Integration of autonomous renewable energy generation systems with different topologies in a smart grid cluster to enhance performance in usual operational situations

Alex Renan Arrifano Manito[1], Kaue Novaes[1], André Ricardo Mocelin[1], Teddy Arturo Flores[1] Melendez, João Tavares Pinho[2] and Roberto Zilles[1]

[1] Instituto de Energia e Ambiente/Universidade de São Paulo, São Paulo (Brazil)

[2] Grupo de Estudos e Desenvolvimento de Alternativas Energéticas/Universidade Federal do Pará, Belém (Brazil)

Abstract

Renewable Energy Systems (RES) using resources found in loco might be an attractive solution to address the needs for electrification in many communities that are unlikely to be supplied by the interconnected grid. Though the design of isolated systems using intermittent renewable sources is discussed extensively, little attention has been given to the integration of autonomous RES for joint operation. The integration allows increased flexibility and modularity, which are important characteristics to improve the overall robustness of the system and tackle unpredicted adversities. This paper presents evaluations and conclusions about Autonomous Renewable Energy Generation Systems (AREGS) integration. The methodology is based on tests on a set of four AREGS operating integrated in a cluster in the Laboratório de Sistemas Fotovoltaicos (LSF) of the Universidade de São Paulo, Brazil, which allows the evaluation of several topologies and different operational scenarios; and also computer simulations for the extension and extrapolation of the evaluated scenarios.

Keywords: Autonomous Renewable Energy Generation Systems, energy management, distributed generation, control strategies.

1. Introduction

Renewable Energy Systems (RES) using local resources might be an attractive solution to address the needs for electrification with fewer environmental impacts, cost and maintenance, especially in the case of remote areas where the grid is not available. These kinds of systems are particularly interesting for countries like Brazil, with many communities that are unlikely to be supplied by the interconnected grid, and for which the only option is the use of isolated generation systems.

RES can use a large amount of primary resources available on site, presenting an advantage when compared to the use of generators operating with fossil fuels. However, the availability of these primary resources is not assured at any given moment, due to their flow-nature rather than stock-nature, which may directly influence the reliability of the system. Moreover, the design of the generation system faces many uncertainties not restricted to the supply side. On many occasions, the demand and the consumption pass through an adjustment phase, since these communities have a considerable amount of pent-up demand and even new consumers with the arrival of new settlers, especially in the early stages of electrification.

This requires the search for solutions to fit the problem in the beginning, while allowing flexibility and modularity to tackle the problem in the face of uncertainty and adversities. Modularity plays an important role for it allows a quick response to changes in the demand that would otherwise represent major modifications to the pre-existing generation system. In this sense, the integration of Autonomous Renewable Energy Generation Systems (AREGS) into a cluster may present a suitable manner to address the risks involved, and even to obtain higher levels of reliability and efficiency than those obtained by a single generation system.

doi:10.18086/swc.2017.03.01 Available at http://proceedings.ises.org

The integration of AREGS is desirable, not only due to the increased flexibility, but also from the point of view of the match between demand and primary resources. In some moments, a single AREGS may underuse its primary resource(s) for there is not enough demand and/or storage capacity left, and in other moments the available energy is not enough to meet the demand. Moreover, in order for a single AREGS to meet the demand at all times, it needs a generation/storage capacity to supply load peaks that seldom occur, increasing the already high initial investments of this kind of system. The integration of generation and storage units into a cluster allows dispatch flexibility between the systems, increases the value of the produced energy, contributes to power quality, and results in an overall more robust power system.

However, the application of such topologies has yet to overcome difficulties and barriers, so that all benefits can be appreciated. It is important to mention that the control of such topologies is more complicated, even if distributed control strategies and multi-agent strategies are applied. The grid forming inverters need a way to coordinate their operation to manage the energy exchange between AREGSs and the operation of all components in a seamless manner. Furthermore, the coordination between the agents involved needs to go beyond the technical level. Economic and even regulatory barriers also need to be overcome, since they may influence several stakeholders from the different integrated areas.

This new operating philosophy for AREGS lacks proof of its efficiency, effectiveness and reliability, both under normal and anomalous conditions, what increases the risks associated with operation and, consequently, decreases the interest in investing in such solutions. There are still questions to be answered on how to deal with the specificities and the operational aspects involved with these kinds of systems, which are critical to the long-term sustainability of the system's operation. In the literature, the design of isolated systems using intermittent renewable sources is discussed extensively, using a variety of techniques and optimization algorithms and works such as Lidula and Rajapakse (2011), Ustun et al. (2011), and Soshinskaya et al. (2014) present several examples of micro-grids installed around the world. However, only recently attention has been given to the integration of AREGS into a cluster for joint operation. For instance, Azaza and Wallin (2017) present and approach for optimizing a multi-micro-grid system using particle swarm. Koraz and Gabbar (2017) present a risk analysis for interconnected micro energy grids. Irfan et al. (2017) present a work on the opportunities and challenges concerning the micro-grid concept. Vasiljevska et al. (2013) present a work on the functionalities under a micro-grid concept.

This paper presents evaluations and conclusions about AREGS integration. The methodology is based on tests on a set of four AREGS operating integrated in a cluster in the Laboratório de Sistemas Fotovoltaicos (LSF) of the Universidade de São Paulo, Brazil, which allows the evaluation of several topologies and different operational scenarios; and also computer simulations for the extension and extrapolation of the evaluated scenarios. The conclusions drawn from the methodology may be used as guidelines for integrated AREGS operation, and even help in the development of proper regulation for this kind of operation.

