MODELING AND SIZING OF LARGE PV-DIESEL HYBRID SYSTEMS WITHOUT ENERGY STORAGE

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ABSTRACT: This paper describes the modelling of components and control strategies for PV-diesel hybrid systems without energy storage, which have been implemented in an online and free-software simulator of PV systems called SISIFO, which is publicly available at www.sisifo.info. Among other features, this software tool allows the prediction of fuel savings for different sizes and types of PV generators, the comparison of selected control strategies and the evaluation of the spinning reserve requirements in systems with multiple diesel generators operating in parallel.
Keywords: PV System, Hybrid, Software, Modelling, Simulation

1 INTRODUCTION

The reduction of cost for PV modules caused by the massive installation of grid-connected systems has increased the economic competitiveness of conventional decentralised PV applications. In particular, there is a renewed interest in PV-diesel hybrid systems, which are the object of this paper, and water pumping systems, which are discussed in a concurrent paper of this conference [1].

Today, largest energy systems for remote village electrification and industrial loads typically rely on conventional diesel generator sets (gensets) sized in the MW range. The addition of PV generators to these stand-alone gensets allows the reduction of fuel consumption and the improvement of genset operation, efficiency and reliability of the electricity service.

There are different configurations for coupling PV and diesel gensets [2]. The most common solution includes energy storage, normally a battery bank, which can be used for different purposes. For example, storing the surplus of PV power or adding its power to that of the gensets for meeting peak load demands, which may increase the potential for fuel saving.

Nevertheless, the inclusion of batteries also increases the cost of the hybrid system and the complexity of control schemes. For these reasons, some authors have presented experimental and economical studies of hybrid systems without energy storage for rural village electrification [3][4]. The simplicity of systems without storage and the reduced investment, operation and maintenance costs are advantages when the retrofitting of already existing diesel systems is concerned. In particular, for remote industrial applications in which the load is nearly constant or peak load demand occurs during daylight hours.

This paper describes the modelling of components and control strategies for PV-diesel hybrid systems without energy storage, which have been integrated in an online and free-software simulator of PV systems called SISIFO (available at www.sisifo.info).

This simulation tool allows the prediction for fuel savings as function of PV size and type, which is required to asses if the hybrid system is cost-effective, i.e., if fuel saving at least compensates initial investment, operation and maintenance costs. Besides, the tool allows the comparison of selected control strategies in terms of their energy performance and the evaluation of the spinning reserve. Simulations are performed in steady-state conditions, which assume that any system variable is constant during each time step, which may be varied from minutes to hours.

The presentation of this paper has been organised with the following structure. Section 2 describes the modeling of system components, focusing in diesel gensets. Section 3 describes the implemented control strategies for a single genset and multiple gensets operating in parallel. Finally, Section 4 presents a simulation example for a real case of study.

2 HYBRID SYSTEM MODELING

The configuration of the simulated PV-diesel hybrid system without energy storage is displayed in Figure 1. The diesel genset may be composed by a single or multiple units (up to N in the figure), which create the low-voltage AC grid that supplies the load. To this grid, PV generators are connected in parallel through standard DC/AC converters, or inverters, designed for conventional grid-connected PV applications.

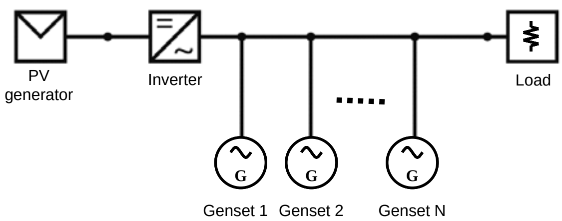

Figure 1: Configuration of a PV-diesel hybrid system without energy storage.

The detailed modeling of the grid-connected PV system is beyond the scope of this paper, but is described elsewhere by the authors [5][6], where the interested reader is referred. It is just worth mentioning that SISIFO allows the simulation of three static and six sun-tracking PV generators. For example, static ground-mounted or building-integrated PV generators in roofs or façades, and one-axis horizontal or two-axes sun-trackers. Sun-trackers generate more energy at higher equipment cost and some of them may be cost-effective in particular energy scenarios at present PV modules prices.

We focus here on the modeling and characterisation of gensets and load profiles. For simplicity, it is assumed that all gensets of the hybrid system are identical. Each genset is composed by an engine, or motor, and an alternating current generator, or alternator, which are modelled as follows.

