Partial AC-coupling in Mini-grids

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INTRODUCTION

This paper defines the concept of partial AC-coupling in a mini-grid, explores its limits and highlights the benefits of a mix of DC and AC coupling. As can be read in [1], it is now well accepted that the hybrid systems offer a suitable solution for the rural electrification. Standard configurations are now the use of a DC-bus, or an AC-bus, or a mix of DC and AC bus. Every single system tends to be a unique mix that a project integrator optimizes. We will focus on the mix, because there are good reasons to make not only DC neither only AC. From there comes the title '*Partial AC-coupling*'.

AC-coupling in mini-grids is generally associated with the use of the V/f droop functions, [4] [5]. With the same droops control method implemented, all kind of elements can be paralleled on the AC-bus: battery inverters, generators, solar inverters, wind turbines with inverters. This paper describes the cases where elements that don't have all the same V/f droops can be connected by the AC. That is the topology we call also '*Partial AC-coupling*', because certain types of elements can be paralleled but not all of them. This understanding opens a few design possibilities to the system integrators.

Electrically, different voltages sources (VS) should not be connected together in a system without a proper synchronization like droops or communication-bus. But a current source (CS) and a VS can be interconnected without problems. Grid-feeding inverters (solar, wind…) are typically CS paralleled with a VS. Generally the VS is the main grid but it can be a bidirectional battery inverter creating the voltage of an islanded grid.

FREQUENCY CONTROL STRATEGY

In an islanded system the battery has a buffer role to maintain the consumption-production balance. The buffer is limited with the battery capacity and there is the necessity to control the production to have a system working safely. In a system like on the figure hereby, if there is more production than demand, the excessive solar goes to recharge the battery. If the batteries are full the power production must absolutely be reduced, stopped or consumed to avoid overcharging of the batteries. This can be done with connection/disconnection of sources with switching circuits, dump loads or other control methods (communication bus …). But a simpler and more cost-effective solution for the control of the grid connected inverter is with the frequency as information vector. A central battery inverter works as a
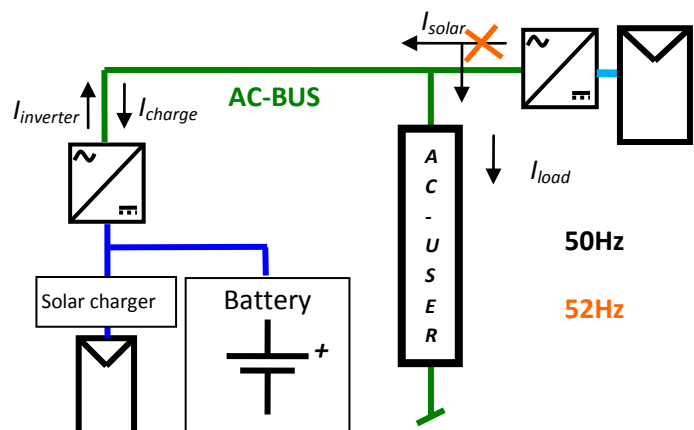
AC-coupled solar inverter and DC-coupled solar charger to a battery inverter

VS inverter (VSI) to provide the islanded AC grid. This VSI has the control of the voltage and frequency in this system. The frequency is modified as a function of the battery status and every producer or consumer on the AC bus can switch on/off according to the information carried out by the frequency:

