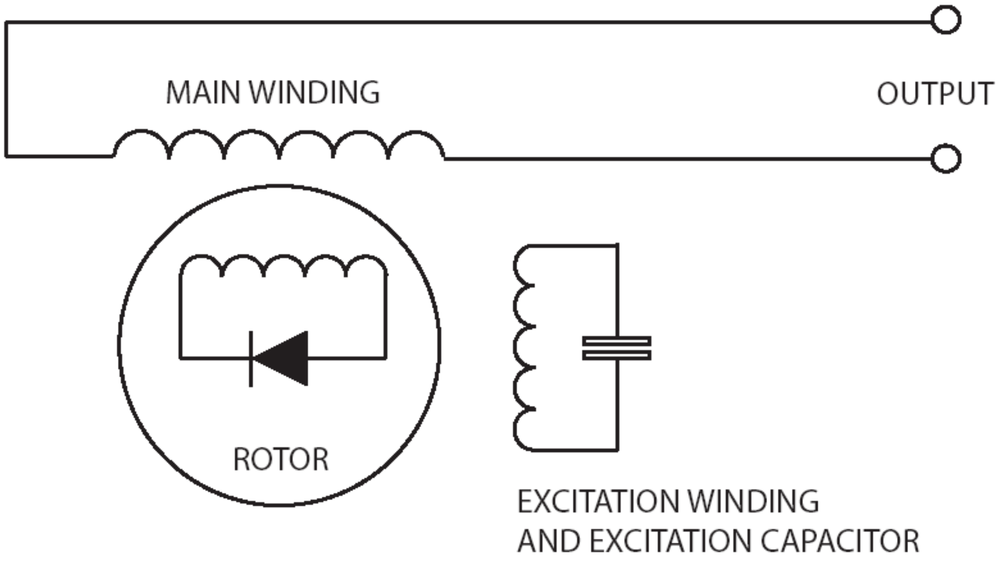


Figure 3: Synchronous capacitor alternator

2.3.3. Generators with brushless, self excited asynchronous alternators.
The asynchronous alternator has a solid rotor (no diodes, no copper windings) and is therefore very robust. Like the capacitor generator, it has limited overload capacity.

Fischer Panda was the only manufacturer in our test using asynchronous generators. Fischer Panda claims excellent high temperature performance, with a rotor that is, in principle, not sensitive to high temperatures, and a water cooled stator.

Output voltage stability: at fixed rpm, output voltage will decrease with load. Output can be stabilized by slightly increasing rpm with increasing load (see Graph 8: frequency as a function of load), or by increasing the capacity of the exciting capacitors.

The output voltage of an asynchronous alternator is sensitive to the power factor of a load. During start-up an electric motor draws a lot of current and at the same time has a very low (lagging) power factor. This can result in a relatively large voltage drop when starting an electric motor with an asynchronous alternator.

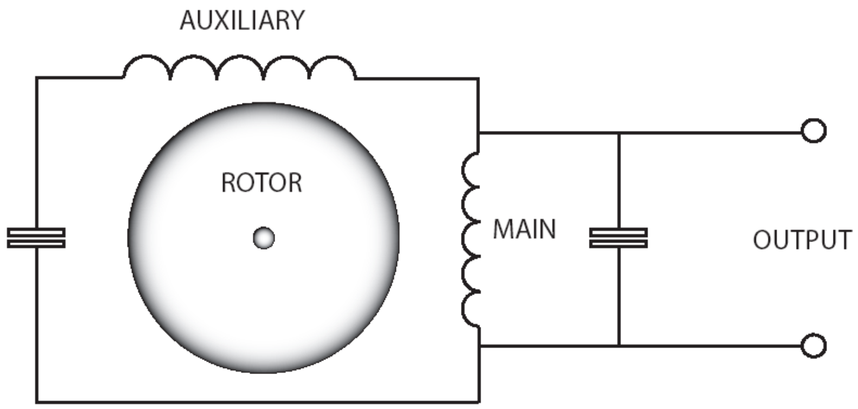


Figure 4: Asynchronous alternator

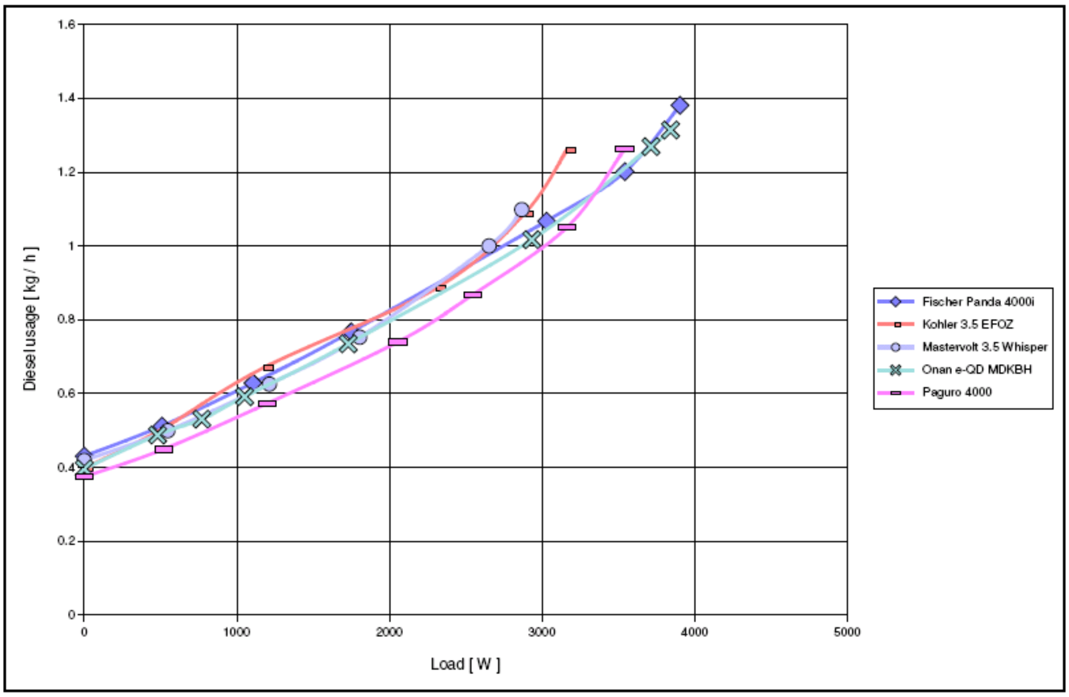
2.3.4. Overview:

Feature	Synchronous AVR	Synchronous Cap	Asynchronous
Rotor	Wound	Wound	Solid (no diodes, no copper windings)
Sine wave	Typical THD: 2%-6% Sometimes looks “dented”	Typical THD:6%-12% Clearly contains harmonics	Typical THD: 2%-6% Smooth appearance
Excitation	Controlled by current flowing in rotor	Controlled by current flowing in rotor	Auto excited by rephasing capacitors
Inrush current and overload capacity	Excellent	Limited	Limited
High temp endurance	Normal	Normal	Excellent, because of solid rotor

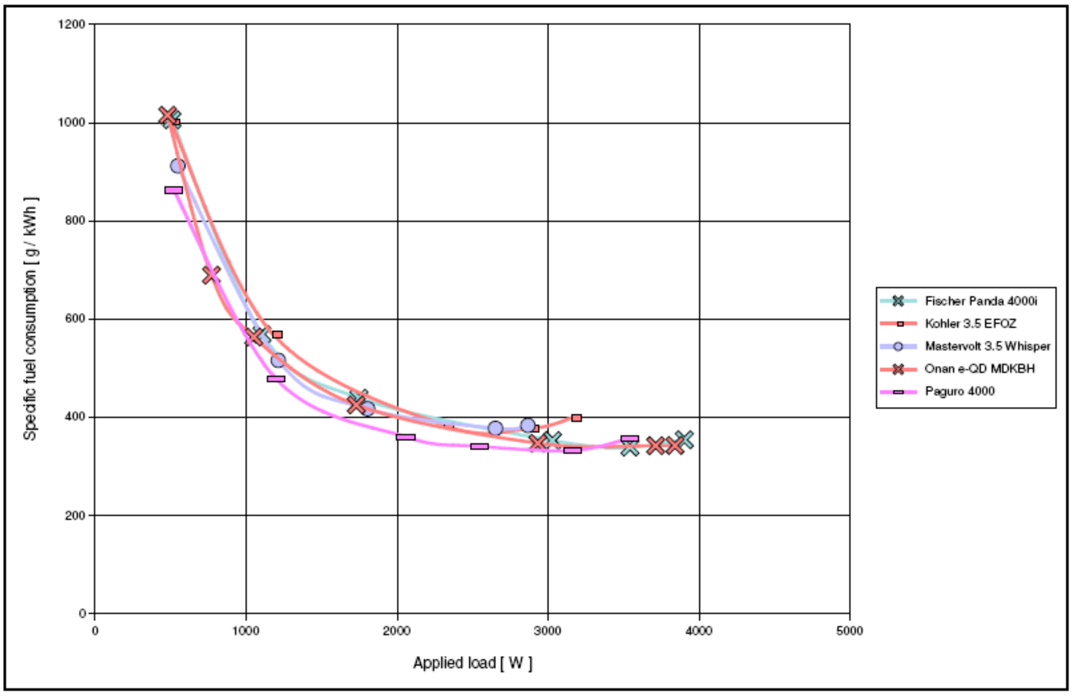
Table 3: Overview of the three alternator types

2.4. The results in graphical form

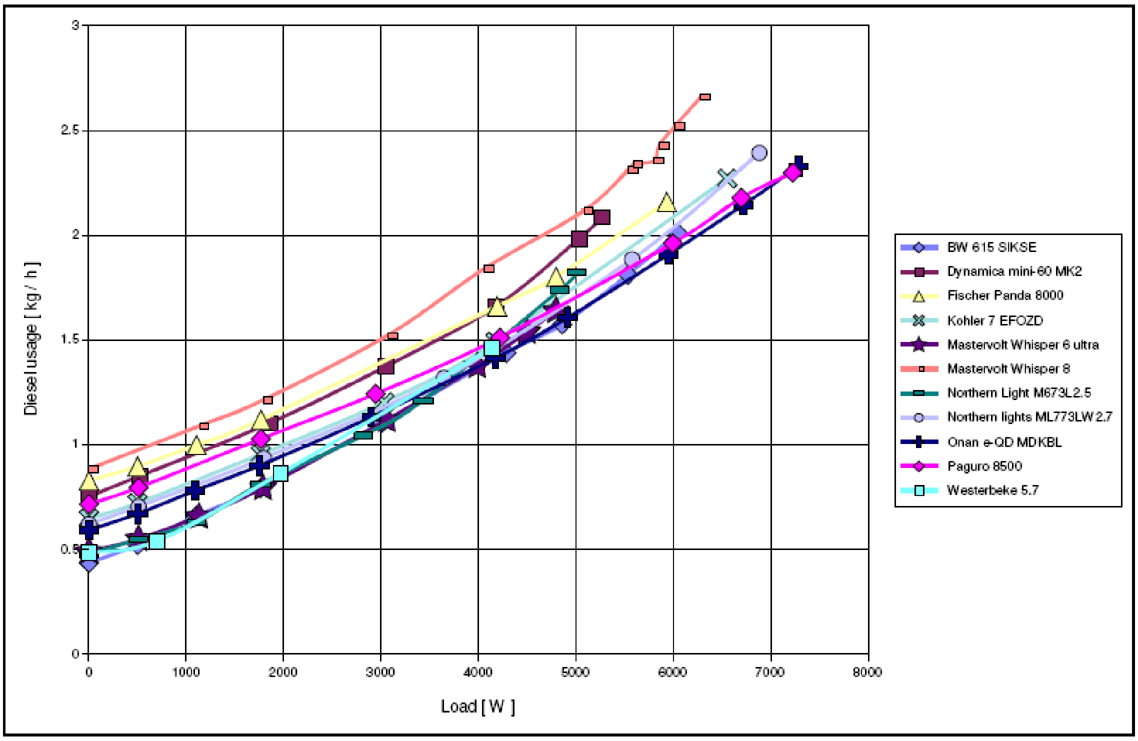
2.4.1. Fuel consumption



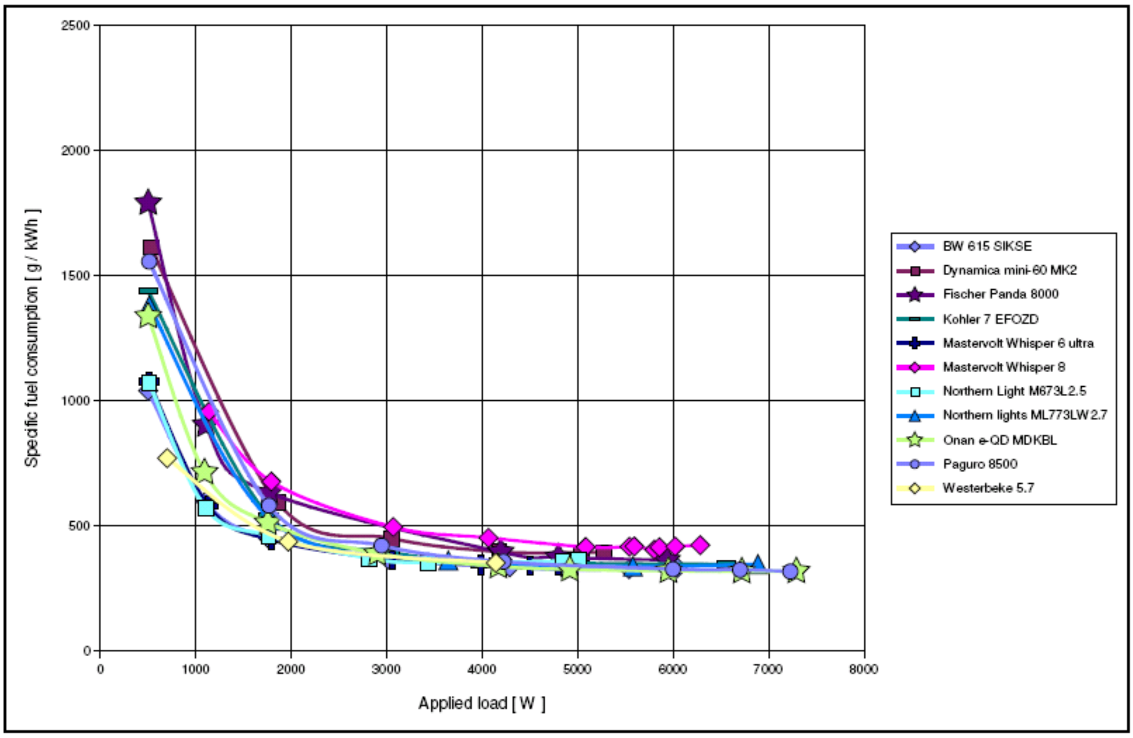
Graph 1: Fuel consumption of the low power generators (3kW-4kW)
Note: this graph shows the total fuel consumed versus the load – i.e. as the load increases, the amount of fuel increases.



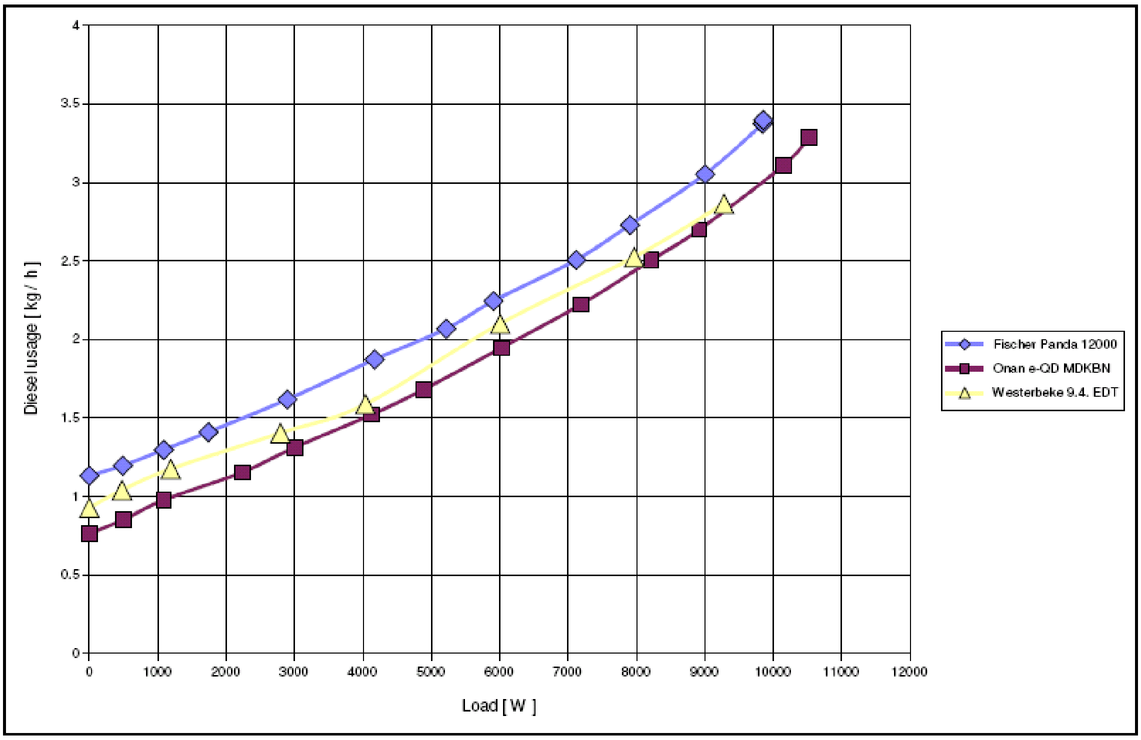
Graph 2: Specific fuel consumption of the low power generators (3kW-4kW)
Note: this graph shows the amount of fuel it takes for each kilowatt-hour (kWh) of energy produced at a given load. What is striking is the high fuel consumption rates at low loads. For example, at a load of 1 kW, it takes around 600 grams of fuel to generate a kWh of output, but at a load of 3 kW, the fuel consumption rate drops to around 350 grams per kWh of output. What we see here is how incredibly inefficient generators are when run at low loads.



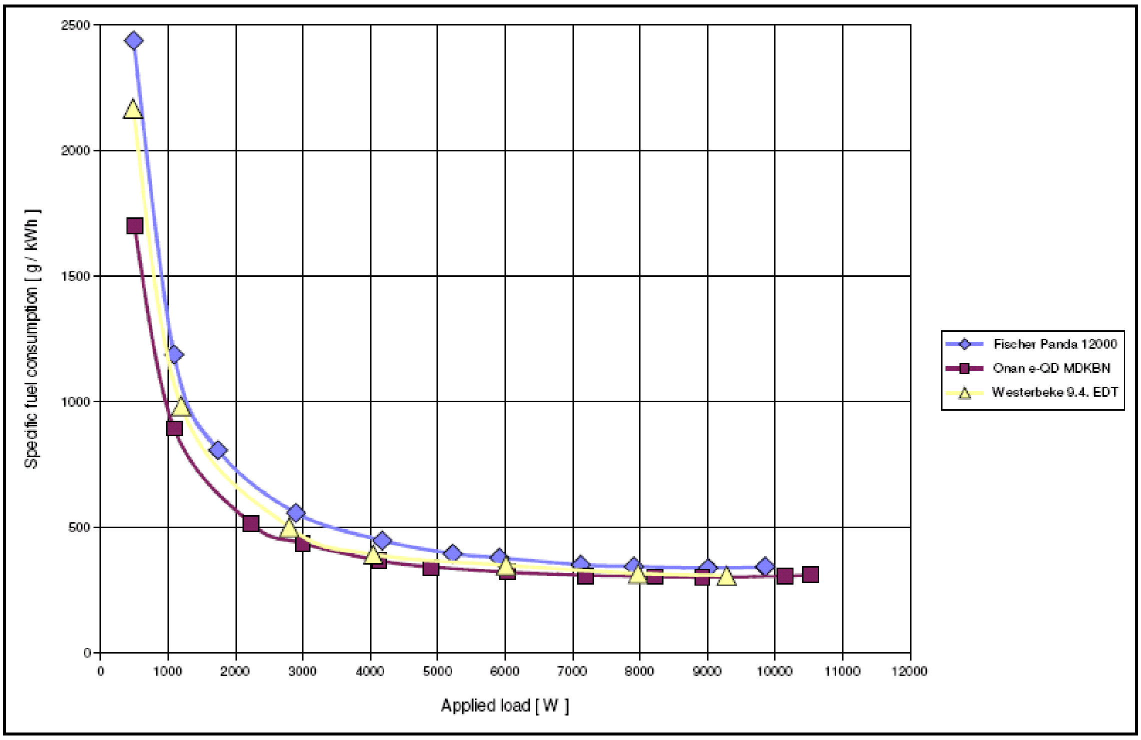
Graph 3: Fuel consumption of the medium power generators (4kW-7kW)



Graph 4: Specific fuel consumption of the medium power generators (4kW-7kW)

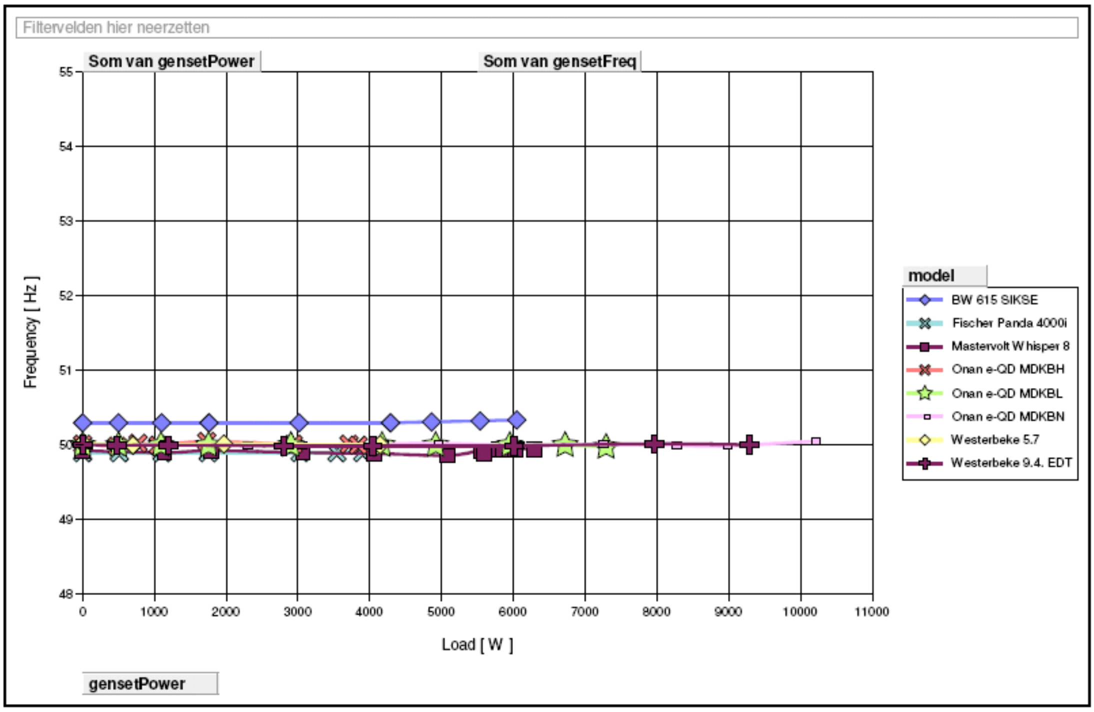


Graph 5: Fuel consumption of the highest power generators (7kW-11kW)

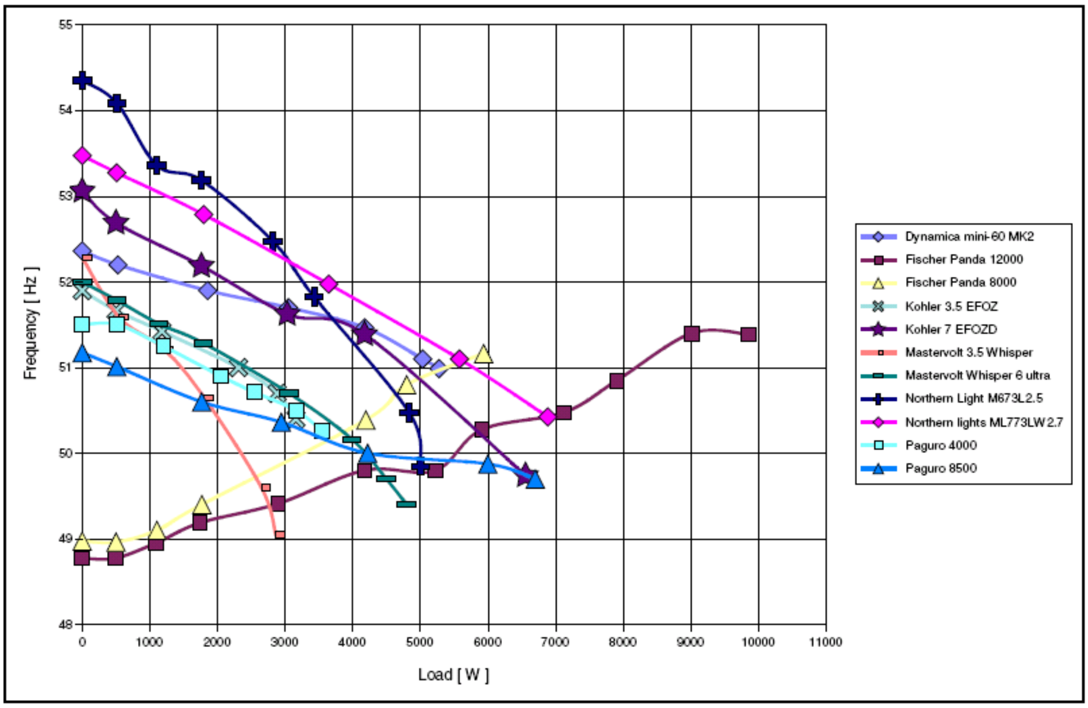


Graph 6: Specific fuel consumption of the highest power generators (7kW-11kW)