2.1 Engine model

Modeling of engines, as well other system components, is based on information provided by manufacturers in their datasheets.

Fuel consumption is calculated from the Brake Fuel Specific Consumption (*BFSC*), which indicates the amount of fuel consumed by the engine per unit of energy as a function of the brake output power. The *BSFC* is given in [gr/kWh], or [l/kWh], and it is normally provided by the manufacturer by means of figures or tables (see Figure 2). Normally, *BFSC* increases at low brake power levels. Hence, as the available PV power increases, the brake power of the engine decreases but at a higher *BSFC*, i.e., engines consume less fuel but they are some less efficient.

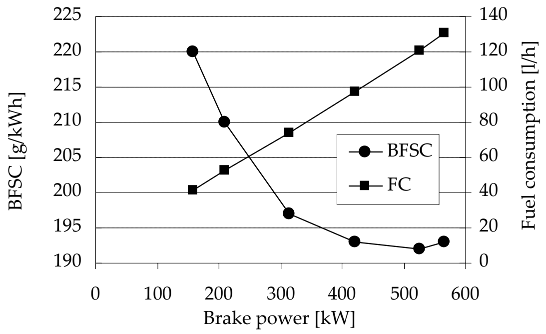

Figure 2: Variation of the the Brake Fuel Specific Consumption (*BFSC*) and fuel consumption (*FC*) as a function of the brake output power of a rated 575kW, constant speed, commercial engine.

Fuel consumption is calculated as the product of *BSFC* and brake power, P_B, whose result is a quasi-linear relation (see Figure 2) that can be approximated by Skarstein and Uhlen model [7]:

$$FC = a \cdot P_B^2 + b \cdot P_B + c \cdot P_{BR} \quad (1)$$

Where *FC* is the fuel consumption, in [l/h], P_{BR} is the rated brake power, in [kW], and *a*, *b* and *c* are constants to be fitted for each particular engine. The quadratic term for P_B was not in the original model and has been added to improve the fitting of fuel consumption for variable speed diesel gensets [8].

In the example of Figure 2, the rated brake power is P_{BR}=575kW and fuel consumption may be fitted with Equation 1 to obtain: *a*=0, *b*=0,217 l/kWh, *c*=0,012 l/kWh and R^2=0,9995. Also from Figure 2, it can be observed that the fuel consumption is not zero at the origin, i.e., with the engine operating at no load. For the previous example, this no-load fuel consumption is 6,9 l/h.

2.2 Alternator model

The alternator is characterized by its rated output power (P_{AR}) and three experimental parameters (k_0, k_1 and k_2), which are used to calculate the power conversion efficiency, η_A, by means the following equation:

$$\eta_A = \frac{P_0}{P_B} = \frac{p_0}{p_0 + (k_0 + k_1 p_0 + k_2 p_0^2)} \quad (2)$$

Where $p_0 = P_0/P_{AR}$ being P_0 the output AC power of the alternator and P_B the brake engine power. Parameters k_0, k_1 and k_2 are fitted from the power efficiency curve provided by the manufacturer.

Starting from output alternator power, P_0, the program calculates the brake power, which, together *BSFC*, allows the calculation of the instantaneous fuel consumption using Equation 1.

2.3 Power rating

The power rating of the genset is indicated by the prime power (*PRP*), which is defined as the maximum output power that can deliver to a variable load and for an unlimited number of hours [9]. Besides this rated power, two other parameters, overload and minimum powers, are required as input data.

Overload, or maximum power, P_{MAX}, indicates the engine capacity to exceed the prime power, usually expressed as percentage of the latter and together with the overload duration. For example, a 110% of the prime power for a period of 1h is usually stated [10]. For some gensets, this overload power is only used for control purposes and the maximum power is limited to the *PRP*. In these cases, manufacturers discourage to use this overload capacity to supply the load and simulations should be performed with P_{MAX} =*PRP*.

Finally, for efficiency and reliability reasons, the engine should operate over the minimum power, P_{MIN}, which typically ranges 30-40% of rated capacity. Operating the engine below this level not only decreases the conversion efficiency, but also this may short the engine's lifetime and increase maintenance costs.

