Assessment of Control Strategies Performance in Stand-alone PV-Diesel System: Simulation and Experimental Test

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***Abstract*— On islanded sites with no access or unstable access to power grid, diesel generator plant is up to now one of the most popular choice for power supply. With renewable technology raising and their price drops, hybrid power system combining such energy and traditional diesel generator offer interesting solution for those sites, by efficiently reducing system operation cost and pollution emission constraints. In this work, photovoltaic (PV)-diesel hybrid system is considered through simulation and experimental test. The analysis focuses on system performance considering different solutions such as advanced control strategy and storage integration. Study methodologies and results will be summarized in this paper.**

Keywords-PV-diesel; hybrid system; advanced control; PV forecast; storage; system performance; simulation; HIL test.

I. INTRODUCTION

Technology innovation and industrial effort in reducing PV plants cost have made this technology an attractive power source. However, due to PV intermittent characteristic, stability of power system with high PV integration rate is still an issue especially in stand-alone location. Many actual industrial solutions available in the market use power limiting control via PV inverter, in order to ensure system power stability in case of high PV production. The use of PV power is not optimized and economic benefits of such systems is reduced. The purpose of this work is to evaluate and compare two approaches to improve both system stability and economical profitability: (1) by means of an advanced control using PV forecast data and (2) using energy storage system. To do so, at first, simulations are carried out for two hybrid plants, the first one is a 100kW plant and the second one is 25 MW plant for a period. Both systems are simulated for 43 days period with different typical PV daily profiles. Rule-based control and advanced control strategies are compared together and then to the system with an energy storage addition. For the comparison, performance indicators are both technical and economical: undistributed energy, generator operation time and fuel consumption. In order to validate those technologies, all control algorithms have been implemented and tested in Hardware In the Loop (HIL) platform, developed in CEA-INES. Modelling and simulation are carried out in the simulation platform SPIDER [1].

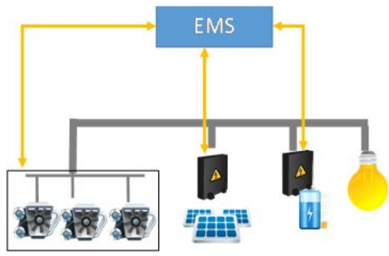

Figure 1 PV-Diesel systems architecture

II. SYSTEM DESCRIPTION

A. System components

The architectures of two studied systems (namely case A and case B) are similar, as described in the Fig.1. Each system is composed of three diesel generators, one PV system, one storage system and loads. The systems are managed by a centralized Energy Management System (EMS). The characteristics of the different elements such as maximum load power, PV peak power and genset nominal power in the system in case A and case B are given in Table 1. Gensets main characteristics of each case are provided in Table 2.

As described in Table 1, system case A represents a small scale power system, which can be found in infrastructures such as farm, military, telecommunication or community sites. In such system, power supply quality requirement can be considered as of a medium level which means that power supply must be continuous for most of time, but short and bare interruptions are allowed. On the contrary, a system represented by case B with much higher power scale (more than 10 MW) are usually installed for big industrial sites. Depending on industrial process, power supply continuity can be highly critical with interruption period tolerance closed to zero. For each system, three different PV power sizes are studied, corresponding to PV integration rates of 50%, 100% and 150% respectively of the maximal load power.

	PmaxLoad	*PVPeak*	*PmaxPRP Genset*
System case A	100 kW	50 kWp; 100 kWp; 150 KWp	3 X 32 kW
System case B	25 MW	12.5MW; 25MW;37.5MW	3 X 8.9MW

TABLE I. POWER SIZING OF TWO SYSTEM CASES

	Pmax ESP Genset	**PminPRP Genset**	**Tstart _cold**	**Tstart _hot**	**T_min _ON**
System case A	3 X 35 kW	3 X 9.6 kW	10 s	10 s	0
System case B	3 X 9.8 MW	3 X 2.7 MW	6 mn	6 mn	60 mn

TABLE II. MAIN CHARACTERISTICS OF GENSETS IN TWO SYSTEM CASES

In Table 2, several of the main characteristics of the diesel generators used in two system cases are listed, where:

- PmaxESP Genset is Emergency Standby Power (ESP) -the maximal power which can be provided by genset, during a limited duration per year;
- PmaxPRP Genset is Prime Power – nominal power which can be provided by genset during unlimited running hours;
- PminPRP Genset is minimal recommended running power of genset, which is usually fixed as 30% of the nominal power;
- Tstart_cold and Tstart_hot are respectively starting delay from a “cold” state and “hot” state;
- T_min_ON is the minimal operation duration of genset for each starting. This constraint limits the number of gensets state change during a period, which is better for their maintenance.