2.4.2. Frequency stability

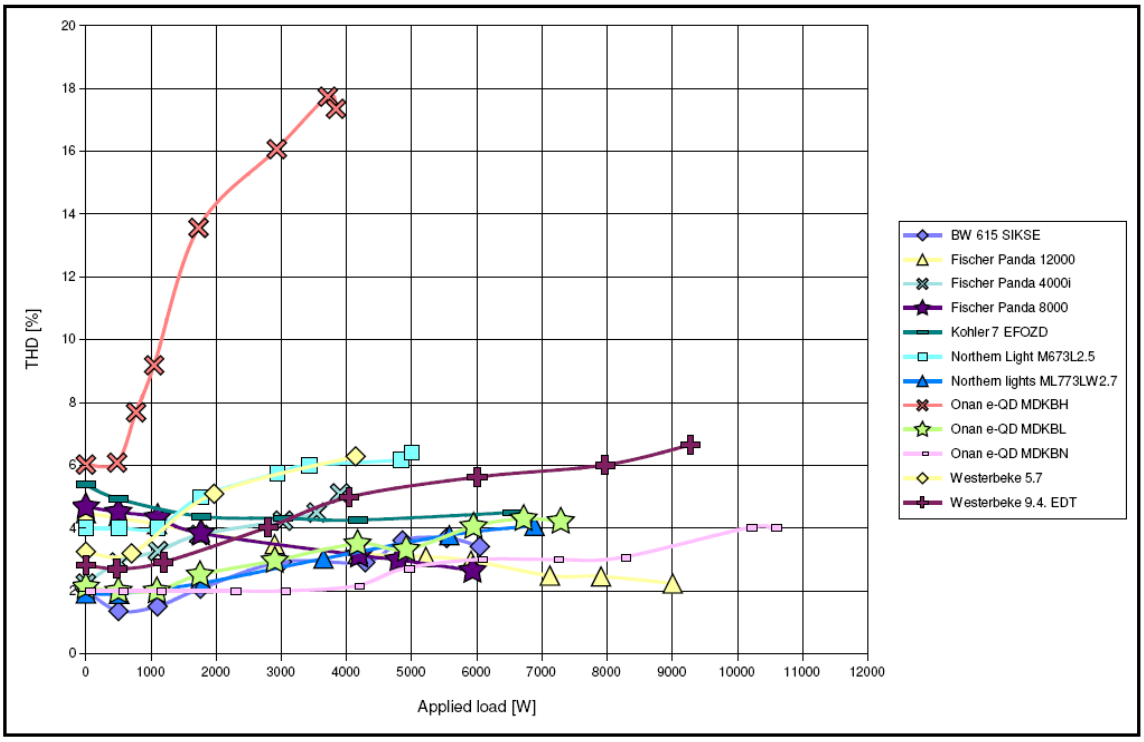


Graph 7: Sets with electronic governors
Note: The frequency of the BW generator can be trimmed to exactly 50Hz

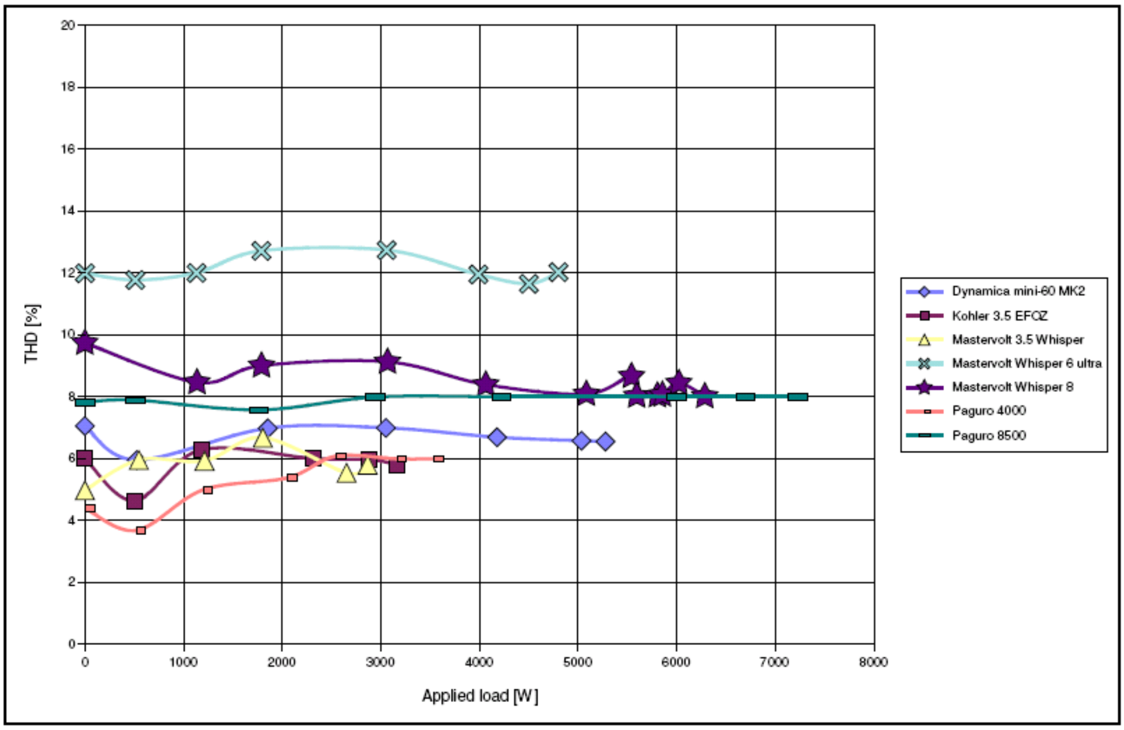


Graph 8: Sets with mechanical governors
Note: The frequency of the two gensets with asynchronous alternators increases with load to stabilize output voltage

2.4.3. THD (Total Harmonic Distortion)

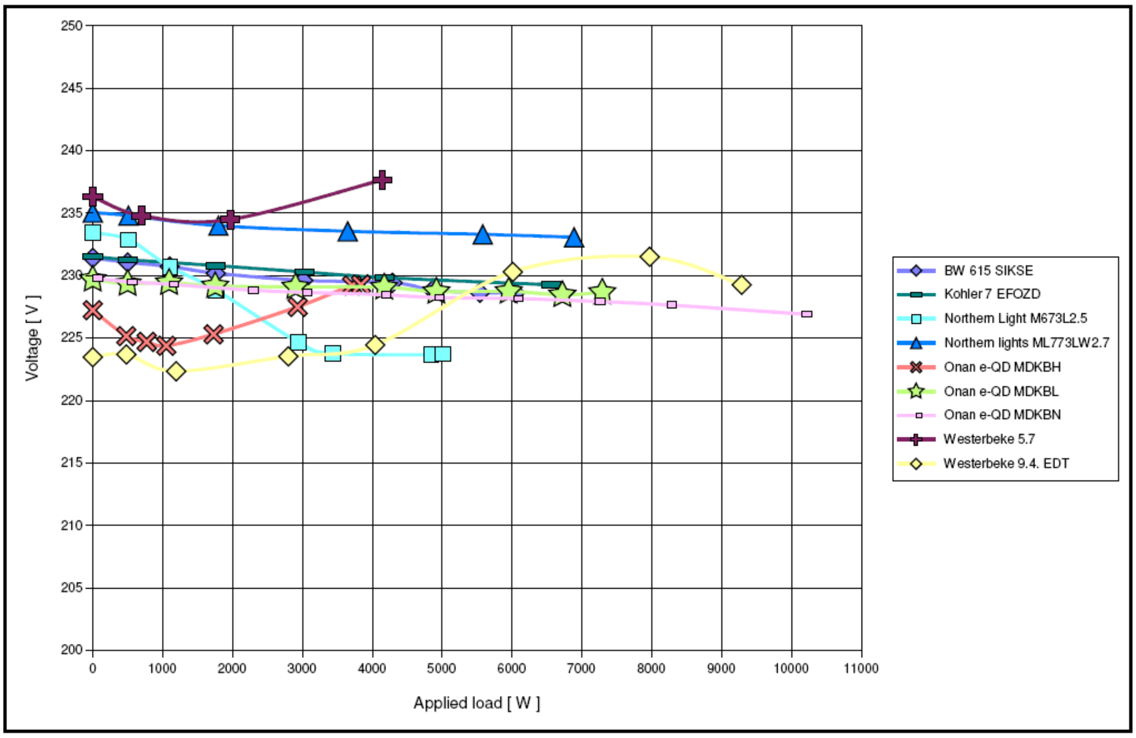


Graph 9: THD of the gensets with a synchronous AVR alternator, and asynchronous inverter generators

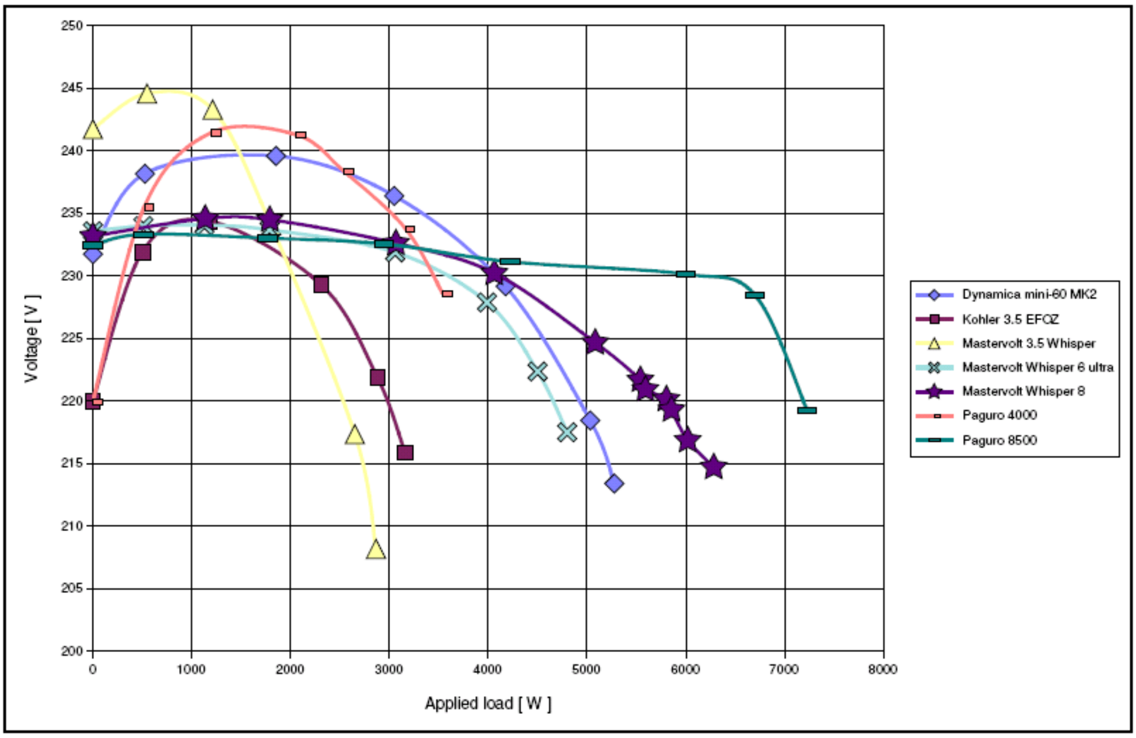


Graph 10: THD of the gensets with a synchronous capacitor alternator
Note the much higher THD in comparison with Graph 9

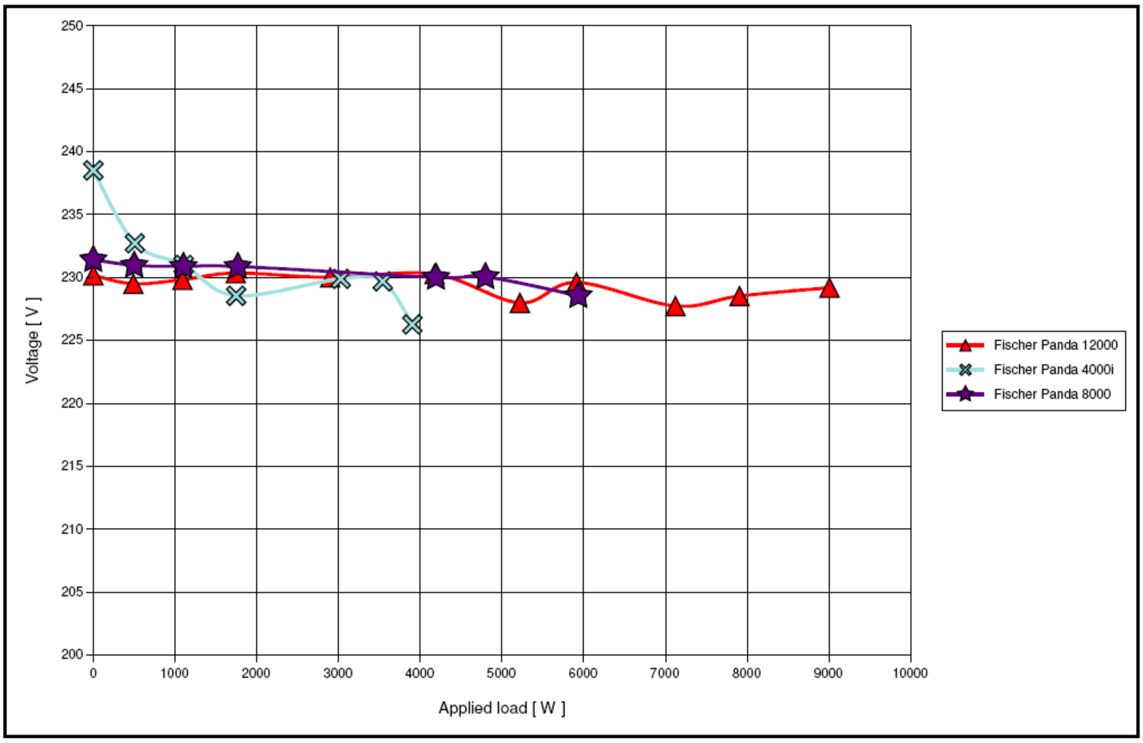
2.4.4. Voltage stability



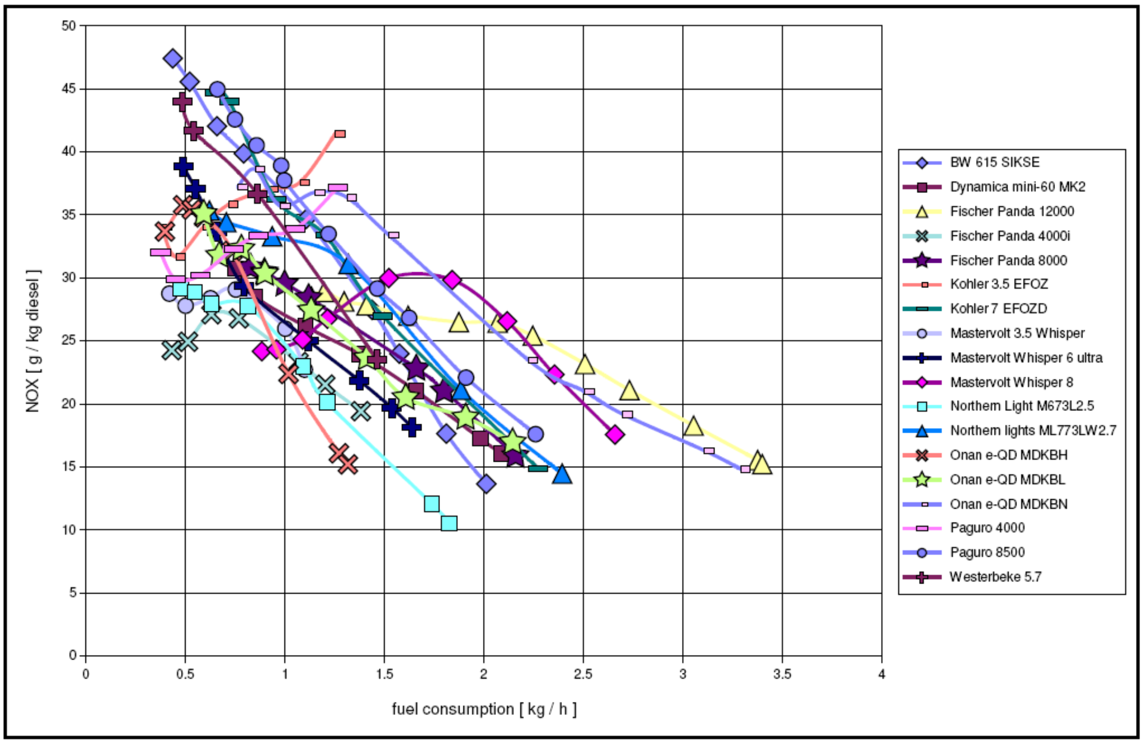
Graph 11: Output voltage stability of the gensets with a synchronous AVR alternator



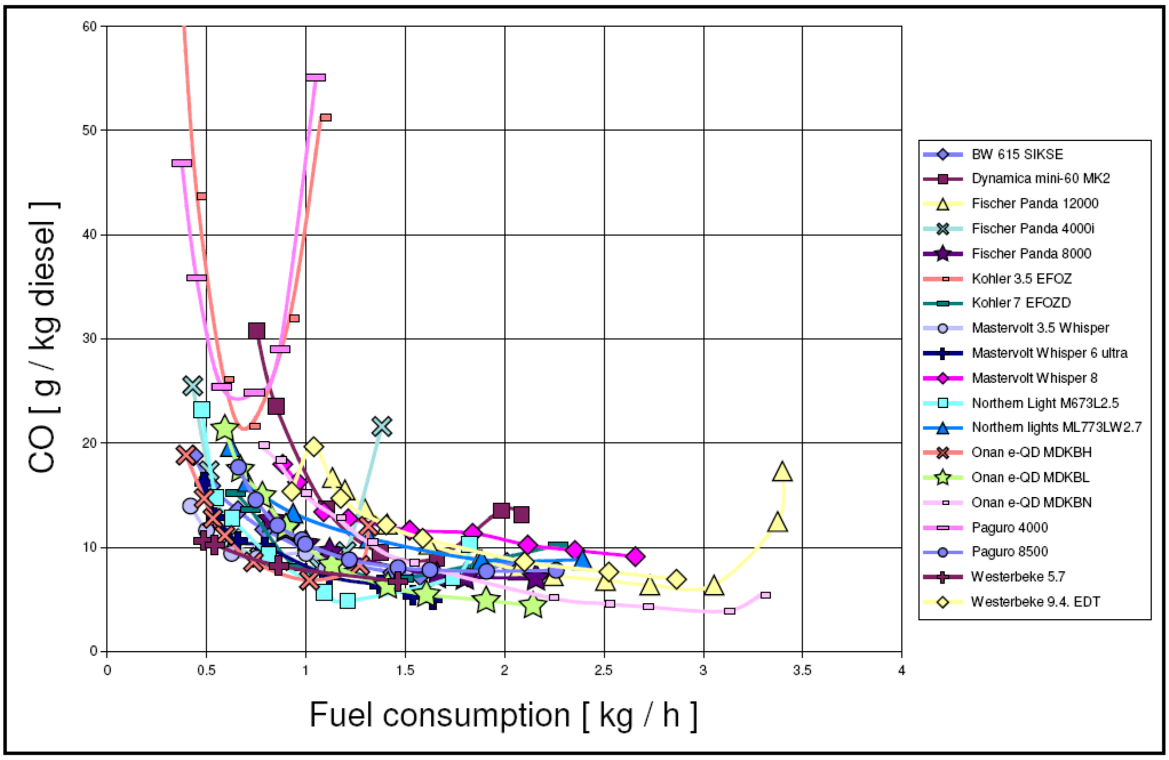
Graph 12: Output voltage stability of the gensets with a synchronous capacitor alternator



Graph 13: Output voltage stability of the gensets with an asynchronous alternator and of the inverter generator

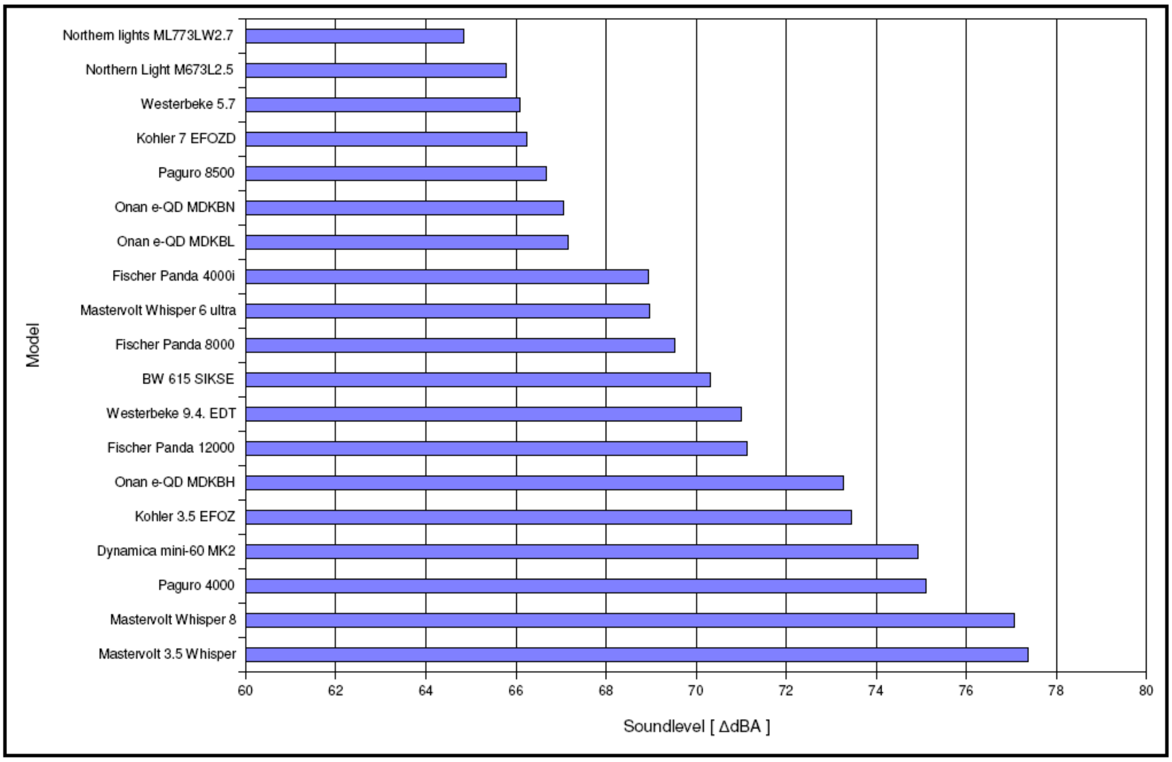


Graph 14: NOx emission as a function of fuel consumption

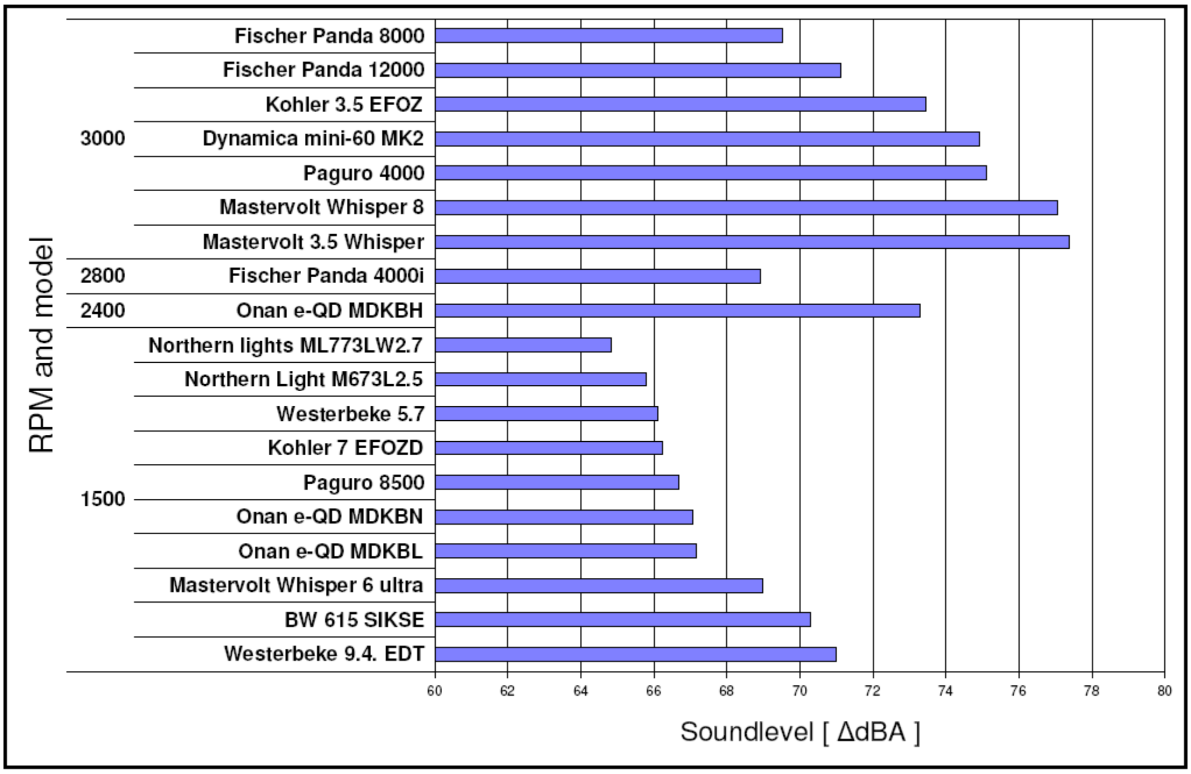


Graph 15: CO emission as a function of fuel consumption

2.4.5. Sound levels



Graph 16: Relative sound levels (no load)



Graph 17: Relative sound levels based on genset speed (no load)

2.5. Discussion of the results

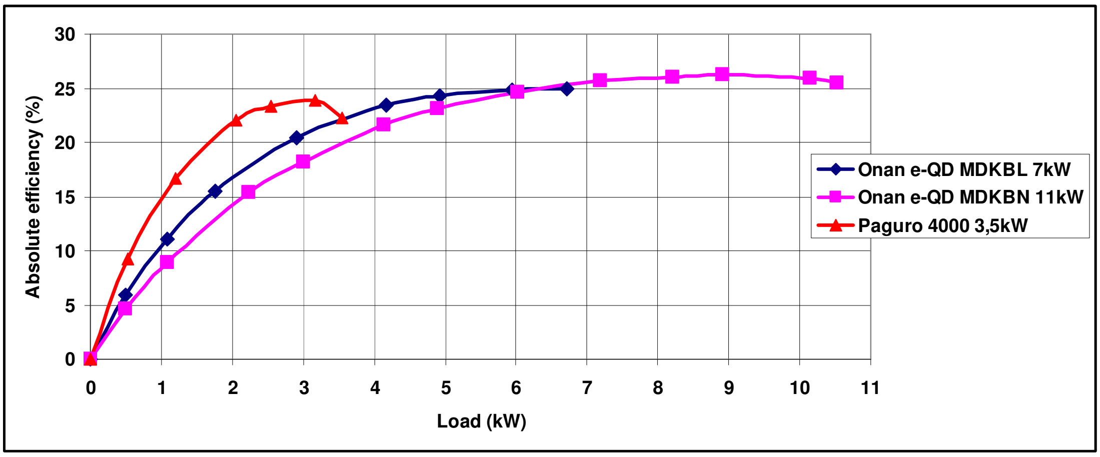
2.5.1. Fuel consumption

- Fuel consumption is similar for all models tested, with the 3000rpm units being slightly more thirsty compared to their 1500rpm counterparts.
- No load fuel consumption is high, ranging from 32% of the full load value for the 3000rpm sets to 22% of the full load value for the highest power 1500rpm set.
- Low load fuel consumption is also high, and remains high until relatively high loads are applied. This is especially the case with the low power generators which do not achieve fuel consumption stability until the load reaches approximately 50% of the full rated output (see Graph 2). The medium power generators achieve fuel stability once the load reaches approximately 30% of full rated output (see graph 4). The high power generators achieve fuel stability once the load reaches approximately 25% of full rated output (see Graph 6).