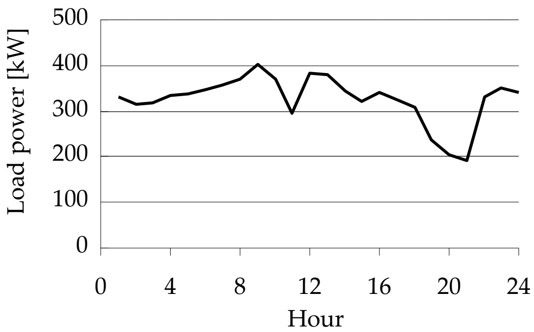

Figure 3: Example of a real load profile from a remote petrol exploitation field.

2.4 Load profile

The load profile may be specified by a times series of power consumption, with any time step, during the period of analysis (typically a year). It is worth mentioning that, despite time step can be varied from seconds to hours, simulations are performed assuming steady-state conditions, in which the above described models can be used.

If a yearly time series of load demand is not available, which is usually the case, the user may specify either a daily load profile that repeats everyday or the simplest case of constant power consumption. Figure 3 shows an example a real load profile from a petrol exploitation field, which will be used for the simulation example described in Section 4.

Since the hybrid systems discussed here have not energy storage, PV power is directly used to supply the load during sunshine hours. Hence, the matching between load consumption and solar generation profiles has a great impact on fuel savings. For example, PV power should be sometimes limited to avoid the operation of diesel gensets below their minimum power.

3 CONTROL STRATEGIES

The design of the hybrid system requires the selection of a control strategy to guarantee the reliability and quality of the electricity service, minimizing the fuel consumption and maximizing the lifetime of system components.

SISIFO includes typical control strategies for regulating the contribution of PV power to the hybrid system, which are described in this section. But, before introducing them, let us describe the implemented control when only the gensets are in operation. SISIFO offers the simulation of systems composed of a single genset and also multiple gensets operating in parallel.

Table I summarises previously defined symbols and other introduced below, which are intensively used hereinafter in discussion.

Table I: Summary of symbols.

Symbol	*Definition*
N_{GEN}	Required number of gensets in operation
$N_{GEN.\ total}$	Total number of gensets in the system
P_L	Load power
P_{MAX}	Maximum genset power
P_{MIN}	Minimum genset power
P_{NET}	Net load (P_L- P_{PV})
P_{OPT}	Optimal genset power
P_{PV}	PV power
$P_{PV,STC}$	Nominal PV power
PRP	Prime power

3.1 Diesel only (single genset)

The single genset is sized to match the peak load demand and it is permitted to operate from P_{MIN} to P_{MAX}. The value for P_{MIN} may be selected within a range of 0% to 50% of *PRP*.

If P_{MIN} is non-zero and the load power is lower than this minimum, some corrective actions should be applied following the recommendations of genset manufacturer. Unless otherwise stated, the actions considered in the simulation tool are either permitting genset operation below P_{MIN} or connecting a dump load to ensure the genset operates at P_{MIN}. Hence, a variable dump power equal to (P_{MIN}-P_L) is connected whenever $P_L < P_{MIN}$.

3.2 Diesel only (multiple gensets)

The operation of multiple gensets in parallel are controlled using two common strategies called here "ON/OFF" and "Optimal". Both strategies allow the disconnection/reconnection of individual gensets to meet the load demand and taking into consideration the required spinning reserve.

The spinning reserve, which is specified as a percentage of the present load demand, indicates the surplus of power that could be supplied immediately by the gensets in case of a sudden increase of load demand. This way, the disconnection of gensets is only permitted if the aggregated rated power of those that remain in operation is equal of higher than the required spinning reserve.

In the ON/OFF strategy, the gensets in operation share the same portion of the load. The system controller starts/stops the gensets when the load power crosses a certain percentage point of the total rated power, which is usually called "set-point".

The number of set-points is equal to the number of gensets in the system less one. For example, for a system with two gensets there is only a set-point at 50%. For three gensets, two set-points at 33% (1/3) and 67% (2/3) etc, and so on.

The starting/stopping of gensets are not performed exactly at set-points but within a hysteresis band around them. Figure 4 displays and example of system operation for three gensets with ON/OFF control and hysteresis band.

