Improving Energy Efficiency with Smart Control Technology – Case Studies and Lessons Learnt

Petra Piclova,
Renewable Energy Segment
ComAp a.s.
Prague, Czech Republic

Abstract **– Hundred percent renewable energy penetration in hybrid microgrids? Certainly! But only with a smart and efficient energy management system which reflect project specifics, considers number of variables and takes them into account in the control algorithm. Running purely on photovoltaic or wind power is attractive, but does the renewables part on site need to be oversized to achieve it? Would not the capital investment then be prohibitive for the site realization? Microgrids are always about a tradeoff between costs and savings. But even the best designed system will not perform well and will not bring the desired savings if operated poorly.**

Keywords-microgrids, control system, diesel gen-set, renewable energy resources, photovoltaic power plant, hybrid system

I. INTRODUCTION

Ten years ago, microgrids was an unknown term for the greater public. Nowadays, every energy market player knows it very well as its variability of usage is vast. On-grid, off-grid, with or without energy storage, with or without gen-sets, all microgrids, but all different. The trend of today is not if, but how. We know that different sources of power can be combined. The question is the energy efficiency – that matters the most.

The topics to be presented in this paper are related to lessons learnt from projects in which ComAp installed and commissioned its hybrid control system. The first part is related to smart power management of diesel gen-sets to utilize their pros – robustness and reliability, in moments when the sun does not shine, the wind does not blow, and batteries are depleted or not even present due to their upfront costs. The second part introduces various microgrids – real projects, their specific features and how they were addressed in the design of the energy management system.

II. MICROGRIDS –TECHNICAL AND ECONOMIC CHALLENGE

Although fluctuating, long-term rise of the oil and electricity price is apparent. Owners of power generation plants that use diesel gen-sets as the prime power suffer from the rising fuel purchase price and transport costs, but it is also the awareness of environmental issues, a falling price of the photovoltaic (PV) technology and the rising need of low power and fuel supply independence which demands reduction of conventional fuel consumption. Microgrids seem to be the perfect match utilizing the benefits of renewable energy while mitigating their negative features – intermittency and no predictability of production. Microgrids are often built by adding PV power plant to an existing diesel gen-sets fleet, but they can be also equipped with wind power plants, however due to demanding construction, legal approvals and higher upfront investment into the wind power plant, PV is prioritized over wind in 90% of microgrids. Therefore, in this paper the renewable energy is often referred to as a PV power plant rather than a wind power plant.

Since the first microgrids emerged, their development over the last decade has experienced a sharp surge. There are no doubts that various power sources can be integrated, but how efficiently they can be operated, not only from the technical, but also from economical perspective is a question. It is clear even to the distribution network operators, that microgrids have significant value not only for the consumers, but also for the utilities as their networks can benefit significantly from the support of microgrids power sources in times when there is a lack of power from regular power plants available.

This paper discusses the technical challenges that occur in the integration of various power resources, fluctuating loads and increasing pressure on economic performance of a microgrid to secure the owner short payback periods and higher return on investment.

III. OPTIMUM RENEWABLE ENERGY PENETRATION IN MICROGRIDS

Ninety percent of globally installed microgrids are so called brownfields – existing power plants where the power supply is provided only from diesel or gas generators and later, they are converted to a "hybrid microgrid" by adding a nonconventional power supply, such as photovoltaic panels or wind turbines. Such intervention poses high demand on the control system which should be in all cases retrofitted to accommodate the higher rate of intermittent power supply, without having a negative impact on the conventional power resources or the reliability of the power supply.

However, even the best control algorithm would not compensate the poor site design of the individual power resources and their sizing. Should the renewable energy part be oversized, the return on investment of the installation can be prolonged significantly, should the photovoltaic or wind power plant size be underestimated in the installed capacity, then the desired fuel savings and paybacks will be anything but satisfactory.

A. Low PV penetration (up to 30%)

The least technical challenge on the control system is imposed for systems with PV penetration below 30% of the overall site rated capacity. Due to the lower proportion of renewables, the diesel gen-sets run 24/7 supplying the majority of the load (at least 70%) and the curtailment of the renwable energy power plant is usually not necessary because the load is never lower then the PV power output. In such case, the PV power utilization is maximized, no curtailment is needed and the control system considers the PV output only as a negative load which does not require any specific regulation, assuming that there is no power cut of the load or a significant and unexpected load drop. However, for such emergency situations when the PV output should be curtailed, a back-up logic within the control system must be designed.