Beside those parameters which are important for PV-Diesel system simulation, genset modelling takes into account genset fuel consumption data. This latter is normally provided by manufacture datasheet under a table format with several measured points. Interpolation between those points is done in order to compute genset consumption at any operation point.

Storage system uses Li-Ion technology electrochemical battery, modelled in a scalable approach according to the battery nominal power and energy capacity.

B. *Control architecture*

PV-System EMS contains two levels control structure as described in the Figure 2, with:

- High level control using forecast data such as PV production forecast and load forecast to compute genset dispatching planning;
- Operational control level with power sharing between production units such as PV production, gensets and storage.

Using the same approach than in previous works [3], three modes of system control were implemented and tested for each study case:

- S1 – a rule-based strategy in which only operational control level is implemented. In this mode, genset dispatching and power sharing is carried out simply based on the net load power, which is the difference between the initial load and PV production.
- S1b –a second rule-based strategy where PV power out from inverter is limited in order to respect genset power restriction. This control offers advantages in terms of system stability but do not optimize the use of PV power. As of its wide application in hybrid system controllers offered in the actual market, system controlled by this strategy is used as reference (Ref) in our studies.
- S2 – an advanced strategy with two levels fully implemented. In the planning level, optimization is carried out in order to anticipate genset dispatching using PV-short terms forecast data. Operational control time step is 10s, planning computation is launched every 2mn for the upcoming hour, or whenever an event happens.

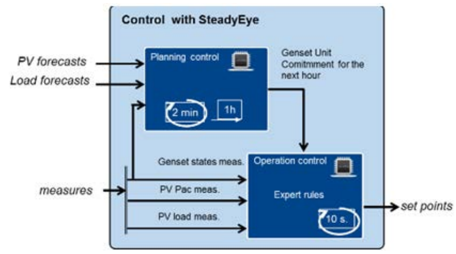

Figure 2 Two-levels control system

C. *PV data*

43 days of PV profiles are tested. Those profiles represent various weather conditions during a year: clear sunny days, days with mixed condition and very cloudy weathers. Some examples are illustrated in Figure 3.

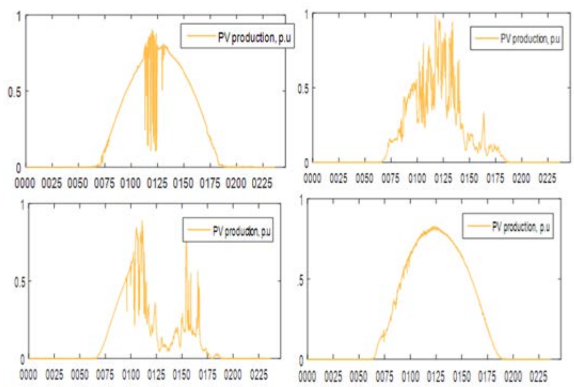

Figure 3 Different PV daily profiles

Absolute values of PV production are scaled with PVPeak values in Table I.

PV production forecast [3] is obtained using a sky-imager installed on site. The camera takes hemispheric photos of the sky every minute. These images are then automatically sent to a server or a local PC. Using image processing algorithms in conjunction with a clouds movement forecast and physical models, the state of the cloud cover is predicted for a very short term along with the plant's production.

The percentiles from 10% to 90% (cf. Figure 4) are provided in addition to the mean expected power P50 (and/or irradiation level – GHI) as confidence indicators. Calculation of percentiles are mainly based on clouds movement uncertainty. The use of confidence intervals (for instance: P20-P80) allows to anticipate risk of irradiance/production drops. The proposed control relies on the percentile P20.

