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The role of storage in emerging country scenarios

Stefano Mandelli[a], Marta Molinas[b], Eugene Park[c], Matteo Leonardi[d], Emanuela Colombo[a], Marco Merlo[a,]*

[a]Politecnico di Milano, Dept. of Energy, via Lambruschini,4, 20156, Milan, Italy
[b]NTNU, Dept. of Engineering Cybernetics, Trondheim, Norway
[c]Nelson Mandela Africa Institution of Science and Technology, Dept. of Materials and Energy Science, Arusha, Tanzania
[d]Oikos East Africa, Arusha, Tanzania

Abstract

Despite the electrical energy scenarios are quite different between industrialized countries and emerging and developing ones, for both contexts, energy storage systems could play a key role in the next future. Specifically, in emerging and developing countries, energy storage systems may allow a cost-effective exploitation of renewable sources in order to cope with energy security for centralized energy systems, but mainly to become a building block of rural electrification by off-grid power systems. In this paper a short overview of energy storage systems within the emerging and developing countries scenarios is reported. Specifically the paper provides a description of the typical configuration for batteries within off-grid systems and an overview of the typical economic models for batteries applications and the regulatory frameworks when off-grid applications are introduced. Finally the description of an experimental project in rural area of Tanzania points out the peculiar characteristics of batteries application in off-grid applications.

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*Keywords:*off-grid systems, rural electrification, renewable, battery, models, economic

1. Introduction

Electrification is the process of powering by electricity and is usually associated with changing over from another power source. This could sound obvious in industrialized countries (ICs) leading to underestimate the role of such a

* Corresponding author. Tel.: +39 02 2399 3762; fax: +39 02 2399 8506.
E-mail address: marco.merlo@polimi.it

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commodity. The USA National Academy of Engineering celebrates *electrification* as the most impacting engineering achievement on everyday life [1] and, as a matter of fact, common people use every day electric energy without a technical knowledge and, most of the time, without having to worry about the price. Vice versa, reliability is becoming a great concern in ICs; indeed the quality and continuity of supply is a mandatory requirement.

Emerging and developing countries (E&DCs) scenario sounds quite different: about 1.3 billion people lack access to electricity and about 82% of these live in rural areas [2]. Moreover, when power supply is available, reliability is often a serious issue and long outages frequently occur. In this context, low electrification rates and low reliability of the power supply is a burden along the process of local development. Energy needs for households, health and education services, and productive activities are not effectively and efficiently met [3]. This motivates, in E&DCs, a different approach to electric energy: reliability is supposed to be an added value and not a mandatory requirement. Everyday life could go on with a limited and irregular amount of energy. For this reason, to evaluate a new social approach to electric energy within the framework of E&DCs is not trivial. Actually in these contexts, when electric energy is available, it is mainly devoted to lighting applications, mobile charging and some other ICT purposes. Mostly in rural areas, recharging mobile phones is one of the most important electricity services. Mobile phones cover long distances where transport infrastructures are inexistent and offer modern services such as bank services, money transfer, and bill settlement [4].

Despite these considerations show that the electrical energy scenarios are quite different between ICs and E&DCs, a common figure can be recognized. Indeed, both for ICs and for E&DCs, *energy storage systems* (ESSs) could play a key role in the next future [5–7].ESSs refer to a process of storing electrical energy into a form that can be restored back to electrical energy when needed using appropriate storage technologies. By merging ESSs with energy systems, electricity can be stored when the demand is zero or low and release when the demand is higher.

Looking the short term scenario, in ICs, ESSs are considered the top notch solutions to promote effective renewable energy sources (RESs) exploitation capable (i) to integrate high percentages of intermittent RESs into modern electric grids, (ii) to lead to more efficient electricity market, and (iii) to reduce carbon footprint and local pollution without increasing the cost of the electricity supply. Similarly, ESSs could be the enabling factor that allows a cost-effective exploitation of RESs in E&DCs. Moreover, in E&DCs, ESSs have been gaining momentum as a mean to cope with energy security for the centralized energy systems [8], and also as a building block for off-grid power systems for electricity provision in rural areas [9–15].