Even though the low penetration provides limited reduction of operation expenses and emissions, is is suitable for sites with highly variable loads where the reliability and lower upfront investment into the renewable energy installation and upgrade of control system is desired.

B. Medium PV penetration (from 30% to 60%)

If the installed capacity in the renewable energy resource is higher than 30%, but still less than 60% of the installed capacity in the diesel gen-sets, or if the renewable energy (RE) covers no more than 60% of the consumption, the overall control algorithm is more robust, as energy storage might be involved to cover potential mismatch between the renewable energy generation and power consumption. The control system must therefore wisely utilize the benefits of the energy storage to maximize the renewable energy utilization and minimize the gen-sets operation time.

In most cases grid-tied PV inverters are used, which means, that if the mains is not available and the site is operated off-grid, it is essential to always keep one gen-set running to provide the voltage and frequency reference. However, even where standalone inverters are used, it is best practice to keep a generator in operation due to its ability to maintain very stable frequency and voltage levels unless Battery Energy Storage Systems (BESS) are used which enable shutting down the gen-set. The master controller in this case prevents the gen-set underloading by curtailing the PV when necessary. Communication with the PV inverters over Modbus or, less preferably, through analog or digital signal, is crucial, as well as their ability to curtail the output upon a command from the master controller.

C. High PV penetration (over 60%)

Systems with renewable energy penetration up to 100% of the overall production capacity minimize the gen-sets operation runtime and prolong the maintenance intervals whilst maximizing the renewables output. Nevertheless, for such high penetration systems when gen-sets are shut down for a certain time, energy storage is necessary. Maintaining reliability of such a complex system puts high demands on the control system which must be designed very thoroughly with respect to all site components´ specifics, such as gen-set operation limits, energy storage operation limits related to their lifecycle and smooth PV curtailment options.

Systems of such high penetration are therefore suitable mainly for sites with stable day load and favorable PV conditions. The control system algorithm must be tuned and optimized ideally on the site.

IV. CONTROL ALGORITHMS DESIGN

It is highly recommended that evaluation of long-term load profile measurements as well as real weather conditions on a site are used as a base for the site design, as only proven data can uncover incorrect assumptions which might lead to unnecessary high dynamic spinning reserve, underutilized renewable resources or underloading of diesel gen-sets, all of which are consequences of inappropriate site design. Poor design, however, cannot be compensated by a sophisticated control system algorithm. Assuming, that the site design has been optimized, the below principles must be obeyed in the control system design.

- Maximized utilization of renewables

Renewable energy should be utilized 100% of the time. There should be only very few occasions in which the PV would be limited on a command and the most common one is to prevent the gen-sets from underloading due to unexpected load spikes. Appropriate dispatch of the gen-sets fleet according to their size and start-up time to accommodate the RE surges must be assured.

- Uncompromised site reliability

In off-grid applications the gen-sets were used to supply 100% of the load 100% of the time. This must not be compromised by adding renewables to the power generation mix. Even though the demand for high efficiency might lead to operation close to the edge of reliability, the reliability is the most paramount attribute of a control system and must be always prioritized over e.g. renewable energy output maximization.

- Automated diesel gen-sets operation

Traditionally most power stations in less developed regions have been manually operated. With the trend towards renewable energy deployment and the vast development of various types of hybrid microgrids, full automation of the existing power stations became inevitable because of the rapidly changing circumstances and their combinations which require immediate and complex control system response that no human operator can ensure. In the past it were the utilities who installed the systems, nowadays it is international corporations – the Engineering, Procurement and Construction companies that install the projects locally and the majority of them have their own Energy Management System.

The control mechanisms have been evolving over the years, from using dump loads to very sophisticated systems using weather and load predictions along with economic analysis of levelized costs of energy from different resources to ensure optimized dispatch. Considering the variety of applications and diverse technical requirements, there is no universal control system and the most suitable ones should be designed by the supplier. Often it might be a combination of approaches to achieve the highest site efficiency.

A. Droop

Power management of diesel gen-set can come in various forms, the two well-known modes are droop and isochronous operation. The droop mode is in fact regulation of kW/kVAr among a group of gen-sets without any inter-controller communication. It is an alternative to the isochronous regulation in which all load sharing and VAr sharing information is exchanged via communication lines, mostly over CANbus or Modbus. The droop regulation is based on set voltage and frequency values which are measured on the common bus. The requested kW and kVAr supply values are calculated by each controller which drives the gen-sets within defined limits to maintain the fixed voltage and frequency limits on the common bus.