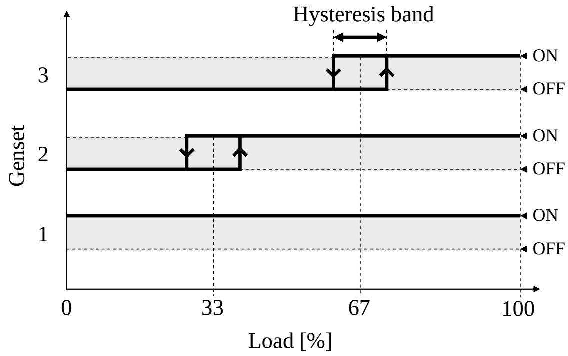

Figure 4: Operation of a system with three gensets with ON/OFF control as a function of load demand. It is assumed that the disconnection of any genset guarantees the spinning reserve.

The Optimal strategy tries to ensure that all the gensets, with the exception of one, operate at much as possible at their optimum power operating point, P_{OPT}, where the fuel consumption is minimal. This optimal point is around 80% of the rated power but any valued can be chosen. The optimal control algorithm has the following steps:

1. The first calculation is to determine the required number of gensets in operation, N_{GEN}, which is equal to:

$$N_{GEN} = Ceiling\,(P_L / P_{OPT}) \qquad (3)$$

2. If only one genset is required in operation (N_{GEN}=1 or $P_L \leq P_{OPT}$), its operation is that described in section 3.1.

3. If several gensets are required in operation (N_{GEN}>1), there are two possible cases:

Case 3-a: $P_{OPT} < P_L \leq N_{GEN,total} P_{OPT}$

In this case (N_{GEN}-1) gensets may operate at P_{OPT}, and one unbalanced genset operates at P_L-$P_{OPT}(N_{GEN}$-$1)$.

Case 3-b: $N_{GEN,total} P_{OPT} < P_L \leq N_{GEN,total} P_{MAX}$

The load power is higher that the addition of optimal powers but lower than the maximum power of the system. Here, we can distinguish two sub-cases.

First, if the surplus (P_L-$P_{OPT}N_{GEN,total}$) does not exceed the maximum power of a single genset, ($N_{GEN,total}$-1) gensets may still operate at P_{OPT}, and the unbalanced genset at P_L-$P_{OPT}(N_{GEN}$-$1)$, which is within its range from P_{OPT} to P_{MAX}.

Second, if the unbalanced genset reaches its maximum power, P_{MAX}, and the load increases in this situation, the balanced gensets must increase its power over P_{OPT} and sharing the same power, which is equal to $(P_L$-$P_{MAX})/(N_{GEN}$-$1)$.

3.3 Diesel (single genset) plus PV

The diesel generator must supply the net load, which is defined as the difference between the load demand and the generated PV power:

$$P_{NET} = P_L - P_{PV} \quad (4)$$

Obviously, the generated PV power reduces the fuel consumption and the power levels at which the genset operates. Here, we can distinguish two cases depending on the load demand. First, if P_L is lower than P_{MIN}, the PV power is cut-off to avoid genset operation below this minimum. Second, if P_L is higher than P_{MIN} the previous equation applies provided that $P_{NET} \geq P_{MIN}$. If $P_{NET} < P_{MIN}$, the PV power is reduced to ensure that at least $P_{NET}=P_{MIN}$ to avoid genset operation below this minimum.

3.4 Diesel (multiple gensets) plus PV

The gensets share the net load, P_{NET}, as described in section 3.2 substituting P_L by P_{NET}. Besides, if the generated PV power, P_{PV}, cause a genset operation below P_{MIN} the PV power is limited to ensure that such genset operates with a minimum power equal to P_{MIN}.

4 SIMULATION EXAMPLE

This section presents a simulation example of a real industrial application powered at present by a single diesel genset. Genset characteristics and load demand are summarised in Table II. Daily load demand is displayed in Figure 3, where the peak load is 402kW, the average value is 327kW, and the minimum load is 193kW. The integration of this profile gives a daily energy consumption of 7840kW. In yearly figures, this gives an electricity consumption of 2861MWh that requires a around 705m^3 of diesel. Figure 5 shows the Sankey diagram for a yearly period, which includes the previous figures together with the brake energy (2995MWh) and alternator losses (4,5%).

Table II: Characteristics of a real application powered by a single diesel genset.

