Mini-Grids with Distributed Energy Generation and Frequency Control

Six years of operational experience of a pilot project in Switzerland

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Abstract – Studer Innotec developed a concept and test site in Switzerland with a distributed mini-grid where different Voltage Source Inverters (VSI) and Current Source Inverters (CSI) where synchronized and controlled together. The system is based on a central inverter which provides voltage and frequency for the island grid (central VSI). Around this common point is the mini-grid: there are distributed inverter-chargers in all the different houses acting as current sources (distributed CSI).

The operation of a pilot project in Switzerland for more than 6 years has validated the concept and provided a robust and stable solution over this time. Different operating modes and types of mini-grid users have been identified. A set of energy management rules has been developed for ensuring the successful operation of the mini-grid. The concept has been extended so other equipment could be integrated, such grid-tied inverters, controlled deferrable loads, and smart meters for controlling loads. In addition, this project provided feedback for future research to improve the control and operation of similar systems.

I. Introduction

In the heart of the Alps, a small community called "Mayens sur le Scex" regroups 32 small buildings, historically used when livestock were at summer pasture, and currently used as summer cottages. These alpine houses generally have electricity with individual solar systems: each house has its own solar PV generator, battery and inverter. The houses usually have a low rate of occupancy and most of the time the batteries are fully charged, and the solar energy is not used. Looking at the whole system, there is a lot of unused solar energy production and the global efficiency is very low.

In a project to improve the electrification of this small community, the independent solar PV systems were linked together in a network of individual systems, with the goal of sharing advantages but not disadvantages, having for example the following situations:

- When a house is occupied, the owner can make use of the all the solar energy produced by the unoccupied houses, which would otherwise not be used. This also helps to reduce battery cycling.
- An unoccupied house must nevertheless keep its batteries full, before sharing its PV production to others. Otherwise, the day when the owner comes back, he or she would be unhappy, having the feeling that others are using his or her energy.

To reach this goal, a specific energy management strategy is implemented in each individual inverter to decide when it shares energy or not with the other users. The novelty of this concept is based on combining individual systems, each with its own investment (each building owner paid for their own system) and interest (self-consumption of the energy produced before the neighbors use it), to share the common benefits together.

II. Concept Description

The system is based on a central inverter which provides reference voltage and frequency for the mini-grid, a voltage source inverter (VSI). A low voltage (LV) single phase distribution line is connected to every house creating the mini-grid. The distributed inverters connected to this line act as current source inverters (distributed CSI), they synchronize with the mini-grid (central VSI) and feed or consume current from it, without modifying the voltage or frequency. In this specific project, the installation of new water distribution pipes allowed to bury electrical cables in the same trenches, thereby avoiding the costs of trenching or installing an overhead power line.

A. Energy Use Optimisation Respecting the Infrastructure Investments

Every user purchased their own private system (distributed CSI). By connecting to the mini-grid, every user maintains ownership of their system, including its benefits and responsibilities, but they can optimise their energy utilisation.

B. Sharing Energy to Improve Global Efficiency

The optimisation of the energy use is achieved by:

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- Maximizing the use of excess energy (feeding into the mini-grid the excess, if allowed)
- Extending the energy resources exceeding the battery capacity and local power (taking energy from the mini-grid if allowed).

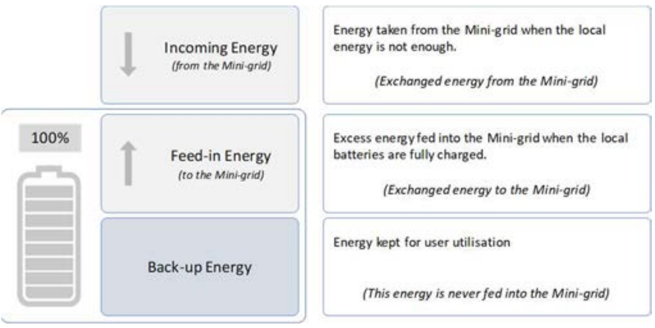

Figure 1. Three energy situations are foreseen

C. *Adapated to Every User*

The energy optimisation with three energy situations could be adapted depending on every user, application, demand, etc.