This is interesting, because it means **a lot of fuel and pollution can be saved by paralleling Multi's to a generator to pick up peak loads, and thereby downsizing the generator and running it at a higher load. Substantial additional fuel savings can be achieved by using the Multi to power light AC loads, with the generator shut down, thereby reducing low-load running hours.**

We selected one generator out of each of the three power ranges that were tested for a more in depth analysis:

Graph 18 shows the absolute efficiency of the three generators. Clearly the absolute efficiency is around 25% at the most efficient load point. This means that even when used at their most efficient load point, only 25% of the caloric content of the diesel fuel (the caloric content of automotive diesel fuel is about 45,6 MJ/kg, or 12,7kWh/kg) is converted into electric power. The remaining 75% is transformed into heat that is evacuated through the exhaust and water cooling.

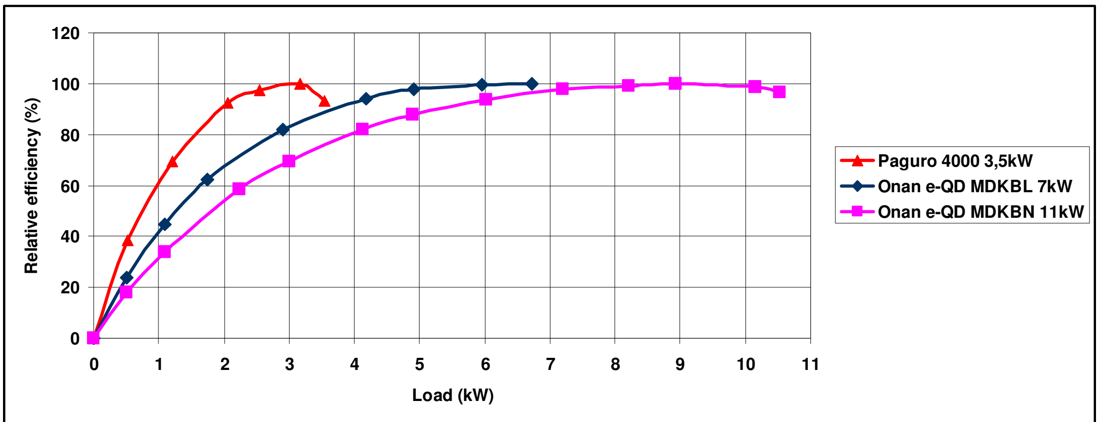


Graph18: Absolute efficiency of three representative generators

Graph 19 shows the efficiency relative to the point of highest efficiency (nearly full load). This graph is very helpful for determining the efficiency of a hybrid system compared to its stand alone generator equivalent (see Chapter 4). Charging and discharging a battery does generate additional losses, ranging from 25% to 35% of the energy that flows through the battery instead of directly from the generator to the load. This means that on average overall efficiency will increase if the generator is shut down when the relative efficiency drops to less than 70%. See paragraph 4.4.3 for a more in depth discussion.

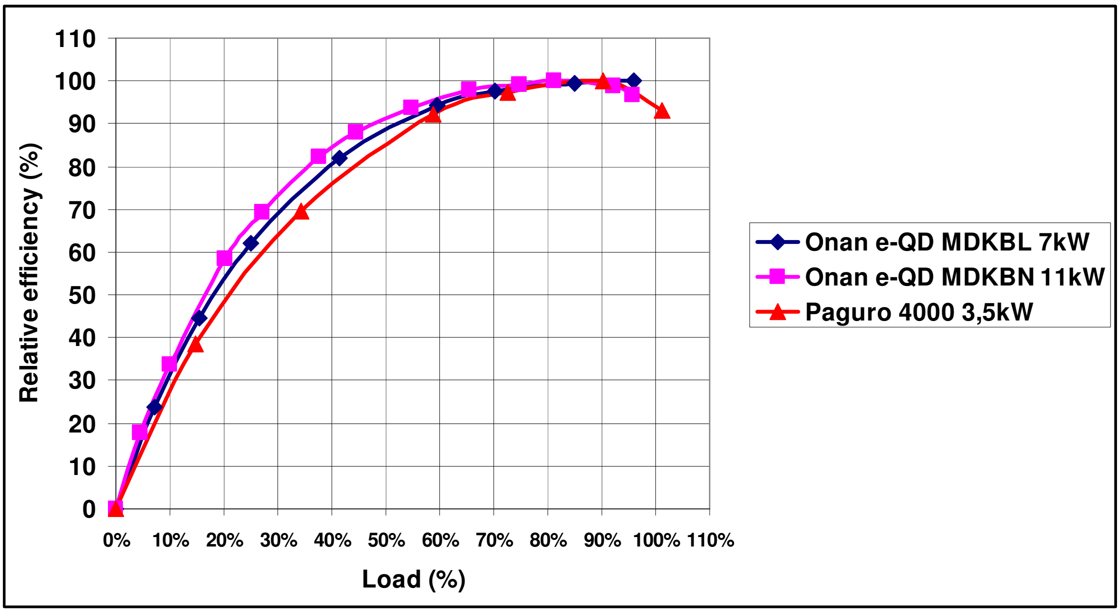
For the three generators the 70% efficiency load point is at:

Paguro 4000 3,5kW:	1,2kW	34% of full rated load
Onan e-QD MDKBL 7kW:	2,1kW	30% of full rated load
Onan e-QD MDKBN 11kW:	3,0kW	27% of full rated load



Graph19: Efficiency of three representative generators relative to the point of highest efficiency

In Graph 20 below the relative efficiency is plotted against % load (full rated load is at 100%). This graph shows that the relative efficiency is very similar over the power range of the generators tested. This means that to calculate efficiency improvement of a hybrid system a good approximation is obtained by using a standard set of relative efficiency data, whatever generator is used within the 3kW to 11kW power range. These data can be taken from Graph 20 below.



Graph 20: Relative efficiency against % load

2.5.2. Output frequency
The difference between electronic and mechanical governors is obvious, with one notable variation: the increasing frequency with load of the Fisher Panda 8000 and 12000. This is because Fisher Panda stabilizes output voltage by using a servo motor to increase the speed of the engine when the load increases, resulting in an increasing frequency.

2.5.3. THD and output voltage
The three classes of alternators – synchronous AVR, synchronous capacitor, and asynchronous - can easily be identified from the graphs, with the synchronous AVR and asynchronous alternators displaying considerably less harmonic distortion and better voltage stability than the synchronous capacitor type.

The Onan MDKBH-50Hz (4kW) stands out because of increasing distortion with load (and it is not clear to us why).

2.5.4. Pollution
All generators tested had conventional diesel engines. All engines were of the direct injection type with a mechanical injection pump. No common rail systems, no particulate filters, exhaust gas recirculation (EGR) or other means to reduce emissions were mounted.

- Measuring **Diesel Particle Matter (DPM) or soot emission** was not feasible because all gensets had a wet exhaust.

- **Carbon dioxide (CO_2) emission** is proportional to fuel consumption: 3,15kg of CO_2 is emitted per kg of diesel fuel. In a hybrid system reduction of CO_2 emission will therefore be proportional to fuel consumption reduction

- **Oxides of Nitrogen (NOx) emission**
  Air is 78% nitrogen by volume. Diesel engines mainly produce NOx by "burning" a small amount of the nitrogen in the air drawn into the cylinder. At the high temperatures encountered in a diesel combustion chamber, the nitrogen combines with oxygen to form NOx. The formation of NOx becomes significant at about 2900°F (1600°C) and increases rapidly as the temperature rises above this threshold. The formation of NOx is caused by a complex combination of factors involved in the combustion event. Time of fuel dispensation, peak pressures, and combustion and exhaust temperatures all affect NOx formation.
  Graph 14 shows that NOx formation per kg of fuel tends to decrease when the load on the

generator increases. This may be due to a lower average peak combustion temperature when more diesel fuel is injected in the cylinder because the excess oxygen decreases. The decrease from no load to full load operation is about a factor of two. **This means that in a hybrid system NOx emission reduction can exceed fuel consumption reduction by a factor of two.**

- **Carbon monoxide (CO) emission**
  Since diesel engines are designed to run lean, i.e., with excess oxygen, they normally do not emit much carbon monoxide (CO) or unburned hydrocarbons. It is only when the engine is operated at its full load limit (defined by the "black smoke limit", beyond which point the fuel cannot be completely combusted) that CO emission rises sharply. This can be clearly seen in Graph 15, were we over loaded the Fischer Panda 12000 and the Fischer Panda 4000i.
  For reasons unknown to us the two generators with a Farymann 18W435 engine had a much higher CO emission than the other generators tested, also when not overloaded. Graph 15 shows that CO emission is high at no load or very low load, then decreases with increasing load, and finally increases again when the black smoke limit is reached. **This means that in a hybrid system CO emission reduction will exceed fuel consumption reduction.**

Fore information on emissions, please see for example
http://en.wikipedia.org/wiki/Emission_standard

2.5.5. Sound level

Reproducing the exact conditions under which the different generator manufacturers measure sound levels would have been too time consuming and too expensive. The sound levels measured should therefore not be seen as absolute values but as relative values, for which we used the symbol ΔdBA, showing how much more or less noisy one generator is compared to another. The results show that one cylinder 3000rpm generators in particular, and 3000rpm generators in general, produce substantially more noise than 1500rpm generators.

Sound levels were measured at no load. At full load the measured sound levels were at most 1dB(A) higher.

2.6. Conclusion: So what?

At first sight the conclusion from Part 1 is that most professional and household equipment will function flawlessly with all generators tested.

But two question marks remained:

- Overload capacity
  When determining the maximum output power of the generators for our voltage against load graphs we noticed that the engine of the ‘capacitor’ generators in general did not stall when load was increased. What happened was that output voltage dropped when output current increased, keeping output power approximately constant, but at a lower and lower output voltage (see Graph 12). The output voltage of all other generators remained stable when over loaded, with the inevitable result that the increasing load ended up stalling the engine. We therefore decided to do tests with a powerful electric motor to see what would happen when these different generator types were hit by a high start-up current. On a boat such equipment may be an air conditioner, a water maker, or a diving compressor.

- Frequency stability
  Some modern household equipment is sensitive to voltage and/or frequency.
  Example: induction cookers. We therefore also tested all generators with an induction cooker.

In Part 2 of the tests, these issues are studied in more detail.

The other subject is the case for the hybrid system.
Part 1 of the tests showed that:

- Generators have a very low efficiency at low load
- Substantial reduction of fuel consumption can therefore be achieved by using a hybrid MultiPlus/battery/generator system instead of a stand alone generator.
- NOx and CO emission reduction will be even more impressive than the reduction of fuel consumption and the related reduction of CO_2.emission.

These results will be discussed in more detail in chapter 4.

3. Results Part 2:
Tests with different loads and with one or more MultiPlus modules in parallel

3.1. Introduction

For Part 2 of the tests, we ran the generators in conjunction with a stacked bank of MultiPlus inverter/chargers. We used the Multis in both PowerAssist mode (see below), and also battery-charging mode.

We investigated the waveform of the generators with and without the Multis in parallel. On their own, gensets with a synchronous capacitor alternator had distorted wave forms. In general, the Multis improved the waveform.

In parallel mode, via the Multis, we set a current limit for the generators (i.e. a maximum generator load) and continued to apply loads beyond this limit, with the Multis picking up the excess. We had the ability to apply a total load that was several times the rated output of the generators. We applied different kinds of loads – our bank of resistive loads, the induction cooker, and the air compressor's electric motor. We wanted to see what would happen to the generator wave forms and voltage. We logged all the resulting data, and captured oscilloscope images of the wave forms, amps and volts for both the generators and the Multis.

We did a few verification tests with Quattro's. The tests showed that Quattro's behave exactly like Multi's.

Next to steady state tests we also did load step tests.
When the load on a generator is suddenly decreased or increased two things happen:
- Engine speed and therefore output frequency increases or decreases before returning to a steady state after the fuel supply has been decreased/increased appropriately by the governor. This process takes time. Because mechanical parts are involved, the reaction time will in general be 0,1s to 1s. A longer reaction time results in a larger frequency deviation. Electronically-controlled governors will in general respond faster than mechanical (centrifugal) governors.
- Likewise, output voltage will increase/decrease with changes in load. To make things even more complex, output voltage is also influenced by rotation speed. The output of 'capacitor' generators and 'asynchronous' generators is especially sensitive to rotation speed.

The dynamic behavior of a generator is therefore a complex matter and totally different from the mains supply. This is because the frequency of the mains (shore) supply does not change when a load is connected - only voltage is influenced. The mains supply is also much less sensitive to the power factor of the load.

In general, we found the gensets with synchronous capacitor alternators or an asynchronous alternator worked well when the power rating of the connected Multi's remained below the rating of the genset. When adding more Multi's the generators became unstable.

Generators with synchronous AVR alternator worked well with a Multi or Quattro power rating of up to 150% of the genset rating.

The type of governor did not seem to have a marked influence. Apparently, the type of alternator is the most important factor.

The best performance was obtained with the inverter-generator (the Panda 4000i): we connected 3 Multi's in parallel, boosting output power by nearly 300%.

The 1.8kW electric motor driving our air compressor had an inrush current approximately three times its running current. The smallest capacitor alternators (3-4kW rated) had insufficient peak power to handle this inrush current. We wanted to see if the Multi's would pick up the peak load, resulting in a smooth compressor start. We found that the voltage of the smallest capacitor generators dropped below the threshold for the Multi's, causing them to disconnect, at which point the Multis would pick up the load on their own.

As noted earlier, we found the induction cooker would trip out with frequency deviations of more than 4Hz. Without a Multi to assist, the smaller generators with mechanical governors had more trouble with the induction cooker than did the other generators.

3.2. Configuring Multi's or Quattro's for parallel operation with a generator

From previous experience we knew that in some cases special settings were needed to operate one or more Multi's in parallel with a generator. This has been confirmed by our testing and could be related to the different technologies (governor, type of alternator) on which the gensets were based. **One of the important results of our test is in fact that we can now predict the settings needed, based on the technology of the genset.** The genset related settings are discussed below. The settings are available on all of our Multi's and Quattro's, except for a special setting needed for the Onan 5.5 MDKBH-50Hz. This setting was finalized soon after our test and will become an optional setting in our VEConfigure software.

3.2.1. UPS feature

If this setting is 'on' and the AC input to the MultiPlus fails, the MultiPlus switches to inverter operation almost instantaneously. As such, the MultiPlus can be used as an Uninterruptible Power Supply (UPS) for sensitive equipment such as computers or communication systems.
However, the output voltage of some small generator sets is too unstable and distorted to use this setting – the MultiPlus will continually switch to inverter operation. To prevent this, the UPS setting needs to be turned off. The MultiPlus will respond less quickly to AC input voltage deviations. The switchover time to inverter operation is slightly longer, but most equipment (computers, clocks or household equipment) will not be adversely impacted.

Recommendation: Turn the UPS feature off if the MultiPlus fails to synchronise, or continually switches back to inverter operation. More specifically:
- The UPS feature should in general be switched off in cases of parallel operation with generators fitted with a synchronous capacitor alternator or an asynchronous alternator.
- Generators with a synchronous AVR alternator have a better dynamic behavior. The UPS feature can therefore be left on more often. If the UPS feature is left on, we recommend setting the no load output voltage of the generator slightly above the nominal voltage (e. g. 235V or more in the case of a 230V model) in order to prevent disconnection of the Multi due to under voltage following a load change.

3.2.2. Dynamic current limiter

This setting has been developed for parallel operation with ‘inverter’ generators which reduce engine speed if the load is low, resulting in less noise, fuel consumption and pollution (this speed reduction is a feature of e.g. the portable Honda gensets). With the dynamic current limiter setting ‘on’, the MultiPlus will start supplying extra power at a low generator output level and gradually allow the generator to supply more until the set current limit is reached. This allows the generator’s engine to get up to speed when the load increases. This setting is also often used for ‘classic’ generators that respond slowly to sudden load variations.

Recommendation:

- During our test we found that this setting should be switched on when operating Multi’s/Quattro’s in parallel with generators fitted with a synchronous capacitor alternator or an asynchronous alternator.
- The dynamic current limiter setting should also be “on” in cases of parallel operation with an inverter generator that is fitted with the variable speed feature, such as the Honda EX7, EU10i and EU20i (not included in the present test). The 4000i from Fischer Panda has a fixed rpm, so this setting can be left “off”.

3.2.3. WeakAC

A badly distorted input voltage waveform from a generator can result in the MultiPlus charger barely operating or not operating at all. If the WeakAC setting is turned “on”, the charger will accept seriously distorted voltage, at the cost of a greater distortion of the input current.

Recommendation: Turn WeakAC on if the charger is barely charging or not charging at all (which is quite rare and was not experienced with any of the generators in this test). Also turn on the dynamic current limiter simultaneously, and reduce the maximum charging current to prevent overloading the generator if necessary.

3.2.4. AC input current limit

This is the AC current limit setting at which PowerControl and PowerAssist come into operation.

PowerControl maximises the use of limited shore current or generator output**.** Because the MultiPlus/Quattro can supply a huge charging current, it can place a heavy load on the shore connection or a generator. Using PowerControl, a maximum total current demand can be set (i.e. onboard load plus charging load). The MultiPlus/Quattro limits the charging current to whatever is available up to this current limit once the onboard AC load has been met.

PowerAssist extends the use of your generator and shore current through the MultiPlus/Quattro “co-supply” feature. This feature takes the principle of PowerControl to a further dimension, allowing the MultiPlus/Quattro to supplement the capacity of the shore current or generator. If the AC load exceeds the maximum current demand set by PowerControl, the MultiPlus/Quattro picks up the excess demand. Where peak power is required only for a limited period, the MultiPlus/Quattro makes sure that insufficient shore or generator power is immediately compensated for by power from the battery. When the load reduces, the spare shore or generator power is used to recharge the battery.

Recommendation: for all generators, set the AC input current limit no higher than the generator’s maximum recommended **continuous** rating (not the intermittent or peak rating).
Mastervolt and Fischer Panda specifically recommend in their manuals that in order to prolong the generating set’s life expectancy, the nominal electrical demand on the genset should be limited to about 70% of the rated maximum load.

3.3. The test set-up

The test rig consisted of three Multi's 24/3000/70 connected to a 24V/400Ah AGM battery bank. With our VE.Bus Quick Configure software we could configure the Multi's for stand alone, two modules in parallel or three modules in parallel operation in a matter of seconds. This enabled us to quickly determine the maximum acceptable number of modules that still resulted in stable operation of the system. The largest generators tested would have accepted more parallel power. We could have supplied this with the parallel Quattro test rig, but unfortunately it was not available in time to be part of the test program.

We measured voltage and current on two digital memory oscilloscopes, one at the generator output, and one at the system output (see Figure 5 below).

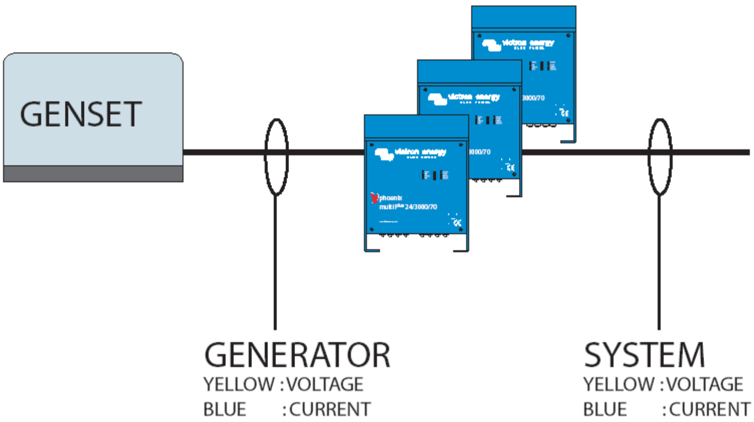
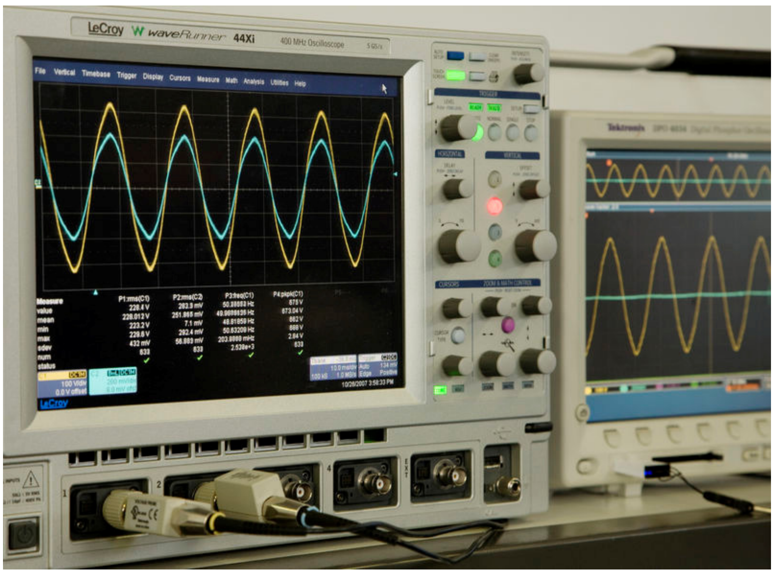


Figure 5: Voltage and current measuring points

The responses of the different generators to our tests are described in paragraphs 3.4 to 3.8. In paragraph 3.9 measurements regarding the dynamic behavior of two generators are looked at in more detail. High temperature tests of the same 2 generators are discussed in paragraph 3.10.

In the following graphs, those that depict 'system' voltage and amps are recording the volts and amps downstream of the generator and inverters. Generally, this involves paralleled generator and Multi outputs. Those graphs that depict generator voltage and amps are measuring the output of the generator.

Photo 4: Two digital oscilloscopes were available to capture waveforms and dynamic stability.



3.4. Low power generators: 3kW - 4kW

The group of low power generators:

Model	rpm	rating	engine	cyl	governor	AC alternator	List price
Fischer Panda 4000i	2800	3,5kW	Kubota EA300	1	electronic	Inverter	7.072 €
Kohler 3.5 EFOZ	3000	3,2kW	Farymann 18W435	1	mechanical	Synchr cap	7.595 €
Mastervolt Whisper 3.5	3000	3kW	Kubota OC60	1	mechanical	Synchr cap	6.292 €
Onan 4.0 MDKBH-50Hz	2400	4kW	Kubota Z402-ESO2	2	electronic	Synchr AVR	6.980 €
Paguro 4000	3000	3,5kW	Farymann 18W435	1	mechanical	Synchr cap	6.400 €

3.4.1. Fischer Panda 4000i

The Panda 4000i is an “inverter generator”. An engine driven permanent magnet alternator produces relatively high frequency AC at 400-500V. This is rectified and then fed to a static transformer less DC to AC inverter.
The advantages are:
- Output frequency independent of engine rpm.
- Excellent frequency and voltage stability because of static inverter technology.
- Excellent overload capacity (dependent on sizing of the static inverter).
- The permanent magnet DC generator is smaller and lighter than a traditional AC generator.

The Fisher Panda 4000i was also (by far) the quietest unit of the low power units tested.

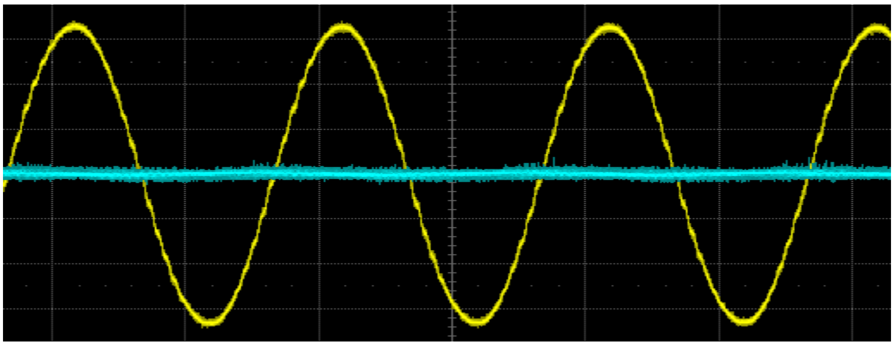
Oscilloscope pictures:

24cro30

Stand alone
No load

Yellow: voltage
Blue: current

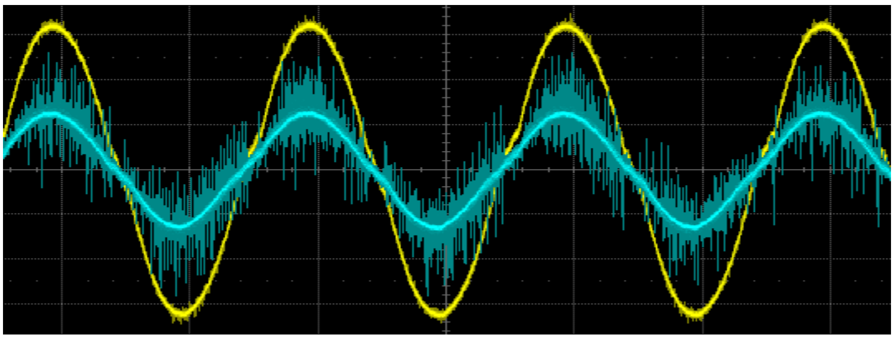
Note the pure sine wave voltage curve



24cro33

Stand alone
With full rated resistive load: 4kW

(max continuous load is 3,5kW)



Note: EMC filter missing, resulting in high frequency disturbance on current signal.