2. Sizing of AREGS

The sizing of AREGS, as commented earlier, is extensively addressed in the literature and must often meet conflicting criteria such as reliability and cost to name a few, making an optimized solution a non-trivial problem. Usually the generation system needs to meet some quality criteria while minimizing costs, though other optimization variables are sometimes used as well. For instance, Fig. 1 exemplifies part of the solution space as a function of the Loss of Load probability (LLP) for a simulation considering a photovoltaic system with storage. The LLP (eq. 1) expresses the proportion of the energy not supplied in relation to the total energy needed by the system during a time period and it is often used as a measure of the reliability of the system.

$$LLP = \frac{\int_{t1}^{t2} P_{not\,supplied} dt}{\int_{t1}^{t2} P_{demanded} dt} \qquad \text{(eq. 1)}$$

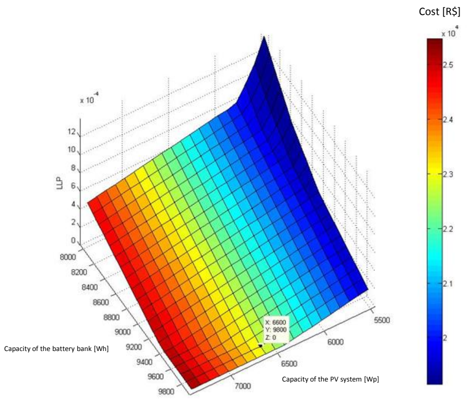


Fig. 1: LLP and cost as a function of the photovoltaic generator and storage capacity.

Fig. 1 shows that the same value for the reliability criteria (in this case the LLP) can be achieved by different configurations of the generator-storage pair with different costs. From the figure, it can also be inferred that the LLP does not present a linear characteristic of decrease, but rather one of saturation, with incremental increases of the capacity of the intermittent source or storage. In the case of the example given in Fig. 1, increasing the rated power of the photovoltaic generator becomes irrelevant past a certain value for a given capacity of the battery bank. The same behavior arises when increasing the capacity of the battery bank while keeping the rated power of the PV generator constant.

Consequently, the amount of generation and storage capacity are not decoupled and need to be proper matched to each other and to the load, otherwise the benefit of an additional investment in the capacity of one component may tend to zero. This is especially true when considering high penetration of non-dispatchable sources, which leads to the question of how to proper tune the generation-storage-load set in rural electrification projects and how to predict the evolution of the communities´ needs over the period of the project.

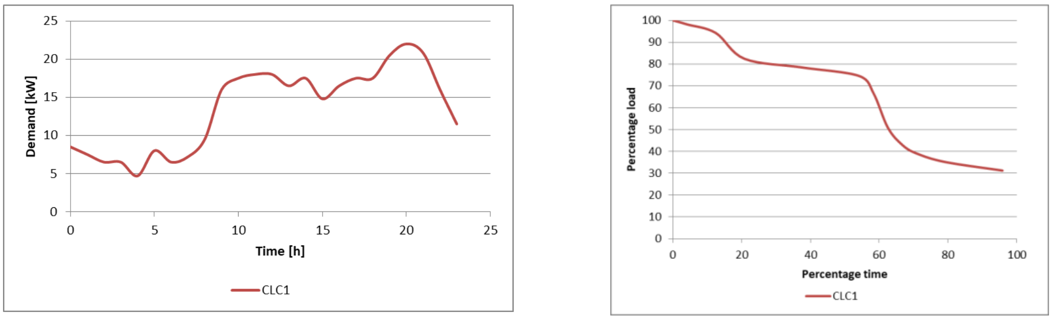
Optimization in the sizing of AREGS is important to maximize benefits of this approach while avoiding the waste of resources. However, optimization, though desirable, requires a reasonable amount of information for making suitable assumptions and decisions for the case at hand. Such information, on many occasions, are not available in rural electrification projects and some of it, such as the evolution of the demand curve over time, are hard to estimate.

Due to the nature of primary resources like solar or wind and to the limited capacity of energy storage, isolated system relying on them, on many occasions, need to underuse their capacity on certain periods and overuse it on others. This occurs due to the variation of the primary resource availability throughout a year and also to its match with the demand to be supplied. This may lead to situations in which the system generates considerably more energy than needed in a time period and yet the Loss of Load Probability (LLP) of the system is not zero.

This scenario of uncertainty leads to the conclusion that being able to respond to unforeseen situations is just as import as a proper sizing in the beginning. This implies that the generation and distribution system should be designed with a level of flexibility in order to avoid the impossibility of an eventual expansion. In a scenario of integrated AREGS, the energy which is not used or stored could be dispatched to nearby systems and increase the robustness and the reliability of all the systems involved due to the increased flexibility in the operation. Moreover, it can add modularity to the systems, since increases in the load peak can be met gradually without having to exchange the grid forming inverters to supply for peak demands that seldom occur. This decreases some of the risks involved with sizing of the system for rural electrification projects by giving more flexibility for the solution to be tailored to fit new scenarios during the operation phase. Clusters of AREGS would be more robust and would have a way to share infrastructure. Moreover, the expansion could be more suited to address new emerging situations.

3. Simulation of a stand-alone AREGS

In order to illustrate and evaluate how an AREGS composed of a photovoltaic generator with storage could benefit from integration with other systems, a scenario was simulated by numerically calculating the energy flow at each time step. The scenario considered a real consumer's load curve (CLC1) of an isolated community. Fig. 2 presents two different forms of observing the load curve. From these figures it is possible to observe that CLC1 presents a high load factor, with a demand close to the peak during most of the day. CLC1 spends 16 % of the time above 90 % loading and 54 % percent of the time with a loading above 75 %. However, when considering rural electrification, due to the relatively small number of households in isolated communities, the characteristic of the load may vary greatly and the demand curve is more sensible to demand increases that are hard to account for and would render the generation system unsuitable to meet the demand.