System characteristic	***Value***
Engine rated power	P_{BR}*=575kW*
Fuel consumption	See Figure 2.
Alternator	P_{AR} *=525kW* k_0*=0,02;* k_1*=1e-4;* k_2*=0,023*
Prime power	*PRP=525kW*
Daily load consumption	7840 kWh (see Figure 3).

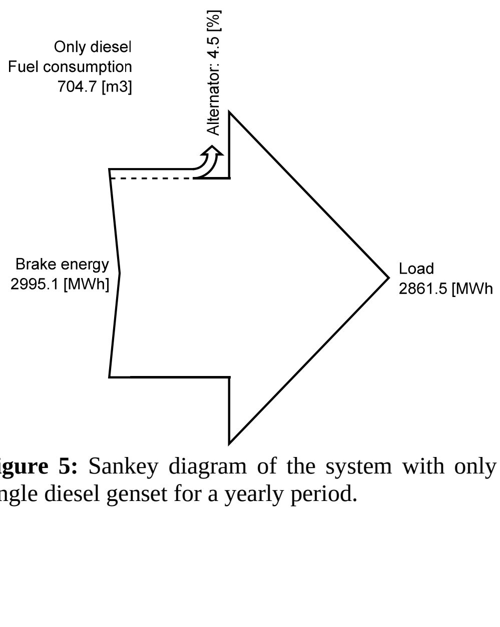

Figure 5: Sankey diagram of the system with only a single diesel genset for a yearly period.

This section illustrates the simpler application of the simulation tool, which is the estimation of fuel savings as a function of the PV power penetration level. The operation of the system is described in section 3.3 considering that P_{MIN} may vary from 0% to 30% of the rated power.

For simplicity, a ground-mounted static PV generator tilted the latitude has been considered, whose nominal power under Standard Test Conditions (STC), $P_{PV,STC}$, may vary from 100kW to 500kW. The nominal power of the inverter has been assumed to be equal to $P_{PV,STC}$.

Figure 6 shows the variation of fuel saving as a function of $P_{PV,STC}$ for different values of P_{MIN}. It can be observed that for P_{MIN}=0% fuel saving increases nearly linear with the PV power in the simulated range. And also that, for a non-zero P_{MIN}, fuel savings deviate towards to the horizontal from a given PV power, which limits the PV penetration level. For example, at P_{MIN} =30%, the fuel saving increases linearly with PV power up to around 200kW. Beyond this point, the extra power capacity has a lower impact on the increase of fuel savings.

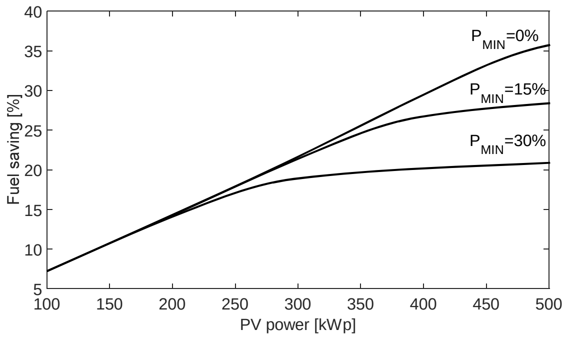

Figure 5: Yearly fuel savings as a function of the installed PV power, $P_{PV,STC}$, using the minimum genset power, P_{MIN}, as parameter.

Besides, the simulator allows a detailed analysis of the hybrid system behaviour. For example, Figure 6 shows the yearly Sankey diagram ($P_{PV,STC}$ =300kW and P_{MIN}=30%) and Figure 7, the diurnal variation of PV, diesel and load powers, during a summer day.

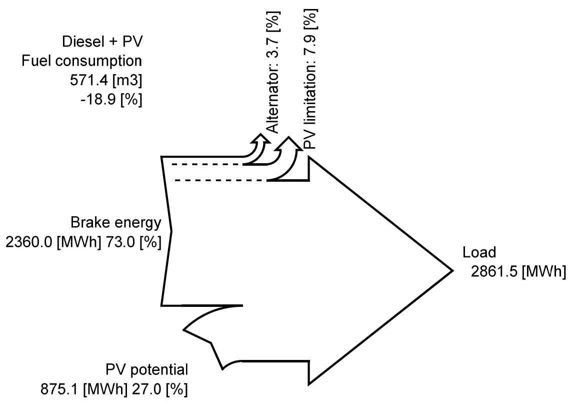

Figure 6: Sankey diagram of the hybrid system, with $P_{PV,STC}$ =300kW and P_{MIN}=30% , for a yearly period.