In this paper an overview of EESs within the E&DCs scenario is reported together with the description of an experimental project in rural area of Tanzania. Specifically the paper is organized as follows: (i) a description of the typical configuration for electro-chemical batteries within off-grid systems (i.e. the typical application of ESSs in E&DCs) are described, (ii) an overview of the typical economic models for ESSs applications in E&DCs and the regulatory frameworks when off-grid applications are introduced, (iii) a case study to point out the peculiar characteristics of the ESSs application in E&DCs is reported.

2. Short technology overview

Electrical energy can be stored in many different forms such as chemical, electro-chemical, mechanical or thermal [6,16]. Hence there is a wide range of EES technologies currently available [5,7,17]. Nevertheless there is no one-fits-all solution for ESSs and one should choose the most suitable technology after carefully considering locality and sustainability.

In E&DCs, small and/or medium sized ESS technologies (typically electro-chemical batteries) are more feasible considering financial and technological readiness. Furthermore in E&DCs, the leading application of batteries is in off-grid power systems (i.e. stand-alone grids, island grids or remote micro-grids). These types of grids usually employ RESs combined with other sources of electricity such as diesel generation. Due to the presence of RESs which introduce short time-scale variations and unpredictable intermittences, these off-grid systems can benefit from the use of batteries to mitigate short-term fluctuations (for ensuring the instantaneous power balance) and intermediate-term energy deficiency.

For these applications, batteries need additional equipment to adapt their output voltage and current to the requirements of the grid to which they are connected (voltage level and waveform synchronization). Depending on the application and system configuration, the *dc* output of batteries needs to be adapted to the *ac* or *dc* voltage level of the grid and a power converter is usually applied for this purpose. Depending on the storage technology and the application, the power converter will enable the connection between two different *dc* voltage levels (for a *dc* micro-grid), or between a *dc* voltage bus and an *ac* voltage bus. For this reason, the most suitable topology used for the power converter will always depend on the particular application. In general, power converters applied to batteries must have the following features: (i) ability to control bidirectional energy flow for controlling the charging and discharging process of the battery bank(s); (ii) high efficiency; (iii) fast response (frequency regulation applications).

Fig. 1 shows a generalized interface for coupling batteries to a single-phase *ac* micro-grid. When the voltage level of the battery system is sufficient, the connection can be directly made via the single-phase bidirectional converter module. When connecting the batteries to a *dc* micro-grid, the most popularly used topology is the bidirectional boost converter (Fig. 2 (a), (b)). These two topologies enable connections to a higher and lower voltage buses and can operate properly against voltage fluctuations coming from the batteries [18,19].