(a) (b)

Fig. 2: Isolated community load curve. (a) Average load curve over day time. (b) Percentage load versus percentage time.

The photovoltaic system was sized considering a location in the state of São Paulo, Brazil. Fig. 3 presents the monthly average irradiation and temperature. Since the system is isolated, a value of three peak sun-hours was considered, even though the annual average is 3.95. This was done to guaranty the supply in the month of least primary resource availability.

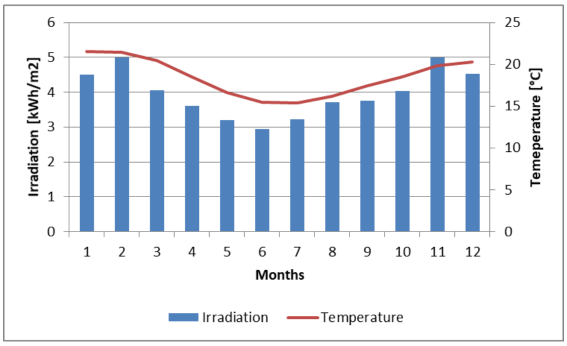


Fig. 3: Irradiation and temperature for the considered location.

The autonomy of the system was set as 2.4 days, which is higher than the minimum of two days recommended by the normative resolution RN 493/2012 (Aneel, 2012). This was done to oversize the battery bank to have a safe margin to unexpected situations. The depth of discharge for the sizing of the batteries was 60 %, which is a typical value for deep-cycle batteries. The round trip efficiency of the battery was considered as 95 %. Tab. 1 presents the values considered for the generator and storage to supply CLC1.

Tab. 1: Generation and storage capacity for CLC1.

Component	CLC1
Generator [kWp]	108.5
Storage [kWh]	1,302

Numerical simulations of the interactions between load, demand, and storage to supply the CLC1 are depicted in

Fig. 4, Fig. 5, and Fig.6. Throughout the year the state of charge profile of the battery varies greatly due to the variability in the primary resource and the amount of generation installed capacity. The system is underused during most of the year, what can be seen by the excess profile (green line), and during the month of June the system is constantly overusing the capacity of the storage. This behavior can be observed in Fig. 5 and Fig.6, which are zoomed in areas (respectively A and B) from the annual profile depicted in Fig. 4.

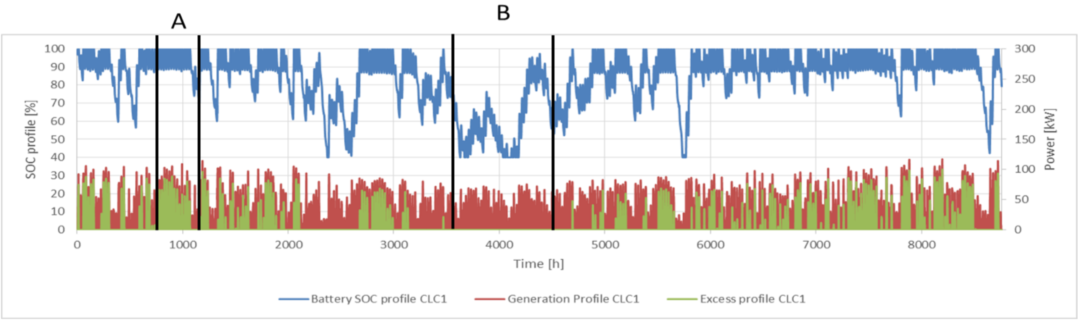


Fig. 4: Interactions between generation and storage to supply CLC1.

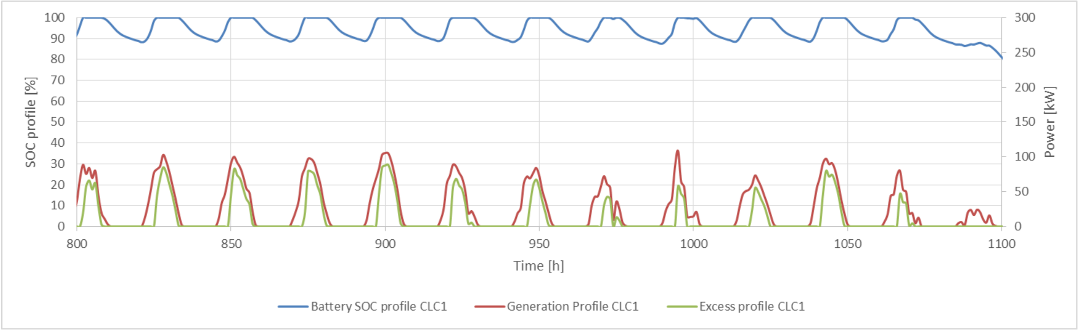


Fig. 5: Interactions between generation and storage to supply CLC1 (from hour 800 to hour 1,100).