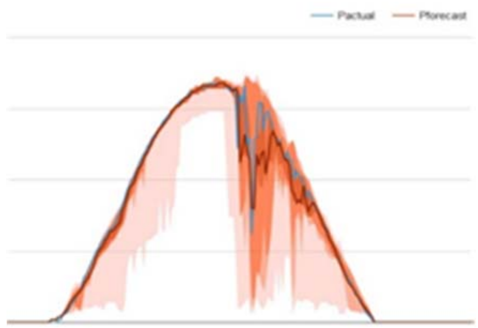

Figure 4 PV forecast percentiles

III. Simulation results

Daily simulations are carried out for two study cases where the participation of each production unit is computed, as the example showed in Figure 5. System performance of each case with each of the three control modes are compared together. For all following analysis, simulation results are expressed using four indicators:

- Undistributed energy in quantity (kWh) and in duration (s), referred as UNE
- Gain in fuel consumption compared to reference method S1b (%)
- Gain in genset operation time compared to reference method S1 (%)

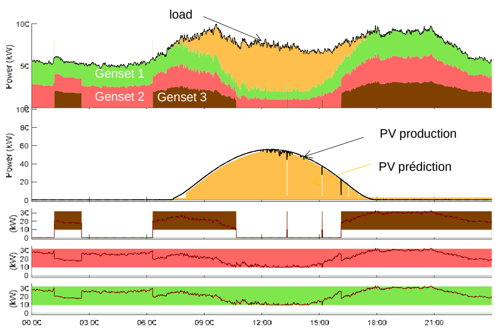

Figure 5 Daily simulation example on study case A, control S2

1) *Study case A*

Simulation results for a 43 days period are presented in Figure 6. Four graphs from left to right and top to bottom represent respectively the undistributed energy quantity (UNE in kWh), in duration (UNE in s), gain in fuel consumption and gain in genset operating time compared to S1b strategy. Each indicator is computed for PV integration rate respectively of 0.5, 1 and 1, corresponding to 50%, 100% and 150% of maximal load power. From these graphs, high quantity of UNE is observe with S1 strategy when PV-rate is high (1 and 1.5). Indeed, these UNE periods happen during specific instants when PV production readily drops and/or load power stiffly increases while the active gensets are operating at high load factor. As the start of a newgenst is not immediate, this situation will cause instability to the system. On contrary, strategy S1b is very stable thank to the permanent power reserve in genset as PV power use is limited. Per consequence, fuel consumption and genset operation time are not optimal in this method. Advanced control strategy S2 offers an interesting compromise of technical and economic criteria compared to rule-based control strategies:

- Compared to control strategy S1, strategy S2 allows to reduce considerably UNE, as planning computation helps to predict PV power drops and adapt genset operation in advance.
- Compared to control strategy S1b, the gain on fuel consumption obtained with S2 strategy is 2% when PV integration rate is 0.5. This gain is increased up to 6% and 10% when PV-rate is 1 and 1.5. The same trend is observed with the gain of genset operation time.

Those results confirm analysis obtained with simulation on four typical PV profile days, which were exposed in a previous publication [3].

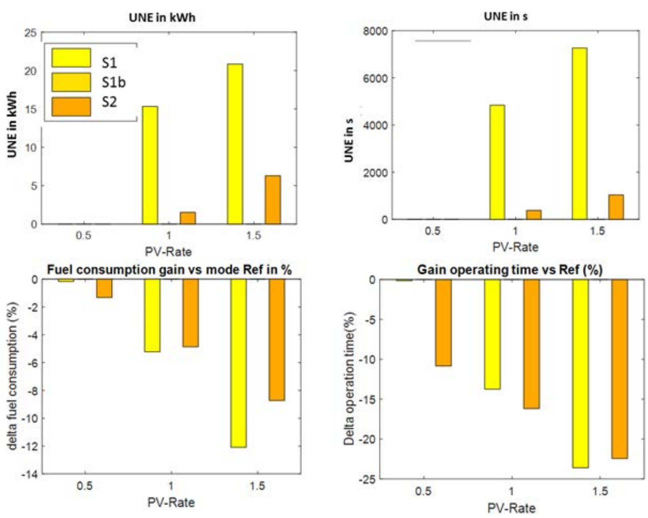

Figure 6 Performance comparison between control strategies S1, S1b and S2 in study case A

2) *Study case B*

Results in Figure 7 illustrate a similar comparison between the three control strategies when applied to the system 'case B'. Again, using advanced control strategy S2 allows a strong reduction of UNE period compared to S1 strategy. Due to critical requirement of the power supply continuity for such system, the period of undistributed energy (UNE) is an important criterion. Also, operation costs related to fuel consumption and genset maintenance represent an important expense for the system operator. Hence, in this case, the choice of using S2 control is both technically and economically interesting.

