IMPACTS OF THERMAL GENERATION FLEXIBILITY ON POWER QUALITY AND LCOE OF INDUSTRIAL OFF-GRID POWER PLANTS

Louis Polleux [1,2], John Sandoval-Moreno [3], Gilles Guerassimoff [1], Jean-Paul Marmorat[1]
1 Center for Applied Mathematics, Mines Paristech PSL, Sophia Antipolis, France
2 Transerval programs, TOTAL R&D France
3 Gas Renewable and Power R&D department, TOTAL, France

ABSTRACT

This study proposes a power quality analysis based on the frequency response of an isolated industrial hybrid power plant. The power system and its control strategy are modelled using MATLAB/SIMULINK and simulated using high resolution irradiance data. The results are used to validate a power quality criterion designed to size a hybrid PV-genset power plant. Finally, an economic analysis shows that neglecting the power quality issues at the sizing stage, it may lead to misjudging the plant's performance.

Keywords: Isolated Power System, Frequency Control, CO2 Mitigation, Techno-Economic Analysis

NONMENCLATURE

Abbreviations	
O&G	Oil and Gas
GHG	Greenhouse Gases
CAPEX	Capital Expenditure
EDDS	Expected duration of degraded supply
RE	Renewable Energy
LCOE	Levelized costs of electricity
LCCO2	Levelized costs of avoided CO2
PID	Proportional – integral – Derivative
PV	Photovoltaic
PM	Phase Margin
GM	Gain Margin
Symbols	
$Kp, T1, T2, T3$	PID controller constants
PV_t	Power of PV plant, time *t*
P_{gen_t}	Power of thermal generation, time *t*
P_{load_t}	Total load power
n	Number of thermal generators
r_{gen}	Ramp-up capacity of generators
$\sum$	Sum operator
$\frac{\Delta I}{T}$	Proportion of PV power drop within time interval T
Δf	Frequency deviation
Δf_{step}	Frequency deviation after step load
ΔP_{imb}	Power imbalance
M, D	Inertia and damping constants

1. INTRODUCTION

In 2017, the industrial sector accounted for 29% of global final energy and was responsible of 18% of global GHG (greenhouse gas) emissions [1]. This major challenge has led the Oil and Gas (O&G) sector to take action on energy efficiency and GHG reduction [2].

It has been recently highlighted that the electrification of industrial processes is one of the main levers for decarbonizing O&G activities [1]. As power generation is generally ensured by on-site thermal facilities, renewable energy (RE) integration is a promising lever to reduce emissions. However, the intermittency of RE poses a challenge to power quality and may jeopardize the power plant reliability.

Research on microgrids has not yet extensively investigated the design of large-scale insulated (off-grid) industrial micro-grids [3]. A typical characteristic of industry is the lack of load flexibility and storage potential due to safety and CAPEX reduction constraints. In addition, strict power quality specifications are imposed on frequency deviation: degraded operation occurs when frequency drops below -0.5% of its nominal value and the operator is forced to enhance load shedding at -3%.

The impact of intermittent resources has been one of the main concerns of stability studies of small isolated systems [4]. The lack of a constant mechanical inertia limits the penetration rate. A robust control strategy is also essential to manage the microgrid frequency response to load fluctuation [5], but appropriate equipment selection remains critical to ensure the system resiliency and quality of power supply.

Very few references draw a link between power quality and micro-grid sizing as proposed in [6]. Yet such a link can be very useful to micro-grid designers to realistically assess the renewable penetration.

This study intends to propose and test a novel and generic approach for determining the maximum amount of PV that a network is able to accept with regards to power quality specifications while accounting for thermal generation flexibility.

In this study, the time spent in transient frequency regime over one day is studied and measured by the Expected Duration of Degraded Supply (EDDS). This indicator is used, in this contribution to establish the power quality for the proposed use case.

2. MICROGRID MODELLING AND CONTROL

The case study proposed in this paper consists in a complete analysis of the hybridization for an off-grid facility located along a crude-oil pipeline (Figure 1). For this system, the oil is transported through the pipeline by means of flow-regulated pumps (14 MW of total load). A photovoltaic (PV) plant is considered to reduce the fuel consumption and therefore, the carbon footprint. The equivalent block diagram of the system in closed-loop is shown in Figure 2, whose blocks are going to be detailed in this section.