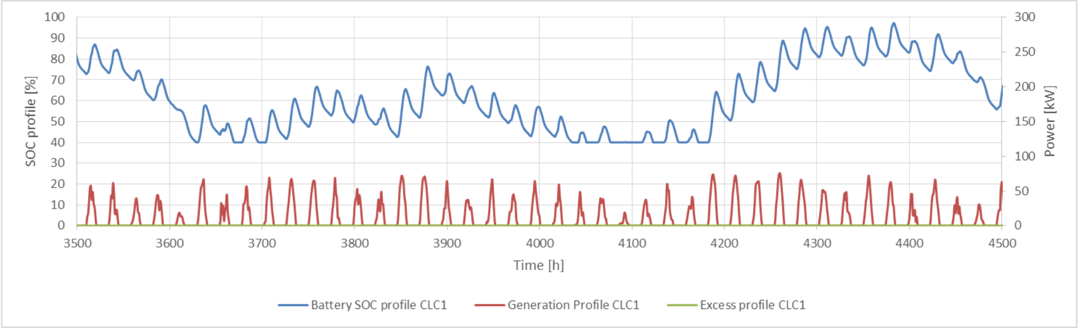


Fig. 6: Interactions between generation and storage to supply CLC1 (from hour 3,500 to hour 4,500).

In the beginning of the year part of the generated energy is not used and is thus wasted. Though the generation system would be able to supply an increasing demand in such months, during the months of low availability, the system would not be able to supply the demand. In this simulation, the LLP of the system was estimated as 1 %, which is an acceptable value. However, the system has little robustness to deal with demand increases.

In order to tackle this problem some alternatives can be used, namely over-dimensioning the system from the start, the use of solar home systems (SHS) to address variations in the predicted demand, the use a dispatchable source, such as a diesel generator or the integration of AREGS.

Over-dimensioning the generation system has the problem of increasing the initial investment, which is already an issue for AREGS, for an infrastructure that may or may not be used. This approach has also the drawback of assuming how the demand will increase over time, which may turn out not to be true and renders the additional investment not suitable or misused.

The use of SHS to account for the additional load may be an option to tackle small loads or when due to some impossibility the AREGS cannot be extended to the new consumer. However, the new system stays isolated from the rest and it is usually less robust since it does not share infrastructure.

A dispatchable source, such as a diesel generator, is desirable in AREGs to supply for periods of low availability of primary resources and reduce the risks associated with intermittent sources like photovoltaics, for instance. However, the option with diesel to tackle demand increases would increase the operational costs of the system and its sensibility to fuel transportation logistics and price. Fig. 7 presents the increase in the hours of operation of the diesel, due to increases in the demand of CLC1. In the simulation, the diesel would supply the power that could not be met by the renewable generation and/or the battery.

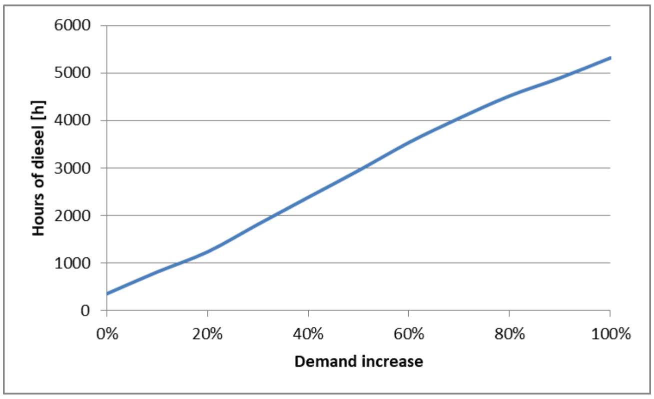


Fig. 7: Interactions between generation and storage to supply CLC1 (from hour 3,500 to hour 4,500).

Though the additional use of the diesel generator could be an option for a short term period, in the long run the operational costs would increase considerably and, as mentioned before, the service would be much more dependable on the fuel supply.

In the case of integrated systems, the additional AREGS could share infrastructure with the existing AREGS. The generation system of the additional AREGS could be smaller than the one that would be needed, if the new AREGS were isolated, due to the capacity of sharing the resources. It is important to mention that the use of one approach does not necessarily exclude the other. An optimized solution can be found by mixing the approaches, depending on the case.

4. Experimental setup and tests

The infrastructure of LSF is composed of four AREGS, each with its respective loads, storage, distributed generation, and grid forming inverters. The whole facility can operate in two main ways. Either the four AREGS are connected to a point of common coupling (PCC), where a diesel generator and the main grid can also be connected, or it can operate as a two levels hierarchy, where AREGS 2, 3, and 4 are connected to the load side of AREGS 1. Moreover, two standby circuits were introduced to allow the connection of temporary components like loads or distributed generation.

AREGS 1 is composed of three SMA Sunny Island inverters of 5 kVA each, forming a three-phase system, a 23.5 kWh battery bank and PV generators connected in the AC as well as in the DC bus with overall installed capacity of 6.71 kWp. AREGS 2 is composed of three Studer Xtender inverters of 6 kVA each, forming a three-phase system, a 19.2 kWh battery bank, and a 2.8 kWp PV generator. AREGS 3 is a single-phase system composed of a 5 kVA SMA Sunny Island inverter, a 9.6 kWh battery bank, and a 1.28 kWp PV generator. AREGS 4 is a single-phase system composed of a 4 kVA Schneider inverter, a 4.8 kWh battery bank, and a 0.4 Wp PV generator. Aside from the AREGSs there is also a 40 kVA diesel generator, which may be connected to all systems. Fig. 8 presents a schematic of the facility implemented at LSF and Fig. 9 presents some of the equipment installed in the laboratory.