- $f = 50Hz$ reference frequency
- $f > 50Hz$ batteries are full/close to full → reduce power production or add loads.
- $f < 50Hz$ batteries are not full/close to empty → load shedding.
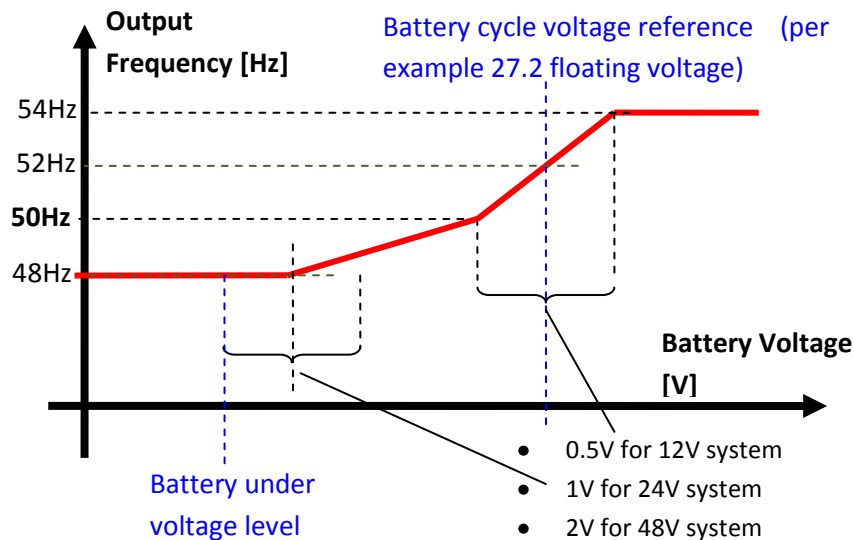
A decrease of the frequency is also added to the system. It is interesting to know also when the batteries are empty with a low frequency of the AC grid. Per example intelligent relays could disconnect loads with when the batteries are low.

USE A STANDARD GRID CONNECTED SOLAR INVERTER

The grid connected solar has become a huge market compared to off-grid which is the natural and historical market for solar. For the ongrid market, much more money was invested and now very good products exist in term of cost and reliability for solar modules and inverters. Those products are not suitable for the small off-grid systems but there is medium size where they can be used, in the range of a few kW, typically in mini-grids. A grid connected solar inverter can be connected to a local AC-grid produced by a bidirectional battery inverter. The grid inverter with standard settings accepts frequencies only between limits required by grid directives, per example for German Renewable Energy Act EEG between 47.5Hz and 50.2Hz for the small units connected to low voltage (see [6] and [7]). When the frequency exceeds 50.2Hz the solar production is stopped. This behavior can be used by the battery inverter to control the grid inverter. Practically a $\Delta f \geq 0.2$ is added to $f_0 = 50Hz$ when the batteries are at the wanted voltage target and this perform an ON/OFF control of the solar inverter.

This system works with different scenarios:
1. There is less solar power than user load: → the grid inverter work as MPPT and all the solar power covers a part of the load need.
2. There is more solar power than user load:
   a. The batteries are not full: → the grid inverter work at MPP and the solar power covers the user load and the excess recharges the batteries.
   b. The batteries are full: → the grid inverter is switched ON and OFF with frequency increase to make the top charge.

PRACTICAL TEST WITH 3 STANDARD GRID INVERTERS

Practical experiments with three major manufacturers of the market are shown. First the stability between a grid connected solar inverter and a Studer battery inverter is tested to assess the robustness of the system. This system has been used for a quite long time in a system called Solsafe, which is a backup for a grid feeding system, see [3]. Coupling battery inverters and grid connected inverter is not only theoretical but a proven concept. In the past, one problem observed was that there were often disconnections of the grid inverter because of the grid tests performed (ENS). This happens because the battery inverter has higher output impedance than the main grid. It is similar to the 'end of line' effect on the main grid. But now, smarter and more stable tests are performed to detect islanding. The new methods used allow working with standalone battery inverters as VS without problems.