- consumer users, benefiting from the energy in the mini-grid (if possible) to consume directly or store for future use (if they have storage).
- productive users, feeding the excess energy not self-consumed to the mini-grid. These users could have a system with or without battery.
- fully interactive with the mini-grid users, consuming their own energy plus energy from the mini-grid and feeding their energy excess to the mini-grid when their battery is full.

D. *Compatible with Common/Private Investment*

The mini-grid is flexible in terms of increasing or decreasing the capacity of the systems, allowing to increase the private investment (enlarge the private user installation) or to increase the common infrastructure (central installation).

E. *Increasing Global Self-Consumption - Reducing Battery Cycling*

The goal is that every user maximizes its self-consumption reducing the battery cycling, but the excess or deficit of energy is shared in the mini-grid to optimise the global energy utilisation. The strategy is “Share the benefits, not the problems”.

- “Share the benefits” is the global system vision to provide users with solar PV energy that would otherwise be wasted.
- “Not the problems” is the energy management strategy that favours the use of local storage for self-consumption, sharing only the excess of energy with the mini-gird;

Each user retains at least as much energy as if they were autonomous with their own off-grid system. The users’ energy needs are satisfied at least as well with the mini-grid as with an autonomous system.

III. The Challenges

The Mayens du Scex project was conceived as a pilot project for demonstrating the feasibility of the technical solution. In addition to the technical challenges, the project faced other challenges coming from the project context.

A. *Lack of Dedicated Communication Bus*

Sharing energy requires a control strategy among the producers. Installing a dedicated communication bus would have added costs, complexity, and a higher probability of failure. In this project there is no dedicated communication bus between the centralized controller and each system. The solution uses a frequency control strategy where no separate communication is required. In a system with limited resources available, a separate communication system would have increased energy consumption.

B. *Energy Availability Self-determined by the Users*

Each user is independent and can fine tune their control method. Every user can decide at every moment how do they interact with the mini-grid, how much energy they keep as backup and how much energy they feed when there is excess energy.

C. *Business/Management Model*

While there is no established business model, there is a clearly defined energy management model defined as follows. The central unit was installed for the common benefit of the users, who contribute to its cost and maintenance. The energy exchange is not monetized according to an economic model.

IV. The Solution

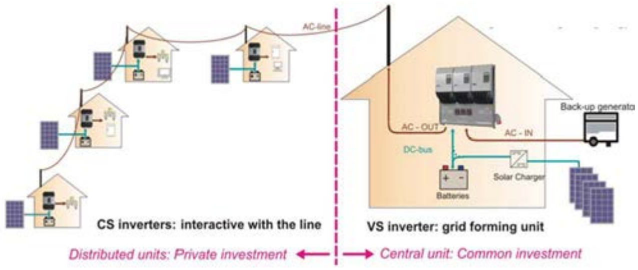

Figure 2. Mini-grid topology

The central VSI is the grid forming unit establishing the voltage, frequency and other grid variables. This is the common infrastructure shared by the community. The distributed CSIs are the user's private systems, they are synchronized with the mini-grid established by the central VSI and they are interactive with the grid in function of the frequency and the status of their batteries.

The central VSI sets the mini-grid frequency and slightly modifies it around 50Hz to communicate with the distributed CSI. The frequency is a very robust information carrier, not influenced by the quality or distance of the distribution line. The voltage is set at the standard 230V (no information is carried by the voltage), the frequency varies between 48 and 54Hz. There is no other communication between the central VSI and the distributed CSI.

The central inverter sets the frequency according to its battery state:

- f =50Hz, reference frequency
- f >50 Hz, central batteries are full/close to full near 54 Hz: a lot of energy available.
- f<50 Hz, central batteries are not full/close to empty near 48Hz: low energy status.

The distributed CSI can determine the approximate central VSI battery voltage from the measured frequency and compare it to their own battery voltage, thus determining if the distributed CSI has more or less energy than the central VSI. The energy management rules determine the behaviour of the distributed CSIs. Decisions are decentralized: each distributed CSI applies the rules for itself without knowing what the others are doing and without communication among the distributed CSI. The energy management rules were established such that the global system should work in a coherent way considering the following criteria:

- The security of the global system ensuring the operational range are respected for every installation.
- Optimize the global system energy efficiency, minimize the losses, and increase the system's lifetime (especially the batteries).
- Every user owns its system. There is a personal investment for each house owner and the energy management must give them satisfaction and a feeling of equity and justice among users.