The advantage of droop control is that controllers from any manufacturer can be grouped no matter of its communication capabilities and is, therefore, the easiest control mode for the system integrators. Nevertheless, due to the zero load reserve kept on the gen-sets, the gen-sets might not react quickly enough to supply the consumption in case of rapid surge of load or, as might happen often in microgrids, in the case of a sudden drop of the PV power plant output due to cloud coverage.

While droop is suitable for a fleet of gen-sets of the same size, smart gen-set power management is needed for systems where the gen-sets are of different rated power. Only then the right selection of the most suitable gen-sets will be ensured to suit the best to the load at a time, without the threat of underloading or overloading the gen-sets. ComAp uses its own algorithm for evaluation of the load and selection of the most appropriate gen-sets based on their rated power, running hours, or priorities.

B. Droop based APC (Active Power Curtailment)

When microgrids became a trend and PV power plants were added to the gen-sets, droop was still used due to its simplicity and no incompatibility issues, however, droop control between PV and gen-set means that the PV shares its output with the gen-sets evenly to supply only as much as the load requires, which in turn means, that the RE resource output is not maximized. And that is by no means desirable.

Therefore, an APC based on droop control can be used; the idea is that only when the gen-set reaches its minimum loading level, which signalizes the energy surplus within the system, a droop mode with the PV is activated. When the gen-sets run above this critical limit, isochronous operation is used [2]. Hence the APC is more efficient than regular droop control, nevertheless still the efficiency of the system is impacted by the load sharing between the PV and the gen-set and so the utilization of the PV power plant is therefore not maximized.

C. Dynamic Spinning Reserve (DSR)

Clouds could result in 80% of online PV contribution being lost within 10-20 seconds. Given that the start-up sequence of a generator is approximately 2-3 minutes, the dynamic spinning reserve functionality ensures that there will always be enough capacity available on the gen-sets to offset rapid supply drops from the PV plant without the risk of overloading generators that are in operation. The DSR is calculated continuously from the actual PV output, is adjusted to the current weather conditions and can be optimized according to the gen-sets conditions. The DRS calculation is designed with this dynamic nature to minimize the load reserve hence ensuring minimum fuel consumption for the back-up power.

The DSR does not function in droop mode, it should be implemented within the isochronous gen-set control mode and ideally as a part of smart gen-set power management which considers not only the rated power of gen-sets, but also their running hours, start-up characteristics and optimize the selection accordingly. Nonetheless, the gen-sets are not the influencers of the DSR value, the DSR can be optimized also accordingly to the penetration level, historic load profile data (at different times of the day) and weather predictions.

D. Demand Side Management (DSM)

Efficient energy production used to be the cornerstone of former debates about the future of energy, meanwhile the optimization of energy consumption has been left aside. Nowadays, it is apparent that just by reduction and smart control of the consumption, the demand on energy production can be reduced almost by a third. And that is a significant portion. But it is not always the case that a load can be cut off. And there even might be moments when the load is higher than anticipated and the distribution network has not scheduled enough resources to supply the load (typically during hot summers or cold winters when overloading of the network power supply may occur very easily.

For these occasions, a demand side management can come into place and provide grid support from dispersed microgrids from around the country. Below is an example of DSM installation.

ComAp Pty Ltd carried out a large-scale installation in a commercial building in the center of Perth's business district. This 43-storey office tower was specifically designed to reduce energy costs. The existing control system was functional, capable of supporting the building load and was maintained at a high level. However, it did not enable the import and export of power for the gen-set group. Therefore, ComAp´s team was responsible for modernizing the emergency backup power control system of the building's emergency power generators. The upgrade was to specifically enable the building to take advantage of a demand management scheme.

This system also ensures that if the grid power supply fails, the generators can automatically switch over and take the building's load, then transfer the load back to the grid when the mains comes back on line or support the grid when there is shortage of power within the district.

V. CASE STUDIES

Diesel gen-sets are nowadays criticized by many mainly for their emissions, but also for the noise, fuel consumption and the need for regular maintenance. On the other hand, they do not deserve such a bad reputation as they are highly reliable, flexible in reaction to load fluctuations, robust, simple rotating machines, more affordable than renewable sources and if well maintened, with very long life cycle. Thanks to all these features, they have been the main and only power sources for many regions in remote areas with no or weak electricity coverage. Yet, they should not be the exclusive power resource and when appropriately combined with renewables, the tradeoffs between the pros and cons of both technologies can be very well optimized.