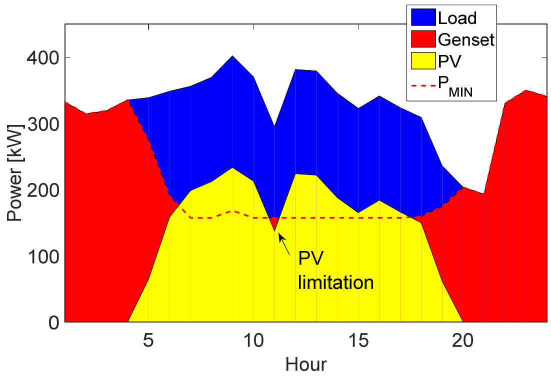

Figure 7: Diurnal variation of PV, diesel and load powers, during a summer day ($P_{PV,STC}$ =300kW and P_{MIN}=30%).

4 CONCLUSIONS

This paper has presented the modelling of components and control strategies for PV-diesel hybrid systems without energy storage, which have been implemented in SISIFO, an online and free-software simulator of PV systems that is publicly available at www.sisifo.info.

Besides, a simulation example of real case study is described, which illustrates some of the capacities of this simulation tool.

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REFERENCES

[1] J. Muñoz, J.M. Carrillo, F. Martínez-Moreno, L.M. Carrasco, L. Narvarte. Modeling and simulation of large PV pumping systems. EU PVSEC 2015, Hamburg.

[2] Wichert, B. PV-Diesel Hybrid Energy Systems for Remote Area Power Generation — A Review of Current Practice and Future Developments. Renewable and Sustainable Energy Reviews 1, no. 3 (September 1997): 209–28. doi:10.1016/S1364-0321(97)00006-3.

[3] Lundsager, Per, and Henrik Bindner. A Simple, Robust & Reliable Wind Diesel Concept for Remote Power Supply. Renewable Energy 5, no. 1–4 1994): 626–30. doi:10.1016/0960-1481(94)90443-X.

[4] Yamegueu, D., Y. Azoumah, X. Py, and N. Zongo. Experimental Study of Electricity Generation by Solar PV/diesel Hybrid Systems without Battery Storage for off-Grid Areas. Renewable Energy 36, no. 6 (June 2011): 1780–87. doi:10.1016/j.renene.2010.11.011.

[5] Muñoz, J., Marroyo, L., Collares-Pereira, M., Tyutyuyndzhiev, N., Conlon, M., Elmoussaoui, A., and Wilkin, B. An Open-Source Simulation Tool of Grid-Connected PV Systems. 28th European Photovoltaic Solar Energy Conference and Exhibition, 2013, 3882–87. doi:10.4229/28thEUPVSEC2013-5BV.4.18.

[6] J. Muñoz et al. SISIFO: An online simulator of PV systems. Technical Reference Manual v1.0. Available at: www.sisifo.info

[7] Skarstein O. Uhlen K. Design considerations with respect to long-term diesel saving in wind/diesel plants. Wind Engineering 13, Nº 2, 1989, 76-87.

[8] Lim, P. Y., and C. V. Nayar. Modeling and Simulation of Photovoltaic-Variable Speed Diesel Generator Hybrid Power System for Off-Grid Rural Electrification. International Journal of Energy Science, February 16, 2012. http://dpi-journals.com/index.php/IJES/article/view/260.

[9] ISO 8528-1:2005. Reciprocating internal combustion engine driven alternating current generating sets. Part 1: Application, ratings and performance.

[10] ISO 3046-1:2002. Reciprocating internal combustion engines. Performance. Part 1: Declarations of power, fuel and lubricating oil consumptions, and test methods. Additional requirements for engines for general use.

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ABSTRACT

This paper describes the modelling of components and control strategies for PV-diesel hybrid systems without energy storage, which have been implemented in an online and free-software simulator of PV systems called SISIFO (www.sisifo.info). Among other features, this software tool allows the prediction of fuel savings for different sizes and types of PV generators, the comparison of selected control strategies and the impact of the spinning reserve when multiple diesel generators are operating in parallel.