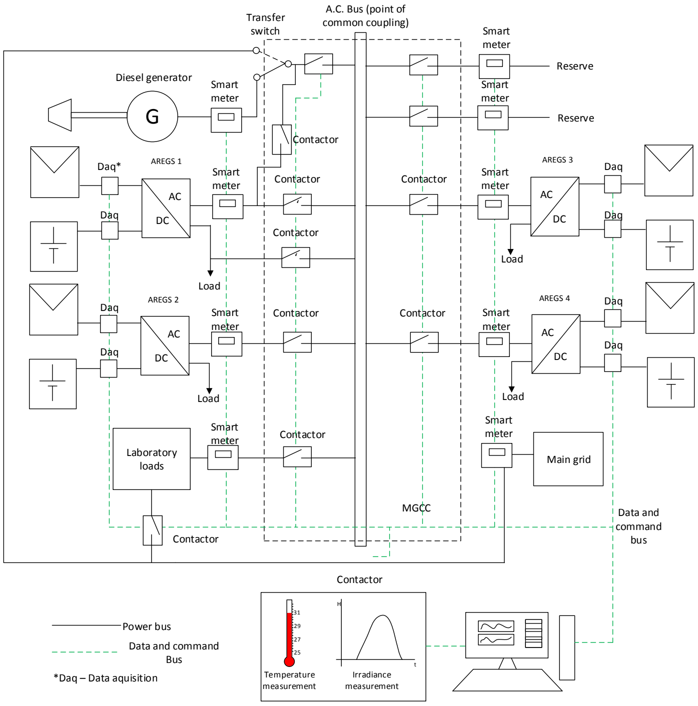
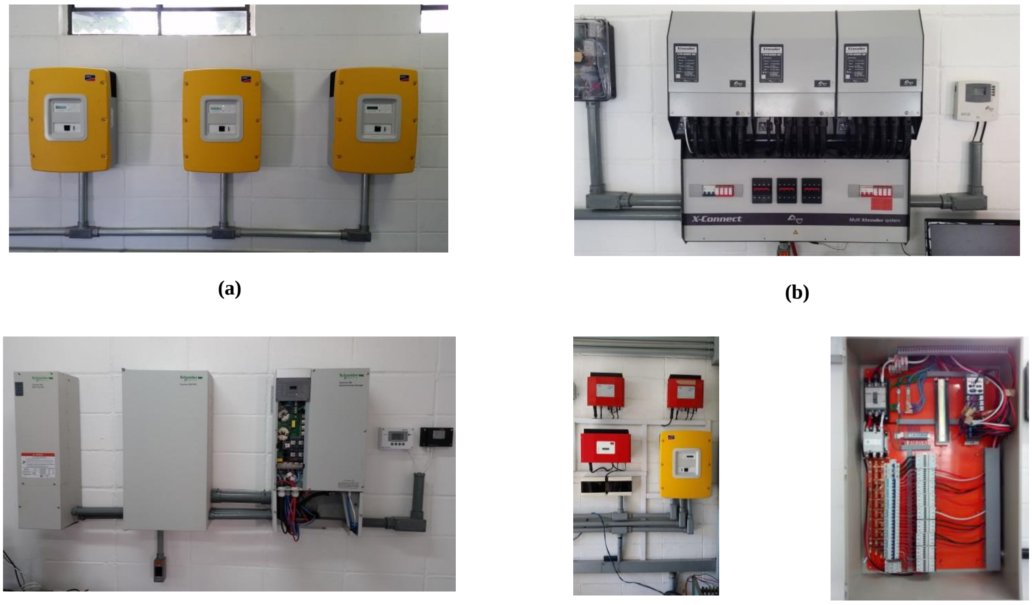


Fig.8: Infrastructure implemented at LSF.


(a)

(b)

(c)

(d)

(e)

Fig. 9: AREGS installed in the LSF of the University of São Paulo, Brazil. (a) SMA three-phase system. (b) Studer three-phase system. (c) Schneider single-phase system. (d) SMA single-phase system. (e) Micro-grid Central Controller.

The facility was designed to enable a high level of flexibility and scalability, which permits to reproduce many real cases in the operation of the whole system, and considers the benefits and drawbacks of many topologies, including different levels of non-dispatchable renewable energy penetration and storage capacity.

Two conditions of multi-micro-grid operation with the interconnection of AREGS were tested. Fig. 10 presents the two conditions tested in the facility. In the condition presented in Fig. 10a (non-cascaded topology), all

AREGS are connected to a dispatchable source (in this case the diesel generator). In this situation, energy exchange between AREGS, though theoretically possible, needs a fine tuning, to avoid the attempt to inject energy in the diesel generator, which could damage it. This topology is more suitable when the dispatchable source is the grid for the parametrization of the AREGS is independent from one to the other. However, this is not the case for most rural electrification projects. This case is more suitable for micro-grids in the urban environment, where each could just feed the excess into the grid.

For rural electrification projects, the situation depicted in Fig. 10b (cascaded topology) is more suitable. In this situation there are two levels of AREGS. The first level (in this case formed by AREGS 1) creates a situation for the other systems that would resemble connecting them to the conventional grid. AREGS 2, 3 and 4 are connected to the load side of AREGS 1 and are able to inject the excess of energy in the battery of AREGS 1 or this excess could be used to support the loads in AREGS 1, which include the other AREGS.

The diesel would be explicitly controlled by AREGS 1. However, the other AREGS would also have an implicit control over the diesel generator, since for AREGS 1 they are loads which can cause AREGS 1 to trigger the diesel generator. In this situation, attention has to be given to the parametrization of all the AREGS as a whole to avoid undesirable disconnections between systems or the waste of potential to dispatch the excess energy.

