Current Assistance Inverter: Opening New Possibilities in Hybrid Systems and Minigrids

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I. INTRODUCTION

The idea of power assistance is already applied in different domains. Many publications treat this subject and the most relevant use of this concept is probably the successful hybrid cars. In [1] and [2] authors have used supercapacitive storage as buffer in railway transportation system for a diesel train. In [3] a similar system buffers the batteries for short term peaks of power for an electric scooter. In rural electrification the main source of energy is often a diesel generator and there are a lot of similarities with the systems of the cited papers above. Underdimensioning a generator compared to the peak load and operating it at a more constant power allows gain in efficiency. In a hybrid system for rural electrification where generator is combined with a bidirectional battery inverter-charger, the energy storage system already exists and the inverter can assume the function of assistance to the source. It is only a matter of proper current control and no additional cost to the system is required: all the hardware already exists. The interest of using a hybrid system instead of a purely diesel run system it not more to demonstrate, it is widely assess with publications like [4]. Here we describe the same kind of system but with more flexibility in energy conversions with some specific control method. The method is not only theoretical but is now practically used in an existing product of the Studer-Innotec Company, the Xtender, and is named Smart-Boost.

II. SYSTEM DESCRIPTION

The inverter is part of a hybrid system. The proposed scheme in our case is a mix of DC-Bus and AC-Bus that allows a lot of flexibility. The generator is considered as an input and the load as the output. The inverter can disconnect the input with a relay. Fig.1 shows the system where we see the inverter-relay subsystem.

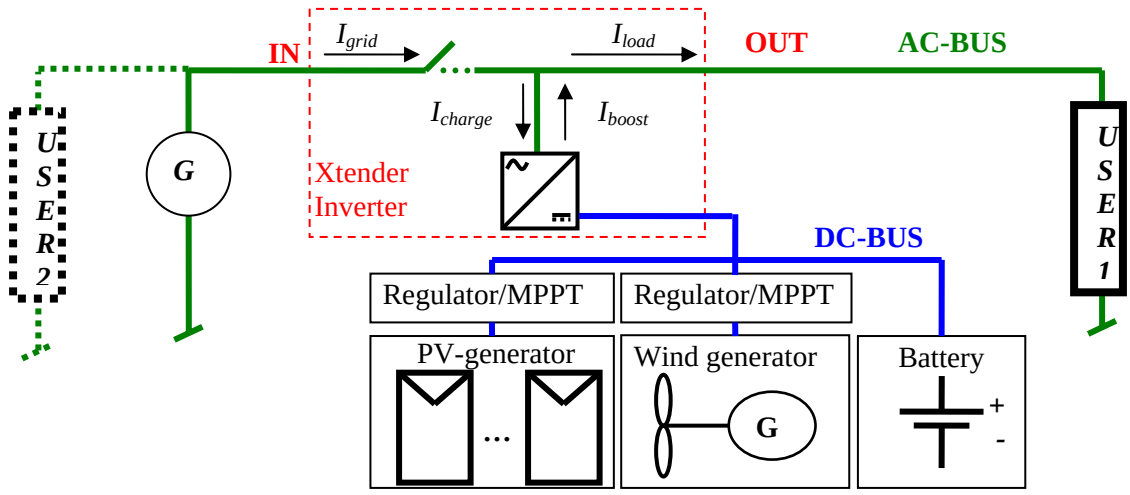

Figure 1 : Typical hybrid system topology for the current assistance inverter.

When the transfer relay is open the inverter is in voltage control mode and supply the end user being the voltage source. When the relay is closed, the voltage source is given by the input and the inverter is operated in current control in a bidirectional mode, charger or current assist. Goal of the Smart-Boost function is to limit what is taken on the input by injecting more or less current. An input limit current is defined and is called the powersharing current I_{PS} .