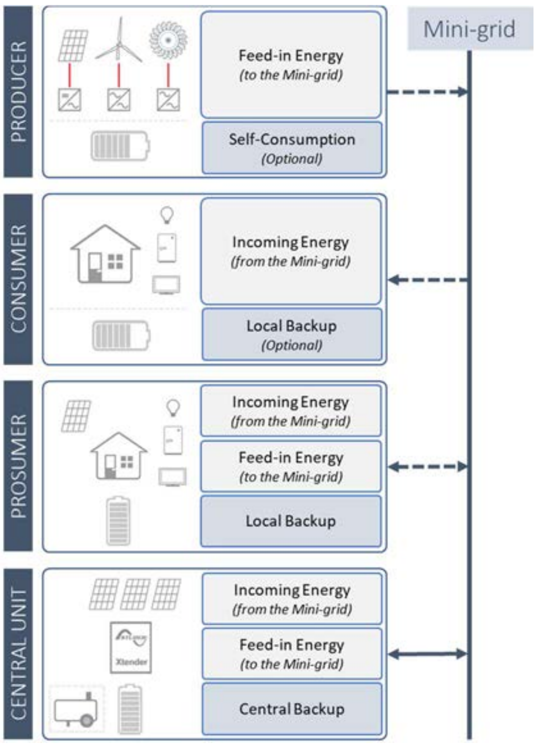

Figure 3. Different type of users in the mini-grid

A. *Type of Users/Actors*

According to the project requirements and considering the previous energy management rules, the following mini-grid actors are defined according to the Figure 3.

B. *Interactive Frequency Control*

Studer Innotec has developed the mini-grid function allowing to perform the interactive frequency control for the mini-grid.

1) *The Central Inverter (VSI)*

The central VSI sets the frequency according to its battery voltage. The frequency of the mini-grid distribution line can be interpreted as the state of energy of the global system.

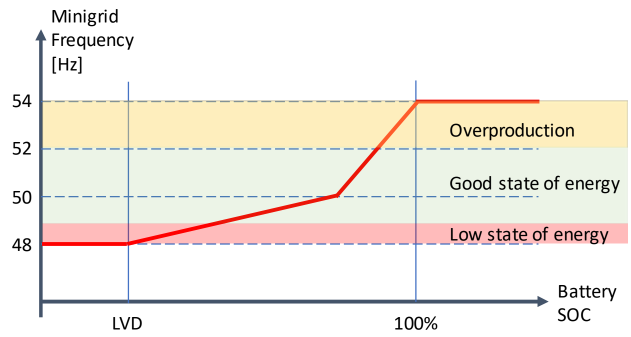

Figure 4. Frequency behaviour of the central inverter according to the battery voltage

There are two different behaviours in this graph:

- Zone A, frequency increase 50-54Hz, mini-grid feeding control.

  The central battery voltage increases during the battery charge cycle. The frequency increases gradually starting at 50Hz and following the battery voltage until reaching 54Hz when the battery is fully charged. As the frequency increases, the distributed CSIs gradually reduce how much they feed into the mini-grid until reaching 54Hz, when there is no feeding into the mini-grid.

- Zone B, frequency decrease 50-48 Hz, mini-grid consumption control.

  The central battery voltage decreases as the battery is being discharged. The frequency decreases gradually starting at 50Hz and following the battery voltage until reaching 48Hz when the battery voltage reaches the low voltage disconnection value. As the frequency decreases, the distributed CSIs gradually reduce their consumption from the mini-grid until reaching 48Hz, when there is no consumption from the mini-grid.

2) *The Distributed Inverters (CSIs)*

Reading the mini-grid frequency, the distributed CSI compares its battery level against the central battery level. This comparison determines the rules applied to the energy exchange in real time. In addition, the following rules will be applied:

- Energy quota. Every user has a daily quota of energy which helps ensure a fair distribution of energy between the mini-grid users when the energy is limited. The energy quota resets every night.
- Power limitation. Like other grids, the maximum power available is limited, calculated considering a

synchronisation factor, to be sure that the central unit is not overloaded.