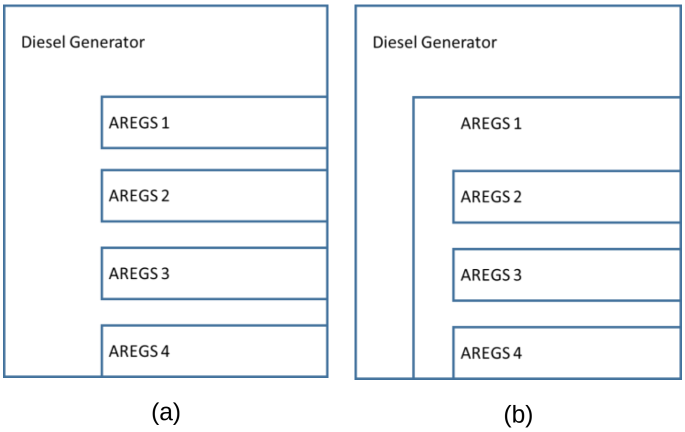


Fig.10: Tested topologies. (a) AREGS connected to a PCC. (b) Two-level AREGS set.

4.1 Experimental setup

In order to compare the two evaluated topologies (non-cascaded topology and cascaded topology), test were carried out. The tests sought to evaluate three scenarios (Case 1, Case 2 and Case 3). For Case 1, the AREGS were assembled in a non-cascaded topology. For Case 2 and Case 3, the AREGS were connected to operate as a cascaded system.

In Case 2 a 2.1 kW distributed generation was connected to the output side of AREGS 3 and the AREGS were parametrized to connect to one another. In Case 3, a 1 kW distributed generation was connected to the output side of AREGS 3. Although the system’s topology remained the same as presented for Case 2, the AREGS were not properly parametrized to allow the injection of power from one AREGS to the other. This was done to emphasize the need for the proper parametrization of all the AREGS, considering the cascaded system as a whole.

Further details from the setup used in the tests for Case 2 and Case 3 are presented in Fig 11. For the purpose of the tests, the distributed generation of AREGS 3 was emulated by the output of a grid-tie inverter connected to a PV emulator at the load side of AREGS 3. This would provide a somewhat controlled environment for the experiments. AREGS 3 was then connected to the load side of AREGS 1.

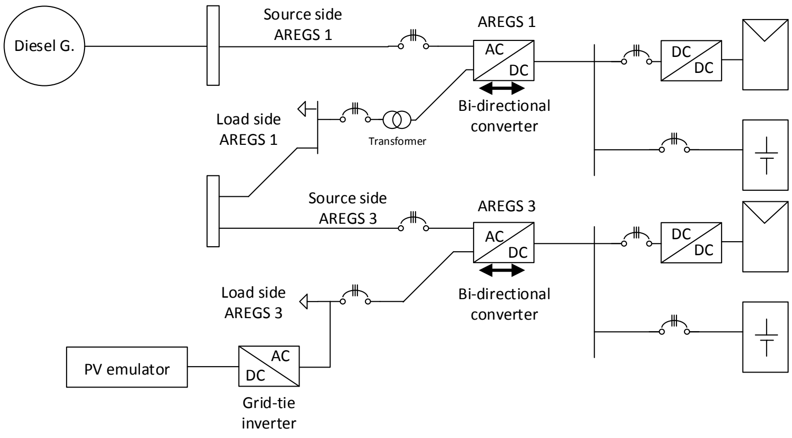


Fig. 11: Experimental setup for Case 2 and Case 3.

4.2 Experimental results

All the results are shown in per unit values and the bases of the system are presented in Tab. 2.

Tab. 2 Bases of the test systems.

Active Power (Pac)	Reactive Power	State of charge (SoC)	Voltage	Frequency	Irradiation
5 kW	5 kvar	100	220 V	60 Hz	1000 W/m^2

When all the AREGS are connected in a non-cascaded topology, the injection of power back to the external source is undesirable, in the case of standalone systems, since it could damage the source (usually a Diesel generator). In such situations the reverse power is usually blocked by the grid forming inverter, which should disconnect from the external source if a small amount of reverse power is measured. Fig. 12 presents the operation of AREGS 1 when all the AREGS have the same external source (a Diesel generator). The distributed generation (PV generator) from AREGS 1 injects power into its battery (consider negative values as power being fed to the battery) until the battery is full. Though there is still primary resource for the PV generator, the frequency is used as a way to limit the injection of power by the distributed generation since the power surplus cannot be used. In this situation, the only benefit is that all the AREGS can share the same external source, but the energy exchange from one to the other would not be possible due to safety reasons, which in turn, diminishes the benefits of interconnection.

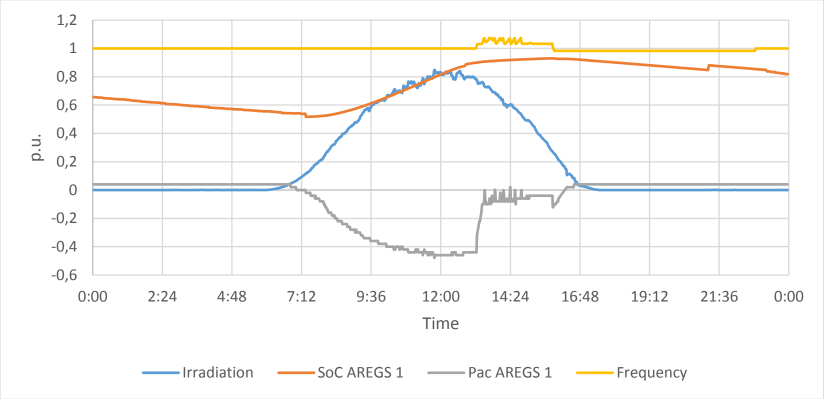


Fig. 12 – AREGS 1 operation when all the AREGS connect to the same source.