MODELLING

ENGINE CHARACTERISTICS:

- Prime, maximum and minimum powers.
- Brake Fuel Specific Consumption (BFSC).
- Single or multiengine systems.

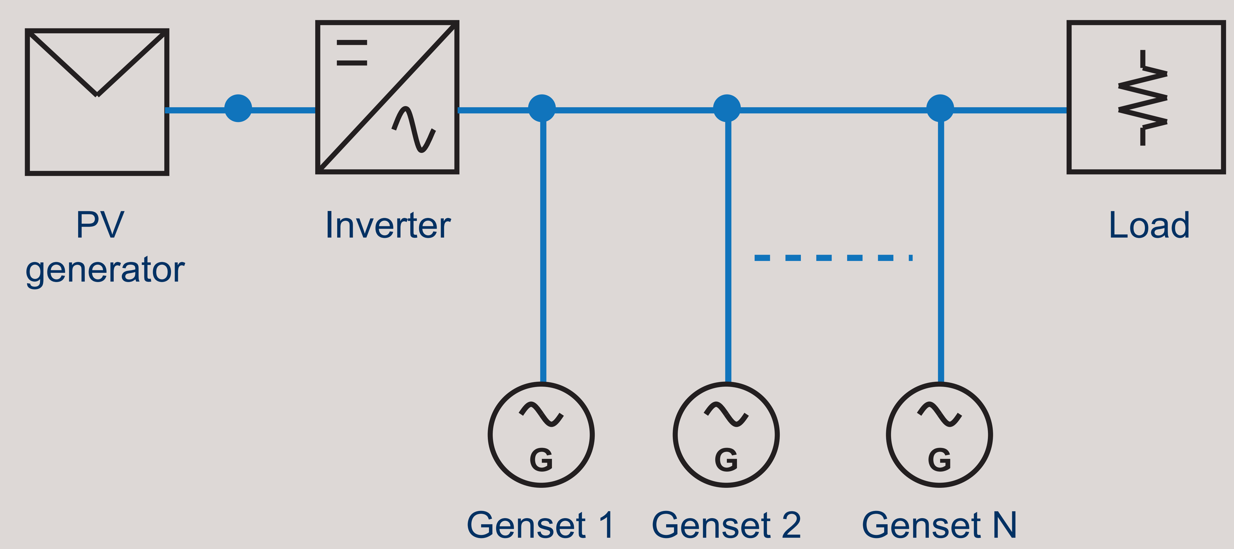
MULTIENGINE CONTROL:

- Implemented strategies:
  - _ ON-OFF with hysteresis band and equal load sharing.
  - _ Optimum operation with unequal load sharing.
- Spinning reserve.

ALTERNATOR: power efficiency curve.