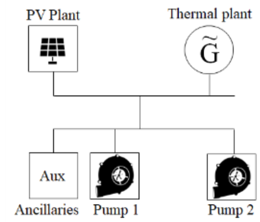

Fig 1 Power generation for a pumping station

For the sake of simplicity, and given the very high inertia of the processes, the overall electric load was considered constant.

2.1 Power generation

To ensure proper modelling of the crude-engine transient behavior, the engine and the electric generator need to be modelled separately. The diesel engine is also modeled in two separate blocks: the fuel injector system and the combustion process similarly to [7].

The engine selected for this study is a typical 5 MW internal combustion engine. Its ramp-up capacity is 1 %/s and its ramp-down capacity is 5 %/s. To account for the ramping capacity of the generator, a ramp limitation block has been implemented. Such constraint imposes a saturation of the power derivative (generator ramping) corresponding to its load acceptance and load rejection capacities (in %/sec).

The power system is modelled following the equation of motion [8], from which the frequency response resulting from a power imbalance is obtained. The power system characteristics can be reduced to an inertia M, which is calculated using the manufacturer's data, and a damping constant D assumed to be 0. The per-unit system is calculated with a 5 MW normalization value.

2.2 Control strategy

In the following sections, the frequency control adjusts the generator power, regarding exclusively the net load fluctuation that results from the uncontrolled PV power and constant load. In order to counter-balance

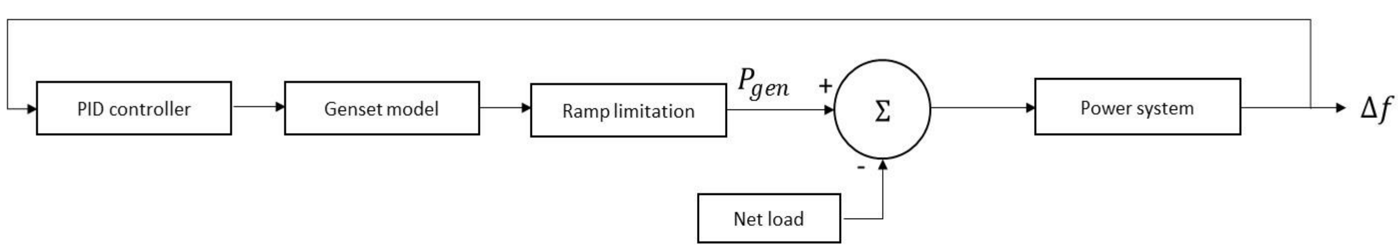

Fig 2 Final single engine control scheme

the effect of load fluctuation, a PID controller (Figure 3) for frequency regulation proposes was implemented. Initially, it was tested a proposition for this controller introduced in [7], However, its performance was not suitable for this case study, specially while assuring the stability over strong load perturbations. It was therefore proposed the PID structure of Figure 3.

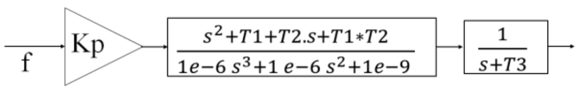

Fig 3 PID controller block diagram

To ensure stable, proper power compensation, a step and margin analysis was performed using Matlab's SISOTOOL and following the procedure detailed in [9], choosing a Phase Margin (PM) above 45º and a Gain Margin (GM) over 6 dB.

With an iterative approach, the controller has been designed to reduce the infinite error. Values of 0.125, 0.250 and 50 were found for T1, T2 and T3 respectively whilst the proportional gain was set at 32.

2.3 PV production scenario

The production of a PV power plant with one-second time-step irradiance data was used for the simulation [10]. After a variability analysis, July 8th was considered as the worst-case irradiance scenario. The power production was calculated from GHI (Global horizontal Irradiance) at 3 different stations to smooth-out the single sensor variability.