Max output power: 4kW (engine stalls at higher load)

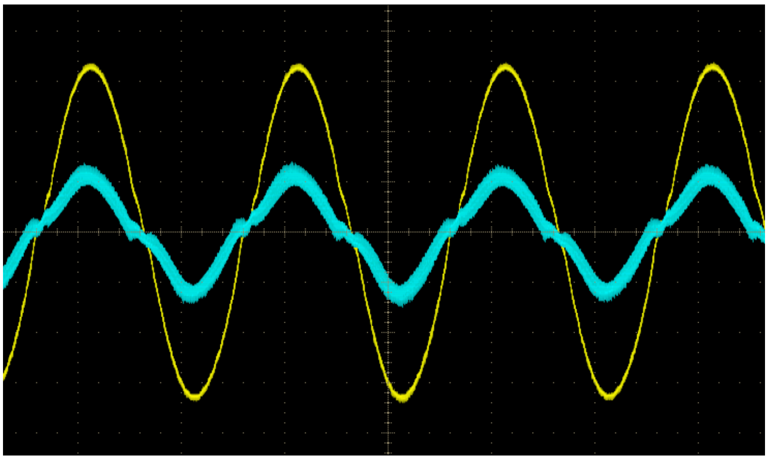
The Panda 4000i started the 1,8kW compressor on its own.
According to Fischer Panda the 4000i also starts the popular Bauer Junior II diving compressor with a 2,2kW electric motor.

We tested parallel operation with 3 Multi's in parallel, up to a total load of 12kW, including the 7kW induction cooker.

24tec49

Operation with three Multi's in parallel in charger mode
Charging current 120A@27V (3.24 kW)

Yellow: genset output voltage
Blue: genset output current (17A/4kW)



Conclusion:
The "output stage" of the Panda 4000i is a static inverter with excellent peak power capacity and wave form. Parallel operation with Multi's or Quattro's is possible up to at least a total 12kW system load (i.e. 300% of the generator's rated output). The Panda 4000i is therefore the most compact and efficient AC generator for applications where the required peak power is high and the average power is low, such as a 12-15 meter boat with an "all electric" galley.

Photo 3: Test bench with three MultiPlus 24/3000/70

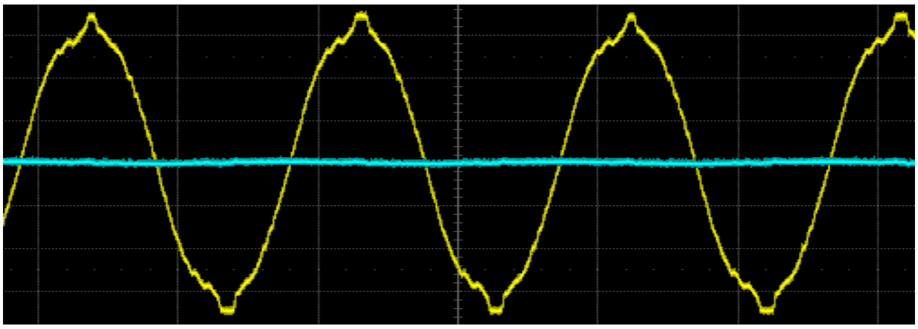
3.4.2. Kohler 3.5 EFOZ, Mastervolt Whisper 3.5, Paguro 4000

These three gensets all have mechanical governors and a synchronous capacitor generator. Behavior is therefore very similar to each other.

Oscilloscope pictures:

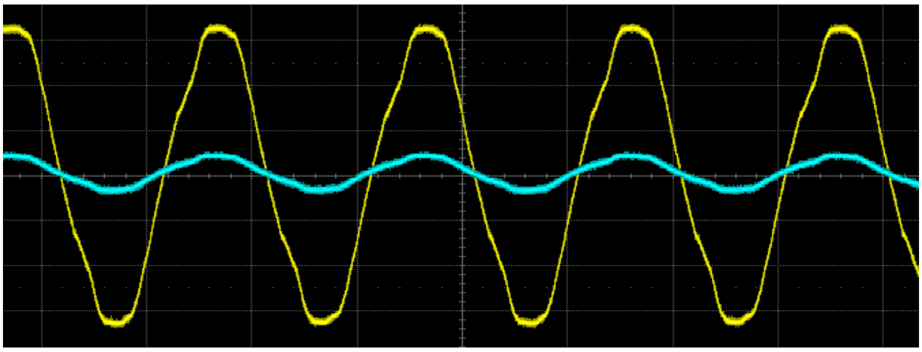
Mastervolt, 24cro11

Stand alone
No load



Paguro, 25cro53

Stand alone with full rated resistive load



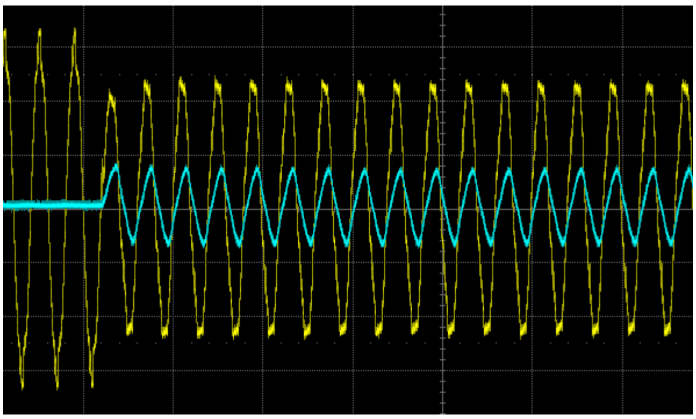
Note: to get a sense of waveform distortion, compare these voltage waveforms to the true sine wave output of the Panda 4000i.

Maximum short term output power measured (the output voltage would reduce to less than 210V at higher loads)

Model	rpm	rating	Max. output measured at 210VAC
Kohler 3.5 EFOZ	3000	3,2kW	3,2kW
Mastervolt Whisper 3.5	3000	3kW	2,7kW
Paguro 4000	3000	3,5kW	3,8kW

Paguro, 25cro54

Stand alone
The gensets did not start the 1,8kW compressor
(Note: according to the manufacturer Volpi Tecno Energia S.r.l. the Paguro 4000 does start the Bauer Junior II diving compressor with a 2,2kW electric motor)



Compressor is switched on here but does not start, therefore current remains high and voltage remains low.

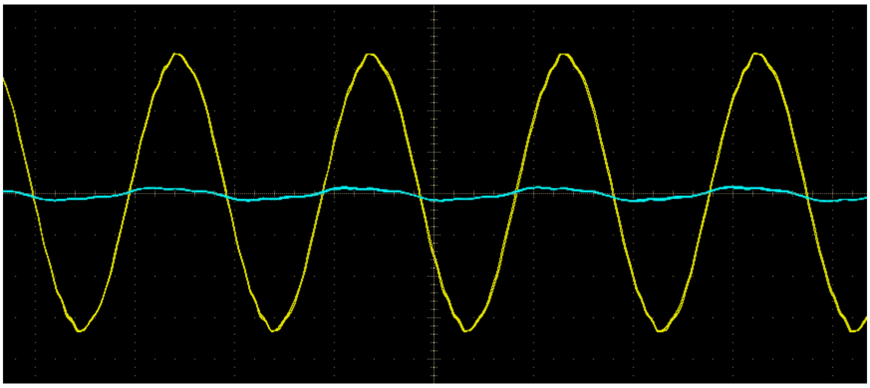
The gensets functioned well in combination with one Multi. Operation tended to be unstable with two Multi's. Parallel operation with a Multi improved the wave form. Parallel operation was tested up to 5.4kW resistive load, and with two induction hobs (5kW).

Kohler, 26tec64

With one Multi in parallel

System output

Low charging current (7A)



Kohler, 26cro65

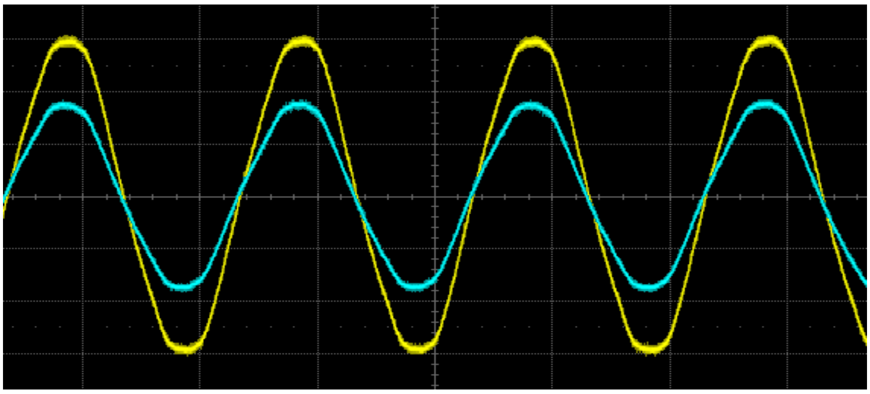
With one Multi in parallel

System output

Resistive load of 5,4kW

PowerAssist set at 13A (3kW) with Multi picking up 2.4 kW

Battery discharge current (to power the Multi): 124A at 24,7V



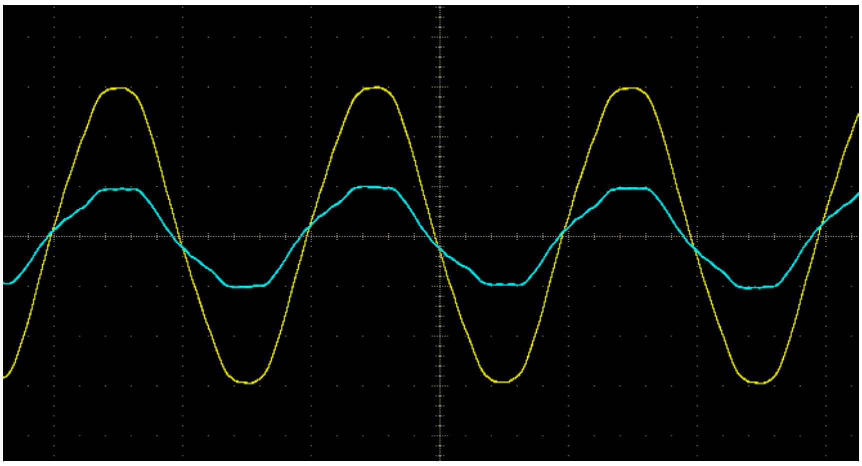
Kohler, 26tec65

With one Multi in parallel

Generator output

Resistive load of 5,4kW

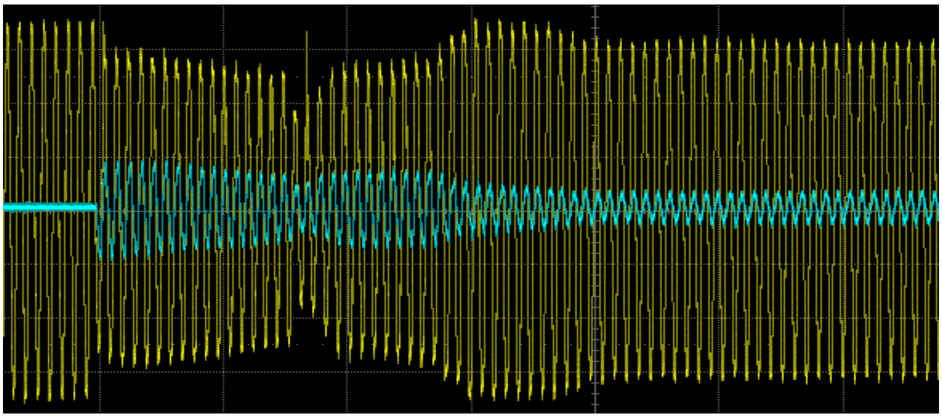
Voltage is identical to the previous picture, but the current (blue line) is output current of the genset only, limited to 13A by the Multi's PowerControl function



Note how the Multi has improved the waveform.

The 1,8kW compressor was started with one Multi in parallel, but in the process the Multi disconnected from the genset because of low generator voltage (despite the UPS setting being off) and switched to independent inverter mode, carrying the load.

25cro55

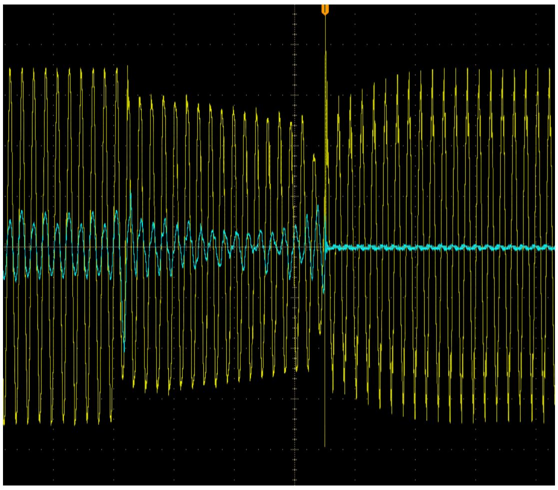


System output with one Multi in parallel

Compressor 1,8kW

Compressor starts, but note the dip in voltage (yellow line). It causes the Multi to disconnect from the generator and carry the load.

25tec58



Generator output with one Multi in parallel

Compressor 1,8kW

Compressor starts on Multi, after disconnection from generator

Note the falling generator voltage (yellow) as the system tries to start the compressor which causes the Multi to disconnect, switching into independent inverter mode, at which point it takes over the compressor load and starts it, while the load on the generator falls to almost nothing (the straight blue line) and the voltage recovers.
The Multi reconnected to the genset and resumed parallel operation after a few seconds.

Conclusion:
The Kohler 3.5 EFOZ, Mastervolt Whisper 3.5 and Paguro 4000 have limited overload capacity, in accordance with the synchronous capacitor alternator technology employed. The Multi would disconnect from the generator under high start-up loads, pick up the load itself, and then reconnect.

Interference between rpm, genset output voltage and Multi load results in unstable operation when more than one Multi is connected.

3.4.3. Onan 4.0 MDKBH-50Hz

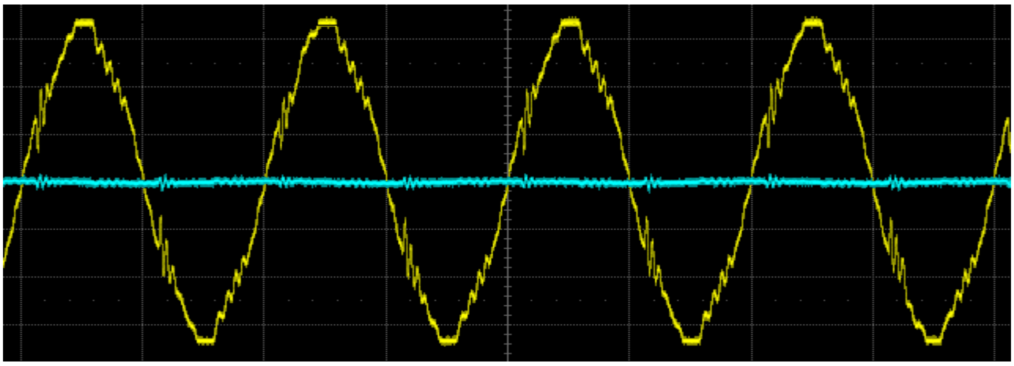
This Onan genset is fitted with an electronic governor. It behaves differently from all other gensets tested, as shown on the THD graph. Another unique feature is the indirect drive, with the engine at 2400rpm and the AC generator at 3000rpm.

Oscilloscope pictures

24cro23

Stand alone

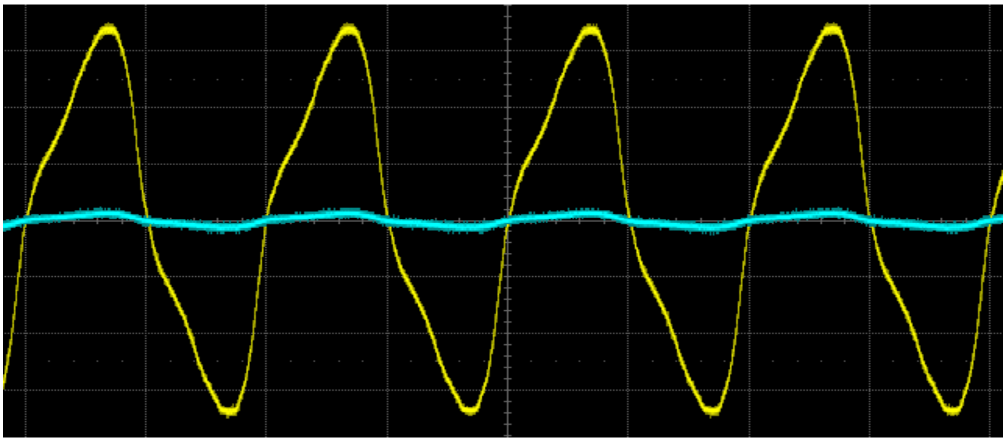
No load



24cro25

Stand alone

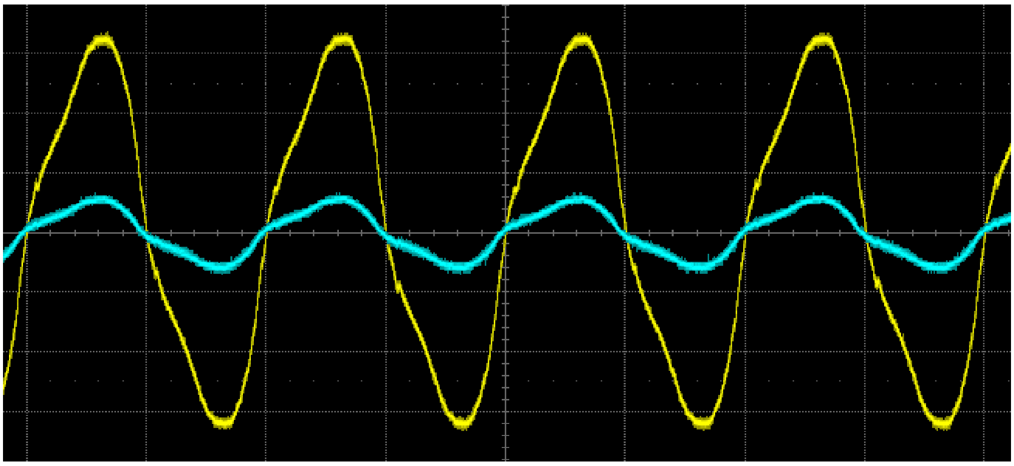
Load 1,8kW resistive



24cro24

Stand alone

Load 3,7kW resistive



Maximum output power measured: 3,7Kw (after which the voltage would drop below 210 volts)

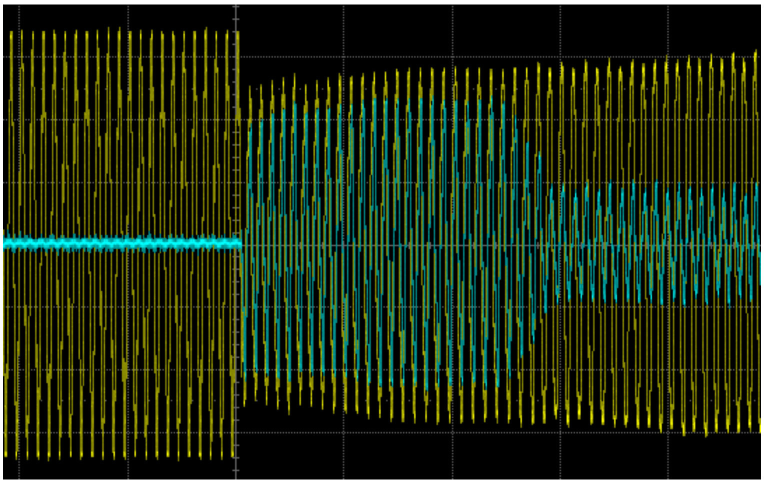
The oscilloscope pictures confirm that distortion increases with load (see THD, Graph 9) which is the opposite of the other generators tested. All professional and household equipment will however function on such a wave form.

24cro26

Stand alone

Starts the 1,8kW compressor

When the compressor is turned on, the high inrush current drops the voltage. Once the compressor is running, the current (amps) falls and the voltage recovers

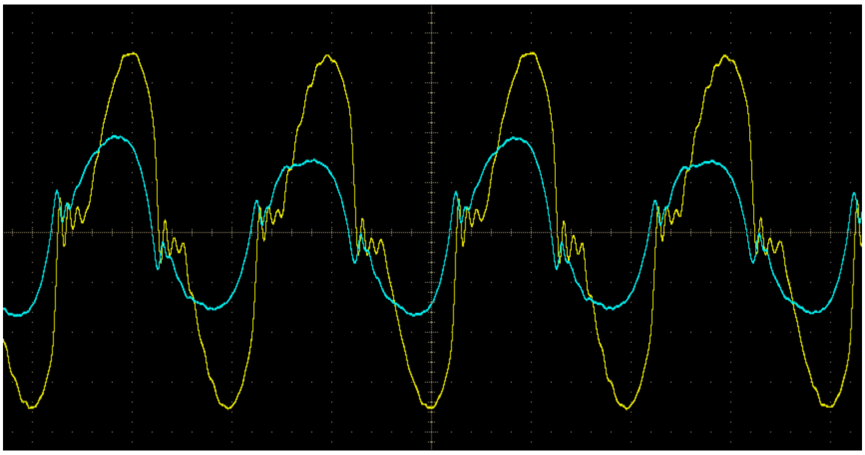


Parallel operation with a Multi improved the wave form, except when charging batteries: see wave form below. Parallel operation was tested up to 10kW resistive load (including a 7kW inductive cooker load).

24tec45

With two Multi's in parallel

Generator output
Charging at 27V/100A (2.7kW)
Note the degradation of the wave form



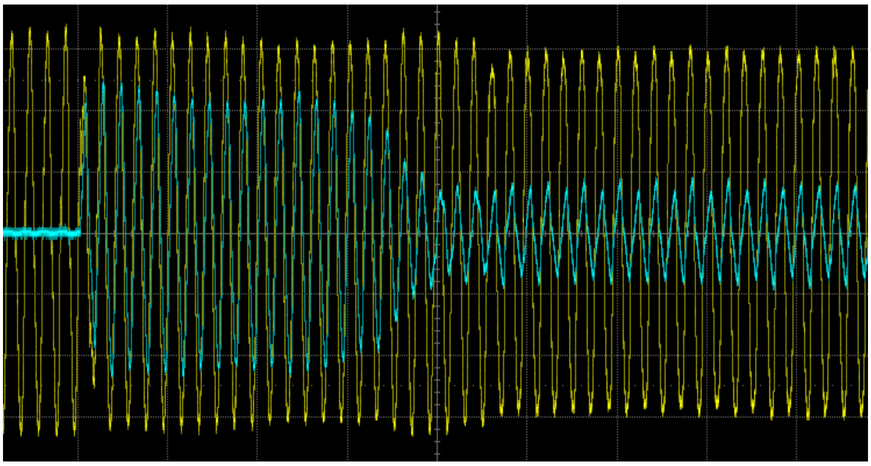
Starting the 1,8kW compressor with two Multi's in parallel

With two Multi's parallel

1,8kW compressor

System output: the blue line shows the high inrush current needed to start the compressor

24tec46

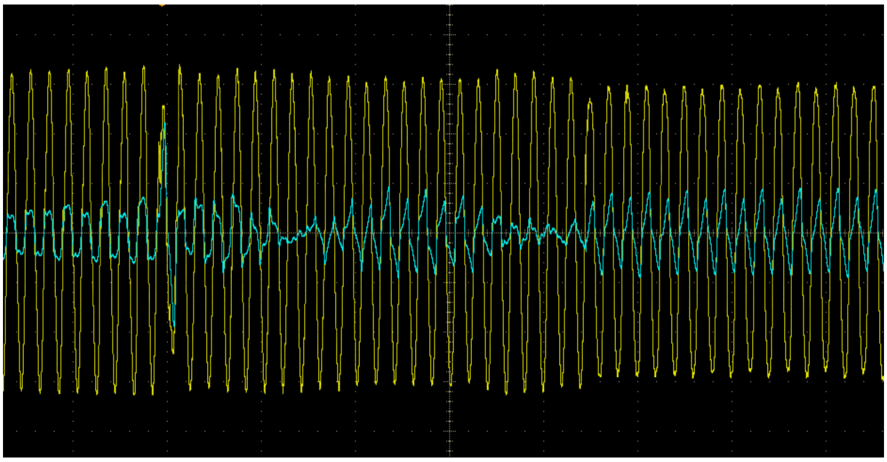


24cro29

With two Multi's parallel

1,8kW compressor

Generator output: note how the generator current and voltage is more-or-less constant. The inrush current shown in the graph above has been picked up by the Multi.



Conclusion:
Due to the distortion of the output voltage, a special "Onan 5.5 MDKBH" setting of the Multis was needed to achieve proper parallel operation. This special setting will be included as an option in our VE-Configure software. With this special setting the genset functioned well in combination with one or two Multi's. Operation was unstable with more than two Multi's.

3.5. Other 3000rpm generators

Model	rpm	rating	engine	cyl	governor	AC alternator	List price
Fischer Panda 8000	3000	6,1kW	Kubota Z482	2	mech/servo	Asynchr	9.423 €
Fischer Panda 12000	3000	9,2kW	Kubota D722	3	mech/servo	Asynchr	11.523 €
Mastervolt Whisper 8	3000	6,4kW	Mitsubishi L2E	2	electronic	Synchr cap	9.802 €
SAIM Dynamica Mini-60 MK2	3000	5,8kW	Perkins 402C-05	2	mechanical	Synchr cap	10.200 €

The Fischer Panda units have an asynchronous alternator, whereas the Mastervolt and SAIM Dynamica unit are fitted with a synchronous capacitor alternator.

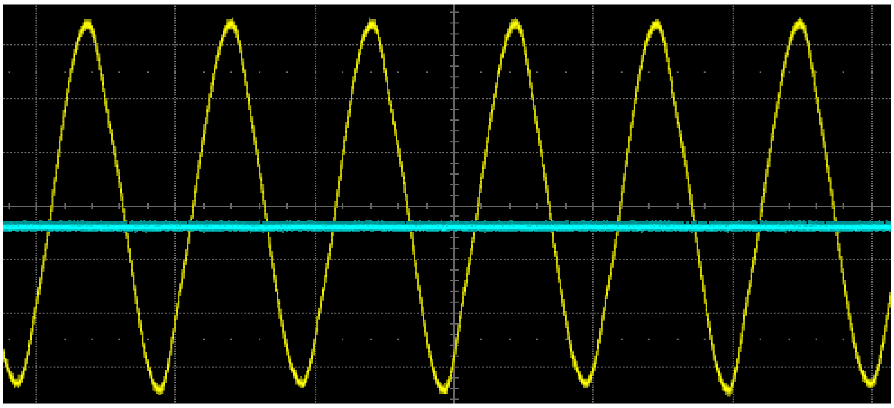
3.5.1 Fischer Panda 8000 and Fischer Panda 12000

Oscilloscope pictures:

Both units produced a very "clean" sine wave. The two pictures below are representative for both models.