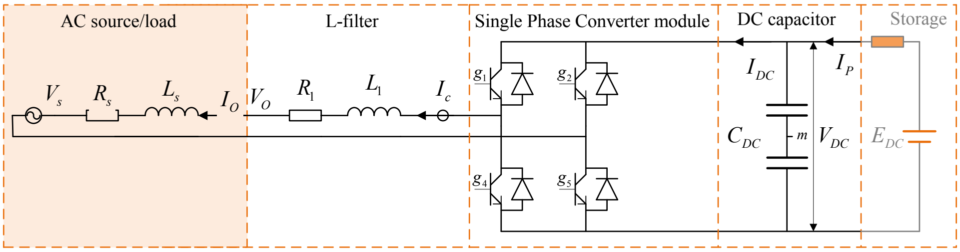

Fig. 1 Generalized interface for coupling batteries to a 1-phase *ac* micro-grid

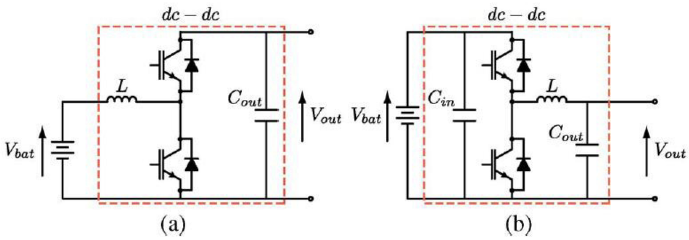

Fig. 2 Buck-boost *dc-dc* converters

In case of high voltage ratio or when isolation is needed between the batteries and the rest of the system, a *dc*/high frequency *ac/dc* stage with a transformer in the intermediate high frequency *ac*-stage (Fig. 3) is used, resulting in significant space and weight reduction compared to a conventional line-frequency transformer. The transformer will electrically decouple the two sides and the converters will provide bidirectional control [20].

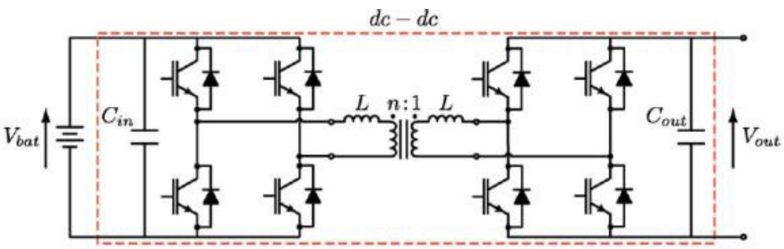

Fig. 3 Isolated *dc-dc* converter

To connect batteries to an *ac* grid, motor or generator, an inverter (three phase two level) has to be used (Fig. 4) [21,22]. Modular energy storage can be built by several strings, and these strings can be connected in parallel to a common *dc* bus by step-up *dc–dc* converters. Then, the *dc* bus is connected to the *ac* grid by an inverter. This topology is shown in Fig. 5, where conventional *dc–dc* boost converters and conventional three-phase two-level *dc–ac* converter are used as coupling and power conditioning system [23].

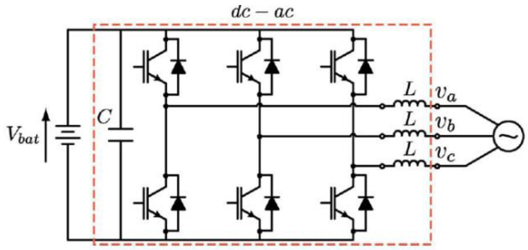

Fig. 4 Conventional *ac-dc* converter (3 phases)

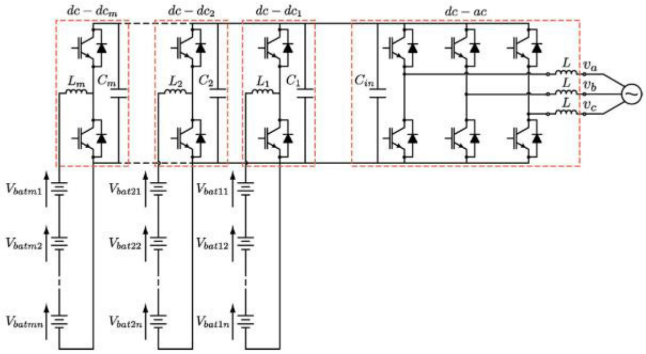

Fig. 5 Modular *ac-dc* converter (1 and 3 phases)

A good understanding of battery performances and degradation throughout life-time functioning can aid in improving user satisfaction and overall reliability for such systems. Accordingly, appropriate batteries models are essential for various kinds of studies such as state of charge (SoC), power quality, lifetime, and transient interactions.Actually, when generally dealing with the design process and analysis of off-grid systems combining different power sources, batteries and power electronics interfaces, two main types of analysis are typically carried out: *energy analyses* and *power stability analyses*.

Concerning energy analyses (e.g. [24–30]), the objective is to identify the main component sizes (i.e. rate power of generators and storage capacity) with an energy planning and/or a techno-economic approach. Such analyses study the system performances throughout its life-time and are typically based on the steady-state solution of the energy balance between energy sources and consumer loads and considering the features of the system components. Different accuracy in the analyses mainly results from the degree of detail in the load/energy source data and in the mathematical modelling of the system components. A typical tool which embraces the main features of the energy analyses is HOMER Energy (e.g. [31–33]).