Various tests were performed with a Studer Xtender inverter and a Solarmax S3000 together. It worked with the default settings for Germany for the S3000 without any parameter modification. Similar tests were performed with a standard SMA SunnyBoy1700 and a Kaco Powador 2002. The stability tests are: load jumps, impedance added between the units, tests of transients that disturbs the voltage and modify impedance of the line,…

Graphic hereby shows one example of the behavior of a system where a S3000 is used with a XTH5000-24 using 40 meters of 10A rated cable to connect the system together with a high impedance (approx. 1.2 Ohm). A load jump of 1kW is done by turning on a halogen lamp (which has a start current very high when filament is cold at start-up). The voltage (yellow) is distorted due to the high load on the high impedance line, but the solar inverter (current in

Voltage (yellow)
Solarmax current (blue)
Load current (pink)

blue) continues its work almost without noticing it.
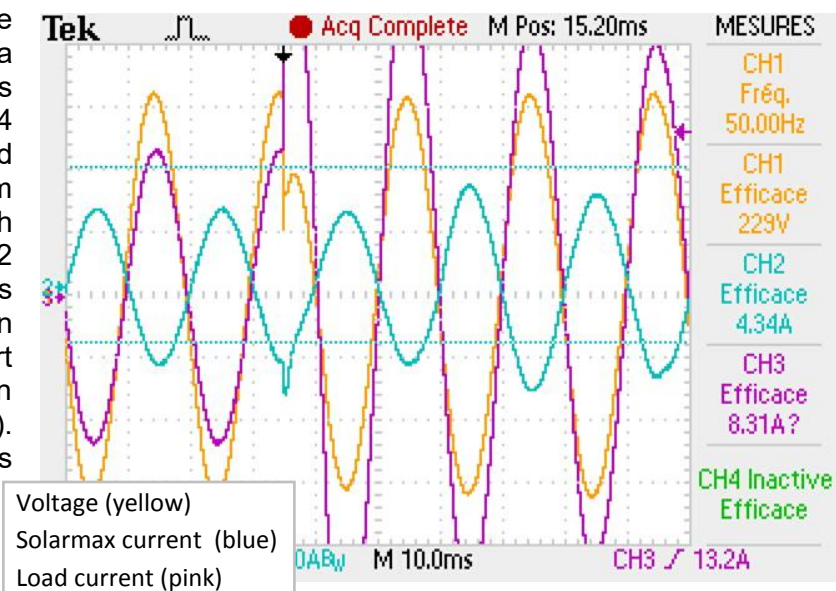
A SunnyBoy1700 with a standard DE configuration is used below with a Studer XTM2400-24. There is a constant user load and a constant 'solar' production given with a DC power supply. When the grid inverter is on, the batteries are recharged (positive current on graphic below) and when off, they are discharged. The battery bank is a quite old 250Ah lead acid battery. With a datalogger function in the Xtender XTM inverter, one point is saved every minute over the day and the behavior of the system can be well seen.

In a first part all the 'solar' power is taken by the empty battery and the voltage rises slowly up to the absorption voltage. The absorption phase was programmed 1 hour and then the voltage goes to the floating level. The ON/OFF control when the frequency rises over 50.2Hz and the 'PWM like' charging of the battery is well observed.