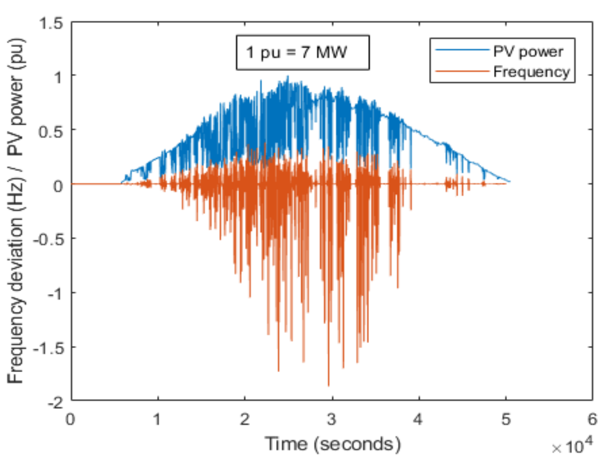

Fig 4 Frequency deviation against PV production for a 4 genset / 10MW PV power plant

2.4 Results

The frequency deviation calculated over the entire selected day is plotted against PV production in Figure 4. The time spent in transient regime (EDDS) was monitored during the simulations of several installed PV capacities and a number of gensets under the irradiance of July 8th. Each dot on Figure 5 corresponds to one simulation and requires 1 hour of processing with an intel Core i5 8th gen.

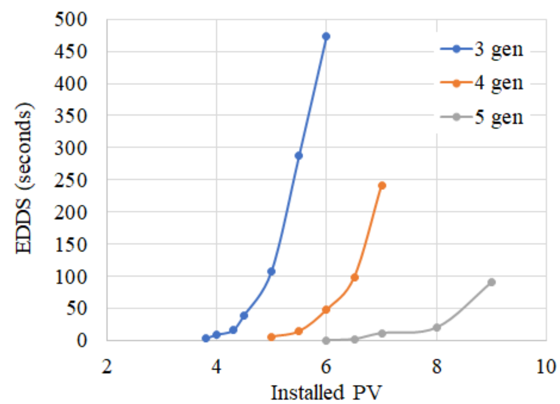

Fig 5 EDDS of several plant configuration

3. DEFINITION OF A STABILITY CRITERION FOR MICROGRID MODELING

The stability criterion proposed in this study was defined according to the genset ramp-up capacities for compensating a PV power drop. This ensures a proper frequency response from the system without needs for analyzing short-period transients. In this part, power quality results simulation are used to set a conservative PV-drop value and make it possible to calibrate the stability criterion for future use in feasibility studies. This can be written as follows for instants t and $t+1$:

$$PV_t + \mathrm{P}_{\mathrm{gen}_t} \geq \mathrm{P}_{load_t} \qquad (1)$$

As the PV is supposed to gradually decrease between *t* and *t+1*, the PV and genset output power can be re-written as:

$$PV_t(1-\Delta I) + \mathrm{P}_{gen_t} + n * r_{gen} * T \geq P_{load_t} \qquad (2)$$

As the load is taken to be constant during the PV drop, we can obtain the maximum PV capacity that satisfies the previous equation by subtracting (1) and (2):

$$PV_t \leq \frac{n * r_{gen} * T}{\Delta I} \quad (3)$$

Where:

- $PV_t, P_{gen_t}, and\ P_{load_t}$ are the rated power of the PV plant, the genset plant and the load
- n and r_{gen} are the number of gensets and their ramp-up capacity in kW/s
- ΔI and T denotes the proportion of irradiance drop ΔI (%) during the time-interval T (s)

Since no methodology was found to assess $\frac{\Delta I}{T}$, an iterative approach was chosen in order to match the maximum PV achievable power with the PV power that gives optimal power quality (EDDS =0) with the simulator.

As shown in Table 1, irradiance drops of $\frac{\Delta I}{T} = 4.2\ \%/s$ show good compliance with the simulator results. According to equation (3), this means that any PV ramp, regardless of its duration, is acceptable provided that its gradient remains below 4.2 %/sec.

In order to enforce these criteria, the maximum PV step-down that can be applied through a calculation of the frequency response using the equation of motion [8, p. 625] is as follows:

$$\Delta f_{step} = -\frac{\Delta P_{imb}}{P_{load}}\left(1 - e^{-\frac{t}{T}}\right) * K \quad (4)$$

With= $\frac{1}{D}$, $= \frac{M}{D}$; $P_{load} = 14\ MW$

The indicator is used to calculate the maximum PV drop so that the response at t=1s remains above -0.250 Hz. Results are shown in Table 1.