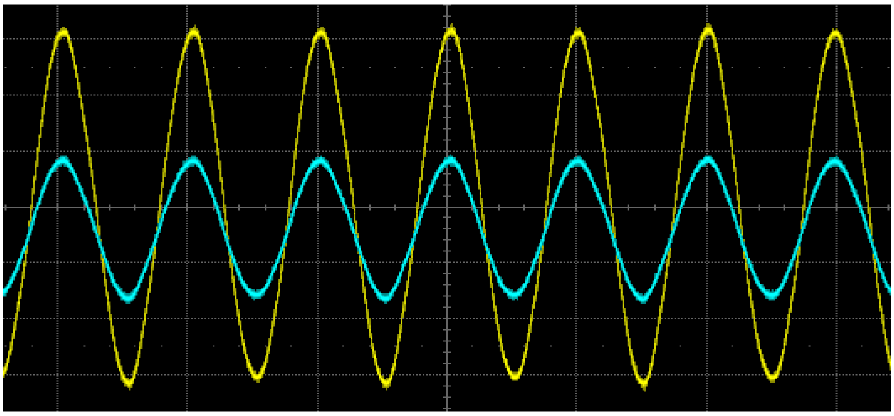
Panda 12000, 24cro34

Stand alone
No load



Panda 12000, 24cro36

Stand alone with full rated resistive load



Maximum short term output power measured (the output voltage would reduce to less than 210V or the engine would stall at higher loads)

Model	rpm	rating	Max short term output measured
Fischer Panda 8000	3000	6,1kW	6,4kW
Fischer Panda 12000	3000	9,2kW	9,7kW

Both units started the 1,8kW compressor and powered the induction cooker.

The Panda 8000 runs well with a maximum of one Multi, the Panda 1200 with a maximum of three Multi's

The Panda 8000 paralleled with one Multi was tested with the induction cooker (7kW) and additional resistive loads up to 10kW. The Panda 12000 paralleled with three Multi's was tested with the induction cooker (7kW) and additional resistive loads up to 15kW.

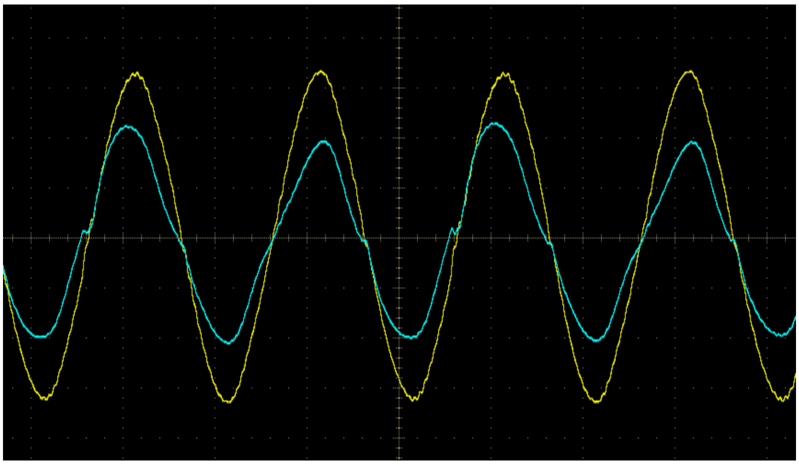
Oscilloscope picture of the Panda 12000 with three Multi's in parallel, in battery charging mode:

Panda 1200, total24tec51

Three Multi's in parallel

Generator output

Charge current
27V/180A
(4.8kW)



Conclusion:
As with the Panda 4000i, the Panda 8000 and 12000 have a clean waveform, and can be paralleled with one or more Multis for a system peak load of between 150% (Panda 8000) and 200% (Panda 12000) of the generators' full rated load.

3.5.2. Mastervolt Whisper 8 and SAIM Dynamica Mini-60 MK2
Both models are fitted with a synchronous capacitor alternator; see Part 1, paragraph 2.3.2.

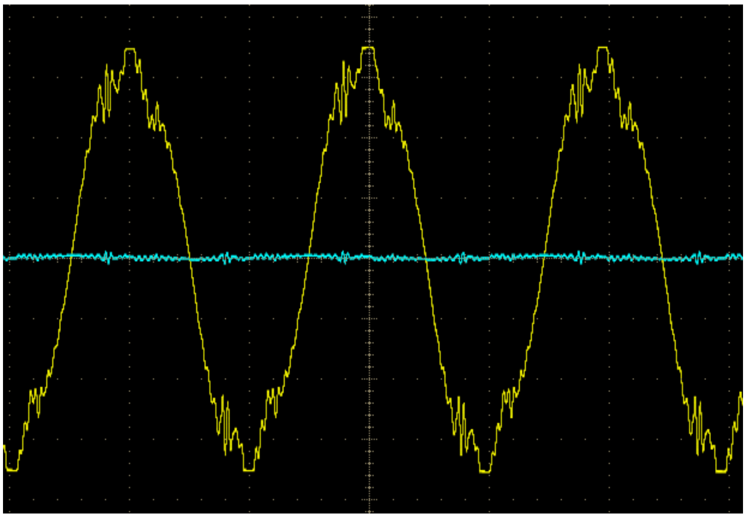
Oscilloscope pictures

The two pictures below are representative of stand alone operation with both models.

Mastervolt, 23tec16

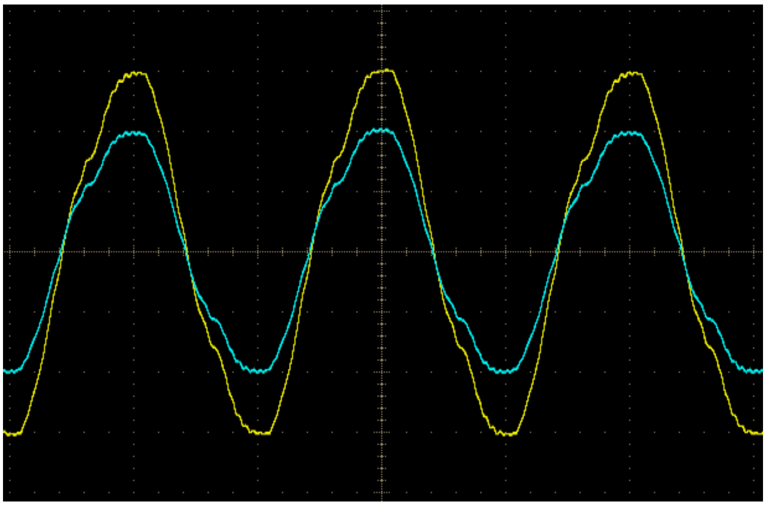
Stand alone

No load



Mastervolt, 23tec18

Stand alone with maximum resistive load (6,3kW)
After which the voltage drops to less than 210V



Maximum short term output power measured (the output voltage would reduce to less than 210V or the engine would stall at higher loads)

Model	rpm	rating	Max short term load measured
Mastervolt Whisper 8	3000	6,4kW	6,3kW
SAIM Dynamica Mini-60 MK2	3000	5,8kW	5kW

Both units started the 1,8kW compressor and powered the induction cooker up to 6kW

Both units ran well with 1 Multi in parallel. They were tested with the induction cooker (7kW) and additional loads up to 9kW.
The Multi's did improve the waveform.

3.6. 1500rpm models with the Mitsubishi L3E engine

Three of the gensets we tested had the same engine. A good reason to discuss these gensets together.

Model	rpm	rating	engine	cyl	governor	AC alternator	List price
BW Generator Techniek 615 SIKSE	1500	5,2kW	Mitsubishi L3E	3	electronic	Synchr AVR	10.005 €
Mastervolt Whisper 6 ULTRA	1500	5,7kW	Mitsubishi L3E	3	mechanical	Synchr cap	9.984 €
Westerbeke 5.7EDT	1500	5,7kW	Mitsubishi L3E	3	electronic	Synchr AVR	9.785 €

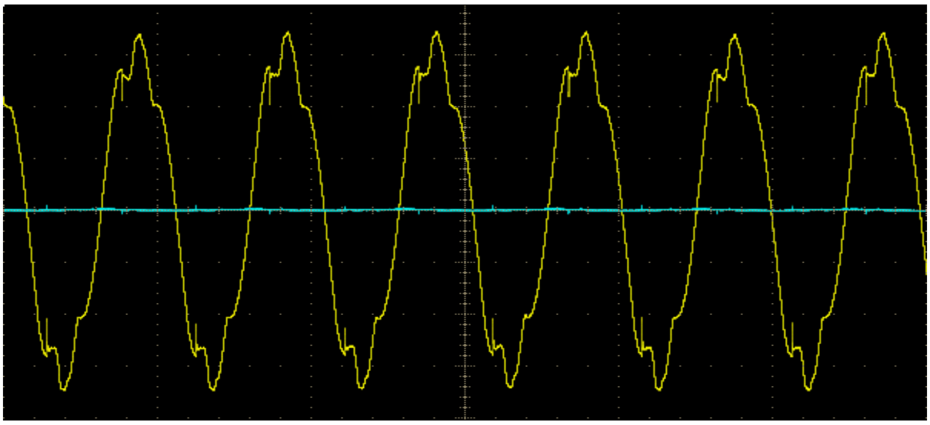
The Mastervolt genset has a mechanical governor and a synchronous capacitor alternator, whereas the other two gensets are fitted with electronic governors and a synchronous AVR alternator.

Oscilloscope pictures, stand alone operation:
One immediately recognizes the synchronous capacitor generator, the Mastervolt 6 Ultra, from its more distorted waveform.

Mastervolt, 23tec01

Mastervolt

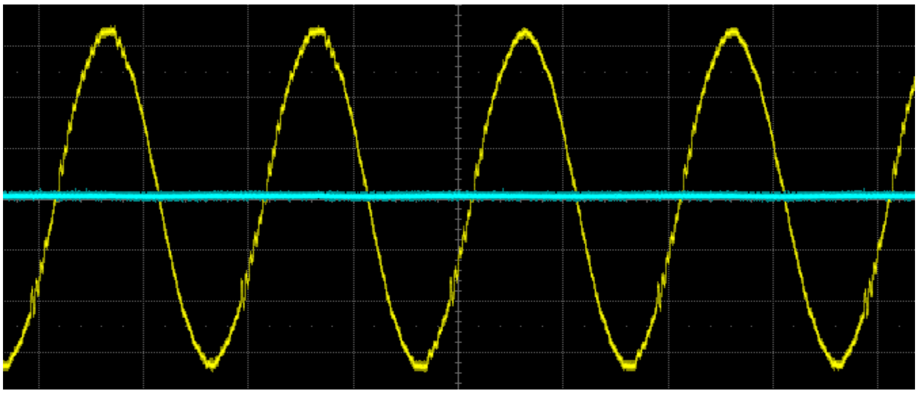
Output voltage, no load



BW Generator techniek, 01cro75

BW Generator techniek

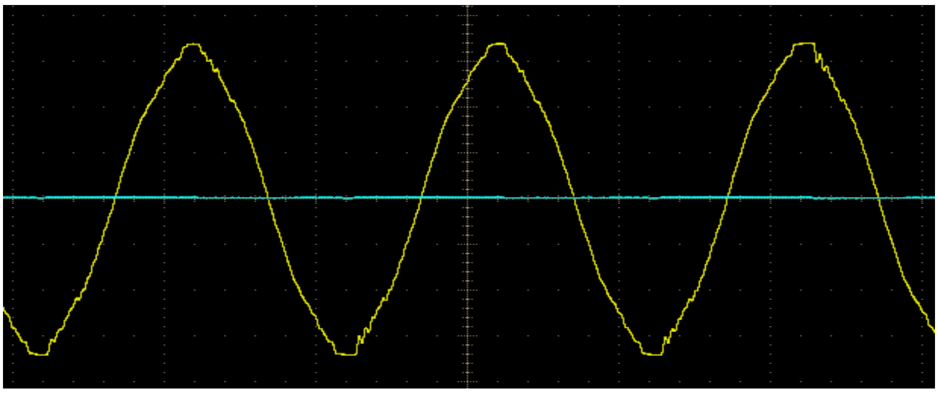
No load



Westerbeke, 23tec14

Westerbeke

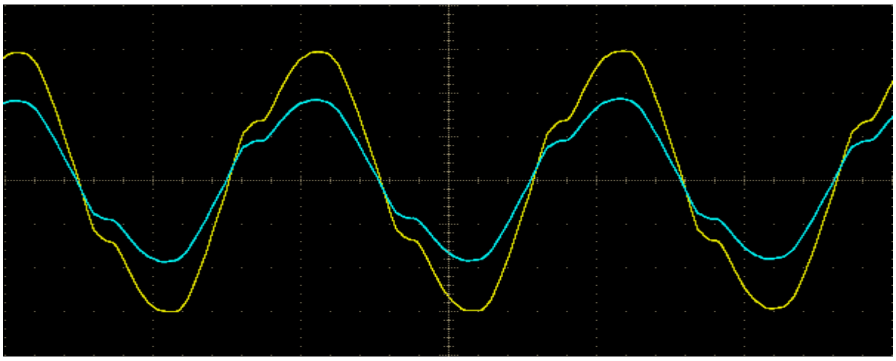
No load



Mastervolt, 23tec05

Mastervolt

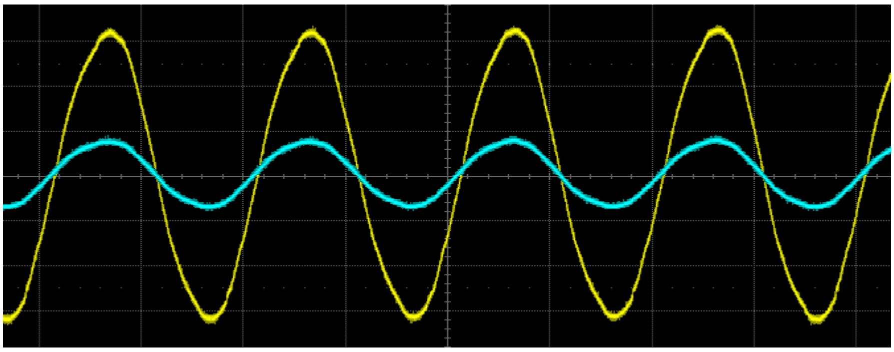
Stand alone with maximum resistive load (5kW) after which the output voltage drops to less than 210V



BW Generator techniek, 01cro77

BW Generator techniek
Load 6,1kW

Engine stalls at 6,3kW (same for Westerbeke)



Max load before engine would stall or the output voltage drop to less than 210V:

Model	rpm	rating	Max short term load
BW Generator Techniek 615 SIKSE	1500	5,2kW	6,3kW
Mastervolt Whisper 6 ULTRA	1500	5,7kW	5kW
Westerbeke 5.7EDT	1500	5,7kW	6,3kW

Parallel operation with Multi's:

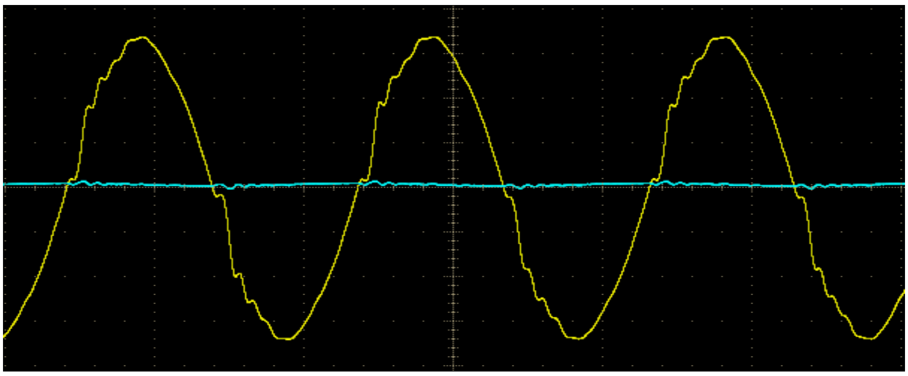
The gensets would operate with a maximum of two Multi's. They were tested with the induction cooker (7kW) and additional resistive loads up to 11kW

The following pictures show how the Multi's improve the waveform of the Mastevolt generator:

Mastervolt, 23tec07

With two Multi's

Generator output: no load
(compare with Mastervolt, stand alone, 23tec01)

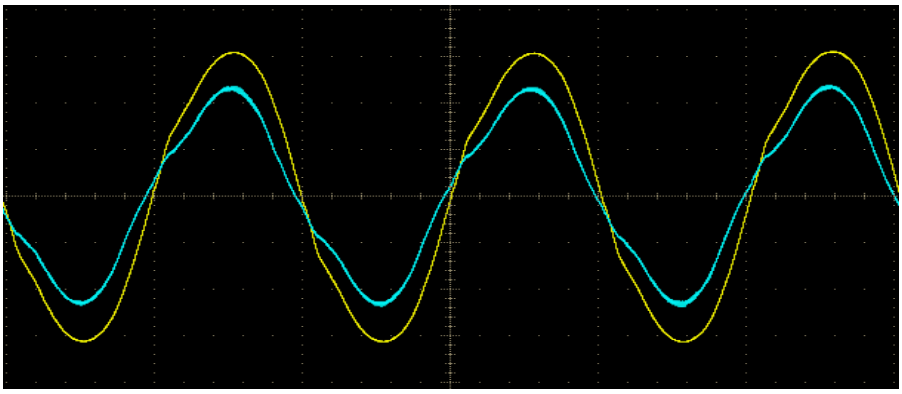


With two Multi's

Generator output:
Load = 7kW induction cooker

PowerAssist limit: 20A

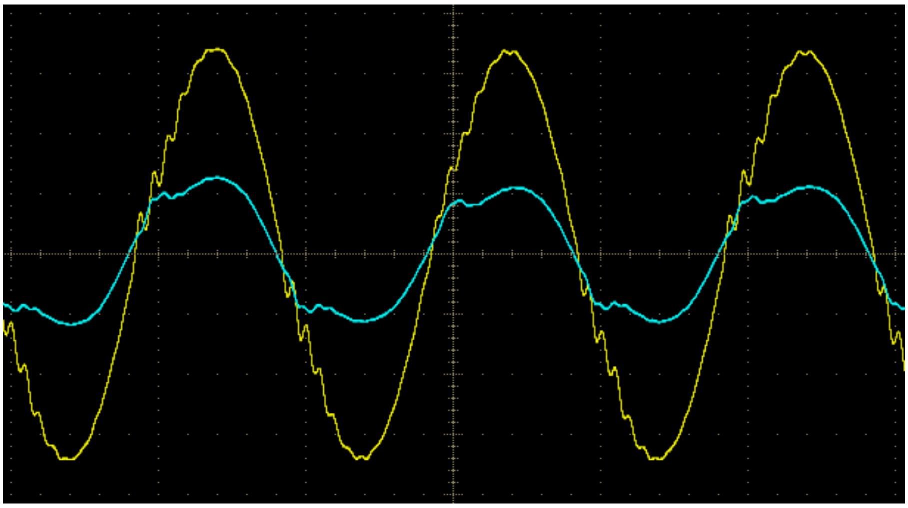
Mastervolt, 23tec08



With two Multi's

Multi's charging battery
Charge current 130A

Mastervolt, 23tec09



Conclusion:

- The AVR generators have a better waveform.
- BW underrates its genset. According to owner Jan Birza, this is to achieve optimum reliability and life expectancy under 24/7 operating conditions in professional marine applications like barges and fishing vessels.

3.7. 1500rpm Paguro 8500

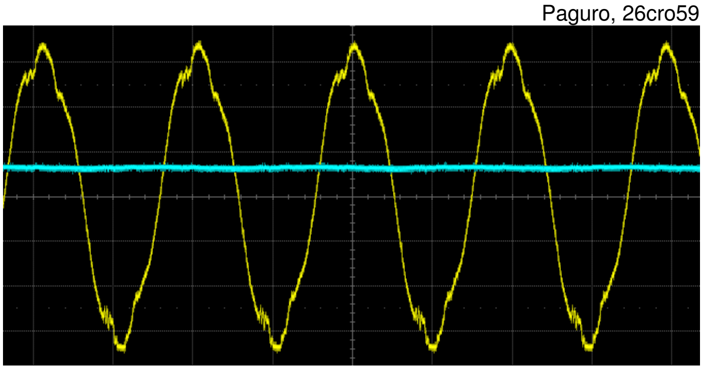
Paguro 8500	1500	8kW	Lombardini LDW1404LG	4	mechanical	Synchr cap	11.400€

The Paguro 8500 and Mastervolt ULTRA 6 were the only 1500rpm gensets with a synchronous capacitor alternator.

Oscilloscope pictures, stand alone operation:

Stand alone
No load

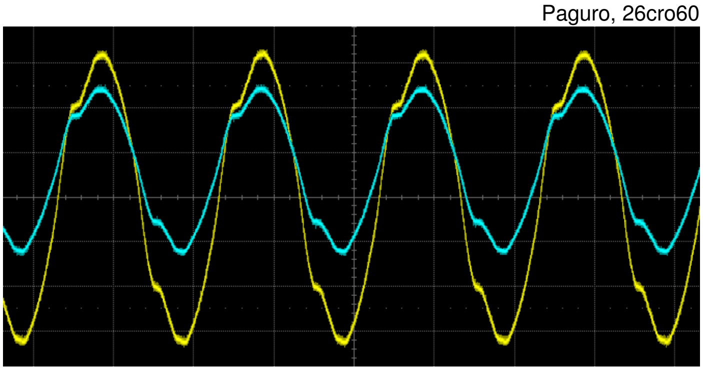
Paguro, 26cro59



Stand alone
Load 6kW

Max load 7,2kW, after which the output voltage drops to less than 210 volts.

Paguro, 26cro60



Unfortunately we could not get the Paguro to operate in parallel with Multi's: system frequency became unstable. Probably the frequency tracking response of the Multi's amplified the frequency correction of the mechanical governor of the Paguro 8500. We were not able to solve this problem during the test. According to the manufacturer Volpi Tecno Energia S.r.l., the Paguro 8500 needs to run for about 100 hours before the governor, which is integrated in the engine, works well.

3.8. Other 1500rpm generators

Model	rpm	rating	engine	cyl	governor	AC alternator	List price
Kohler 7 EFOZD	1500	6.5kW	Yanmar 3TNV76	3	mechanical	Synchr AVR	10.290 €
Northern Lights M673LD2	1500	4,5kW	Lugger L673L	3	mechanical	Synchr AVR	7.779 €
Northern Lights M773LW2	1500	7kW	Lugger L773L2	3	mechanical	Synchr AVR	10.010 €
Onan 7.0 MDKBL	1500	7kW	Kubota D1105-BG-ESO1	3	electronic	Synchr AVR	9.500 €
Onan 11.0 MDKBN	1500	11kW	Kubota V1505-BG-ESO1	4	electronic	Synchr AVR	11.600 €
Westerbeke 9.4EDT	1500	9,4kW	Mitsubishi S4L2	4	electronic	Synchr AVR	11.875 €

All these 1500rpm gensets have an AVR controlled alternator.
Onan and Westerbeke have an electronic governor.

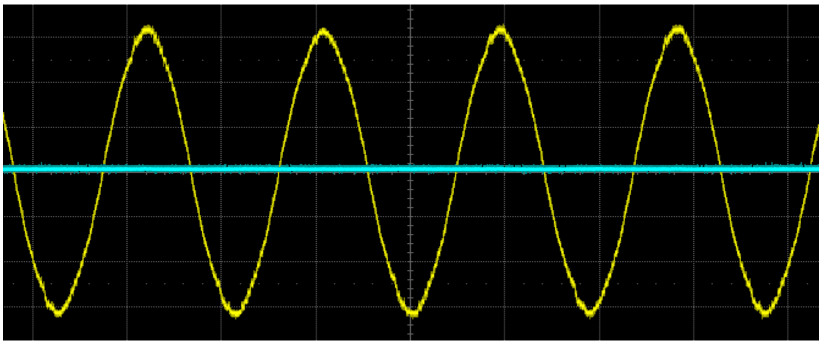
Some wave forms looked even better than others, but all were clearly of “AVR” quality.

Some oscilloscope pictures:

Northern Lights, 25cro50

Northern Lights M773LW2

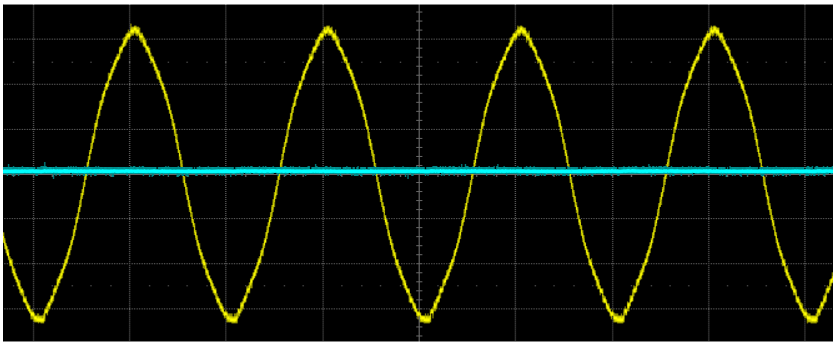
Stand alone
No load



Westerbeke, 25cro48

Westerbeke 9.4EDT

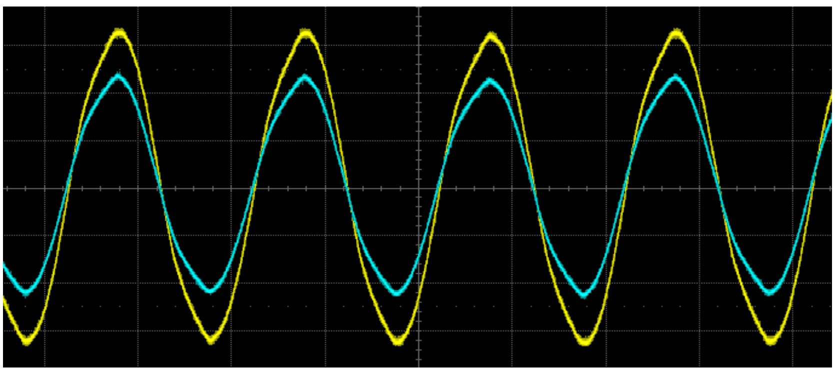
Stand alone
No load



Onan, 26cro73

Onan 7.OMDKBL

Stand alone
Max. resistive load 7,4kW



All models worked well with Multi's.