III. SMART-BOOST

Considering a load with a current of any form or phase, it can be described with a Fourier series:

$$I_{load}(t) = \underbrace{a_{load-active-fundam} \cdot \sin\left(\frac{2\cdot\pi}{T}\cdot t\right)}_{\text{Fundamental active}} + \underbrace{\begin{aligned} & b_{load-reactive-fundam} \cdot \cos\left(\frac{2\cdot\pi}{T}\cdot t\right) \\ & + \sum_{n=2}^{N=\infty}\left[\begin{aligned} & a_n \cdot \sin\left(\frac{2\cdot n\cdot\pi}{T}\cdot t\right) \\ & + b_n \cdot \cos\left(\frac{2\cdot n\cdot\pi}{T}\cdot t\right)\end{aligned}\right]\end{aligned}}_{\text{Reactive fundamental and harmonics}} \qquad \text{Eq. 1}$$

With power assistance, we often think about a useful power, the active power. But in reality any type of loads can be connected by a user and especially in hybrid systems. A pure active power like a resistive load is rarely seen in an islanded system because energy is too precious to be used to heat resistors. The $b_{load-reactive-fundam}$, the a_n and the b_n factors of eq.1 can be significant compared to the $a_{load-active-fundam}$ factor. Electronic loads, low consumption light bulbs have high harmonic contents. Motors and improperly compensated fluorescent tubes have a reactive component. One application where power assistance is interesting is for starting pumps (water pumping, fridge, air conditioning) because during the start of the motor the current can be up to 3-5 times the nominal value and precisely in that case where power assist would be useful the load current is highly reactive. If some active power is boosted, and the load has reactive and harmonic components, the input current cannot be fully under control. Injecting more active power than the demand in a micro grid will cause instabilities in the whole system. Fig. 2 illustrates the problem of active power injection on a typical CFL bulb current. The solution proposed is to recognize the load pattern and assist the source with a current similar to the one of the load. This method called Smart-Boost, can be resumed with the following law:

$$I_{boost} = \lambda \cdot I_{load} \qquad \text{with } 0 \le \lambda \le \lambda_{\max} \le 1 \qquad \text{Eq. 2}$$

This method requires a fast acquisition of the current real shape. It must be faster than the fundamental and the main harmonics. Second requirement is a fast current regulation loop of the inverter current which was performed with a numerical state space control at 12kHz. With the Smart-Boost control a step was made to go from the traditional idea of power assistance to a current assistance system. We reversed the idea that we must help the source with power and found a system that takes a part of the load and therefore supports the source appropriately as seen on figure 3.

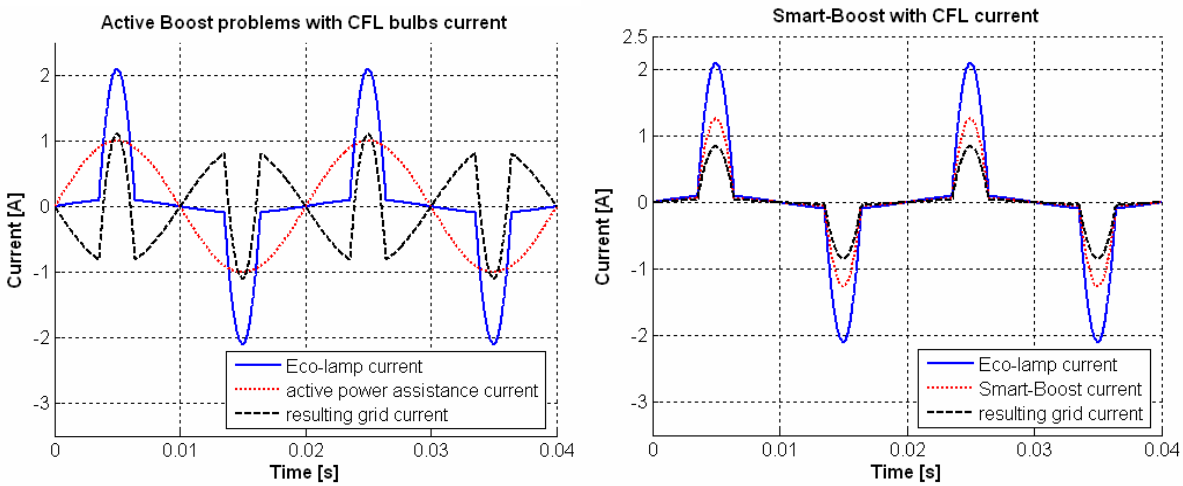

Figure 2 and 3: Active power assist and Smart-Boost on a load with high harmonic components (CFL bulb).