Number of genset	**3**	**4**	**5**
EDDS=0	3700 kW	4800 kW	5900 kW
Stability criterion	3571 kW	4761 kW	5952 kW
$\Delta\ PV_{max}$ **(step)**	322 kW	429 kW	535 kW

Table 1 Comparison of maximum achievable PV power

Figure 6 shows that the maximum PV step-down presented in Table 1 (9.5%) is greater than the acceptable PV ramp-down given by $\frac{\Delta I}{T}$ (4.2 %/s). Following the sizing rule (3) with a solar variability of 4.2%/sec, the system is either resilient to a PV ramp-down of 42% over 10 seconds or to a sudden PV drop of 9.5%. This enables us to conclude that the sizing rule is conservative enough to assess the acceptable PV capacity to be installed.

4. INTEGRATION INTO ECONOMIC ANALYSIS

4.1 Economic and CO_2 abatement performance assessment

At the sizing step, installed PV capacity is driven by an economic analysis of its performance over a finite lifetime (20 years for example) as performed in [11]. In this section, the plant's LCOE and CO_2 abatement costs

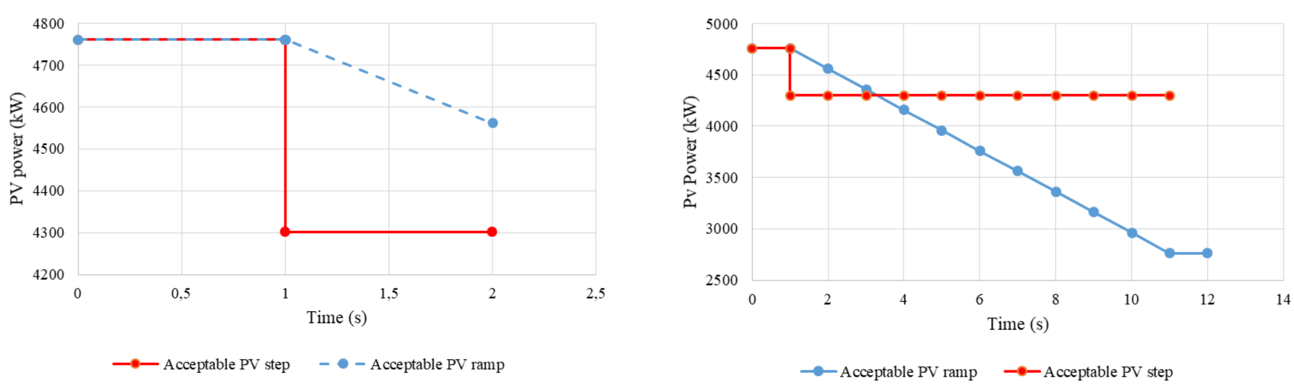

Figure 6 Example of acceptable PV drop & ramp over 1 sec (left) and over 10 sec (right) for 4 generators

PV capacity (kW)	0	3000		5000		7000	
Stability limit applied	-	Yes	No	Yes	No	Yes	No
LCOE ($/kWh)	66.1	66.6	66.6	67	67	68	67.3
CO_2 abatement	0%	4.2%	4.2%	6.9%	6.9%	8.6%	9.7%
LCCO2 ($/t$CO_2$)	-	58.5	58.5	59.4	58.5	74.58	58.5

Table 2 Example of acceptable PV drop & ramp over 1 sec (left) and over 10 sec (right) for 4 generators

(LCCO2) are calculated to evaluate the economic viability of the hybrid power plant. The stability criteria detailed above are integrated into the economic evaluation to account for the operator's maximum acceptable PV capacity (3750 kW in this case study).

The PV stability limitation is integrated so that PV capacity shortage is applied as soon as the PV production exceeds the limit. In this part, no high-resolution time-series are needed since the stability limitation accounts for the short-term dynamics. The PV production allowed is evaluated using the annual solar energy available on site given by HOMER's hourly irradiance data [11].

One specificity of upstream O&G projects is the very low value of fuel costs, since the oil used to power the engine has not reached the delivery point. As a result, the fuel cost is much lower than the market price ($30/barrel in this study).