- Low power mode. If there is low consumption, the distributed CSI can switch down to a standby mode. Only the central unit is providing the power. The system self-consumption is kept as low as possible to avoid unnecessary use of the limited resources.

The behaviour of the system is represented in the figure 5 showing the state of the central VSI versus the state of the distributed CSI. This is represented with the frequency given by the central VSI and an equivalent frequency of the distributed CSI (representing the battery level after the frequency comparison).

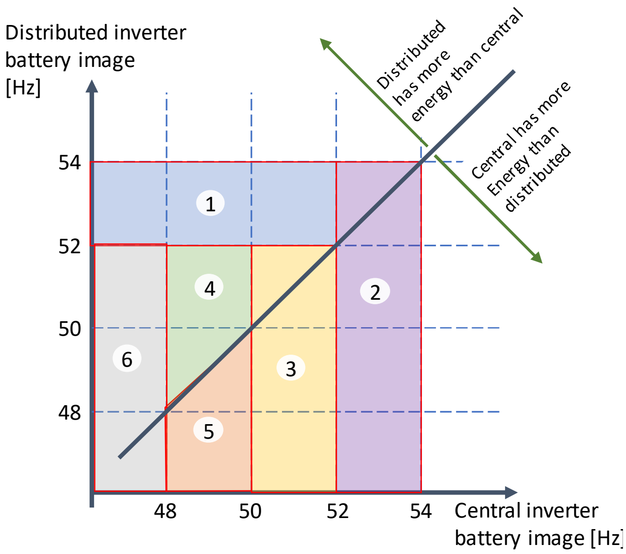

Figure 5. Energy management rules

Zone 1: The distributed battery is fully charged. The central battery is not fully charged. The distributed CSI will feed all the energy excess into the mini-grid. This energy will charge the central battery and/or be used by other users.

Zone 2: The central battery level is close to 100%. Feeding into the mini-grid by the distributed CSIs is limited.

Zone 3: The central battery level is high. The distributed CSI can use power from the mini-grid to supply its loads and to charge its battery up to the central battery level. The quota is not applicable in this zone, so the distributed CSI can take as much energy as needed from the mini-grid.

Zone 4: The central battery and the distributed battery are both at medium level, but the central battery level is lower than the distributed battery. The distributed CSI can use power from the mini-grid to supply its loads but not to charge its battery. The energy taken from the mini-grid is limited to the user quota. When the quota is reached the distributed CSI will operate autonomously, using energy from its battery.

Zone 5: The central battery and the distributed battery are both at medium level, but the central battery level is higher than the distributed. The distributed CSI can use power from the mini-grid to supply its loads and to charge its battery up to the central battery level. The energy taken from the mini-grid is limited to the user quota. When the quota is reached the distributed CSI will operate autonomously, using energy from its battery.

Zone 6: Battery security zone. The central battery is fully discharged, the distributed users disconnect from the mini-grid and keep operating autonomously (off-grid). This situation will not be reached when the exchange rules are correctly applied.

C. *Advantages*

The mini-grid with interactive frequency control solution for the "Mayens sur le Scex" project has been successfully implemented and it has been running for more than 6 years. The most important advantages from this solution compared to the situation before the mini-grid was created are:

- The Studer mini-grid solution allows to go beyond the traditional centralized system power by adding more distributed power on the mini-grid at any time.

- The solution is reliable and robust, in case of a problem in the central unit, the rest of the users are independent and able to keep their energy consumption with their own system. In case of a problem in one of the user's system, the rest of the users and the mini-grid keep operating at full capacity.

- The high flexibility in the configuration and adaptability to future demand leave ample room for upgrades in the system, either at the central and private levels. Each user can increase their system in three variables: energy production (solar), energy storage (battery) and power (inverter).

- The fact that there is no dedicated communication bus implies no data management and no centralized supervisor or intelligence to manage the system. The distribution line through the frequency is the carrier of the information resulting in a very robust and straightforward solution.

- The solution is compatible with many different types of users, adapting the strategy for all user needs. Along with the project life, different strategies have been adjusted for the users, keeping the user autonomy and energy independency always as the key elements.

- The combination of individual systems in a complete larger system allow the private users to benefit from the larger-scale of the project, for example in logistics, transport, costs, lobby for regulations, etc.

V. EXPERIENCE – LESSONS LEARNED

During the implementation and operation of the project some adjustments were made to continuously improve system performance.