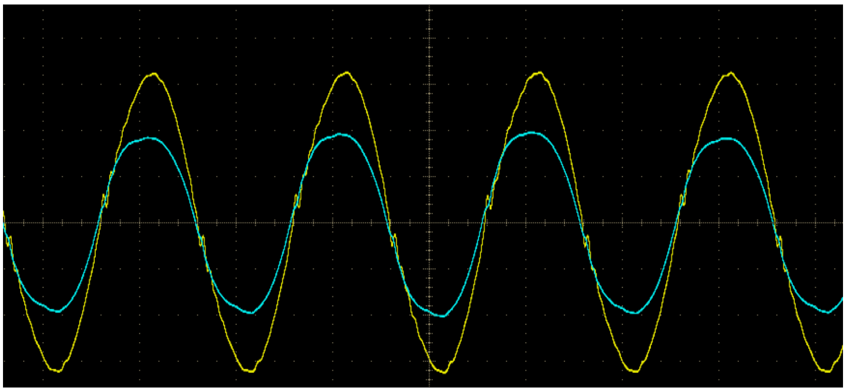
Example of parallel operation with three Multi's, in battery charging mode:

Westerbeke 9.4EDT

With three Multi's in parallel

Generator output Charging at 27V/180A (4.8kW)

Westerbeke, 25tec57



Results are summarized in the table below:

Model	rpm	rating	Max stand alone short term load	Max number of Multi's	Tested with resistive load up to
Kohler 7 EFOZD	1500	6.5kW	6kW	3	12kW
Northern Lights M673LD2	1500	4,5kW	4,8kW	2	9kW
Nortern Lights M773LW2	1500	7kW	7,2kW	3	15kW
Onan 7.0 MDKBL	1500	7kW	7,4kW	3	15kW
Onan 11.0 MDKBN	1500	11kW	10,5kW	3	15kW
Westerbeke 9.4EDT	1500	9,4kW	10kW	3	15kW

Note: We could not test with more than than 3 Multi's, because we had 3 Multi's on our test rig.
Also the maximum load we had available was limited to 15kW.

3.9. Dynamic response

3.9.1. Comparative dynamic response of "AVR" and "Capacitor" generators

In paragraphs 3.4 to 3.8 we report our findings regarding operation of generators with and without Multi's in parallel. We conclude from the tests that alternator technology is important. We found that generators equipped with a synchronous AVR alternator responded "better" to a sudden load change than generators equipped with a synchronous capacitor alternator or an asynchronous alternator. The UPS setting of the Multi's could be left on when paralleled with AVR alternators, but should switched off when paralleled with the other generators. (Switching off the UPS setting reduces sensitivity to voltage dips. The unwanted penalty is a longer voltage dip when the generator is stopped and the Multi has to take over the load.)

The most commonly used alternator technologies in the range of gensets tested were "AVR" and "Capacitor". We chose the following two generators that we thought were good representatives of these technologies to test the dynamic response in more detail:

Model	rpm	rating	Max stand alone short term load	Max number of Multi's	Tested with resistive load up to
Onan 7.0 MDKBL	1500	7kW	7,4kW	3	15kW
Mastervolt Whisper 6 ULTRA	1500	5,7kW	5kW*	2	11kW

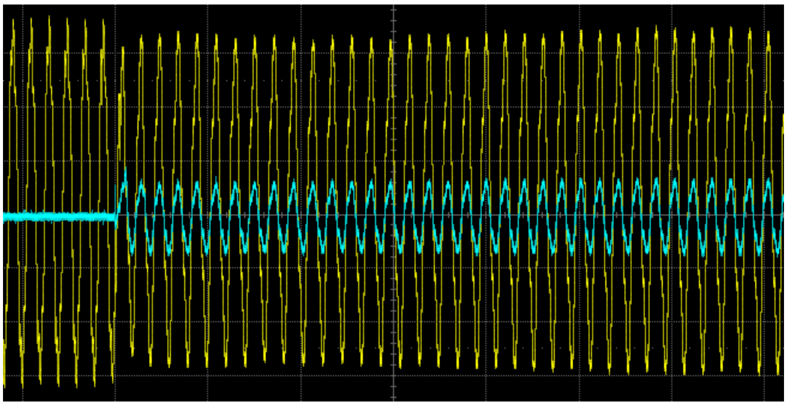
* after which the voltage drops below 210 volts

3.9.2. Stand alone operation, Mastervolt Whisper 6 ULTRA

09cro81

Load step from no load to 5kW resistive load (i.e. 5 kW resistive load turned on)

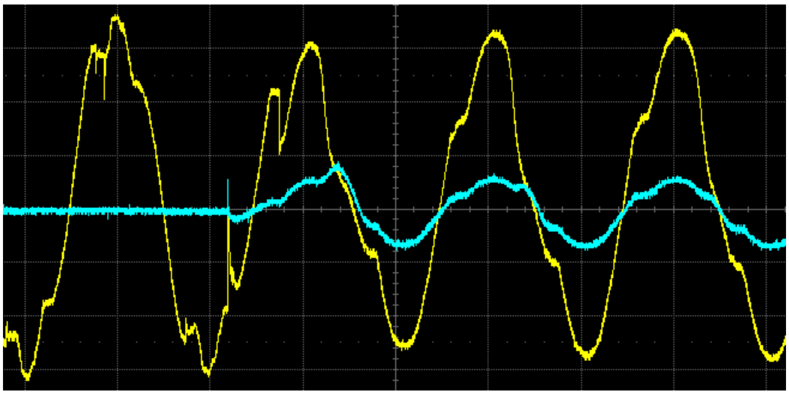
Voltage drops from 234V to about 200V during one cycle and then increases to 210V steady state.



09cro82

Load step from no load to 5kW resistive load

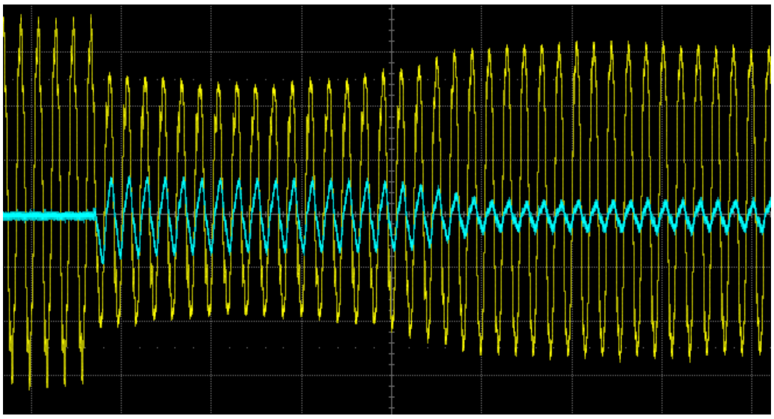
Expanded time base



09cro83

1,8kW compressor switched on. No other load

Voltage drops from 234V to about 155V during about 15 cycles and then increases to 210V steady state.

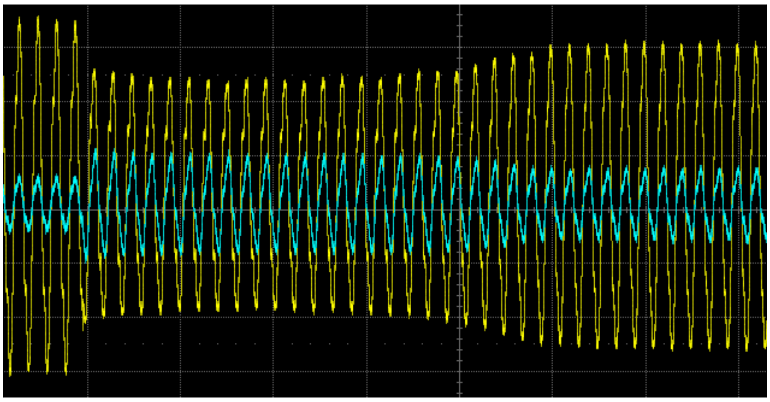


09cro79

Steady state load 3,7kW 1,8kW compressor switched on.

Surge load during compressor start-up:
3.7 + 5.4 = 9.1 kVA

Steady state load when compressor running:
3.7 + 1.8 = 5.5 kW

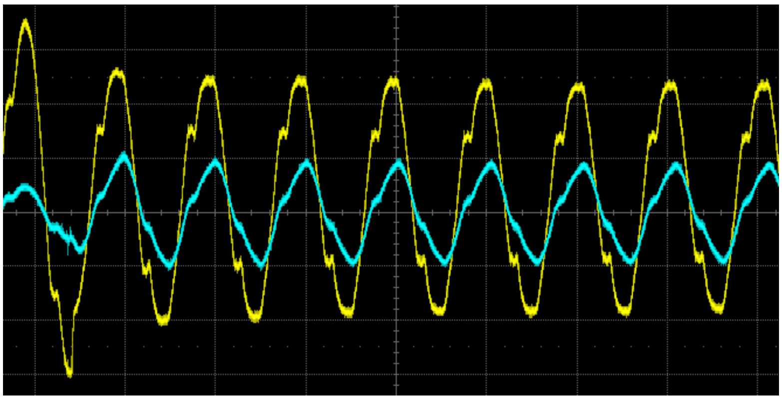


Voltage drops from 228V to about 165V during about 17 cycles and then increases to 205V steady state (load more than 5kW)

09cro8

Steady state load 3,7kW 1,8kW compressor switched on

Expanded time base

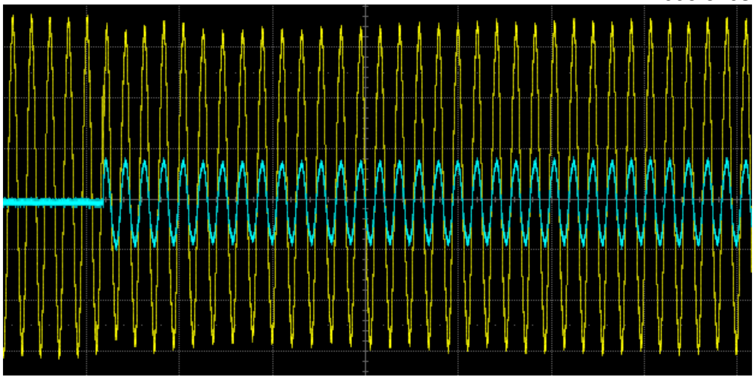


3.9.2. Stand alone operation, Onan 7.0 MDKBL

09cro103

Load step from no load to 7kW resistive load

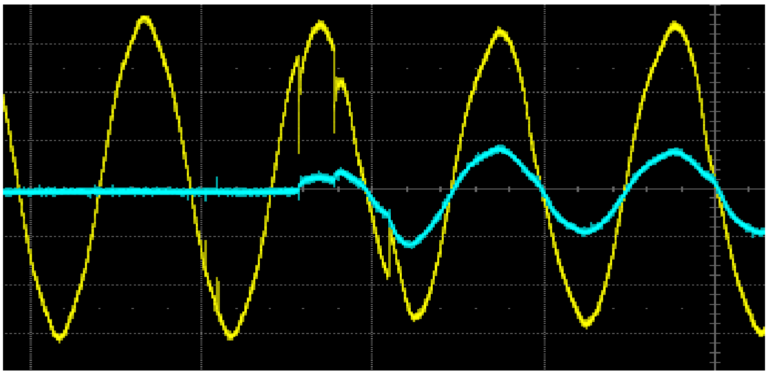
Voltage drops from 230V to about 207V and then increases to 228V steady state.



09cro104

Load step from no load to 7kW resistive load

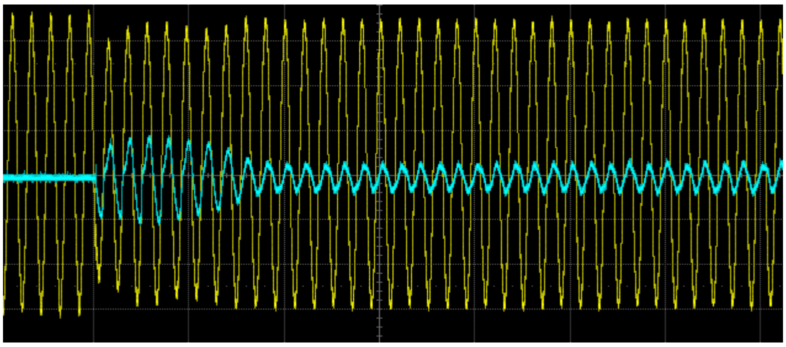
Expanded time base



09cro101

1,8kW compressor switched on. No other load

Voltage drops from 230V to about 186V during one cycle and then increases to 227V steady state.



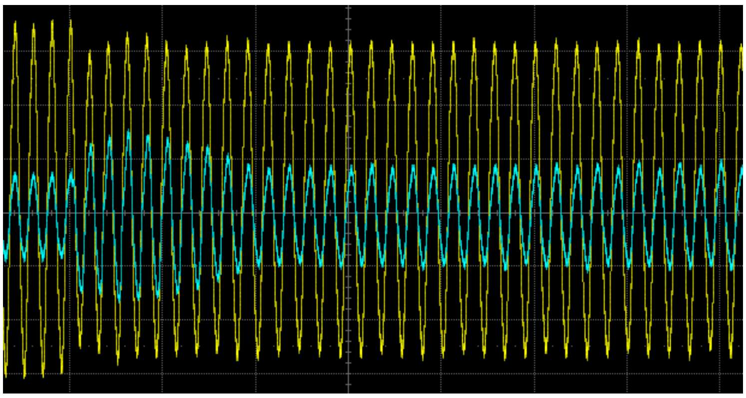
09cro98

Steady state load 6,3kW

1,8kW compressor switched on.

Surge load during compressor start-up: 6,3 + 5,4 = 11,7kVA

Steady state load when compressor running: 6,3 + 1,8 = 8,1kW



Voltage drops from 228V to about 192V and then increases to 210V steady state (generator in overload, engine stalls after a few minutes)

3.9.2. Stand alone operation, conclusion

Both gensets responded quite well when a resistive load was suddenly applied:

- The Mastervolt 6 ULTRA: voltage dropped from 234V at no load to about 200V (-14,5%) during one cycle when a resistive load of 5kW was applied.
- The Onan 7.0 MDKBL: voltage dropped from 230V at no load to about 207V (-10%) during one cycle when a resistive load of 7kW was applied.

Starting the 1,8kW compressor was quite another matter.

During start-up an electric motor draws a lot of current and at the same time has a low (lagging) power factor[2)]. Capacitor alternators are known to show a relatively large voltage drop when starting an electric motor (see par. 2.3.2)

- The Mastervolt 6 ULTRA, with a 3,7kW resistive load already connected: voltage drop from 228V to about 165V (-28%) during about 17 cycles (0,34 seconds). With no load connected prior to starting the compressor the result is even worse: the voltage drops 34% during 15 cycles (0,3 seconds).
- The Onan 7.0 MDKBL, with a 6,3kW resistive load already connected: voltage drop from 228V to about 192V (-16%) during about 1 cycle (0,02 seconds). During the start-up period the load on the Onan was 6,3 + 5,4 = 11,7kVA, which means an overload of 11,7 – 7 = 4,7kVA.

The 1,8kW (2,5 Hp / 8 Amp) single phase compressor motor that we used for our tests is not uncommon onboard boats:

- A 13 meter cruiser is typically cooled with a 24.000 BTU (7kW cooling capacity) air conditioner powered by a 1,8kW motor. The locked rotor amps (= start-up current) of such a motor will range from 300% (the motor in our tests) up to 600% (!) of running Amps, depending on brand and application.
- The popular Bauer Junior II diving compressor is equipped with a 2,2kW motor
- A 100 liter / hour watermaker is typically powered by a 2,2kW motor.

A voltage of 165V or even less for several cycles will affect other equipment: computers may reset, as well as modern household equipment such as electric cookers, washing machines or dishwashers.

3.9.3 Mastervolt 6 ULTRA with two Multi's in parallel

We first tried to run the system with the UPS setting on, and the dynamic current limiter (DCL) setting off. With these settings the Multi's would not connect to the generator because of the distorted wave form.

We then turned the UPS setting off, and kept the DCL off. Under these conditions we could run the system with resistive loads. When starting the compressor, however, the Multi's disconnected from the generator. The compressor started on the Multi's, and the system reconnected after about 20s. Disconnection is acceptable as long as the system load does not exceed the capacity of the two Multi's. Disconnection in the case of a total load exceeding the capacity of the two Multi's (up to the sum of the generator + Multi's = 10kW) would result in overload of the Multi's.

With the UPS setting off and the DCL setting on, the Multis never disconnected.

See pictures below.

[2)] Due to this lagging power factor the true load (in kW) is substantially lower than the apparent load (in kVA). The 300% start-up current drawn by the motor therefore translates, strictly speaking, to a start up load of 5,4kVA and not 5,4kW.

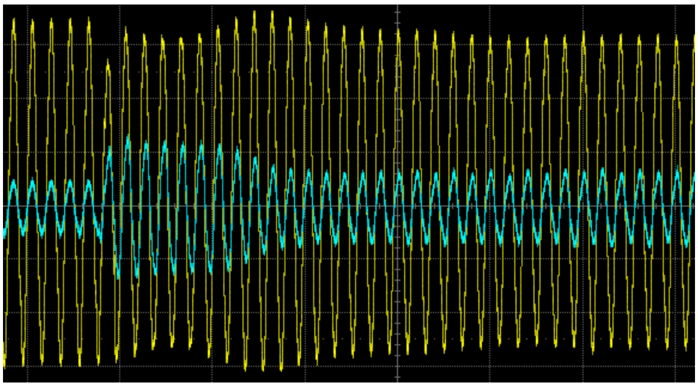
09cro92

System output

Steady state load 4,4kW
1,8kW compressor switched on.

Dynamic response much better than without Multi's (compare with 09cro79)

Total load during compressor start-up:
4,4 + 5,4 = 9,8kVA



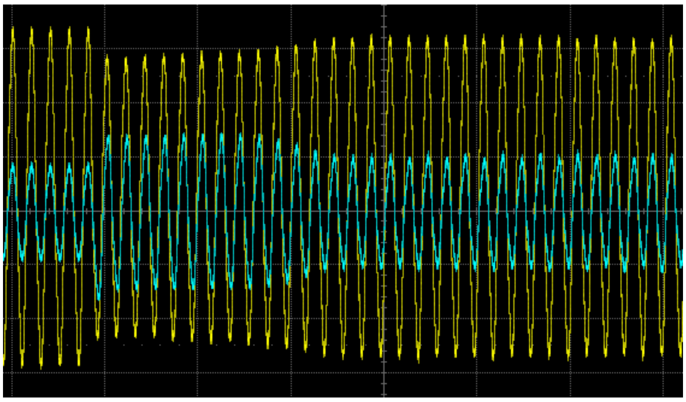
09cro114

System output

Steady state load 6,8kW
1,8kW compressor switched on.

Dynamic response much better than without Multi's (compare with 09cro79)

Total load during compressor start-up:
6,8 + 5,4 = 12,2kVA



Steady state load after compressor start up:
6,8 + 1,8 = 8,6kW

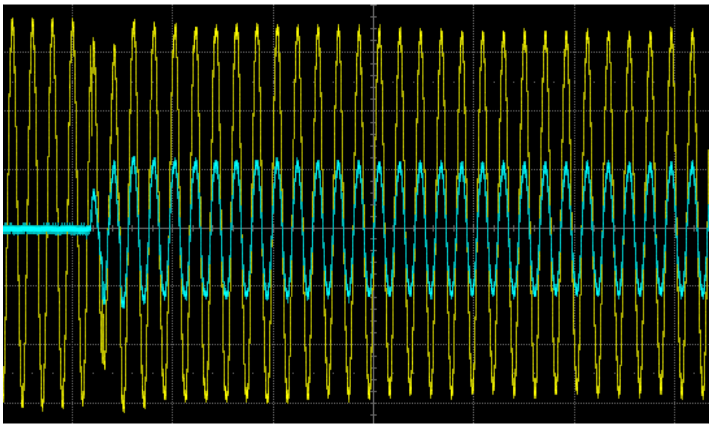
3.9.4 Onan 7.0 MDKBL with two Multi's in parallel

The Onan powered all loads with the UPS function on and the DCL off.

09cro113

System output

From no load to 8kW resistive load



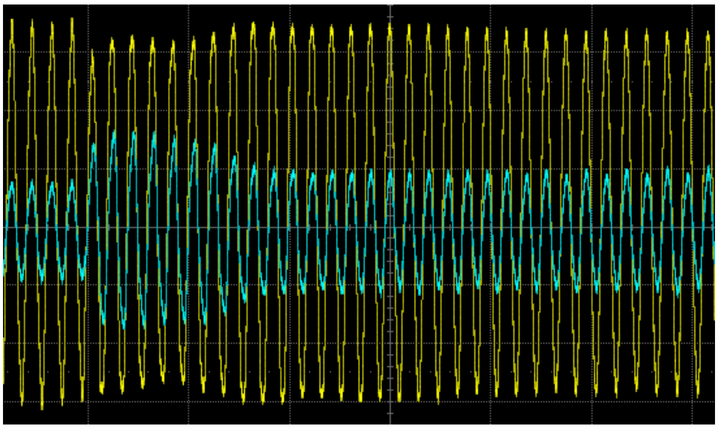
09cro114

System output

Steady state load 6,8kW
1,8kW compressor switched on.

Total load during compressor start-up:
6,8 + 5,4 = 12,2kVA

Steady state load:
6,8 + 1,8 = 8,6kW



3.10. Generator operation at 50°C

Marine generators often must operate in hot engine rooms or machinery space.
We therefore ran the Mastervolt Whisper 6 ULTRA and Onan 7.0 MDKBL for several hours at full load at a 50°C ambient temperature. Both units passed the test.

We also determined the maximum load at 50°C:
- Mastervolt 6 ULTRA: 4,7kW (maximum load at 25°C is 5kW)
  Output voltage dropped to 210V at this load
- Onan 7.0 MDKBL: 6,7kW (maximum load at 25°C is 7,4kW)
  Engine would stall at a higher load.

Note: The International Organization for Standardization (ISO) rates engine rooms at 60°C; the American Boat and Yacht Council (ABYC) rates them at 50°C.

3.11 Conclusion: not all generators are equal

Part 2 of the tests revealed important differences between generators:

3.11.1 The stand alone generator: tests with different loads and short duration overload capacity.

All alternator technologies discussed gave satisfying results with resistive loads as well as with an induction cooker. We also tested all generators with a 1.8kW electric motor that powered an air compressor. The motor had a relatively low locked rotor amp (LRA) rating of 300% of the running current (LRA is in general between 300% and 600% of running current).

The electric motor test revealed striking differences between the different alternator technologies. The Fischer Panda 4000i 'inverter' generator started the electric motor, but none of the 3 – 4kW 'capacitor' generators started it. All the higher rated generators started the electric motor.

We wanted to look into this electric motor matter in more detail, but because of time limitations we had to make choices.

The most common alternator technologies used in the marine area are the 'synchronous capacitor alternator' and the 'synchronous AVR alternator'. Low power generators (3 – 4kW) in general are of the capacitor alternator variety, while higher powers in general are 'AVR'. We therefore decided to spend some more time comparing two representatives of these two technologies: the Mastervolt 6 ULTRA (5,7kW 1500rpm) and the Onan 7.0 MDKBL (7kW 1500rpm).

The general tests as well as the comparative tests showed that the (more expensive) AVR alternator outperforms the capacitor alternator for all electrical properties measured. However, not all electrical properties are of equal importance. Most equipment found on boats will function flawlessly with all generators tested. The only concern we had was starting electric motors, and the related problem of short duration overloads.

Starting electric motors (on board a yacht electric motors are used to power air conditioning, the water maker and/or a diving compressor). For the tests an air compressor with a 1.8kW electric motor was used. (It should be noted that we tested only one electric motor. Other motors with other loads may give different results).

The Onan 7.0 MDKBL with AVR alternator started the electric motor. Voltage dropped from 230V to about 168V during one cycle.

The Mastervolt 6 ULTRA with capacitor alternator also started the electric motor, but output voltage dropped from 235V to 155V during about 15 cycles when starting the motor. This means that other connected loads such as an induction cooker, a washing machine or dishwasher or a computer may trip out when starting the electric motor.

The reason for this striking difference is partly because the Mastervolt is a lower-powered generator, but mostly because an electric motor is an extremely inductive load during start up, and capacitor alternators are not suitable to power inductive loads.

Ride through short duration overloads. Lamps, power supplies and battery chargers may also draw a high start up current. If the generator is already carrying a substantial load when additional loads are switched on, the ability to carry an overload for up to second without substantial voltage loss is a desirable feature. Capacitor alternators are self limiting. Therefore, their output voltage will drop when overloaded. AVR alternators are not self limiting and can carry substantial overloads during short periods. The Onan 7.0 MDKBL supplied up to 11,7kVA at 210V (the engine would stall after a few seconds of overload). We did not have time to measure the overload capability of all "AVR" generators, but it can be safely assumed that most if not all AVR generators will ride through a short duration (less than 1 second) overload of at least 150% of rated power while maintaining output voltage at 210V or more.

3.11.2 Parallel operation with one or more Multi's or Quattro's.
Not surprisingly, the best results were obtained with the 'inverter' generator and the 'AVR' generators.

Three MultiPlus 24/3000/70 could be paralleled with to the Fischer Panda 4000i, boosting system output to 12kW. The output of the AVR generators could be boosted by a factor of two or more. The standard settings of the Multi's could be used, resulting in no break in the transfer of the load when stopping the generator or when switching from generator to shore-side supply.

The output of 'asynchronous' generators and 'capacitor' generators could be boosted by a factor of 1,5 to 2. The big advantage here is that the Multi's stabilize the output when an electric motor is switched on. The output stability of the hybrid system is therefore much better than a stand alone 'asynchronous' generator or a 'capacitor' generator. The settings of the Multi's had to be changed (simply by dipswitches in the product) to be less sensitive to voltage dips and harmonic distortion of the generator.

3.11.3 Electronic or mechanical governor?
In terms of the behavior with the Multi's, we could not find a marked difference between generators with a mechanical governor and generators with an electronic governor. The influence of the alternator was much more important.
Obviously, an electronic governor has the advantage of accurate frequency control so that AC synchronized clocks will also be more accurate.

4. The case for a hybrid system

Reducing fuel consumption, pollution and maintenance of the generator

4.1 Introduction

The tests have shown that a MultiPlus/battery/generator hybrid system can be built with all generators tested, the best results being obtained with 'inverter' and 'AVR' generators.