Test of SB1700 with standard DE settings
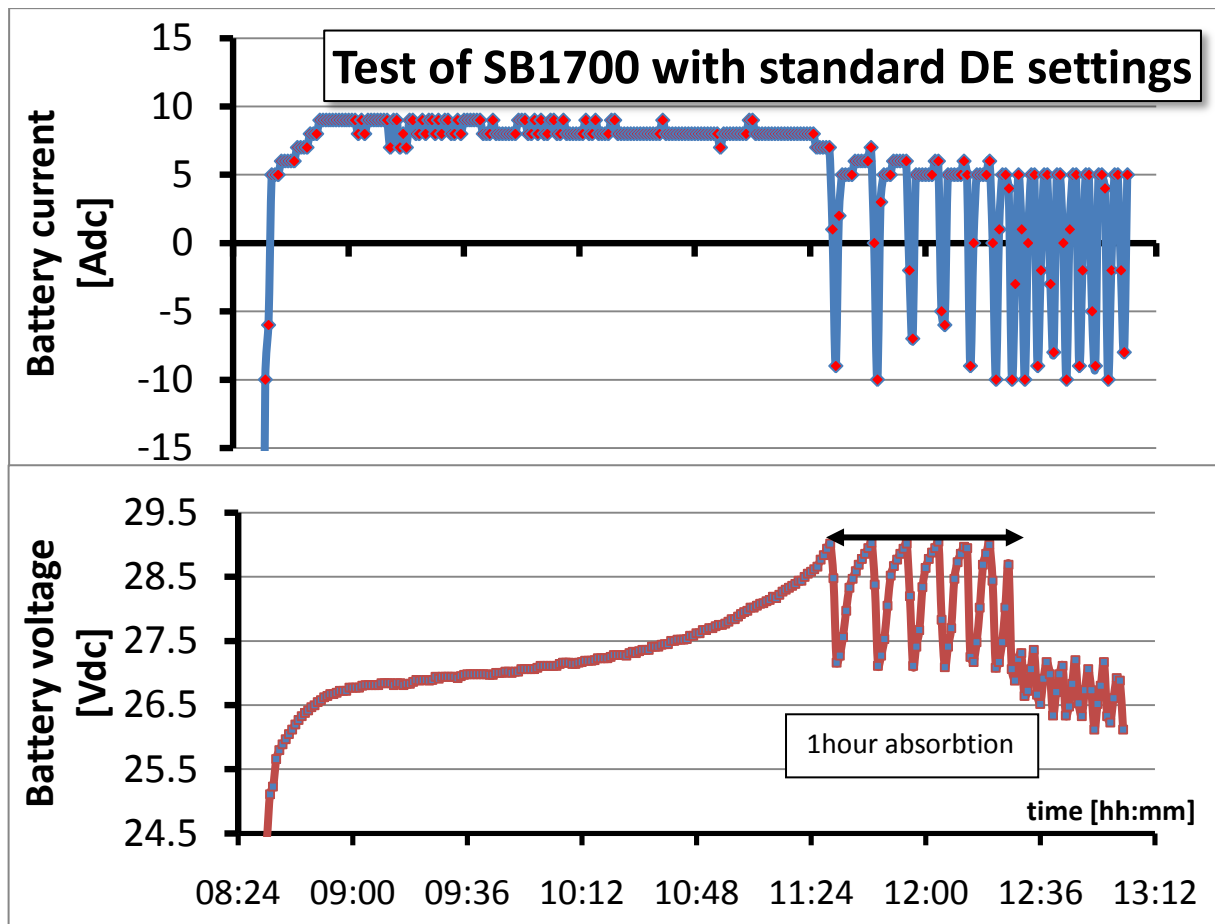
From the tests a few points were observed:

- The battery after the absorption phase is quite well charged because the voltage comes back immediately when the grid inverter turns on again.
- With the effect of the ON/OFF control, the mean voltage on the battery at the end is a little bit under the floating voltage. The floating voltage should be set a little bit over the normal value so that the mean and not the peak voltage reach 27.2V for a proper end of charge (to guarantee that there is the maximum amount of energy in the battery at the end of the sunshine.
- With a smaller battery compared to the load/injected power, the hysteresis on the voltage is higher. The battery should have a minimum size compared to the charger size.
- All the standard inverters don't have the same behavior programmed. Per example the Solarmax S3000 stops 20minutes after a couple of overfrequency errors.
- If the max frequency can be modified and there is more than one grid inverter, it is interesting to stop one after the other, per example first stops at 50.2Hz, a second at 50.5Hz. Then we can modulate the power production with two steps.

Artificial cycling of the battery

With the ON/OFF control method some energy is put in and out of the battery all the time during the topping charge. There are microcycles done. What is the effect of this on the battery lifetime? Battery is a costly and sensitive component in the system. It must be handled with care. [8] discusses more about microcycles for renewable energy systems and show that the energy throughput question is important.