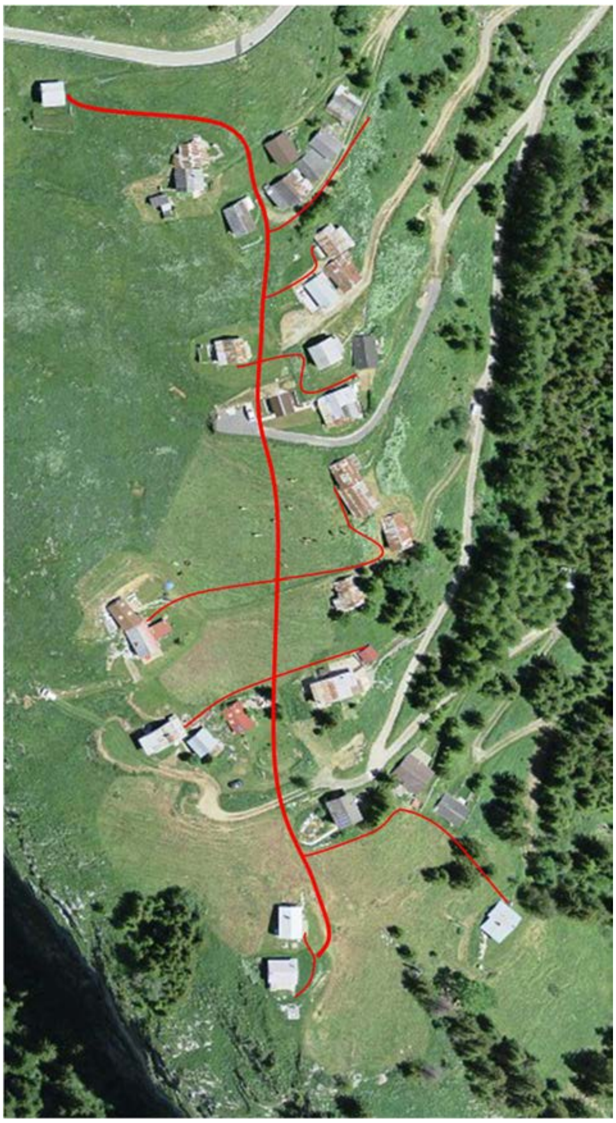

Figure 6. Aerial view of the "Mayens sur Scex" mini-grid

- The first concept solution was deliberately conservative in terms of security. User feedback led to an increase in the user energy quota and power limitation, increasing the user's benefit of the mini-grid.
- Given the rapid evolution of communication technologies, if a dedicated communication protocol would have been chosen at the conception of the project, it would now be outdated, making future extensions more difficult.
- Before the "Mayens sur Scex" project, every individual user had a generator as backup source of energy. With the mini-grid, the use of generators has been dramatically reduced, resulting in economic, environmental and noise level benefits for the community.
- The flexibility of the mini-grid solution enables the technology to be adapted to all needs depending on the type of community and how the community evolves. The user satisfaction is very high as the solution can be adapted to cover all different user situations at all times.
- The importance of social aspects for correct system performance cannot be overstated. The local community is a crucial contributor to project success and significant time and resources should be budgeted to manage expectations and help users learn to make the most of the mini-grid. This project has greatly strengthened the community cohabitation of Mayens Sur le Scex.

Figure 7. Return of experience from more than 6 years of operation

VI. PERSPECTIVES

Although the technical concept has demonstrated to be a reliable solution for these projects, some paths for further development have been envisaged to enlarge the mini-grid possibilities.

Including smart metering and establishing a business model for the energy transactions will be the gate to attracting private investment and enabling further development of mini-grid projects in communities.

The application of lithium batteries, especially for the central battery, will translate into more flexible energy and power quotas. Lithium batteries typically allow for higher discharge rates and cycles compared to the lead-acid batteries used for this project.

Flexibility will make the mini-grid compatible with different technical solutions for enlarging the variety of applications that could be integrated:

- AC Coupling solar/wind/hydro inverters

The frequency behaviour is directly compatible with the use of AC-coupling. A grid connected solar/wind/hydro inverter can be connected anywhere on the mini-grid to provide further renewable energy in the system. The frequency of the mini-grid will be increased when there is no more consumption from the distributed users and no more storage capacity left. The grid inverter will reduce its output power according to this frequency shift. The necessary balance production-consumption-storage of the mini-grid can be maintained this way. Thus, an AC-coupled energy source system could be a common investment for the common benefit of the community.