Concerning power stability analyses ([34–37]), the main objective is to address the study of power system stability employing electrical quantities (i.e. current and voltage) and verifying the proper functioning of each single component and the interactions among them. Such analyses are based on circuit models of the components and on the solving of the related equations within the continuous time-domain. They are typically carried out for short intervals (from few to tens of seconds) in order to study the developments of the monitored electrical quantities and to verify the proper system functioning under particular circumstances. When the issue of the power supply quality is addressed, voltage and frequency (*V* and *f*) values are the key analyzed quantities.

According to these analyses classifications, some of the typical models for electro-chemicals batteries are briefly referred to in the following. For optimization, economic, and reliability evaluation of power system applications, the battery power and SoC in terms of kW and kWh, respectively, can be modelled by the equations reported in [38]. Based on the models reported in [39] an equivalent circuit for a battery is presented in Fig. 6. This model can be simulated in power system analysis software (PSCAD, Matlab Simulink, etc.) to study the electromagnetic transients and dynamics of the battery.

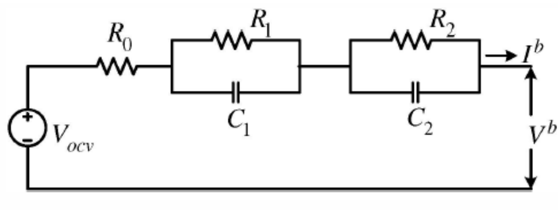

Fig. 6 Second order Randle model

For small-scale dynamic studies, Fig. 7 represents a simplified linearized battery model [40], where P^{b*} and P^b are the reference power and actual output power for the battery respectively; E^b is the state of energy; where P_{max} and P_{min} are the maximum and minimum charging power; and T_b is the time constant for the battery. The model can be utilized to study the small signal stability, e.g. frequency deviations in any power system.

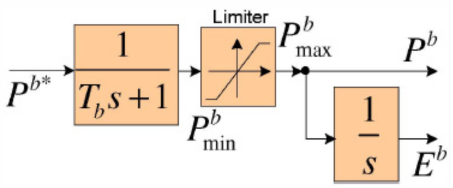

Fig. 7 First order battery energy storage model

In order to effectively determine the lifetime of a battery, it is necessary to understand how the different operational modes, namely charge, discharge and rest, influence the charge capacity. The aging model presented in [41] considers the reduction in capacity with usage while neglecting the effects of rest periods while in the aging model in [42] considers also rest or relaxation periods, when no external current is being drawn.

As the battery bank needs a power converter to connect to the electrical grid, for grid interaction studies the complete model of battery and converter needs to be represented. In off-grid operation special attention needs to be put on the synchronization aspect, the passive filter on the *ac* side, and the potential interaction between the converter operation and the passive elements of the electrical grid. A detailed electromagnetic model with switching action, modulation and control is expected to reveal potential interactions between the battery converter and any other converter or component in the system (transformer, electrical machines, etc.). Such a detailed model can be simulated in EMTDC/PSCAD and Matlab Simulink [39,43].

Finally, the design procedure, especially in rural E&DCs scenario, has to properly take into account the economic costs of the solution that means that frequently the optimal battery is economically not viable and, consequently, more cheap solution has to be adopted. An example are resistive dampers (i.e. dump loads) which dissipate on air the generated power not required by the user loads managing the energy balance and reducing the oscillations. Such solutions, obviously, dissipate energy and are senseless in ICs applications, vice versa, due to the “low” value of energy and to the different power quality constraints, in E&DCs this could be a solution to relieve the batteries design or, in some extreme cases, to completely replace the batteries.