In the following paragraphs design of a hybrid system is discussed with the help of an example: electric power for an average 4 person household. It will be shown that the most important data needed to size a hybrid system are the average and peak electric power requirements.

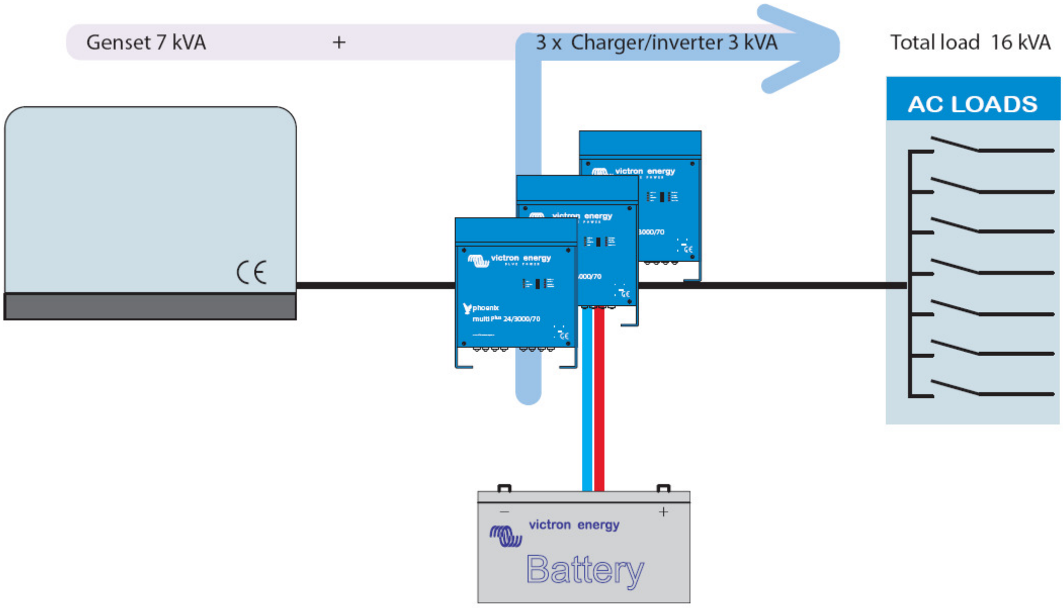


Fig. 5: A parallel hybrid system

4.2. The 'average' 4 person household

4.2.1 Defining the average household

World wide, several hundred million households are not connected to a utility grid. For our example we look at the wealthier subset of households that can afford the equipment that is found in the average western home. Several studies of the electric power needs of such households have been published. See for example:
http://www.ecbcs.org/docs/Annex_42_Domestic_Energy_Profiles.pdf
http://mail.mtprog.com/CD_Layout/Day_2_22.06.06/1400-1545/ID170_Almeida_final.pdf

Today, the electric equipment of the average western home can also be found in a large group of boats and motor homes. The user wants the same level of comfort as at home, and technology is available to achieve this. Special boat or motor home related loads are negligible compared to the power needs of the average household. The average 4 person household example is therefore applicable to land based, land mobile and marine situations.

4.2.2 Shore power

The only extra constraint when comparing an off-grid house to a boat or a motor home is shore power. The shore power that one usually finds on the camping ground or in the marina is limited.
In Europe shore power ranges from 4 to 16 Amps at 230V, while the grid connection of a house ranges from 32 Amps single phase to 32 Amps 3 phase (which is equivalent to 96 Amps at 230V single phase).
In North America shore power ranges from 30 to 50 Amps at 120V, single phase, to 50 amps at 240V split phase. The typical American house has somewhere between a 100 and 200 Amp, 240V, split phase supply.

4.2.3 Power consumption of the average household; the bottom up method

One approach to determining power needs is 'bottom up': list all equipment, power needs and average use. In Table 4 we list appliances that can be found in nearly all western homes. We call these the 'standard appliances' or 'standard loads. The loads have been sorted according to how much time, on average, they are switched on. This classification is very helpful: contrary to intuition, the low power 'always on' loads consume more energy than high power, short duration loads.

The energy need of the four categories of standard loads is summarized in Graph 21.
Of course every household will use the electric equipment in a different way. The table can easily be adapted to a particular household. We also list three loads that quite common but not present in every household: the 'special' loads. Except for the electric cooker or kitchen stove these special loads are extremely energy hungry, as shown in Graph 22.

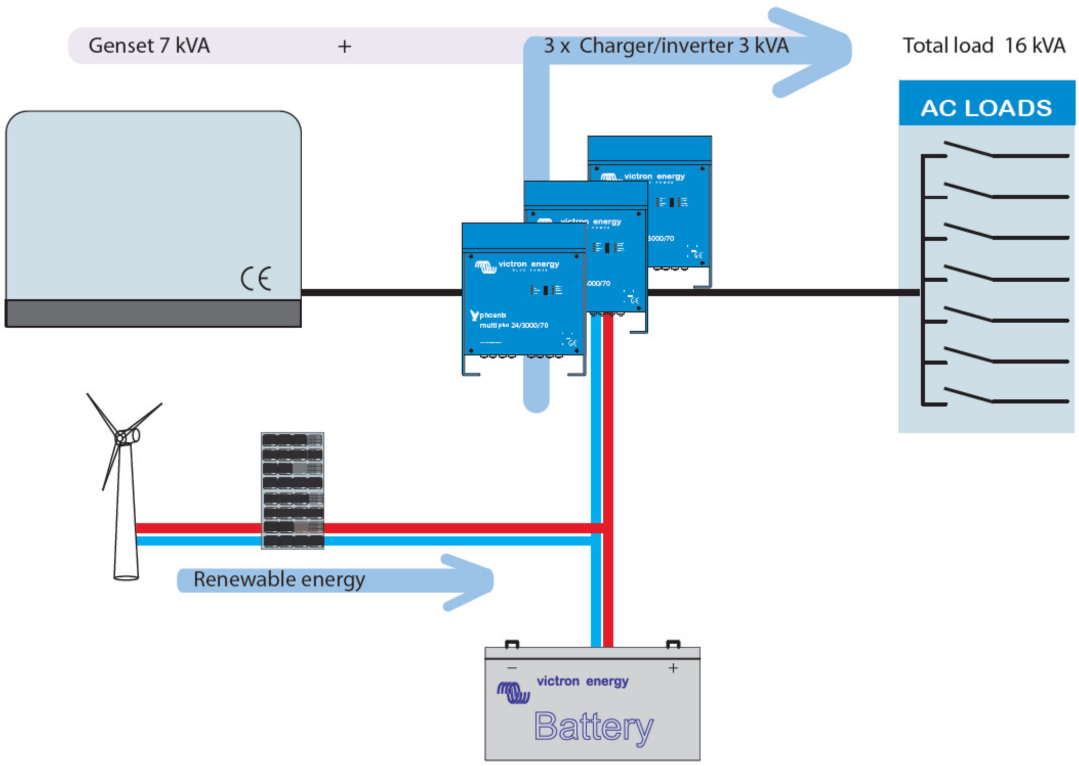
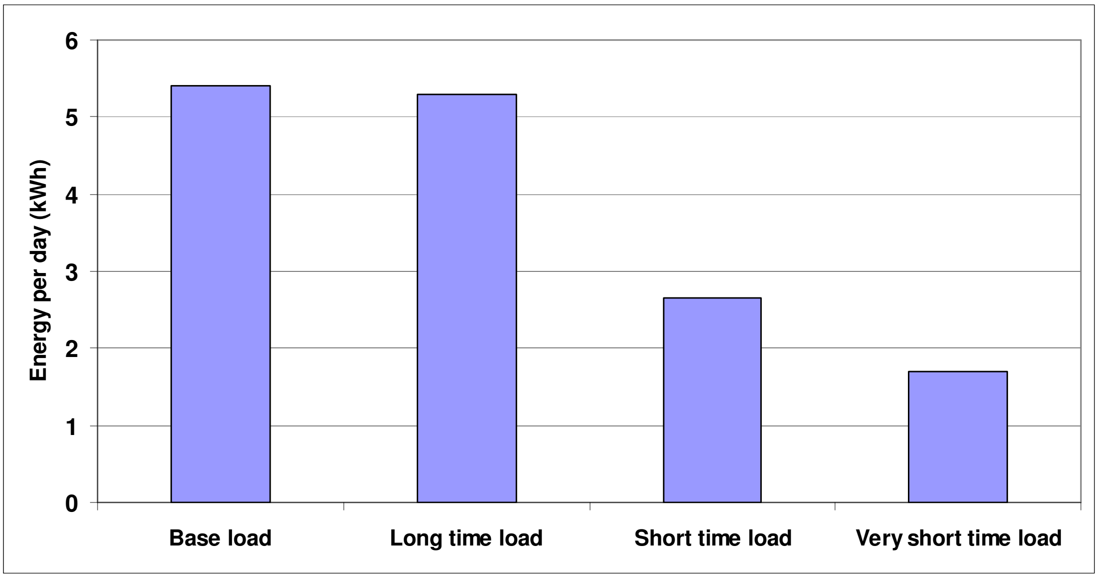


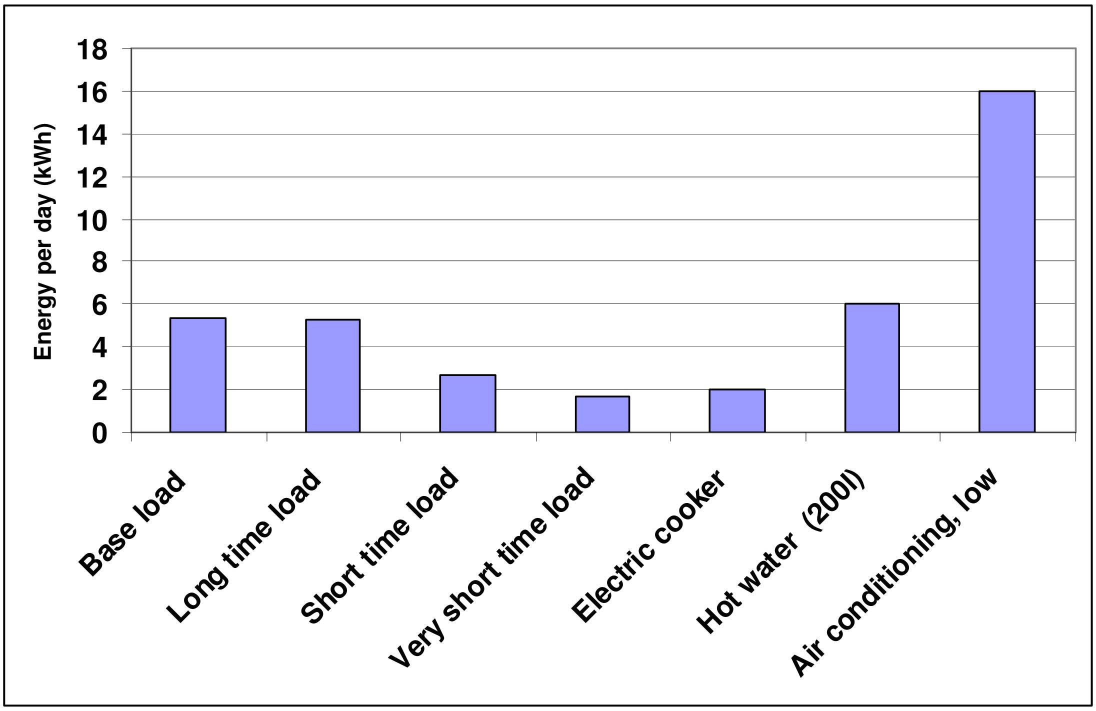
Fig. 6 Parallel hybrid system with renewable energy

Base load equipment that is always on	**Average power consumption**	**Average hours per day**	**Energy per day**	**Energy per year**		**Maximum power consumption**
	kW	**hr**	**kWh**	**kWh**		**kW**
Refrigerator	0,10	24	2,3	840		0,18
Freezer	0,07	24	1,6	584		0,12
Standby power	0,06	24	1,5	548		0,06
(TV, VCR, printer, modem, etc)						
Base load	**0,23**	**24**	**5,4**	**1971**		**0,36**
Equipment with long on time (more than 1 hour per day)	**Power consumption when on**					
TV	0,10	4	0,4	146		0,10
Computer	0,25	10	2,5	913		0,25
Efficient lighting	0,50	4	2,0	730		0,50
VCR, Radio, etc	0,10	4	0,4	146		0,10
Long time load			**5,3**	**1935**		**0,95**
Equipment with short on time (average 10 minutes to 1 hour per day)						
Dishwasher (every day)		1	0,9	329		3,0
Clothes washer (every second day)		0,5	0,5	164		3,0
Clothes dryer (every second day)		0,5	1,3	475		3,0
Short time load			**2,65**	**967**		**9,0**
Equipment with very short on time (average less than 10 minutes per day)	**Power consumption when on**					
Oven	3,0	0,1	0,3	110		3,0
Vacuum cleaner	0,8	0,1	0,08	29		0,8
Microwave	1,5	0,2	0,3	110		1,5
Coffee maker	1,0	0,4	0,4	146		1,0
Hair dryer	1,0	0,2	0,2	73		1,0
Toaster	1,2	0,1	0,12	44		1,2
Electric kettle	1,5	0,2	0,3	110		1,5
Other (e.g. blender, tools, etc)			0,5	183		
Very short time load			**1,7**	**621**		**10,0**
Total			**15,1**	**5493**		**20,3**
Special loads						
Electric cooker	7,0		2	730		7,0
Hot water (200l)	1,5	4	6	2190		1,5
Air conditioning, low	2,0	8	16	5840		2,0
Air conditioning, high	8,0	8	64	23360		8,0

Table 4: Bottom up household electricity load calculation



Graph 21: Average daily energy consumption of the four categories of 'standard' loads



Graph 22: Average daily power consumption including the 'special' loads

A few remarks:

- Base load should not be neglected!
  Graph 21 shows that, contrary to intuition, the base load consumes most of the energy. It pays to invest in an efficient refrigerator and freezer. For a more in depth discussion, see chapter 4 of our book 'Energy Unlimited':
  http://www.victronenergy.com/upload/documents/Book-EN-EnergyUnlimited.pdf
- Regarding lighting, we assumed that all classic filament lamps have been replaced by fluorescent, halogen and/or LED lighting. If not, the lighting load will increase to some 700W or 2,8kW per day. The biggest daily load of all!

- At the end of the table we list some heavy loads that may or may not be present, in order of increasing energy needs. The electric cooker, although having a very high peak power, consumes much less energy than one would think. Again, see http://www.victronenergy.com/upload/documents/Book-EN-EnergyUnlimited.pdf.
  Heating water requires lots of energy. Alternatives to using electricity are gas heating, a solar water heater or using generator waste heat (cooling water from a water cooled generator). Daily hot water consumption (at 55°C) per person ranges from 50 liters average in Europe to nearly 100 liters in North America. In Table 4 we assumed a European household of 4 persons, that is 200 liters of hot water per day. If electric heating is used, the daily hot water load will amount to 50% of the 'standard' electricity load.
  Air conditioning: anything is possible. Air conditioning can be a bigger load than all other loads together. As a very, very rough approximation, one can say that the average daily energy consumption of air conditioning is about 6kWh per room or cabin. The average electric heating would require about 12kWh per room or cabin.
- The right hand column of Table 4 lists the peak power consumption. The total of the four standard load categories adds up to 20kW.
- The load calculated in Table 4 is the **average** daily load. Daily load can easily be **twice as much** on some days: guests in the house, more washing, cooking, etc. This is shown very clearly in Graph 22, and in 23 below.

4.2.4 Power consumption of the average household: logging power consumption

Data available on the internet shows that average household consumption, excluding HVAC (heating, ventilation and air conditioning) ranges from 5kWh to 25kWh per day.
This coincides with our experience powering off-grid houses, boats of 14m to 20m, and 10m or longer motor homes.

It should be noted that our bottom up consumption table is on the optimistic side. This is due to our assumption that, because of the off-grid situation, the household would be relatively energy conscious, using efficient lighting, turning the computer off when not in use, etc.

Intra-day data are also available, but not very useful. The sampling interval of 5 to 15 minutes that is generally used is too long to capture short duration peak loads, and one cannot see which loads are on. The generated profiles, shown in Graph 23 and 24 below, taken from http://www.ecbcs.org/docs/Annex_42_Domestic_Energy_Profiles.pdf
are much more instructive, because they show the individual loads.

4.2.5 A note about peak power consumption

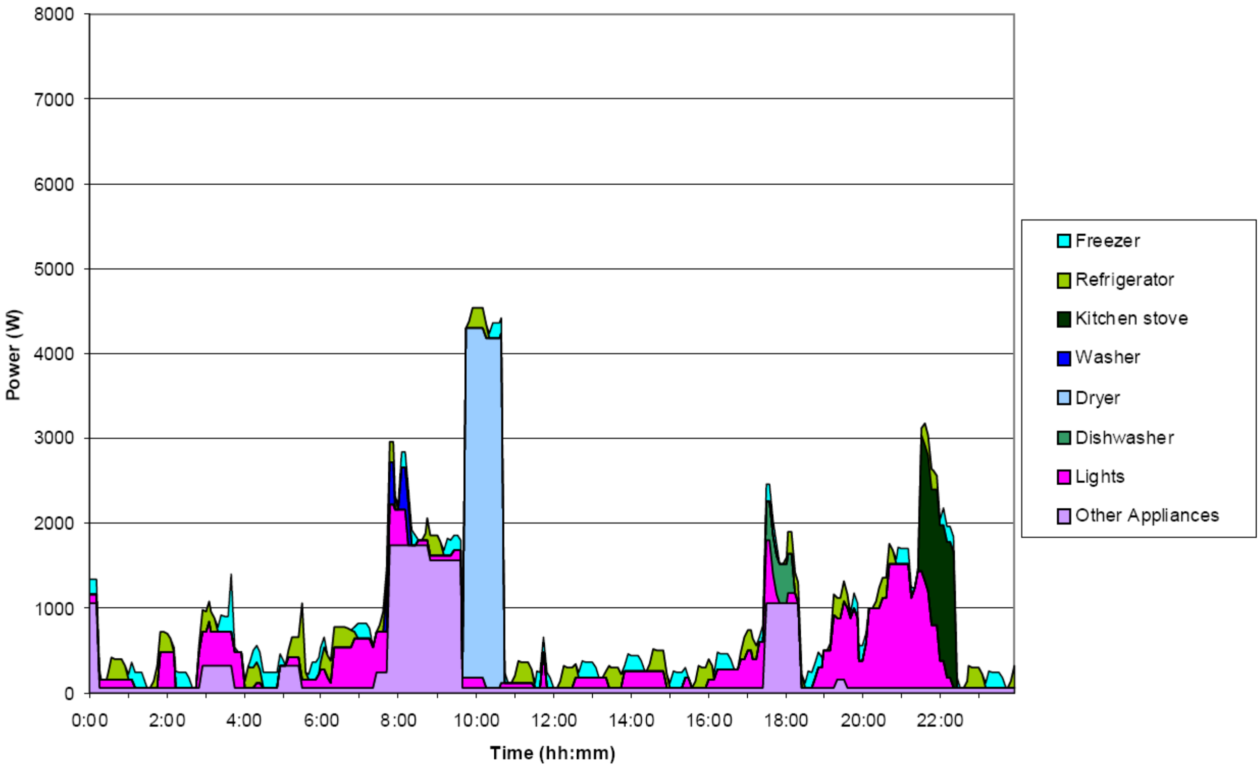
The right hand column of Table 4 lists peak power consumption if all appliances are switched on and drawing current simultaneously. The total of the four load categories adds up to 20kW. An electric cooker would increase peak power to 27kW, or 27kW / 230V = 117A from a single phase 230V supply. This is an extremely high and also very theoretical value.

Graphs 23 and 24, although based on the same appliances as used for Table 3 (except for less efficient lighting), show maximum values at any one time of 4,5kW and 7,2kW respectively.

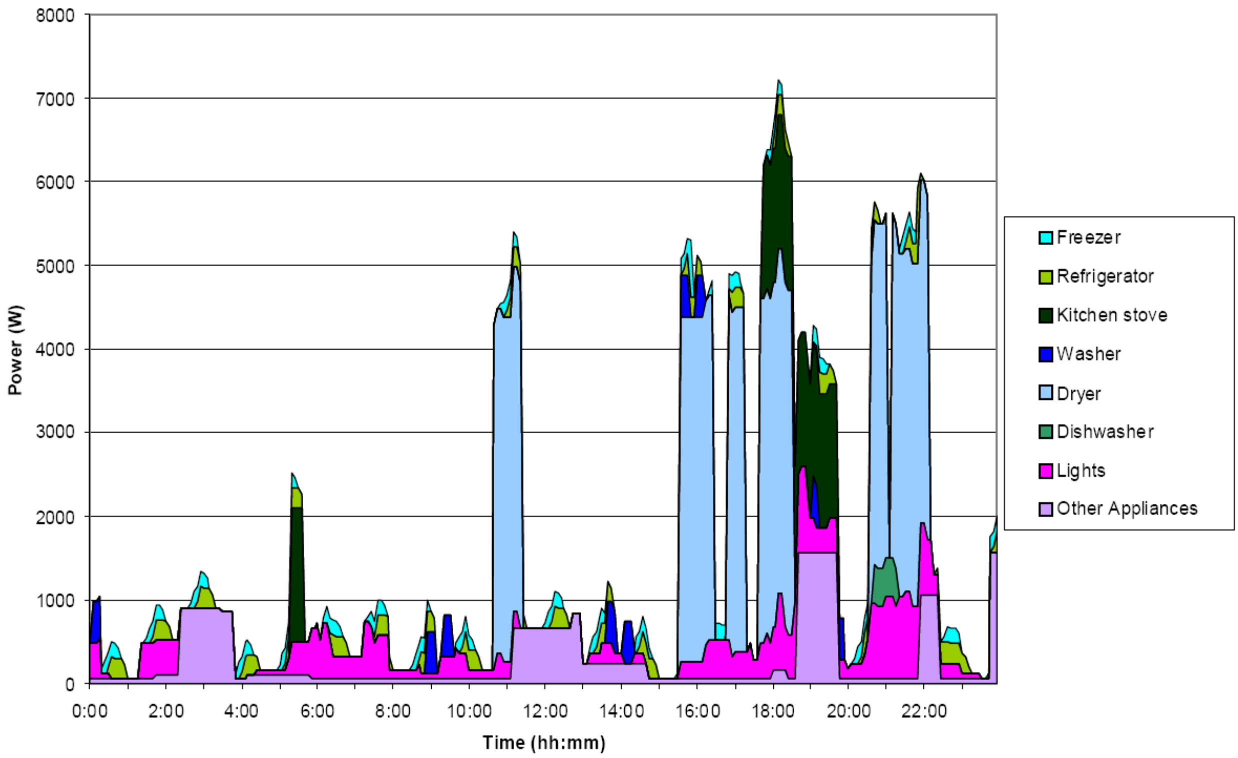
The question is: what is realistic?

In Graph 23 and 24 the power demand has been averaged with a time constant of 5 minutes or more. Therefore short power peaks as drawn by a microwave switched on for two minutes only, or the heating elements of the dish washer and the clothes washer coming on for a few minutes are either not shown or averaged to a lower value.

The conclusion is that the method used in Table 4 to calculate peak power exaggerates reality, and that looking at Graph 23 and 24 results in under estimating peak power.
This is in accordance with our field experience. With thousands of households using our equipment we can safely say that (excluding air conditioning and electric space heating) in most cases the peak power draw is limited to 10kW, and that 20kW is almost never exceeded.



Graph 23: Example of average daily load distribution (total daily load 22kWh, mainly because of less efficient lighting than assumed in Table 4)
Important: loads have been averaged with a time constant of 5 minutes or more: the sharp ‘needles’ due to the heating elements of the dish washer and the clothes washer coming on for a few minutes are not shown.

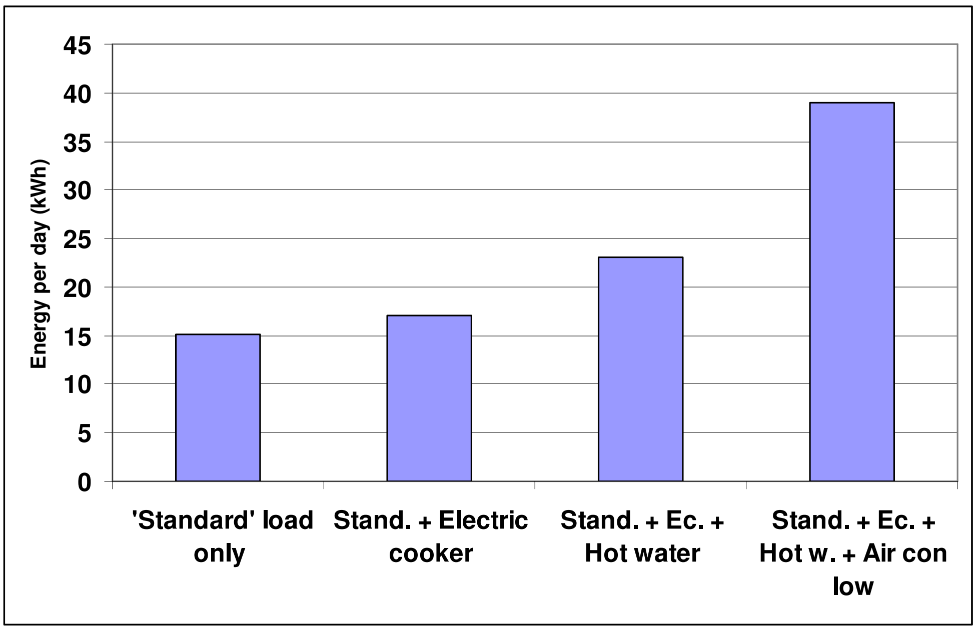


Graph 24: Same household as in Graph 23, but more use of the kitchen stove, washer and dryer (total daily load 40kWh)

4.3. Sizing the generator, inverter/charger and batteries for a 'standard' 4 person household

4.3.1 Energy need per day

As shown above, 15kWh per day is a good average, without 'special' loads
Graph 25 shows the average power needs including 'special' loads
(intensive air conditioning has been left out).



Graph 25: Total daily energy need of the standard household showing the influence of the 'special' loads

For our example we will take a closer look at the 'standard load + electric cooker' option: 17kWh per day[5)].

Once the system has been designed for this option it is very easy to adapt it to the other options shown in Graph 25.
A typical 'standard load + electric cooker' load profile is shown in Graph 23. The main difference between the household simulated in Graph 23 and Table 4 is the much higher lighting load. In Graph 23 lighting with classic filament lamps is assumed while in Table 4 efficient lighting is assumed.