There are more than 600GW of baseload diesel gen-sets globally [1]. All these sets can be combined with RE and are therefore available for conversion to a hybrid microgrid which would lead to significantly less pollution and emissions from exhaust gases.

Below are a few examples of realized hybrid projects for which ComAp designed and installed a hybrid control system.

A. Power station at Rarotonga, Cook Islands

Rarotonga has been an operational power station of four slow speed gen-sets on a small island in the Pacific Ocean. While PV power plants are being installed on the island to eventually reach 75% of daytime loads, new high-speed sets were installed there and are waiting for commissioning. There were other residential PV power plants already installed on the island but are not part of the Rarotonga plant hence they are not dispatchable. The load is residential and varies slightly throughout the day.

The system was operated manually with high levels of spinning reserve; often the sets were operating at only 50% load to be able to absorb the PV supply changes, which comes at a very high cost in terms of fuel consumption as this rapidly increases per unit cost of generation as load decreases from the optimum level. Therefore, ComAp Pty Ltd has upgraded the site by replacing the control system, installing new governors and Automatic Voltage Regulators, implementing automatic synchronizing and using Dynamic Spinning Reserve on the high-speed sets to provide short-term capacity until larger sets can be put on line (we can bring the first set on line within 15 seconds and further sets within 30 seconds). The new high-speed sets have a much flatter consumption curve that leads to significant cut of fuel consumption. In addition, by changing the operating philosophy so that slow speed sets operate on base load, and the DSR is kept on the high-speed sets, the efficiency of the power plant operation has increased significantly. The system also automatically re-prioritizes the generators based on hours run to ensure generators are equally exposed to wear and tear, and to assist with engine service planning. During the installation it was observed that the PV provides only 90% of the installed power due to dust and salt on the panels hence the DSR was cut additionally.

The key to successful integration of the RE into the existing system was the utilization of the high-speed and slow-speed gen-sets to provide optimized base load with the necessary DSR. What would be recommended for such conditions is utilization of load and weather forecast to optimize the DSR value.

B. Hybrid system integration at Kiribati

The Republic of Kiribati is an island nation in the Pacific Ocean. Tarawa, one of Kiribati's 33 atolls originally used, as most of the islands in the Pacific, diesel generators to generate 100% of its electricity. To reduce the dependency on diesel imports a 500 kWp photovoltaic power plant was built on the island, to be integrated into the public electrical grid. Today the PV plant covers around 10% of Tarawa's electricity consumption but the plan is to increase this number by installing more PV in the future.

Originally, the control system was hardwired utilizing relay logic, timers and hand switches to manually operate the plant. Nevertheless, such a setup was unable to react to the constantly changing power output from the PV plant hence ComAp installed and commissioned a fully automatic system with a hybrid interface featuring DSR and smart power management on the gen-sets.

As a result of the project, Kiribati is forecast to see a reduction of 578 tons of CO_2 emissions and 83,380 liters of diesel fuel each year saving them a cost of US$214,000 per year.

C. Burgos Wind Power Plant

The Burgos Wind Farm is the largest wind farm in the Philippines and in Southeast Asia, covering 600 hectares, it generates about 233 gigawatt-hours of electricity a year, enough to power more than a million households. This wind power plant is not a hybrid microgrid per se as the diesel gen-sets are installed there only as backup power system for occasions with too strong winds when the turbines are automatically shut down to prevent damage.

The control system evaluates the turbines operation and immediately starts a bank of gen-sets under the so called Start Up Synchronization mode which starts the gen-sets, synchronizing them and allows them to pick up load from the turbines automatically within 20 seconds.

VI. LESSONS LEARNT

ComAp has, to date, automated a high number of power stations in the Pacific Islands, to name a few - Bora Bora in Tahiti, Rarotonga, Mangaia and Atiu in the Cook Islands, Wallis, Fortuna and Lifou in New Caledonia, Vanuatu, Fiji, Kiribati, etc. All the islands used to run on diesel only, however with their ambitious target to get to 95% of renewables by 2020, they have worked hard on phasing out diesel gen-sets as prime power and installing PV panels to utilize the abundance of sunshine. This transition has indeed imposed a challenge on the existing power system with such high PV penetration. There are many aspects which determine the success of such a transition towards almost 100% PV, resp. renewables penetration, and thoughtful control system design is one of them. Even though all the projects were different, there are certain attributes which all the projects have in common.