3. Short economic models and regulatory frameworks overview

It is possible to identify four relevant applications of batteries in connection with the supply of electricity services in E&DCs: (i) small household systems for private use (typically with PV array), (ii) isolated mid-size systems (1-100kW) for institutional and private use, (iii) micro-grids and (iv) grid connected generating or back-up solutions. The four applications respond to different economic models, type, technology and size of storages, challenges and regulatory frameworks.

Household PV systems in the range of 10-100W, 9-200Ah battery, are usually paid upfront by final users. The relative high costs and the limited access to credit, especially in rural areas, is one of the most relevant barriers for their dissemination. The retail cost of a reliable household PV system is 3-4, 5€/W (average retail price recorded in Tanzania in 2014 for a 60W panel, 100Ah battery, controller and 150W inverter is 220-280€ according to battery type) for an *ac* system with a PV/battery ratio of 1:1.5. These systems are kept as simple as possible, sometimes in *dc* only and the choice of the equipment is mainly done on a cost basis often at detriment of system reliability. The cost of the battery accounts for some 30% of overall cost when a lead low maintenance leisure battery is chosen, and up to 50% with a maintenance free gel, AGM battery. The bulk of the household domestic market is privately driven, in some cases the technology has been promoted by national policies which are occasionally supported by cooperation-aid resources [44]. Some projects add micro credit mechanisms, especially when the system is combined with small income generating activities such as mobile charging, small shops, and barber shops. The battery is the most critical component of the system, it is expensive and has a shorter lifespan compared to other components. It is easily damaged by an inaccurate system design. Indeed, on local markets it is possible to find a huge variety of battery brands without quality control and adequate labelling. Access to retailers is limited and so it is product choice. Often installations are done with second hand products or automotive batteries. To overcome those problems, in many African countries, in recent years, a number of PV providers are offering off-grid solar services in the form of leasing [45]:

- customers pay a monthly bill rather than the full system cost in advance;
- providers are the owners which install and maintain the systems at the beneficiaries' premises;
- gel type batteries are used;
- the standardization of the system suggests to oversize the PV module, cheaper than batteries, in order to limit the risk of excessive battery discharges.

A second area is represented by isolated installations ranging from 1-100 kW with some larger installation up to 1 MW. The demand is mainly coming from public institutions, schools, hospitals, health centers, small productive initiatives and site specific activities such as mines, touristic resorts, and telecommunication. With the exception of this latter group, usually able to pay for its own electricity infrastructure, public or cooperation aid economic resources are the main driver of the sector. Where there is no electricity infrastructure, on the other hand, it is difficult to find relevant economic activities able to finance their own systems. In those marginal areas diesel generators are still the most viable option. No matter how expensive their running cost is, the investment is limited, they can be moved without the need of a technician and their final cost is mostly variable. As regards the battery technology choice, this is usually defined by the economic capacity of the donor or investor. Lead–acid low maintenance and maintenance-free batteries are mostly seen in those applications. In larger and well financed installations, especially in the telecommunication sector, the 2V tubular batteries, offering a higher number of cycles, are often used. When considering lithium batteries, despite leveraged kWh costs of lithium are comparable to lead-acid batteries (when considering the potential depth of discharge and the number of cycles) lithium batteries are rarely seen. Indeed, the initial investment cost is a barrier both for investors and donor agencies. Moreover inverters need to be configured to run with lithium batteries and this is not always possible with the limited technology options with local suppliers. Finally, a PV system that offers 24h services needs energy efficiency devices and a proper management. As a matter of facts, it is the battery stock to be easily exposed to system sizing mistakes.

Battery packs are often overused and their lifetime reduced. Beneficiaries will hardly have the economic capacity to replace the battery once exhausted and economic mechanisms have to be in place in order to assure the sustainability of the infrastructure.