IV. DEPLOYMENT IN HYBRID SYSTEMS

A hybrid system is a combination of different energy sources to provide electrification in remote areas. Many combinations of systems with renewable and non-renewable energies, with solar, wind, hydro have been proposed. There have also been a lot of discussions about topologies like AC-Bus or DC-bus; both have advantages and disadvantages in precise circumstances but in the end no standard is chosen yet. Every single system tends to be a unique mix of those elements that a project integrator optimizes. Here we keep out of those concepts and propose a component that can be integrated in any grid because it is not a voltage source that must be synchronized to others by any way (communication or droops functions), but a controlled current source that has no impact on the grid voltage. The possibilities given by this function can precisely help the integrator to optimize a system. By nature the Smart-Boost feeds a part of the load connected to its output and nothing goes back into the rest of the grid. It doesn't disturb the power balance on its back because it only feeds the user load. The injected current is automatically adapted to the load connected at a very fast regulation speed. That means any type of source (generator, existing minigrid, …) even with fluctuating voltage and frequency can integrate this component and its current assistance ability. This is an advantage because existing equipment is not always compatible with predefined balancing rules (droops) or communication systems and an existing system is often too expensive to be replaced with all compatible devices.

Here we propose a few application of the Smart-Boost function in minigrids.

- There are new ways to make the integration of renewable energies. There are many isolated site that runs with generators as main source of power. The equipment in place is operational but there is the will to integrate renewable energy. Give power to the user with Smart-Boost is a way to integrate a renewable source connected to the DC in the AC system. A special control described below optimizes the renewable part.
- It offers possibilities to extend existing systems with load shifting. Most of time with population increase or consumption increase, a generator can provide enough energy over time but can not supply the peak power. The power assistance can cover those peaks and allows continuing to run on the same main source.

1. New minigrid structure

In planning a new system, the smaller dimensioning of the generator saves initial costs. It runs at a more constant power and a better efficiency and this saves fuel consumption. The generator is chosen to provide band energy and the inverter can make peak power shaving.

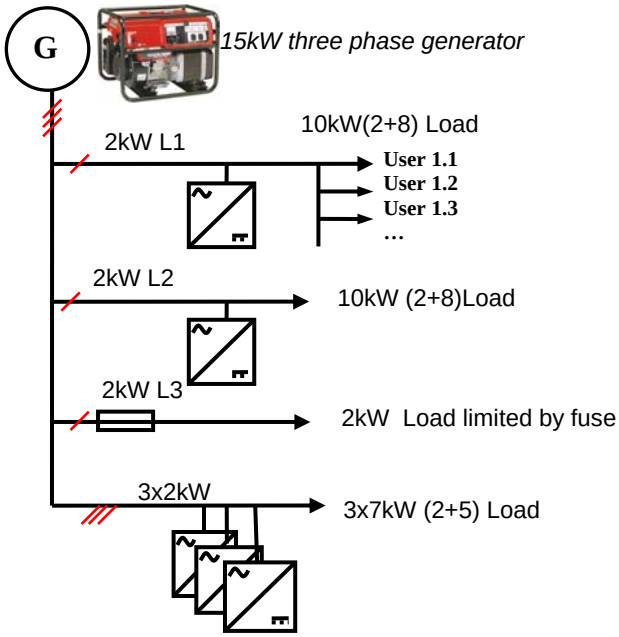

Figure 4 : example of a system made of 15kW three phase generator with 2x Xtender 8kW and 3x Xtender 5kW: total 46kW

Figure 1 represents a simple system with one inverter and one source. But there can be many inverters used in current assistance with different powers mode in a scheme like on fig. 4. In a big system there is never a single load requiring the total installed power, then the power can be splitted between different current assistance inverters. A village to electrify can be organized in different groups having the same access to a common service, the generator, with the same amount of energy allocated by the maximal input current. The storage can be distributed and used independently for each group. The storage dimensioning can be done to do the peak power shaving only, which requires quite small batteries, or on a longer term energy storage for each group autonomy when generator stops.

The reliability of this structure is high because every group can be independent of the other ones, the inverter working as a UPS for its own group. The generator can be stopped and groups with an inverter have their own supply; one group can fail and the other ones keep on. From the basic common service (the generator or a grid), lines are dimensioned smaller than if it must cope with peak power. Addition of solar is possible in such a system without power-balance problems. The solar panels are connected to the DC and boost function integrate the energy in the system. If the constant load during the day is important, a grid injection inverter can be directly used as it is shown in [5]. Another point with the Smart-Boost function is the fact that it is possible to keep a smaller one phase generator even for a quite high peak power system instead of going to a larger three phase generator. It is harder to find a big one phase generator but drawbacks of three phases are that only one third of nominal power is available on each phase and there are the phase balance problems that come along.