A. The threat of underloading gen-sets

There is widely spread concern about diesel gen-sets underloading. Such concern is relevant, however operating a diesel gen-set at a load level below 30% of its nominal capacity is harmful only if it lasts for extended periods during their lifecycle. If there is a need to operate the gen-set below its 30% nominal capacity for short periods of time, e.g. to accommodate a surge of PV output in between clouding events in order not to shut the gen-set down for few minutes and then start it again, followed by higher loading (from 60 to 100% of its rated power) will mitigate the effects of underloading. The most prevalent consequence of underloading is the engine exhaust slobber or so called wet stacking which occurs due to low heat in the cylinder allowing unburned fuel and oil deposits to leak through the exhaust slip joints. The slobber on its own does not indicate a problem with the engine, neither harms the engine right away, but it signals a possible underloading issue which, if not addressed, might lead to deposit build-up behind the pistons and cylinders. Such a condition might then lead to worse performance, power losses and accelerated wear of components, which could then require more frequent maintenance [3].

B. The fear of overloading gen-sets

Overloading of a diesel gen-set is another concern that occurs when a microgrid control system is designed, but it is very similar to the above discussed issue of underloading – if used only short-term for temporary periods in justified cases, e.g. before a next gen-set is started, the impact on the gen-sets wear and tear is minimized. Prime power gen-sets are designed to run in a range from 85% to 100% of their nominal power, therefore they are designed to handle higher loads rather then lower loads.

Nevertheless, smart power management always takes into account the nominal rated capacity, safety load reserve and on top of that, in microgrids, also the dynamic spinning reserve to prevent the gen-set operation dropping out of the designed parameters.

C. The myth of high DSR

High DSR should ensure the maximum reliability of a system. Nevertheless, the DSR does not have to be equal to the actual PV power output if the conditions on the site allow for smart optimization of DSR, such as availability of high-speed gen-sets, favourable weather conditions with an abundance of irradiation, and a stable, noncritical load. In such cases DSR as high as the actual PV output is unnecessary, or even undesirable because it would significantly prolong the payback period and return on investment to the PV power plant.

Knowing the specific details of the particular site parameters allows for minimized DSR and not only maximizes the financial returns, but also reduces the exhaust emissions released to the atmosphere, which is the ultimate goal of power plants hybridization.

VII. Conclusion

Microgrids are undoubtedly the future of power systems. They are reliable, environmentally friendly and technically robust. If designed and operated correctly by a control system that reflects all site specifics, they can combine favorably all positives of renewables and gen-sets, and minimize their negative features, such as renewable energy intermittency and gen-sets´ high fuel consumption. Even though some microgrids are grid connected, they should always be able to run independently on the grid, in an off-grid mode and thus supply remote regions independently, preventing large blackouts.

Nevertheless, off-grid mode imposes high demands on the overall stability of the electrical installation due to lower inertia in the system and thus requires a more robust control system which would ensure stable voltage and frequency, prevent overloading and underloading of gen-sets, and maximizes the PV/wind power intake. If an energy storage is used, the control algorithm must reflect its recommended charging and discharging characteristics to maximize its lifecycle and utilize wisely its capacity in the overall site operation.

Although it might seem straightforward, it is important to mention that just by automation of the gen-sets control the efficiency of the site operation can be improved by about 20% compared to manual operation and it is therefore essential to the hybrid microgrid control system design. On top of that, the ability to control the RE resources within the area is a must, as well as optimization of the DSR value which is the critical component of microgrid operation. Last, but not least is the utilization of weather forecast in the optimization of the DSR calculation.

Pacific Islands are also a great example of how alternative fuels can replace diesel to satisfy the requirements on costs and emissions cuts. The use of bio-fuels such as coconut oil often requires a two-tank system so that the engine starts, warms up and cools down on diesel but runs most of the time on the bio-fuel. Such combination of the operation requires certain modification of the operational logic but is easily achievable.

References

[1] Microgrids: a rapidly growing global market – where are the opportunities? Delta Energy and Environment Ltd, May 2017

[2] R.Tonkoski, Student Member, IEEE, L.A.C. Lopes, Senior Member, IEEE, and D. Turcotte, Member, IEEE, “Active Power Curtailment of PV Inverters in Diesel Hybrid Mini-grids”

[3] Brian Jabeck “The Impact of Generator Set Underloading” White Paper, October 2013, CAT