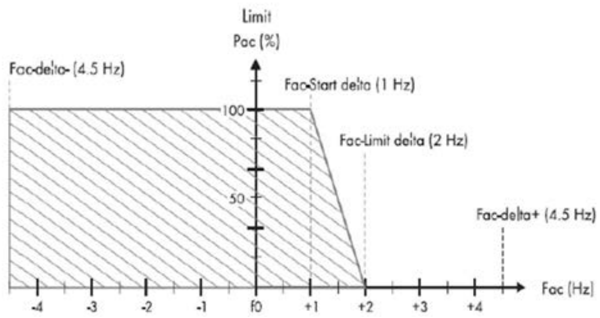

Figure 8. Frequency shift control for AC-coupling grid-tied inverters

- Smart Meters (EDA Dispensers, TTA/Circutor)

The Universal Dispenser from Circutor/TTA is a smart meter controlling power and energy. The user tariff is tied to an Energy Daily Allowance (EDA). The dispenser will check the frequency of the mini-grid and will apply a different tariff based on the frequency: restriction (higher tariff when the mini-grid available energy is low), bonus (lower tariff when there is excess of energy available in the mini-grid). Thus, the final user consumption is encouraged when there is enough energy available and it is discouraged when the available energy is limited.

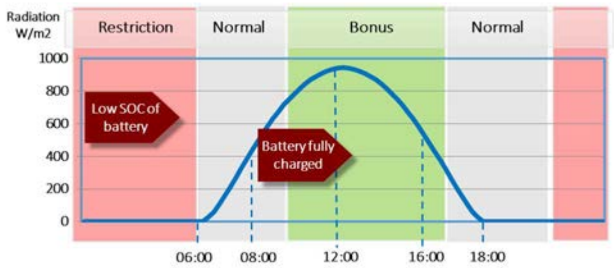

Figure 9. EDA tariffs based on the frequency and battery status

- Deferrable loads using excess of energy (AC ELWA-F®, MY PV)

There are existing loads that are compatible with the frequency control. While charging the battery has priority, once the battery is fully charged, the AC ELWA-F starts using excess energy for hot water heating. The AC ELWA-F´s linear power control works, similar to a grid connected inverter, with high-frequency switching power electronics.

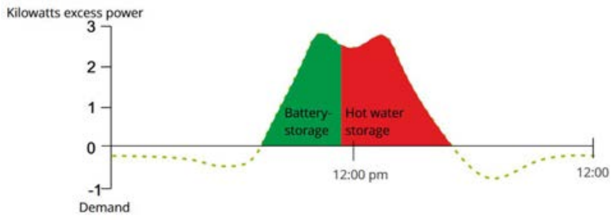

Figure 10. Hot water storage when the battery is fully charged

VII. Conclusions

The main project objective was to test the different technical aspects and analyse the impact of them in an existing community, "Mayens sur le Scex", where the users had an individual energy system and they were looking for a more efficient solution in which they could collaborate for a better global energy service for the community.

The flexibility for further extensions or changes is ensured given that adding or removing a user from the system has a very low influence on the global system. In addition, the reliability of the global system results in an extremely low rate of service interruption. Every installation keeps its autonomy, therefore when there is a problem in one installation, the other users will keep operating with the mini-grid as usual. If there is problem in the central unit, the rest of users are still autonomous to keep running their system independently without having any influence on their loads.

The system is fully stable independently from any external control, communication, or infrastructure. The simple and robust electrical infrastructure is the heart of the system and the information carrier. Once the solution is implemented there is no interdependence with third parties demanding higher level of control, engineering, communication, etc. The solution can be adjusted and modified according to the users' needs without having to be adjusted in terms of control infrastructure.

The mini-grid concept has received great feedback from the community where it has been tested, responding and adapting to their needs and improving the previous situation of individual home systems. For Studer, the "Mayens sur Scex" project is a very successful example, which sets the path for further development to integrate new possibilities and facilitate the mini-grid development for community electrification worldwide.