Beside those new technological possibilities, there is a reflexion to do around the sociological organization of the minigrid. Here we have a component that allows to add personal investment (per example an own solar panel) to the common service (the minigrid). We could have a standard fee for the same common service and then each group can add its own power and energy for himself. This is an open subject that is not developed further in this paper.

2. Efficiency of the boost function and fuel saving with a generator

The Smart-Boost inverter associated to a generator can work as standard hybrid system, where generator is turned on only to cover energy shortage and recharge the batteries. In a normal system the generator must be dimensioned for the peak power of the load. With the current assistance function it is possible to subtract the inverter power to the load peak power to dimension the generator. Beyond the gain in initial cost with the under dimensioning of the generator or the technical possibility to have more loads on the same existing generator, we must consider the efficiencies in the global system to know if the Smart-Boost function must be recommended systematically when planning an installation because of running costs.

For one quantum of energy boosted, it was charged before, and the relationship between the charged and the boosted energy is:

$$E_{grid-charged} = \frac{E_{boosted}}{\eta_{inverter} \cdot \eta_{cycle} \cdot \eta_{inverter}} \qquad \text{Eq. 3}$$

With reasonable mean value for the efficiencies of the inverter $\eta_{inverter} = 0.9$ and the battery cycle efficiency $\eta_{cycle} = 0.8$ we find the energy charged for a given energy boosted later is 1.48 times higher. This is a quite high value and to assess the energy efficiency of the system, we have to consider the fuel consumption of a generator as shown on fig.5. On this graphic we see that due to the no load consumption it is very interesting to choose a smaller generator. Most of the day a generator with or without Smart-Boost would run at the same load, only energy of peaks of power must be boosted and re-stored after. This represents a small amount of energy that is cycled with efficiency of equation 3. But underdimensioning the generator, all the base-load energy directly given by the generator to the user load has an improved efficiency as shown on fig. 6. The final balance is found with the band energy amount compared to the peak energy amount. A simulation of the two systems on the same typical load profile is made, with two different sizes of generators with and without Smart-Boost. The efficiencies of the system are taken into account and the consumption of the generator is obtained with an integration of the curves of figure 5 with the generator power over the day.

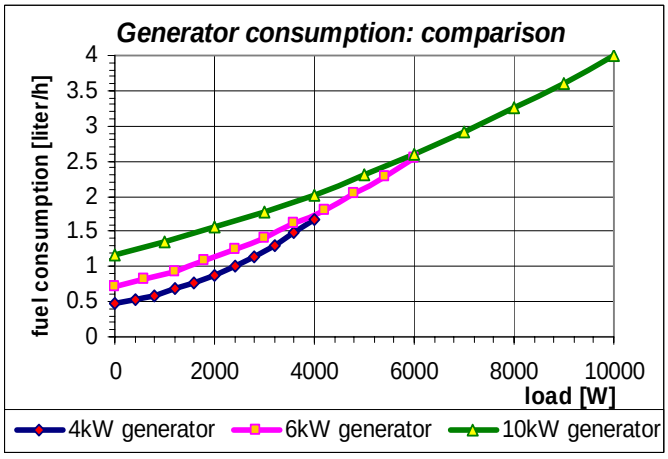

Figure 5: Consumption generators of different sizes

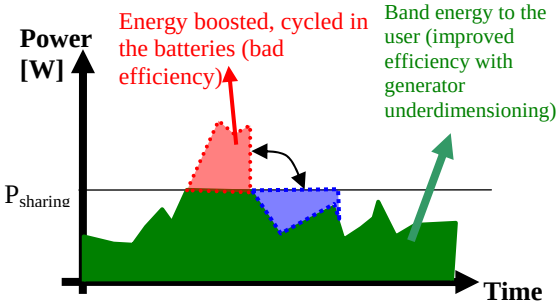

Figure 6: Peak shaving

For the simulations of the system done, we consider small hybrid system made of one inverter and one generator. The generator size is initially 6kW to cover the peak load. It can be under dimensioned to

4kW with the Smart-Boost function. With the given load profile of figure 7 and the generator running all the day.