There is a graphic that is given by battery manufacturers that correlate the depth of discharge (DOD) and the number of cycles.   Generally this relationship is interpreted in the way that a low DOD is good for the battery life time. But actually at 40% DOD the number of cycles is about the double than the one with 80% DOD. The energy in transition through the battery is then about the same, and the real use of the battery is about the same.

If the graphics is interpreted in term of energy, the energy going in and out of the battery is $E = DOD \cdot n$, we can say that using at 40%DOD for 3600 cycles

OPzS Endurance in cycles (Hoppecke)

a battery there is $E = 0.4 \cdot 3600 = 1440$, for a battery capacity normalized to 1. And using at 80%DOD for 1650 cycles a battery there is $E = 0.8 \cdot 1650 = 1320$. The 'quantity of use' or 'energy throughput' of the batteries decreases little with a high DOD, less than 10% of energy difference between 40% and 80% DOD. From the cycle number figure, the following graphic of the energy through the battery can be plotted.

OPzS Endurance in energy, normalised battery capacity
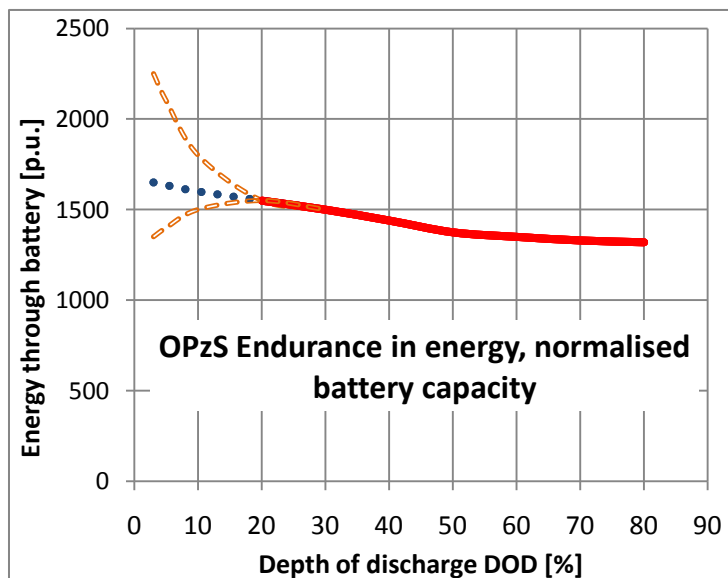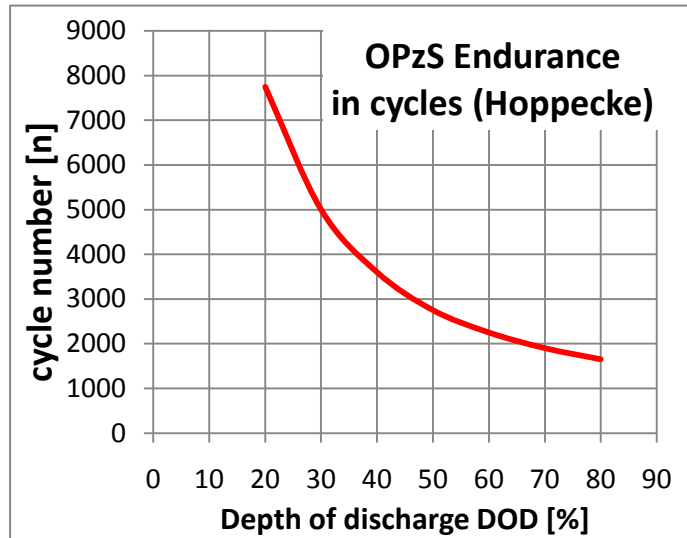
Conclusion of this graphic is that the battery lifetime is more or less given with a given quantity of energy over 80%. Manufacturers give the warning that the battery should not be used over 80%DOD.

If the battery energy throughput is given, then the microcycling has an impact on the battery lifetime. We have to determine if this is relevant or not compared to normal use. Factor that influences this is how many times a day this microcycling is done, and this depends mainly on the balance of the load profile compared to the solar production profile.