In the Case 2, the distributed generation from AREGS 3 charges the battery of AREGS 1, as shown in Fig. 13. Some of the power, however, is still injected into the battery of AREGS 3 until the battery is completely charged.

A drop in the injection of active power occurred due to the supply of reactive power into the PCC as shown in Fig. 14. The reactive power was being injected due to the use of a transformer to connect AREGS 1 to the PCC, causing the grid-tie inverter to change its operation point to supply also reactive power.

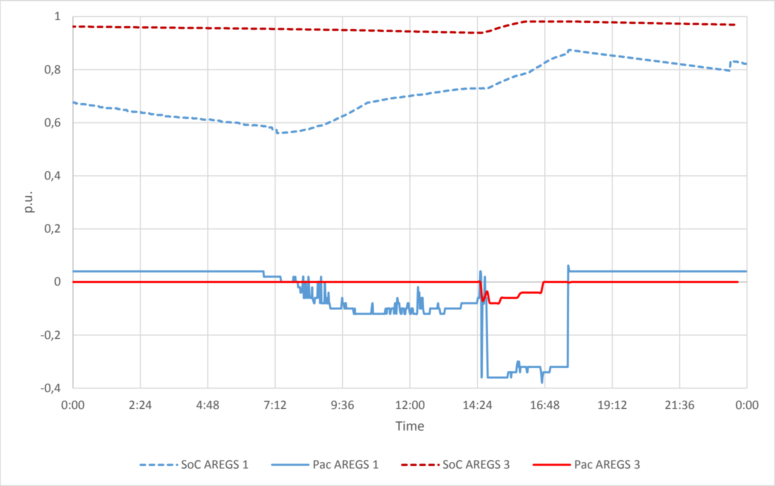


Fig. 13: Power exchange between AREGS (Case 2).

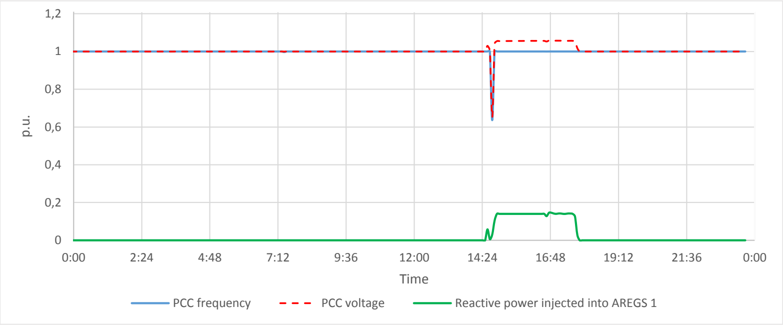


Fig. 14: Frequency, voltage and reactive power profile for Case 2.

During this period, there was no noticeable frequency deviation, however, there was a voltage rise at the PCC of 6%. This points to the fact that though some of the power may be injected into the other AREGS, there could be a deterioration in power quality at the PCC due to excess generation, similar to what happens in a conventional distribution grid with high distributed generation penetration if proper measures, such as power limitation, are not implemented to account for the moments when power quality deterioration occurs.

As stated before, the battery from AREGS 1 provides a security layer that would prevent any of the other AREGS from injecting into the diesel generator. Had the AREGS been assembled having a common coupling point with the Diesel generator (non-cascaded topology) and no measures were taken to block reverse power, such operation wound represent a risk in the case of an isolated power system, since the AREGS could perceive the Diesel generator as a load, especially when the Diesel generator powers off. During the period in which the rotor is decelerating the control of the AREGS could perceive a frequency drop try to inject power into the diesel generator.

In Fig. 15 it is shown that the proper parametrization of all AREGS connected to the cascaded micro-grid should be considered as a whole, otherwise the benefits of such topology can be hampered. In the situation depicted in Fig 15 (Case 3) though there is an excess in power in AREGS 3, it does not inject power into AREGS 1. Instead it limits the power injected into its own battery by causing a frequency rise at the point where the grid-tie inverter is connected. The limitation in the injected power and the frequency rise can be observed in Fig. 15 and Fig. 16 respectively. In this situation there is no noticeable voltage rise at the coupling point with the grid-tie inverter since the voltage at the output of the bi-directional inverter from AREGS 3 is the reference of the system, the same does not occur in the Case 1. Fig. 17 presents qualitatively how the voltage behave in Case 2 and Case 3.

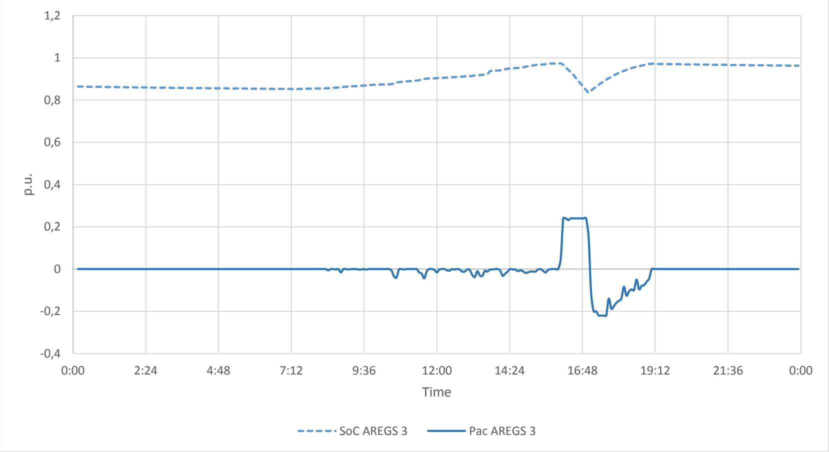


Fig. 15 – Power limitation due to AREGS 2 not connecting to AREGS 1 (Case 3).