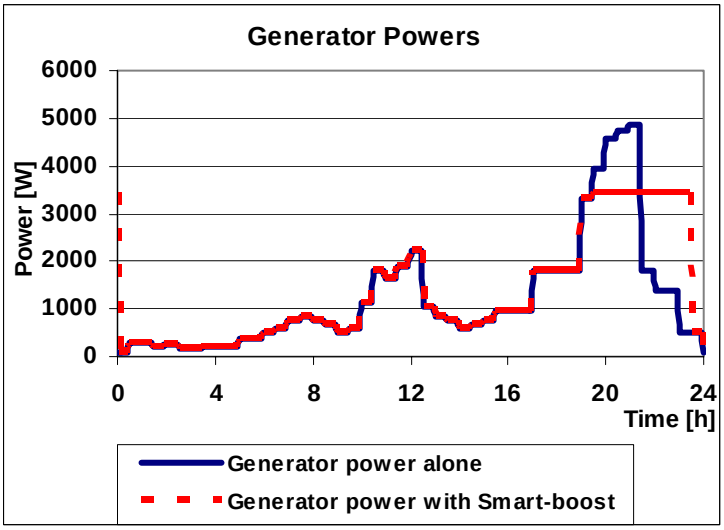

Figure 6: Power profiles without and with Smart-Boost

The 6kW generator running all the day consumes 20.6 liters of fuel. Now with a 4kW generator and the boost the daily consumption is 16.1 liter. We have about 25% of fuel saving. This means 1642 liters per year which represent a considerable amount of money for the fuel and also time spent on refueling and transportation of fuel. We see with this simulation that the boost function can save fuel consumption with the underdimensioning of the generator, even if the cycling of boosted energy in the batteries has a bad efficiency. The initial cost of the generator is lower and running costs for the fuel also, but we pay the inverter and batteries more as initial cost. A second case is probably more relevant for hybrid system: the generator is stopped during part of the time and batteries recharged when running. A running time during the day from 10h to 22h is used for this example. In that case there is an inverter even without Smart-Boost, and then it is not an additional cost in the initial system. The 6kW generator consumes 15.65 liters and the 4kW consumes 13.38 liters, there is 14% less fuel burned.

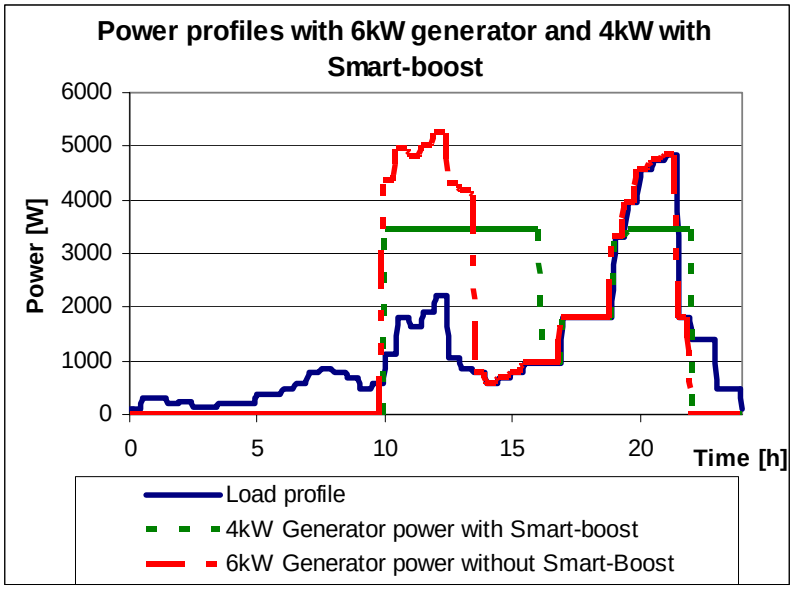

Figure 7: Power profile in a hybrid system where generator is stopped during the night.

Compared to a generator alone system, we see that the hybrid system gives an important improvement of fuel efficiency on the same power profile because the generator is stopped during all the night when the load is low and then in addition to that the use of the Smart-Boost gives still some more gain. Another case would be the automatic start and stop of the generator and the use with solar panels. Simulation of one case wouldn't be representative of the diversity of hybrid system, but we can already mention following points:

- For the case with a lot of solar and the generator is turned on sporadically only when there is energy shortage, the running costs with fuel consumption is less important, but the lower initial cost of the underdimensioned generator is an advantage.
- For the cases with little solar and long run time of the generator we are close to the second example where we demonstrated 14% gain.
- If no underdimensioning is wanted, the Smart-Boost makes the system more powerful when the generator is running for the same initial price. It can help to manage more loads in the future.