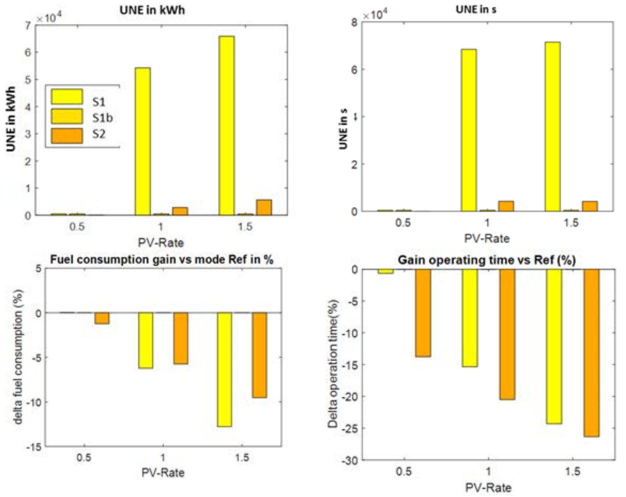

Figure 7 Performance comparison between control strategies S1, S1b and S2 in study case2

B. Benefits of energy storage intergration

In parallel to system control improvement, energy storage is often used as a solution to ensure hybrid system stability. As a result, in terms of energy storage system cost, storage sizing is a central question. To do so, similar simulations are repeated on system cases A and B for different storage capacities.

Storage system with battery is combined with S1 control, and programmed to be discharged during genset start delay periods. Otherwise, battery is charged when genset and PV power are higher than load power. Storage maximal power is a sizing parameter. For each case, nominal energy is computed so that storage can stand for all gensets consecutive starts.

1) Study case A

Figure 8 and *Figure 9* illustrate the comparison between system performances with strategies S1, S2 without storage and then with storage of maximal power of 10%, 15%, 20%, etc. up to 100% of PV peak power. Comparison focuses on UNE performance and only for high PV-rate of 1 and 1.5. One can observe that in this case, a storage system size of 10% of the PV maximal power is enough to cover all instability caused by strategy S1. The sizes of corresponding storage system is respectively 5kW/0.013kWh and 7.5kW/0.02kWh. In reality, the use of electrochemical battery for such cases are not really appropriate. High power with limited energy storage technology such as super capacitor can be better adapted for this application if the obligation of zero interruption is required here. Otherwise, due to limited system operation cost, S1b strategy control can be a good option. In that case, a complete cost benefice analysis is to be carried out in order to get an optimal PV-rate, taking into account system investment cost and PV surplus production.

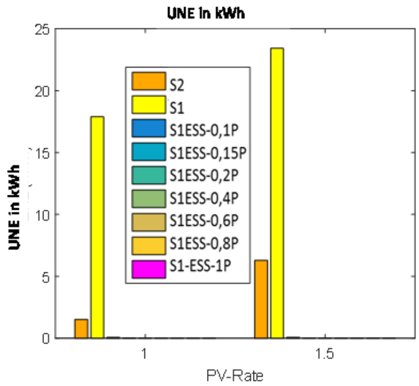

Figure 8 UNE comparison between control strategies S1, S2 and S1 with storage in study case A

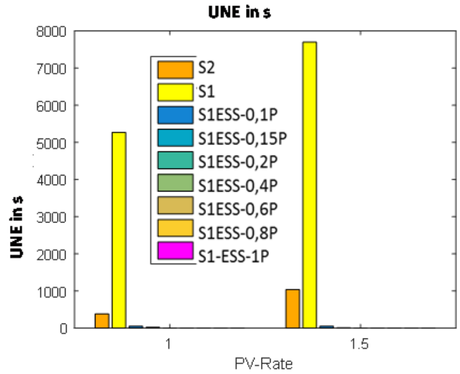

Figure 9 UNE comparison between control strategies S1, S2 and S1 with storage in study case A