Graph 23 shows that during the 3 hour high load periods, the average load is about 3kW.
Assuming efficient lighting:
- During the 21 hour low load period, the average load is 380W (0,38kW).
- During the night period the average load might even be much lower: 230W according to Table 4.

General remarks about the different elements of the system before the different options are looked at in more detail:

4.3.2 The generator
With a hybrid solution, the best times to run the generator are the high load periods, when the load exceeds 30% of the generator rating (see paragraph 2.5.1). If the additional load created by battery charging is included, a high (and therefore fuel efficient) load is easily achieved, as will be shown below.

Looking more closely at Graph 23, one sees two high load periods: from about 8.00 to 11.00 hr, and then again from about 20.00 to 22.00 hr. Total: 3 to 6 hours.

[5)] Please note:
- The average AC load corresponding to 17kWh energy per day is only 17kWh / 24hr = 700W.
- The average AC current at 230VAC is 700 / 230 = 3A
- When supplied by a 24V battery, a 700W load will draw 700 / 24 = 29A

4.3.3 The battery

For the example, a 24V battery bank has been chosen.

A typical efficiency and battery capacity calculation:

- **Battery load:**
  With a hybrid system, the load will typically run on battery power during the two low load periods, each lasting for about 10 hours.
  Average energy consumption during each of the low load periods is 0,38W x 10hr = 3,8kWh.

  Efficiency of the inverter/charger/battery interface:
  In order to take into account AC to DC, DC to AC and battery charge-discharge losses, we assume a discharge voltage of 21V and a recharge voltage of 30V. This corresponds to a an efficiency of 21 / 30 = 0,7 (70%).
  At 70% efficiency, out of every kWh that goes into the inverter/charger/battery system only 0,7kW will be supplied to the load. The rest is transformed into heat.

  This efficiency has been estimated as follows:
  The kWh efficiency of a battery, when charged and discharged at I_{10} (charge and discharge current amounting to 10% of the capacity) is approximately 85%.
  (see for example http://www.sonnenschein.org/PDF%20files/GelHandbookPart2.pdf paragraph 6.3)
  If a battery is discharged or recharged at a very high rate, efficiency will be much lower: 80% or less.
  Cycling a battery in a **partially discharged state** (see our book ‘Energy Unlimited’, par. 2.5.6), as is often the case in a hybrid system, can increase efficiency to about 90%.
  The inverter charger has about 94% efficiency under optimal conditions, both when charging the battery and when supplying the load. In practice average efficiency will be lower, and there will be additional losses in the cabling, shunt and fuses. In our experience, 90% to 92% efficiency both when charging the battery and when supplying the load is a good average. In practice the efficiency of the inverter/charger/battery interface will therefore be around 0,91 x 0,91 x 0,85 = 0,7.

  Note that a system with a 48V battery would be more efficient, because of lower DC currents and a higher inverter/charger efficiency: about 75% instead of 70%.

- **Battery capacity:**
  Average discharge current during the low load periods: 380W / 20V = 19A.
  Discharge in Ah: 19A x 10hr = 190Ah.
  When cycled twice a day, the capacity taken from the battery during each cycle should preferably not exceed 50% of the rated capacity. Therefore the minimum battery capacity is 19A x 10hr x 2 = 400Ah.
  In practice, if weight and space are not an issue, a capacity on the order of 600 to 800Ah will improve battery lifespan and provide some margin for ‘non standard’ days.

- **Additional energy needed due to the losses in the inverter/charger/battery interface:**
  Total energy supplied to the load during battery operation: 0,38W x 20hr = 7,6kWh.
  Total energy consumed including conversion losses: 7,6kWh / 0,7 = 10,9kWh.
  Total additional energy needed because of the AC to DC, DC to AC and battery charge-discharge losses: 10,9 – 7,6 = 3,3kWh, or 20% more than the 17kWh daily consumption.
  Because off the hybrid system the total energy need has increased from 17kW to 17kW + 3,3kW = 20,3kW.

Clearly, the hybrid system generates additional losses. The efficiency of a generator operating at low loads is, however, so terribly bad (see Graphs 18 to 20) that the hybrid solution nevertheless dramatically improves overall performance, as will be shown in paragraph 4.4.

4.3.4 The inverter/charger, option one: low power inverter/charger for night-time low load periods only

A MultiPlus C 24/1600/35 for example.

- The 1600VA inverter will power the base load. A sudden additional load such as a washing machine will however cause the MultiPlus to go into overload protection mode, and the AC supply will shutdown.
  To prevent this, the generator must be on-line before any heavy load is switched on.
- The 35A charge current is quite low: nearly 6 hours are needed to recharge 190Ah.

In practice, this option works well if the inverter/charger supplies the base load during the night, and the generator is on during the day.

4.3.5 The inverter/charger, option two: high power parallel inverter/charger to substantially reduce generator size and running hours

This is the option of choice for our 4 person household:

- Inverter power should be sufficient to support heavy loads until the generator is on-line.
- A load dependent automatic generator start signal can be generated by the inverter/charger. In addition a ‘battery discharged’ signal to start the generator can be provided by a battery monitor. Completely automatic system operation is therefore possible.
- With reference to paragraph 4.2.5, the combined ‘Multi/Quattro-generator’ rating should be 10kW to 20kW.
- Due to the powerful battery charging capability of the Multi or Quattro, less than two hours of generator operation is needed to recharge 190Ah (battery operating in **partially charged state**, see our book ‘Energy Unlimited’, paragraph 2.5.6).

4.4 Electric power for the off-grid household: an overview

Standard load + electric cooker option: 17kWh per day
Load distribution within the day: as in Graph 23

4.4.1 Most AC loads can be on at the same time, max. load 20kW, generator running 24/7.

- Average load of the 20kW generator: 17kWh / 24hr = 0,7kW, or 3,5% of full load.
- Fuel consumption (1500rpm generator): 1,2kg/hr = 1,5l/hr - **36 liters/day.**
- CO_2 emission: approximately 3,15kg/kg – **130kg/day**
- NOx emission: approximately 35g/kg – **1,5kg/day**
- CO emission: approximately 20g/kg. – **0,8kg/day**

4.4.2 Sequential use of equipment, max. load 10kW, generator running 24/7.

- Average load of the 10kW generator: 17kWh / 24hr = 0,7kW, or 7% of full load.
- Fuel consumption (1500rpm generator): 0,9kg/hr = 1,1l/hr - **26 liters/day.**
- CO_2 emission: approximately 3,15kg/kg – **95kg/day**
- NOx emission: approximately 35g/kg – **1,1kg/day**
- CO emission: approximately 20g/kg. – **0,6g/day**

4.4.3 Most AC loads can be on at the same time, max. load 20kW, generator off during the night (17/7 operation)

The traditional solution is to install a 20kW generator and a small inverter (1,6kW for example) for the night. Assuming a night time base load period of 7 hours, the result is as follows:

- Generator run time: 24 – 7 = **17 hr/day**.
- Inverter/charger run time: 7hr/day, average load 0,23kW, total energy supplied 0,23 x 7 = 1,6kWh.
- Additional energy needed due to interface losses: 1,6 / 0,7 – 1,6 = 0,7kWh.
- Average generator load: (17 + 0,7)kW / 17hr = 1kW, or 5% of full load.
- Fuel consumption (1500rpm generator): 1,3kg/hr = 1,5l/hr - **26 liters/day.**
- CO_2 emission: approximately 3,15kg/kg – **95kg/day**
- NOx emission: approximately 35g/kg – **1,1kg/day**
- CO emission: approximately 20g/kg. – **0,6kg/day**
- Minimum battery capacity (24V): (1,6kWh / 20) x 2 = 160Ah
  Recommended battery capacity: 320Ah
  The 80Ah taken from the battery every night will be recharged during day time.

- If this solution is chosen for a boat or mobile home, the shore power connection needed would be (at 230V): 20kW / 230V = 87A (!).
- Average shore current: 17kWh/24hr = 700W, and 700/230V = 3A.

Clearly, the shore current situation is far from satisfying. More inverter power is needed to reduce shore current required.

4.4.4 Sequential use of equipment, max load 10kW, generator off during the night (17/7 operation)

Now we can install a 10kW generator, and again a small inverter for the night.

- Generator run time: **17 hr/day**.
- Inverter/charger run time: 7hr/day, average load 0,23kW, total energy supplied 1,6kWh.
- Additional energy needed due to interface losses: 1,6 / 0,7 – 1,6 = 0,7kW.
- Average generator load: 1kW, or 10% of full load.
- Fuel consumption (1500rpm generator): 1kg/hr = 1,15l/hr - **20 liters/day.**
- CO_2 emission: approximately 3,15kg/kg – **73kg/day**
- NOx emission: approximately 35g/kg – **0,8kg/day**
- CO emission: approximately 20g/kg. – **0,46kg/day**

- Minimum battery capacity (24V): (1,6kWh / 20) x 2 = 160Ah
  Recommended battery capacity: 320Ah
  The 80Ah taken from the battery every night will be recharged during day time.

- Shore power connection needed (230V): 10kW / 230V = 44A.
- Average shore current: 17kWh/24hr = 700W, 700/230V = 3A.

Down sizing the maximum load has improved fuel consumption and reduced shore current.
In North America a 240V / 50A shore supply is frequently available. Not in Europe!

4.4.5 Assume most AC loads can be on at the same time, max load 20kW, and install a parallel hybrid system

Install a hybrid system consisting of a 10kW generator running in parallel with two stacked 5kVA Quattro's.

- **Generator:**
  The 10kW load limit of the stacked 5kVA Quattro's will hardly ever be exceeded. Generator run time is therefore determined by total amount of energy (kilowatt hours) required and by the time needed to recharge the battery to at least 80% capacity (battery operating in partially discharged state).
  Assuming about 20kWh energy needed (this includes 3kW interface losses), and running the generator at 8kW (80% of full load capacity), the minimum run time is
  20kWh / 8kW = 2,5hr.
  The most logical run periods according to Graph 23 would be from 9.00 to 11.00 hr in the morning and from 21.00 to 22.00 hr in the evening. Total 3 hours.
  During this time the generator will supply on average 3kW directly to the house appliances, total energy 3kW x 3hr = 9kWh. The remaining 20kWh – 9kWh = 11kWh must be supplied through the Quattro's. This means a total capacity to be recharged per day of
  11kWh / 20V = 550Ah and an average charge current of 550 / 3 = 183A during 3 hours. The Quattro's can do that. In practice, allowing for a generator stop delay, generator run time will be longer. We will therefore work with a more realistic **4 hours**. Running 4 hours, the generator will also supply more energy directly to the house appliances, say 10kWh instead of 9kWh.
- Quattro inverter mode run time: 24 – 4 = 20hr. Average load
  (17 – 10)kWh / 20 = 0,35kW.
- Additional energy needed due to conversion losses: 7kWh / 0,7 – 6 = 3kW.
- Average generator load: 20kWh / 4hr = 5kW, or 50% of full load.
- Fuel consumption (1500rpm generator): 1,7kg/hr – 2l/hr – **8 liter/day.**
- CO_2 emission: approximately 3,15kg/kg – **29kg/day**
- NOx emission: approximately 25g/kg – **230g/day**
- CO emission: approximately 10g/kg. – **90g/day**

- **Battery (24V):**
  Total energy to be supplied by the Quattro's: 7kWh. Assuming that the same amount of energy is required during the two periods of inverter operation, the Quattro's would discharge the battery twice a day with (3,5kWh / 20V) = 175Ah. With 50% max Ah draw the minimum battery capacity is 175Ah x 2 = 350Ah.
  With both 5kVA Quattro's charging at full capacity charge current will be 240A, and when supplying 10kW to the load, discharge current will be 10kW / 20V = 500A. An AGM battery can do this (for a few minutes), but service life will be short and the efficiency of the inverter/charger/battery interface will be substantially less than the 70% that was assumed. Therefore, unless space and weight are very important, battery capacity should preferably be increased to 1000Ah or more.

- **Shore power:**
  The 2 stacked Quattro's will supply 10kW. The maximum load on the shore connection will therefore be (20 – 10)kW / 230V = 44A
  Average shore current: 17kWh/24hr = 700W, 700/230V = 3A.
  The shore power connection needed can be reduced further by adding one more Quattro. The maximum shore power needed will then be (20 – 15)kW / 230V = 22A. Accepting a small overload on the Quattro's during the (exceptional) event that the load really increases to 20kW, connection to 16A shore power is now within reach.

4.4.6 Assume sequential use of equipment, max load 10kW, and install a parallel hybrid system

Install a hybrid system consisting of a 7kW generator running in parallel with two 3kVA Multi's.

- **Generator:**
  The 6kW load limit of the stacked Multi's will hardly ever be exceeded. Generator run time is therefore determined by total amount of energy (kilowatt hours) required and by the time needed to recharge the battery to at least 80% capacity.
  Assuming about 20kWh energy needed (this includes 3kW interface losses), and running the generator at 5,6kW (80% of full load capacity), the minimum run time is
  20kWh / 5,6kW = 3,5hr.
  Including a generator stop delay, the run time would be around **4 hours**. The most logical run periods according to Graph 23 would be from 9.00 to 11.00 hr in the morning and from 20.00 to 22.00 hr in the evening. Total 4 hours.
  During this time the generator will supply on average 2,5kW directly to the house appliances, total energy 2,5kW x 4hr = 10kWh. The remaining
  20kWh – 10kWh = 10kWh must be supplied through the Multi's. This means a total capacity to be recharged per day of 10kWh / 20V = 500Ah, and a charge current of 125A during 4 hours. The Multi's can do that.
  Multi inverter mode run time: 24 – 4 = 20hr. Average load (17 – 10)kWh / 20 = 0,35kW.
- Additional energy needed due to conversion losses: 7kWh / 0,7 – 7 = 3kW
- Average generator load: 20kWh / 4hr = 5kW, or 71% of full load.
- Fuel consumption (1500rpm generator): 1,65kg/hr = 1,9l/hr – **7,7 liters/day.**
- CO_2 emission: approximately 3,15kg/kg – **28kg/day**
- NOx emission: approximately 18g/kg – **160g/day**
- CO emission: approximately 7g/kg. – **60g/day**

- **Battery (24V):**
  Total energy to be supplied by the Multi's: 7kWh. Assuming that the same amount of energy is required during the two periods of inverter operation, the Quattro's would discharge the battery twice a day with (3,5kWh / 20V) = 175Ah. With 50% max Ah draw the minimum battery capacity is 175Ah x 2 = 350Ah.
  With both 3kVA Multi's charging at full capacity charge current will be 140A, and when supplying 6kW to the load discharge current will be 6kW / 20V = 300A. A 350Ah AGM battery can do this, but service life will be short and the efficiency of the inverter/charger/battery interface will be substantially less than the 70% that was assumed. Therefore, unless space and weight are very important, battery capacity should preferably be increased to 800Ah or more.

- **Shore power:**
  The 2 stacked Multi's will supply 6kW. The maximum load on the shore connection will therefore be (10 – 6)kW / 230V = 17A
  Average shore current: 17kWh/24hr = 700W, 700/230V = 3A.
  Accepting a small overload on the Multi's during the (exceptional) event that the load really increases to 10kW, connection to 16A shore power is now within reach.
  The shore power connection needed can be reduced further by adding one more Multi. The three stacked 3kVA Multi's can supply practically any load condition without generator or shore power. For stable operation, and to prevent the shore circuit breaker from tripping in case of load transients, the minimum shore current needed per Multi is 3A. With 3 Multi's on board, the shore power connection should be at least 9A.

4.4.7 Overview

Paragraph reference	4.4.1	4.4.2	4.4.3	4.4.4	4.4.5	4.4.5	4.4.6	4.4.6
Energy need per day	17kWh	17kWh	17kWh	17kWh	17kWh	17kWh	17kWh	17kWh
Generator/inverter run time	**24/7**	**24/7**	**17/7**	**17/7**	**4/7**	**4/7**	**4/7**	**4/7**
Sequential use of equipment	no	yes	no	yes	no	no	yes	yes
Maximum power draw	20kW	10kW	20kW	10kW	20kW	20kW	10kW	10kW
Generator	20kW	10kW	20kW	10kW	10kW	10kW	7kW	7kW
Inverter/charger	-	-	1,6kVA	1,6kVA	10kVA	15kVA	6kVA	9kVA
Recommended battery (24V)	-	-	320Ah	320Ah	1000Ah	1200Ah	800Ah	1000Ah
Generator run time	24/7	24/7	17 hr	17 hr	4 hr	4 hr	4 hr	4 hr
Average load	3,5%	7%	5%	10%	57%	57%	71%	71%
Fuel/day	36 liter	26 liter	26 liter	20 liter	8 liter	8 liter	7,7 liter	7,7 liter
CO_2 emission per day	130kg	95kg	95kg	73kg	29kg	29kg	28kg	28kg
NOx emission per day	1,5kg	1,1kg	1,1kg	0,8kg	230g	230g	160g	160g
CO emission per day	0,8kg	0,6kg	0,6kg	460g	90g	90g	60g	60g
Maximum shore current needed	87A	44A	87A	44A	44A	16A	16A	9A
Average shore current needed	3A	3A	3A	3A	3A	3A	3A	3A

Table 5: Electric power for an off-grid household: overview

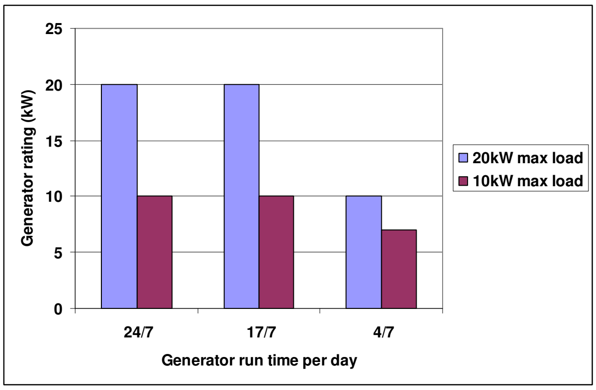
In the off-grid household example, the focus was on decreasing running hours of the generator. Depending on peak load and maximum shore power, this resulted in four parallel hybrid system solutions as summarized in the four right-hand columns of Table 5. System efficiency improved dramatically because the generator, when on, operates at a high load and therefore high efficiency. During the low load periods the generator, running with 10% relative efficiency or even less, was off, and the load was supplied by the inverter/charger/battery system, with 70% efficiency.

Exactly the same hybrid configuration and battery capacity can be used for a household load including water heating (6kWh additional energy needed) and/or limited air conditioning (16kWh additional energy needed). The additional loads can be taken care off simply by increasing the load and operating hours of the generator (as long as the air conditioning is limited during the night, otherwise additional battery capacity will be needed). The Multi's/Quattro's will pick up any peak loads that would otherwise overload the generator.
[Reinout, Rob Warren atr Climma has demonstrated quite convincingly that you can run modest overnight air conditioning loads off the size of battery banks you are proposing]

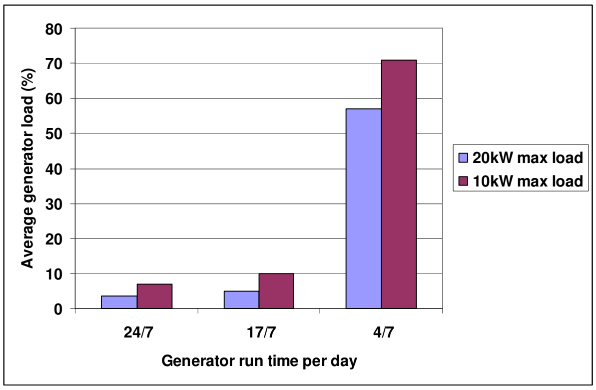
What changes would be needed if the daily energy need would increase to say 70kWh, the power needed for a bigger boat or a small hotel?
As long as peak load remains within the 10kW to 20kW limit, and as long as the air conditioning is off during night time, again the same hybrid configuration and battery capacity can be used. In case of the 10kW generator and PowerAssist kicking in at 8kW, generator run time would increase to 70kWh / 8kW = 9hr per day, and in case of the 7kW generator run time would increase to 70 / 5,5kW = 13hr per day.
The efficiency improvement will result from the generator being off during the night time low load period, and running at its maximum efficiency load point during the day.

Renewable energy
Obviously, with the storage battery already there, renewable energy from solar panels, a wind generator or other sources (e.g. regeneration on a sailboat with hybrid propulsion) can easily be implemented, further reducing fuel consumption and pollution.

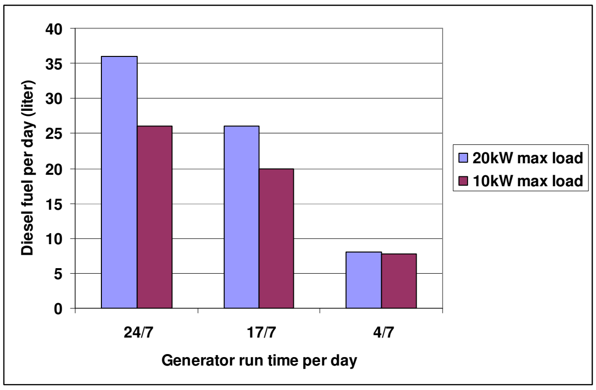
Graphical overview:



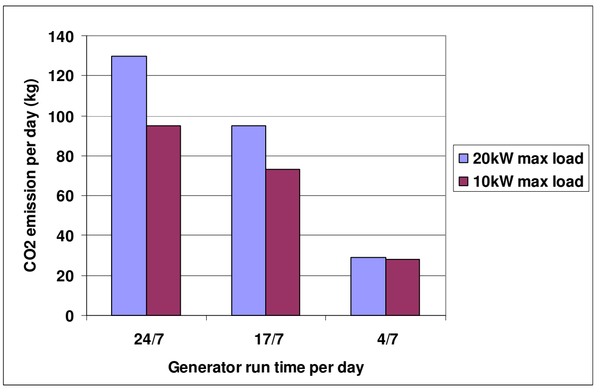
Graph 25
Reduction of generator rating and run time
Run time could be reduced to 4 hours per day.



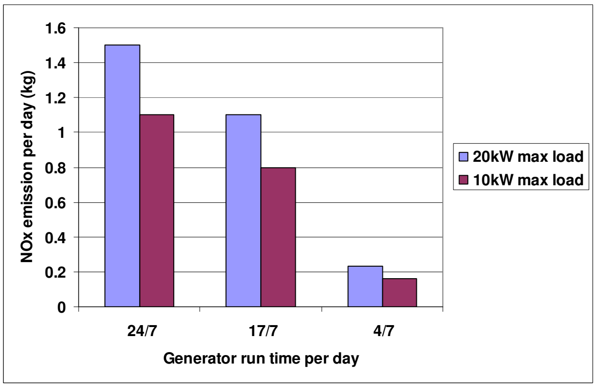
Graph 26
Shows the average generator load increasing from less than 10% to more than 50%



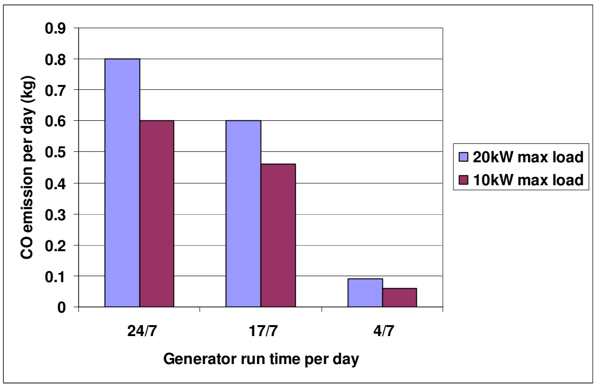
Graph 27
Diesel consumption reduced to 8 liters per day.



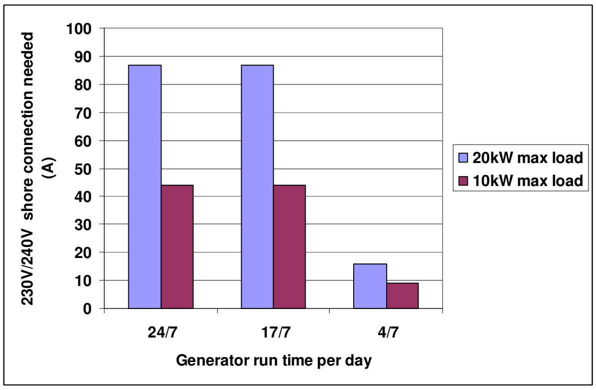
Graph 28
CO_2 emission is reduced proportionally to diesel consumption.



Graph 29
NOx reduction is even more dramatic, because the relative NOx emission reduces when load increases (see Graph 14).



Graph 30
Similarly, CO emission is also reduced by a higher factor than diesel consumption.



Graph 31
The parallel hybrid approach also helps reduce to an acceptable level the shore power needed.

5. Conclusion: what we learned from the test

5.1. All generators tested are suitable to power most loads found in an off-grid house, boat or mobile home. The 'AVR' and 'inverter' generators are the better choice to supply inductive loads, such as electric motors, and to ride through short time overloads.

5.2. All generators had the same fuel consumption profile. No load and light load fuel consumption was higher than expected, strengthening the case for a parallel hybrid system.

5.3. Emission of NOx and CO per kg of fuel consumed reduced substantially with increasing load, again strengthening the case for a parallel hybrid system.

5.4 Although all generators tested had a sound enclosure, sound levels varied more than we expected.

5.5. Our MultiPlus and Quattro inverter/chargers operate in parallel with nearly all generators tested. The best results were obtained with the 'AVR' and 'inverter' generators.

5.6 The inverter/charger/battery in a parallel hybrid system generates additional losses. The additional losses amount to approximately 25% (48V battery) or 30% (24V battery) of the energy that is routed through the inverter/charger/battery instead of directly from the generator to the load.

5.7. The efficiency of the generators tested reduced to less than 70% of the most efficient load point at around 30% load (Graph 20). A 24V parallel hybrid system will improve efficiency compared to a stand alone generator when the generator would otherwise run for long periods at less than 30% of its rated load. Down sizing the generator will increase the efficiency even more.

5.8. Down sizing generators will increase the average load. This will reduce carbon formation and maintenance to an unknown extent, and will increase life expectancy. The substantial reduction in generator running hours achieved in a hybrid system will amortize the generator investment over a longer period of time. There will be a concomitant reduction in noise and exhaust emissions, resulting in a significant lifestyle improvement.

Our testing has demonstrated a compelling case for hybrid power systems using the paralleling technology of our MultiPlus and Quatro inverter/chargers.