Per example if there is always less solar power connected to AC than loads, then there is never the necessity to stop the grid inverters and there is absolutely no microcycling and no impact on the battery life time. Another scenario would be that there are no loads at all and solar is produced. In that second case there is also surprisingly no impact on the battery life time. Because energy is only going into the battery, not out of the battery, there is no cycling. There is cycling in between those two cases, when there are loads and solar and the same time and there are less loads than solar power available.

Data under 20% DOD were not available. So we made the assumption that the tendency continues similarly. If this expectation is correct for the mentioned OPzS battery, you could make around 55000 cycles at 3% DOD and 330000 cycles at 0.5%DOD. For the example given above with the SB1700, 1 minute at 500W load with 26.5V battery represents 500/60/26.5=0.31 [Ah] which is 0.12%DOD (1375000 cycles). There can be 20 microcycles

of 0.12% a day during 188 years. The effect on the battery lifetime with that number of microcycles of that energy amount is low.

From the theory and experiments described above, we conclude that it is possible to use a standard grid-inverter in a mini-grid with an ON/OFF control performed by the frequency change. But to minimize the artificial cycling of the battery, it is important to have a load profile with loads at the same time as the solar production, or to have little energy going out of the battery when the grid inverter is OFF.

POWER REDUCTION IN FUNCTION OF THE FREQUENCY

The 2009 EEG grid code (see [6] and [7]) has set new requirement and one is particularly interesting for our application, it is an active power derating in function of the frequency. When the frequency increases, the grid connected inverter doesn't simply stops but reduces its power linearly between 50.2Hz and 51.5Hz. This rule is set for medium voltage and high voltage and is not applied for low voltage yet. When this will be implemented generally it will be very interesting for the offgrid systems. By changing a little bit its output frequency, the battery inverter will be able to control the solar production in an island grid to match production-consumption-storage balance. It will be a precise control instead of an ON-OFF control and will avoid the microcycling. Technically this behavior is not very complicated to implement in the low voltage solar inverters, it is just control software. But up to now, the interest from the various manufacturers was low due to the small size of the offgrid market and still smaller size of the minigrid market.

This behavior can be already tested now with the SunnyBoy inverters; they can be parameterized to work this way, even for inverters connected to low voltage 230V/50Hz line. And it is the most sold grid inverter on the market. The second most sold manufacturer on the market, Kaco, has in every product a reduction of power of 50% between 50.2Hz and 51.5Hz that can be set with the 'Activate BDEW' parameter (Medium Voltage Directive).