2) Study case B

In the same way as in case A, simulations are carried out on study case B, in order to compare asystem with various sized storage addition and a system without storage controlled by strategies S1 and S2. Comparisons in terms of undistributed energy for the different simulations are displayed in Figure *10* and Figure *11*. Obviously, adding storage to rule-based control S1 allows to reduce UNE quantity and period. The higher is the size of storage, the better is system stability. In case of this MW size system, storage power size needed for an equivalent UNE to control S2 is 40% of maximal PV peak power (0.4P), meaning 10MW/3MWh and 15MW/4.5MWh for PV-rate of 1 and 1.5.

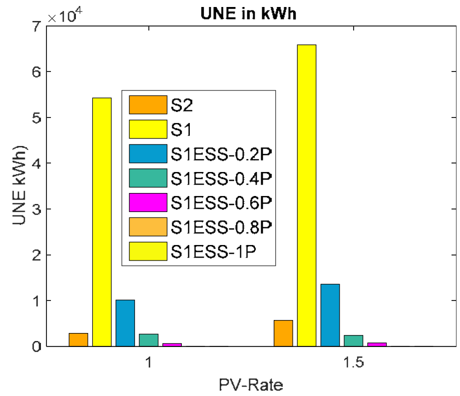

Figure 10 UNE comparison between control strategies S1, S2 and S1 with storage in study case B

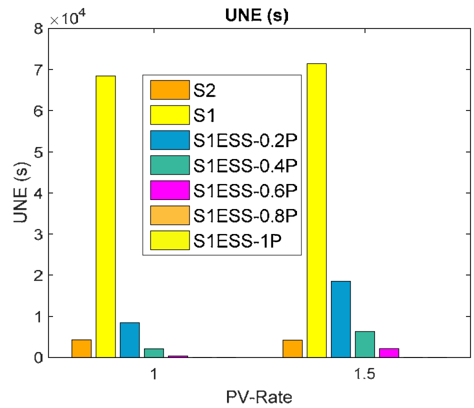

Figure 11 UNE comparison between control strategies S1, S2 and S1 with storage in study case A

IV. EXPERIMENTAL RESULTS

Benefices of using advanced control and adding storage to rule-based control are proven according to simulation results. In order to validate those solutions in real system operation, experimental testing is performed on CEA-INES platform. Test system configuration is similar to the system described in the study case A. System monitoring and control is set up through a SCADA system which monitors the different element of the test platform.

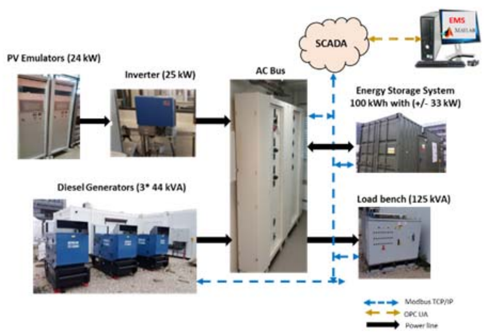

Figure 12 PV-Diesel hybrid system used for test

In order to assess the system behavior, the different strategies (control strategy S1, control strategy S2 and adding storage), are tested. The experiment is therefore conducted using on three real diesel generators, a load simulator, and a PV simulator – connected to real PV inverters. Li-Ion battery technology is used for the storage system, which is sufficiently sized to cover power interruptions due to total PV production loss. Test period is 10 minutes.

To underline the difference between the different stratgeies, a high power variation situation is created by increasing load power together with a PV production drop at 6th minute (360s). In case of strategy S1, as shown in Figure *13*, high power demand is at first answered by the active genset. Once this latter reaches its limit power defined by the control strategy, starting order is sent to the second genset. However, during start delay of around 10s, power balance cannot be kept, inducing the drop of system frequency. The first genset is thus disconnected driving to system power outage. As showed in Figure *14*, with control strategy S2, PV production drop was predicted beforehand. Therefore, two gensets were planned at 6th minute instead of one genset,power outage event is then avoided. For the case with storage addition, as illustrated in Figure *15*, during genset start delay, the storage is discharged to complete the production balance. Once the second genset is active, energy discharge from storage is stopped. The system continuity is ensured with two gensets.