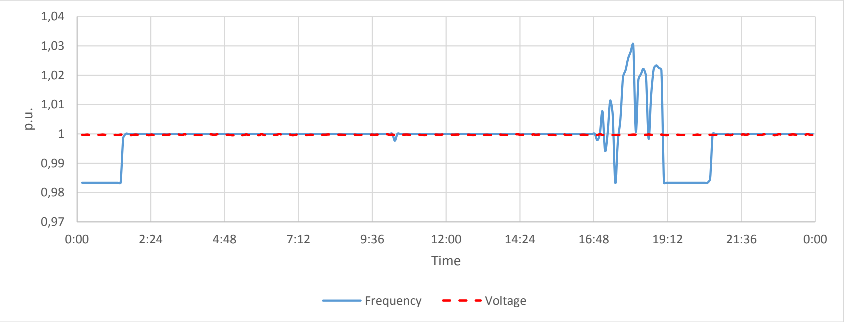


Fig. 16 – Frequency and voltage profile for Case 3.

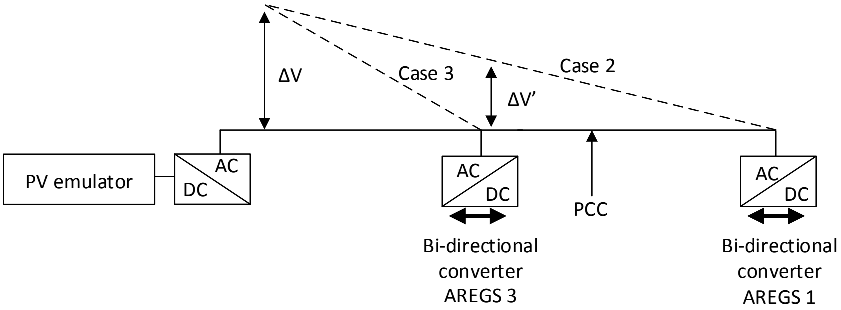


Fig. 17 – Voltage profile for the cascaded tested topologies.

5. Conclusions

Recently, attention is being given to the interconnection of micro-grids in multi-micro-grid topology. This is attributed to the new features that are being introduced in grid-forming inverters and that allow new topologies for the operation of micro-grids.

The ability to interconnect micro-grids and even stack them in a hierarchy improves the sustainability and robustness of the system as a whole, especially in rural electrification projects, where due to all the uncertainties regarding the demand and the evolution of the demand over the years of the project need to be robust and flexible to respond to changes. Consequently, the generation and distribution system should be designed with a level of flexibility in order to avoid the impossibility of an eventual expansion.

During the tests, the use of a two-level set of AREGS was found to be a suitable topology to attribute modularity and scalability to the rural electrification solution. However, attention has to be given to the proper parametrization of the cascaded system as a whole and to the effects that the connection would produce at the PCC. It is emphasized that usually, standalone systems like the ones evaluated in this paper constitute relatively weak grids, and, therefore, more susceptible to power quality issues like voltage rise. In the case presented in the tests, voltage at the PCC could be a control signal for power limitation from the distributed generation if the voltage falls out of acceptable values.

The integrated AREGS can improve the management of energy and add modularity to deal with unpredicted situation. In order to study these problems the Laboratory of Photovoltaic Systems of the University of São Paulo implemented a test facility using the four available AREGS to form a smart micro-grid, which is being used both for research and capacity building.

6. References

Aneel, Agência Nacional de Energia Elétrica. Resolução normativa Nº 493. 2012. Available at: http://www2.aneel.gov.br/cedoc/ren2012493.pdf. Accessed in 02/10/2017.

Azaza, M., Wallin, F. Multi objective particle swarm optimization of hybrid micro-grid system: A case study in Sweden. Energy, 123 (2017), pp 108-118. DOI: 10.1016/j.energy.2017.01.149

Irfan, M., Iqdal, J., Iqdal, A., Iqbal Z., Riaz, R. A. Opportunities and challenges in the control of smart grids. Renewable and Sustainable Energy Reviews, 71 (2017), pp 652-674, DOI: 10.1016/j.rser.2016.12.

Koraz, Y., Gabbar, A. Risk analysis and self-healing approach for resilient interconnected micro energy grids. Sustainable Cities and Society, 32 (2017), pp 638-653. DOI: 10.1016/j.scs.2017.05.010

Lidula, N. W. A., Rajapakse, A. D. Microgrids research: A review of experimental microgrids and test systems. Renewable and Sustainable Energy Reviews, 15 (2011), pp 186-202. DOI: 10.1016/j.rser.2010.09.041

Soshinskaya, M., Crijns-Graus, W. H. J., Guerrero, J. M., Vasquez, J. C. Microgrids: Experiences barriers and success factors. Renewable and Sustainable Energy Reviews, 40 (2014), pp 659-672. DOI: 10.1016/j.rser.2014.07.198

Ustun, T. S., Ozansoy, C., Zayegh, A. Recent development in microgrids and example cases around the world – A review. Renewable and Sustainable Energy Reviews, 15 (2011), pp 4030-4041. DOI: 10.1016/j.rser.2011.07.033

Vasiljevska, J., Peça Lopes, J. A. Matos, M. A., Integrated micro-generation, load and energy storage control functionality under the micro-grid concept. Electric Power System Research, 95 (2013), 292-301. DOI: 10.1016/j.epsr.2012.09.014