4.2 Results & discussion

The stability limit does not impact the LCOE for a 3000 kW PV plant. However, the LCOE increases for 5000 kW and 7000 kW PV power plants, as the amount of curtailed electricity rises.

Table 2 shows that hybrid solutions are found to be more expensive than fully thermal power plants (lowest LCOE). The only benefit of such a project would therefore be to reach CO_2 reduction targets. The CO_2 abatement costs are similar for all PV capacities when no stability limitation is considered as the amount of CO_2 avoided is proportional to the solar production. However, the cost of reducing more than 7% of the total CO_2 production is significantly increased when the stability is considered. Finally, it can be concluded that a carbon tax of $60 /t$CO_2$ would allow a reduction of up to 7% of CO_2 emissions while ensuring the financial balance.

However, while $60/t$CO_2$ seems to be sufficient to reduce 9.7 % of the CO_2 (with 7000 kW PV), the re-evaluation using stability criteria showed that a carbon price of $75/t$CO_2$ would be required to ensure the financial balance.

5. CONCLUSION

In this study, a basic modelling of a thermal generator was used to simulate the power quality of a hybrid power generation unit for a pumping station. Simulations were carried out for several plant architectures and enabled us to design and calibrate a sizing criterion for PV generation depending on the generator's flexibility and the variability of the irradiance. This criterion was enforced using frequency deviation calculation.

The plant performance was then calculated considering economics and CO_2 reductions. For this calculation, a capacity shortage was applied when the PV power exceeded the stability limitation. The results showed that the performance can be over-estimated when no stability limitation is set. This enabled us to re-evaluate LCOE and CO_2 abatement costs.

This study aimed to show the scientific community the interest of considering short-term dynamics, such as power quality, at the early design stages of an industrial power system. Finally, it could provide some guarantees to operators given that reliability constraints are among the main challenges facing industrial hybrid power plants.

REFERENCES

[1] IEA, *World Energy Outlook 2018*. IEA Publications, 2018.
[2] R. Davies, "A report from the Oil and Gas Climate Initiative September 2018," p. 60.
[3] G. Guerassimoff, *Microgrids: pourquoi, pour qui?* Presses de Mines, 2017.
[4] K. M. Banjar-Nahor, L. Garbuio, V. Debusschere, N. Hadjsaid, T.-T.-H. Pham, and N. Sinisuka, "Study on

Renewable Penetration Limits in a Typical Indonesian Islanded Microgrid Considering the Impact of Variable Renewables Integration and the Empowering Flexibility on Grid Stability," in *2018 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, Sarajevo, Bosnia and Herzegovina, 2018, pp. 1–6.

[5] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. de Vicuna, and M. Castilla, "Hierarchical Control of Droop-Controlled AC and DC Microgrids—A General Approach Toward Standardization," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 158–172, Jan. 2011.

[6] Q. Fu *et al.*, "Microgrid Generation Capacity Design With Renewables and Energy Storage Addressing Power Quality and Surety," *IEEE Transactions on Smart Grid*, vol. 3, no. 4, pp. 2019–2027, Dec. 2012.

[7] M. Datta, T. Senjyu, A. Yona, T. Funabashi, and Chul-Hwan Kim, "A Coordinated Control Method for Leveling PV Output Power Fluctuations of PV–Diesel Hybrid Systems Connected to Isolated Power Utility," *IEEE Transactions on Energy Conversion*, vol. 24, no. 1, pp. 153–162, Mar. 2009.

[8] P. S. Kundur, *Power system stability and control*. Mc Graw Hill Education (India) Private Limited, 1994.

[9] G. F. Franklin, J. D. Powell, A. Emami-Naeini, and H. S. Sanjay, *Feedback control of dynamic systems*, 7. ed., Global ed. Boston, Mass.: Pearson, 2015.

[10] M. Sengupta and A. Andreas, "Oahu Solar Measurement Grid (1-Year Archive): 1-Second Solar Irradiance; Oahu, Hawaii (Data). Available : https://midcdmz.nrel.gov/apps/rawdata.pl?site=oahugrid;data=Oahu_GHI;type=zipdata. [Accessed: 21-jun-2019]

[11] "HOMER - Hybrid Renewable and Distributed Generation System Design Software." [Online]. Available: https://www.homerenergy.com/. [Accessed: 19-Mar-2019].