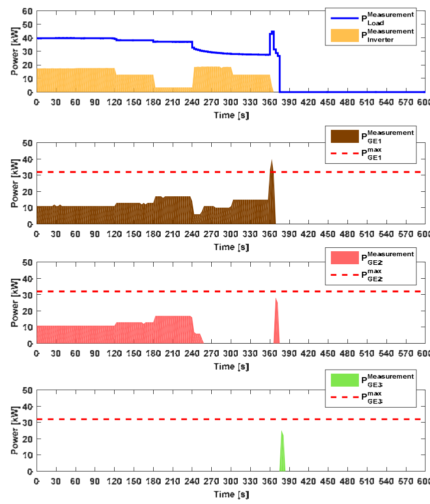

Figure 13 Power outage situation with S1 strategy

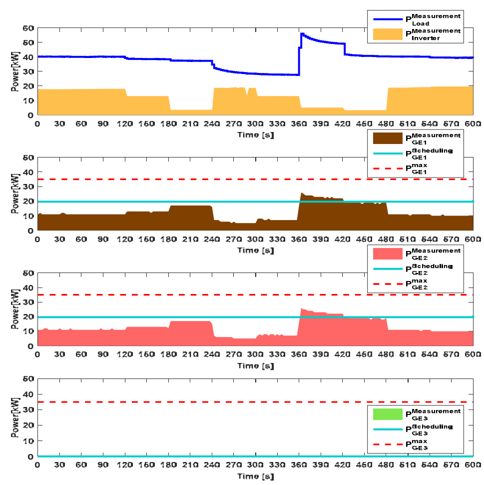

Figure 14 Power outage situation avoiding with S2 strategy

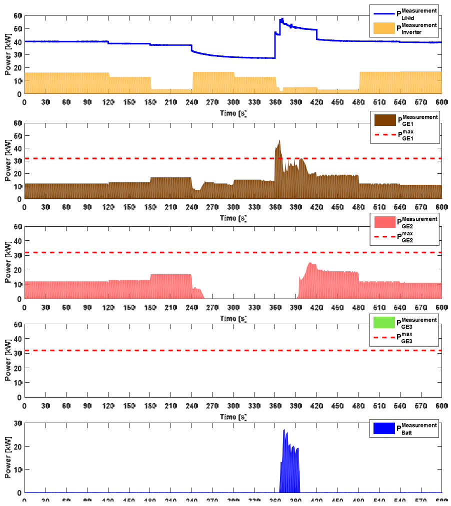

Figure 15 Power outage situation avoidng with storage integration

V. Conclusion

Control strategy plays an important role for optimizing the benefits of PV integration into a stand-alone system. In this work, PV-Diesel system operation has been evaluated with different control strategies and then with storage addition, through simulations and experiment test procedures. Results have highlighted the benefits of both approaches for the hybrid system stability: using advanced control based on PV short-terms forecast data and integrating storage system. Studies with two system sizes with various PV-rates and daily profiles are designed to consolidate the results. Experimental tests indicate those methods feasibility and validate the implementation of control algorithms into the system EMS of real PV-Diesel system. Although on-going investigation in PV forecast accuracy is expected to clarify better the gain of the advanced control approach, this is definitely an interesting alternative option to the use of storage system.

References

[1] F. Bourry; Advanced Simulation Platform for the Integration of Photovoltaics into Power Systems: SPIDER, PVSEC, Munich, 19-24 Jun

[2] 2016. Standard ISO-8528-1:2005

[3] Steadysun, Fiche Steady Eye, Online, Available: :http://steady-sun.com/wp-content/uploads//Fiche-SteadyEye-A4-EN-20160614.pdf

[4] T.-P. DO, F. BOURRY, and X. LE PIVERT, 2017 "Assessment of Storage and Photovoltaic Short-term Forecast Contribution to Off-grid Microgrid Operation," *Proceedings* IEEE PES ISGT Europe 2017,ID 1243.