A third area is represented by application of RESs and batteries in micro-grids. Micro-grids are a common electricity market feature in countries with scattered settlements and low population density. They are usually supplied by diesel generators or hydropower plans. They may be owned by national electricity companies, local cooperatives or municipalities. The tariff structure of the supply may be regulated or unregulated and the supply cost equalized or not within the electricity tariff according to each nations legislation and ownership status. The cost of battery bank makes the access of intermittent RESs a limited option for micro-grids. When diesel supplied micro-grids are operated by the national electricity companies (e.g. Nicaragua, Burkina Faso), the capital cost to convert them in RESs systems is often excessive when compared to other investment priorities in the electricity sector. In some cases PV panels are added to the micro-grid to reduce the load on the diesel generators, but usually, in those contexts, the peak time demand is at dusk when PV are not useful. Most renewable/hybrid micro-grid experiences come from cooperation projects [46,47]. The battery stock of the infrastructure has to be combined with smart metering solutions in order to deliver to final consumers the right price signals of battery usage. In a PV system, for instance, the cost of electricity consumption is different according to the availability of the sun and the level of discharge of the battery.

A forth application of batteries it is for back-up purposes for customers already connected with the electricity national grid. The back-up systems assures electricity quality and continuity of service in contexts with recurring voltage fluctuations and interruptions. Most economic activities in E&DCs with unreliable electricity services have a back-up unit. The size of the systems varies from small UPS units to larger systems. Battery back-up systems are combined with diesel generators or hybrid systems, to face longer period of service interruption. Those systems are alternative to the use of the electricity grid. Their installation is privately financed. There is no or little experience of battery systems charged by RESs exchanging electricity with the grid. This option would increase the generation capacity of emerging markets, favor the distributed penetration of renewables combined with storage and contribute to reduce service interruption [48]. This issue is confined to national legislation initiative and little support is found from international cooperation efforts. Indeed, batteries for grid management in presence of a high penetration of intermittent RESs are not a market option yet in E&DCs.

The legislation and regulation affecting batteries use is to be sought in the different electricity service tiers. In most markets the development of off-grid installations for auto-consumption it is an unregulated activity. In some cases the principle is defined in primary legislation (e.g. Senegal: art 24, Loi n° 98-29 du 14 avril 1998 relative au secteur de l'électricité), in other cases a threshold is defined and under a given capacity, such as 1MW, no license is needed (Tanzania, Electricity act, 2008, section 18, comma (2) and (3)) and no regulation applies. The recent development of hybrid micro-grid to supply a number of customers outside the framework of national electricity companies has often seen the project implementer to seek consultation with national regulatory authority to approve proposed service tariff (In Cape Verde (Monte Trigo) the regulatory authority has been involved in tariff setting for 39kW PV mini-grid system [46]. In Guinea Bissau (Bambadinca) the regulatory authority is involved in tariff approval of 1MW hybrid diesel-PV mini-grid [49]). In this case the presence of batteries implies innovative methodologies for tariff setting. Ad hoc meters have been developed in order to better price electricity in stand-alone batteries supplied systems [50]. Smart meters help to design tariff options able to reflect battery costs. The lifetime of a battery, hence its cost, is given by the number of cycles and the depth of discharge. Using electricity when batteries are fully charged does not generate any costs; on the contrary a kWh consumed when the battery is at 40% of discharge is more costly than a kWh at 10% discharge rate.

A coherent legislation on batteries as in EU legislation (DIR 2006/66/EU) is not found in E&DCs and regulation affecting batteries such as quality standards and labelling is found within national bureau of standards [51,52]. Whereas an increasing number of small independent systems, mainly PV with batteries, are installed by final consumers to assure electricity quality and availability, the lack of regulatory option, such as net-metering, prevents those systems to exchange electricity with the grid. Limited experiences are found in Cape Verde and the Gambia [53]. The introduction of net-metering like regulation in emerging market will have a number of advantages with considerable impact on the battery market:

- to make PV systems more competitive compared to diesel, as back up option for customers connected to the grid;
- to speed up electrification of those rural areas close, but not yet reached, by the national grid. Those area, economically dynamic, are postponing investment in off-grid systems which will become redundant once the grid is extended;
- to help in the setting of technical and economic rules assuring a standardized product quality of PV/battery installations.