Test of SB1700 with frequency power control
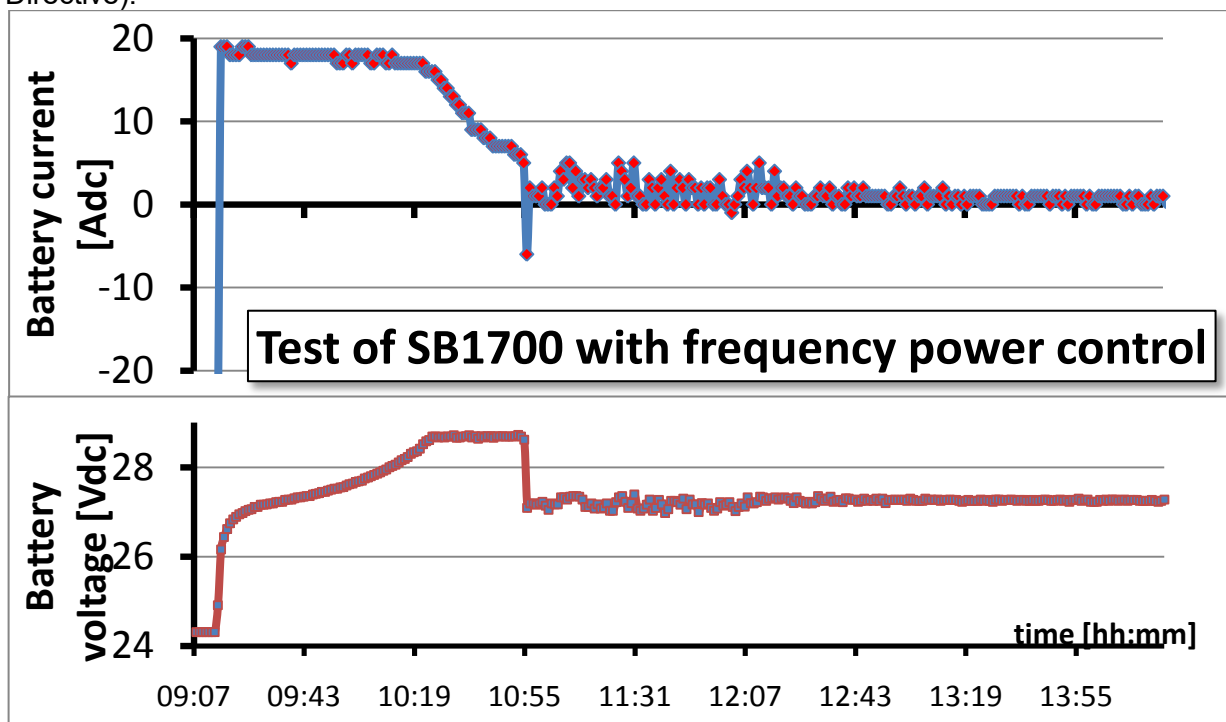
We can see a clean absorption phase with the current reduction and floating voltage done without microcycles. If the voltage oscillates a little bit around the floating voltage, this is not important as long as the energy flux is unidirectional.

NETWORK OF BATTERY INVERTERS WITH DIFFERENT CONTROL MODE
Other elements than the solar grid inverter can be used in this system with a centralized VS. On the AC-bus, standard battery inverter/chargers can be connected, if they are in current-control mode (CS). It is possible to distribute battery inverters in the minigrid and make them work together without V/f droops as long as there is only one voltage source in the system. We obtain a system with a central VS and distributed CS. The reliability of this minigrid is high, because each battery inverter with a transfer relay can work on his own as a UPS, if there is a problem elsewhere in the minigrid.
More than that, each CS-inverter can have its own solar charger (or other sources) connected to its DC side and is able to share this energy with the rest of the mini-grid because it is bidirectional. The global energy management can be done with the frequency of the minigrid.

MIXING DC AND AC COUPLING: EFFICIENCY AND ROBUSTNESS
Considering the efficiency, AC-coupling and DC-coupling are not similar.
The power profile determines the total efficiency again:
- If there is excess solar production during the day and it must be stored into the batteries, DC-coupling has a better efficiency.
- If the solar energy is directly used, there is one conversion less with the AC-coupling.

Following computation is done to compare both cases with assumptions:

Grid inverter efficiency:	$\eta_{grid-inv} \cong 0.96$
Battery inverter efficiency:	$\eta_{batt-inv} \cong 0.93$
DC solar charger efficiency (with MPPT):	$\eta_{batt-charger} \cong 0.95$
Battery storage efficiency:	$\eta_{batt-cycle} \cong 0.8$

Energy produced by the grid-connected solar inverter must be stored for the night time:
$$E_{back-AC-coupled} = E_{solar} \cdot \eta_{grid-inv} \cdot \eta_{batt-inv} \cdot \eta_{batt-cycle} \cdot \eta_{batt-inv} = E_{solar} \cdot 0.664$$
Energy produced during the day by the grid-connected solar inverter is directly used by user:
$$E_{direct-AC-coupled} = E_{solar} \cdot \eta_{grid-inv} = E_{solar} \cdot 0.96$$
Energy produced during the day by the solar charger connected to DC:
$$E_{back-DC-coupled} = E_{solar} \cdot \eta_{batt-charger} \cdot \eta_{batt-cycle} \cdot \eta_{batt-inv} = E_{solar} \cdot 0.706$$
Energy produced during the day by the solar charger connected to DC and directly given to user: $E_{direct-DC-coupled} = E_{solar} \cdot \eta_{batt-charger} \cdot \eta_{batt-inv} = E_{solar} \cdot 0.883$