3. Extension of an existing system

In rural electrification there is often the problem of extension of an existing system. Many different reasons lead to this: population augmentation, development of a small industry, augmentation of the comfort wanted by the users… When this happens, it often means the collapse of the system because the power demand is over the production capacity. Very often it can be whatever system that is in place and working. This was already paid and has a value. Not any devices can be connected to it for extension of the system.
The inverter with the Smart-Boost function can help to extend such a system overriding the two bottlenecks: power and energy:

- Dispatching the peak power over some more time, allows having more user until the mean power which mean energy, is not sufficient. This prevents the collapse of the system due to a high peak power. Inserting an inverter with batteries between the load and the source add the inverter power to the source.
- Even on a running generator it is possible to integrate renewable energies in the system with the Smart-Boost. This can add the missing energy for a system.

The figure 4 could be a typical case of such an application. In the beginning it could have been made of a 15kW generator only that is upgraded by steps to a 46kW by adding inverters. This ability to handle higher peaks of powers for short time can help to prevent collapse of the system with short term load per example when starting a pump. It gives more flexibility between the short term needs which is instant power and the longer term needs which is energy. There is a better decoupling of those points which is always interesting when planning a project.

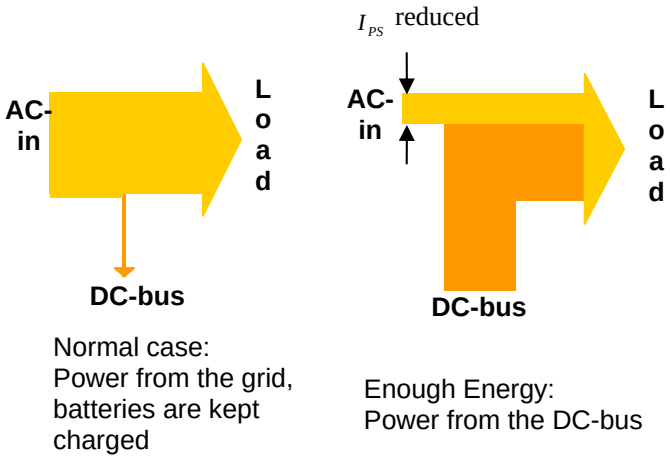

Figure 8 : DC priority algorithm

4. Integration and optimization of renewable energies

There are many microgrids running on a fuel generator only and it is wanted to be extended with new renewable energy sources. As explained the proposed Smart-Boost function makes a load oriented injection of current and doesn't disturb the rest of the minigrid upstream. This mean we can integrate it in virtually any type of system (main grid, generator, minigrid with changing frequency

…) without being concerned about the power production-consumption balance. The Smart-Boost can be a very powerful interface between an AC-bus and a DC-bus. If the boosted energy comes from the renewable connected on the DC side as seen on figure 1, the integration of DC renewable is done. To optimize the renewable energy use, an adaptive algorithm was developed which is the DC priority or solar priority.
Principle of the DC priority is an automatic reduction of the input limit I_{PS} in function of the DC voltage V_{DC}. This is done from a priority voltage $V_{priority}$. If there is a DC power producer, it make the DC-bus voltage rise and this is measured by the inverter which diminished the input limit and therefore cover more of the load power with power coming from the DC side. At a given operating point the DC-bus voltage is constant; there is no cycling of the renewable energy in the battery but a direct reinjection toward the AC loads. Under the priority voltage it works at the normal I_{PS} allowing the underdimensioning of the generator as seen above.

V. CONCLUSIONS

In this paper we showed how starting from the idea of power assistance, we solved uncontrollability under particular loads by developing the Smart-Boost which is a load current assistance. This method is able to work correctly with any kind of loads and any kind of source. This new concept of current control opens doors and perspectives in microgrids. There are new technical possibilities especially in the extension of existing systems and underdimensioning in planning new systems.

The Smart-Boost function was developed and tested successfully for a new inverter produced by the Studer-Innotec company called the Xtender. The inverters now exist in 12, 24 and 48V which are standard battery voltage found in island systems. Many tests have been done to find out the limits and problems that can occur with the Smart-Boost in parallel of the main grid or on a wide range type of generators, from 1kVA to 60kVA. Those practical experiments helped to develop a very robust Smart-Boost function adapted to the field application.

VI. REFERENCES

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