4. An experimental project: Energy4Growing project in Ngarenanyuki

The project Energy4Growing (E4G), promoted by a research group of the Politecnico di Milano, aims at studying, developing and implementing an off-grid power system to supply electricity to the school of Ngarenanyuki, a rural village in Tanzania. Specifically, the project investigates hybrid micro-grid architecture suitable to interface RES technologies and energy needs in the most reliable way while exploiting advanced regulations and control techniques. The hybrid micro-grid will combine the power systems already available in the school (i.e. a run-off-river micro-hydropower (MHP) plant and a back-up petrol generator) with new installations of PV panels and lead-acid battery pack together with an Interface Converter.

Beside the R&D interests, the E4G project aims at improving the power supply service of the secondary school of the Ngarenanyuki village (Fig. 8). Here 460 students attend the school and 85% of them are resident in the school facilities which include classrooms, offices, dormitories, library, kitchen, teachers' houses, etc. .

Fig. 8 Ngarenanyuki Secondary School, Arusha (Tanzania)

The main power source of the school is a run-off-river MHP plant based on a 3.2 kW Banki turbine coupled with 1-phase synchronous generator. The turbine always works at full capacity according to the stream flow and the frequency regulation is based on a 4 kW dump load which dissipate on air the generated power not required by the user loads (Fig. 9). The water flow to the turbine is diverted from a stream which is managed by local farmers. Therefore water availability is highly variable during the day and according to the season. This require to have an operator of the MHP plant which manually regulate the turbine distributor in order to keep at proper level the water pressure in the penstock.

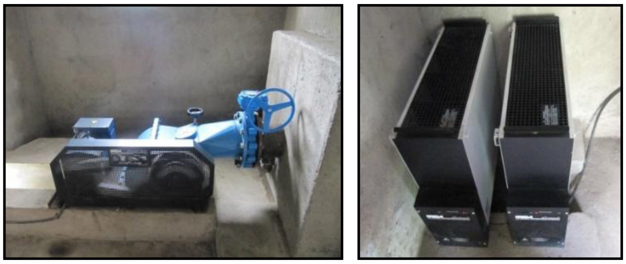

Fig. 9 Banki turbine and generator – Dump loads

Due to the unpredictability of the available water and hence to the discontinuity of the power supply via the MHP plant, the school installed also two back-up systems:

- a pack of 8 x 100Ah/12V Chloride Exide batteries which can be charged via the MHP plant thanks to a 2.4 kW charge inverter;
- a 5 kW petrol generator which is manually switched on and off. Indeed, due to the high running costs, it is used when the MHP plant is off and the battery pack are unloaded and only for special reasons (i.e. school celebrations, etc.).

The power supply is managed in the control room by means of a toggle switch which permits to choose the power source to be used, while a group of breakers permits to connect/disconnect specific loads. At the moment, the operation of the system is managed by an operator which checks the proper working conditions of the hydro turbine, selects the power source to be employed and operates the loads. Despite the operator (which is not available h24) and the school staff have got a fair practical experience as regards the system functioning, the system management is far from being effective and efficient, and hence several blackouts occur.

With respect to the E4G project, a main project purpose is to improve the power supply service of the school by increasing the generating capacity and by adopting an Energy Management System capable of effectively and efficiently integrating the different power sources. According to this aim, the hybrid micro-grid proposed by the E4G project will combine the power systems already available with new installations of PV panels and lead-acid batteries by means of an Interface Converter (IC) with specific control units. Fig. 10 shows the architecture of the micro-grid:

- Q1 is the *dc/ac* control board connecting the PV and the battery pack to a double *ac* bus system via the IC. The IC can enable two different operation modes: (i) PV and batteries in parallel with the MHP plant or the petrol generator, (ii) PV and batteries in stand-alone functioning;
- Q2 is the *ac* board which comprises: (i) the devices to monitor the micro-grid status, (ii) the PLC with specific logics to manage the energy flows, (iii) the Human Machine Interface.