Efficiency on solar energy	DC-coupled	AC-coupled
Energy stored in battery	70.6%	66.4%
Energy directly used	88.3%	96%

There is not a big difference: 3.5%, between using AC or DC coupling for energy stored in batteries, and a little bit bigger difference on the direct use during the day: 8% at the advantage of AC-coupling that avoids one conversion.
This is true only for a modern solar battery charger with MPPT included. The values are very different if the solar regulator is a traditional series or shunt. It is quite well accepted that a MPPT can give up to 30% more energy during a day compared to a direct connection to a battery (if the battery is never full!). The ideal case for efficiency is direct use of AC-coupled solar energy and storage for night time of the DC-coupled solar. But practically, install two different types of solar systems, is probably not interesting. The installer will prefer a simpler system with only one connection philosophy even if there are a few little percents of efficiency to gain. The mix of AC and DC is interesting on another level: for the robustness of the system. If AC is not present for any reasons, the solar grid inverter cannot work. That is a weakness in the system: the solar production depends on the proper operation of the battery inverter that creates the AC; the
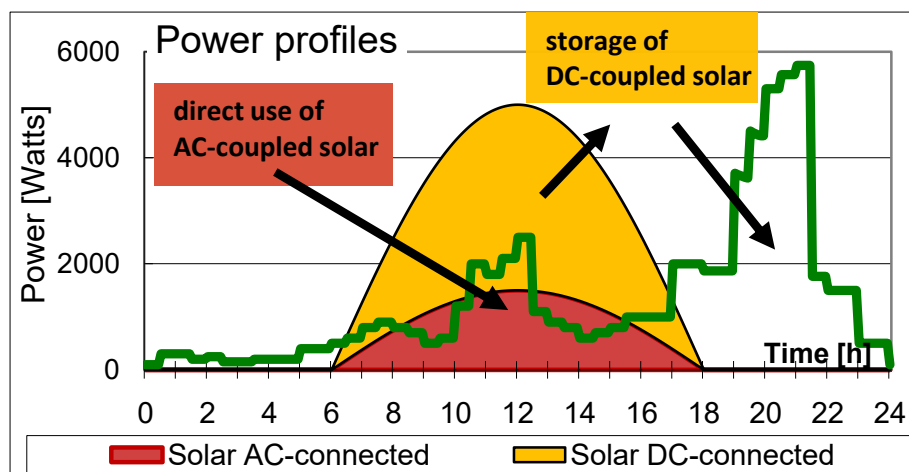
battery charging depends on two components instead of one. Per example if the batteries are empty after a few rainy days, the battery inverter stops in order to protect them. And when the sun comes back the grid connected inverters don't start if there is no AC. With AC-coupling only the system can be blocked in this situation. If there is solar at the DC, it can recharge the batteries the next sunny day and all the system can restart again. Then we propose to always have a part of solar to DC when using AC-coupling: partial AC-coupling.

CONCLUSIONS

Partial AC-coupling:

- It is feasible to make AC-coupling of some compatible elements without V/f droops. Standard elements available on the market were tested.
- Optimum design for efficiency is a share of the solar modules between DC-coupling with a solar charger and AC-coupling with a grid inverter according to the load profile.
- Partial AC-coupling is better in term of robustness; it is more reliable to have at least a part of the solar production connected directly to DC, or even only DC coupling.

The presented concepts are not only theoretical but were implemented and tested on real products available on the market. Many tests have been done to find out the limits and problems that can occur with the use of grid connected and standalone inverter together. Many combinations were tested and it was found robust enough to be used in the field with the precautions mentioned about microcycling.

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