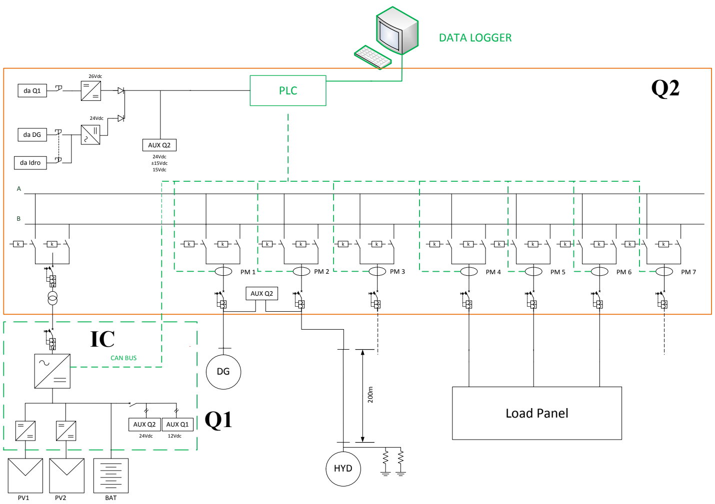

Fig. 10 Hybrid micro-grid architecture for Ngarenanyuki site

In this regard, some issues can be highlighted considering the integration of the battery bank within the actual power supply system of the school. Currently, during the system functioning, the dump loads keep the balance between the generation and the consumption sides while assuring the stability at 50 Hz of the power supply. On the other hand, the stability is preserved to the detriment of dissipated energy on air by the dump loads. The proposed architecture can limit the dissipated energy; nevertheless, it brings about issues as regards the control of the system stability as well as the life-time performances of the battery pack. Indeed the battery pack can be operated in order to absorb part of the power on the dump load thus minimizing the dissipated energy and increasing the system efficiency. On the other hand this may increase the charge/discharge cycles of the battery pack thus decreasing its lifetime. Therefore it is necessary to analyze the functioning conditions of the battery pack, as regards the energy flows, in order to optimize the system control logics aiming at the longest life-time. Nonetheless, the control logics that coordinate the operations between the battery pack and the dump loads can compromise the system stability. Indeed dealing with the energy flows in order to optimize the battery pack/dump loads functioning can come into conflict with the energy flows control for the proper system frequency regulation. Therefore it is necessary to analyze the control logics with regard to the system components reaction times, the rates of change in the power flows that can occur during the system functioning, the system inertia, etc.

5. Conclusion

Among the available ESSs, electro-chemical batteries are the main choice to support the implementation of off-grid renewable-based power systems. Actually, this solution is often the most appropriate to address the issue of rural electrification in E&DCs. Here the well-known bounds of RESs (stochastic behavior, i.e. unpredictability, un-dispatchability, intermittence) are locally mitigated by different requirements of the electric supply service. Indeed, in rural areas, local conditions can be largely improved even with a limited and slightly irregular increase in the available amount of energy.

In this frame, batteries already play a pivotal role together with renewable-based technologies. The paper has addressed this topic by describing the typical configurations capable to adapt batteries output voltage and current to the requirements of the grid to which they are connected. Specific economic models have also been recognized at rural level to properly support off-grid renewable-based power systems. The paper has also addressed this topic by describing four relevant applications of batteries in connection with the supply of electricity services and the last developments in the regulatory framework.

Finally, a case study (the E4G project) has been presented to show the complexity of developing an off-grid system implementing a storage solution. As a matter of facts, despite the large number of projects involving ESSs in E&DCs' rural areas, really few figures are available about performance monitoring of the power plants, check of batteries degradation and, last but not least, the social feedback, i.e. the feedback from the people that manage, do maintenance, use, the technologic infrastructure. Within E4G project a Facebook group (*www.facebook.com/energy4growing2014*) has been created and new ICT social technologies are proposed as a low cost effective approach in order to promote a knowledge divulgation for such scenarios: "technology is not an end in itself, but a means to an end", that's why the project name is Energy for Growing.

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