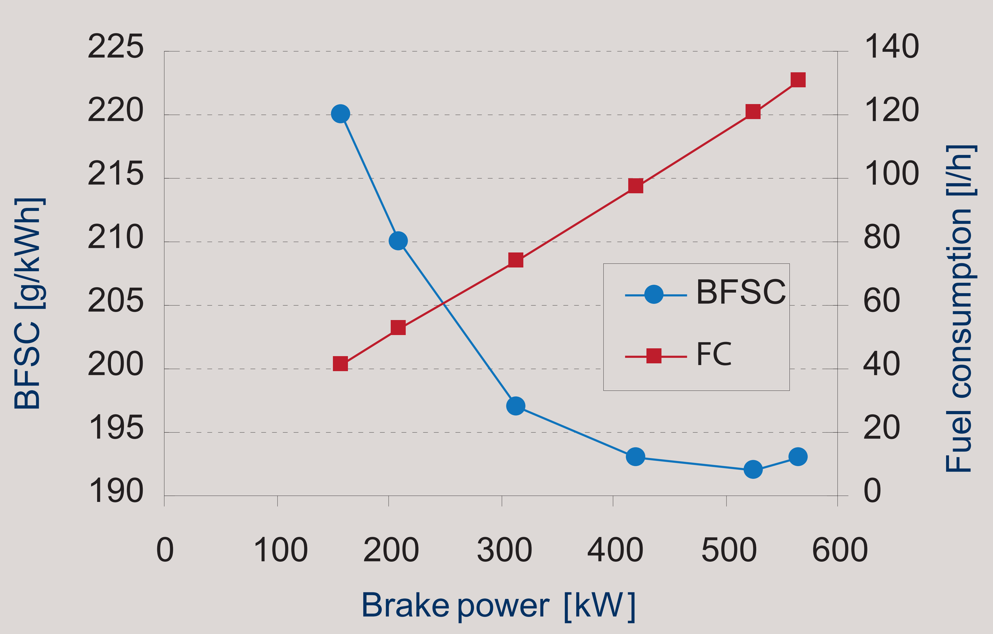
CONSTANT OR VARIABLE LOAD PROFILES

Configuration of a PV-diesel hybrid system without energy storage



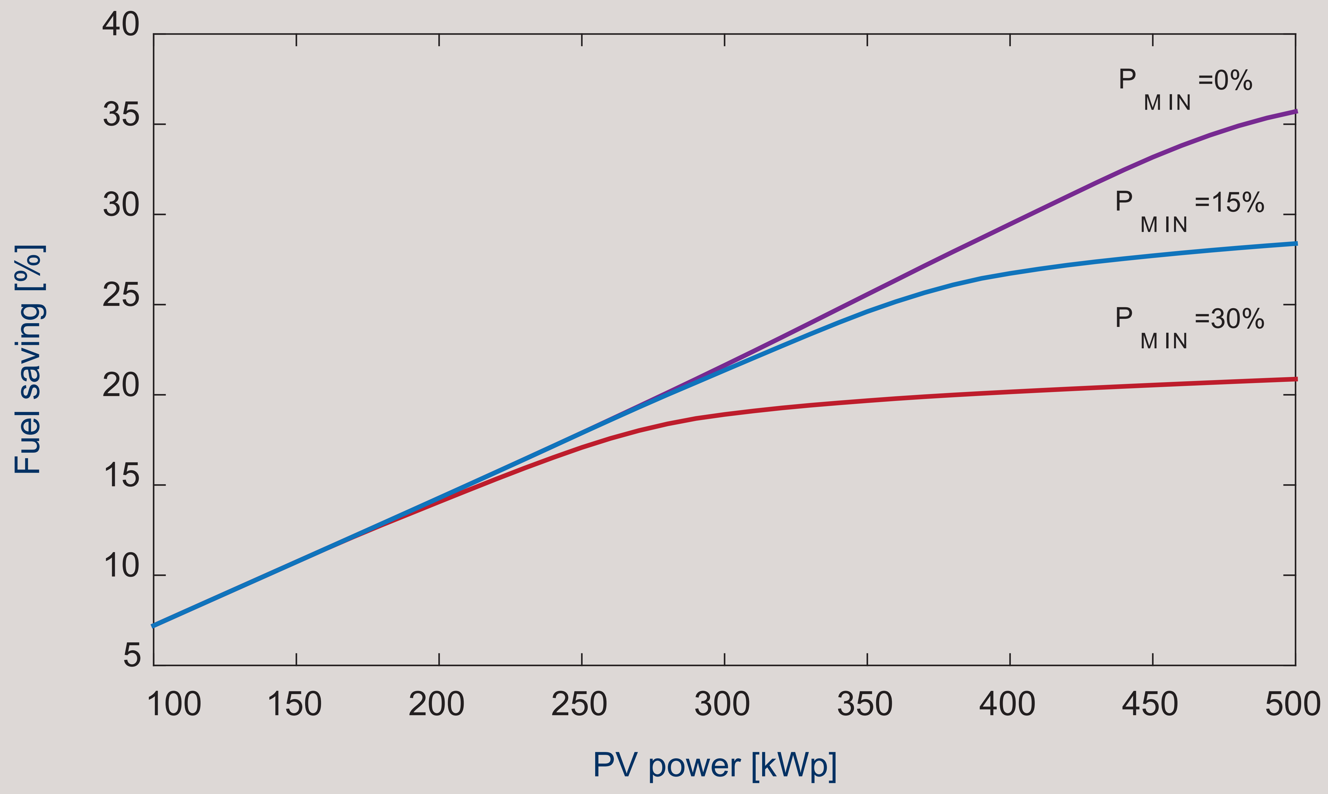
SIMULATION EXAMPLE: RETROFITTING OF AN EXISTENT 575 KW DIESEL GENERATOR

BFSC and fuel consumption (FC) of the existing 575 kW rated constant speed diesel engine

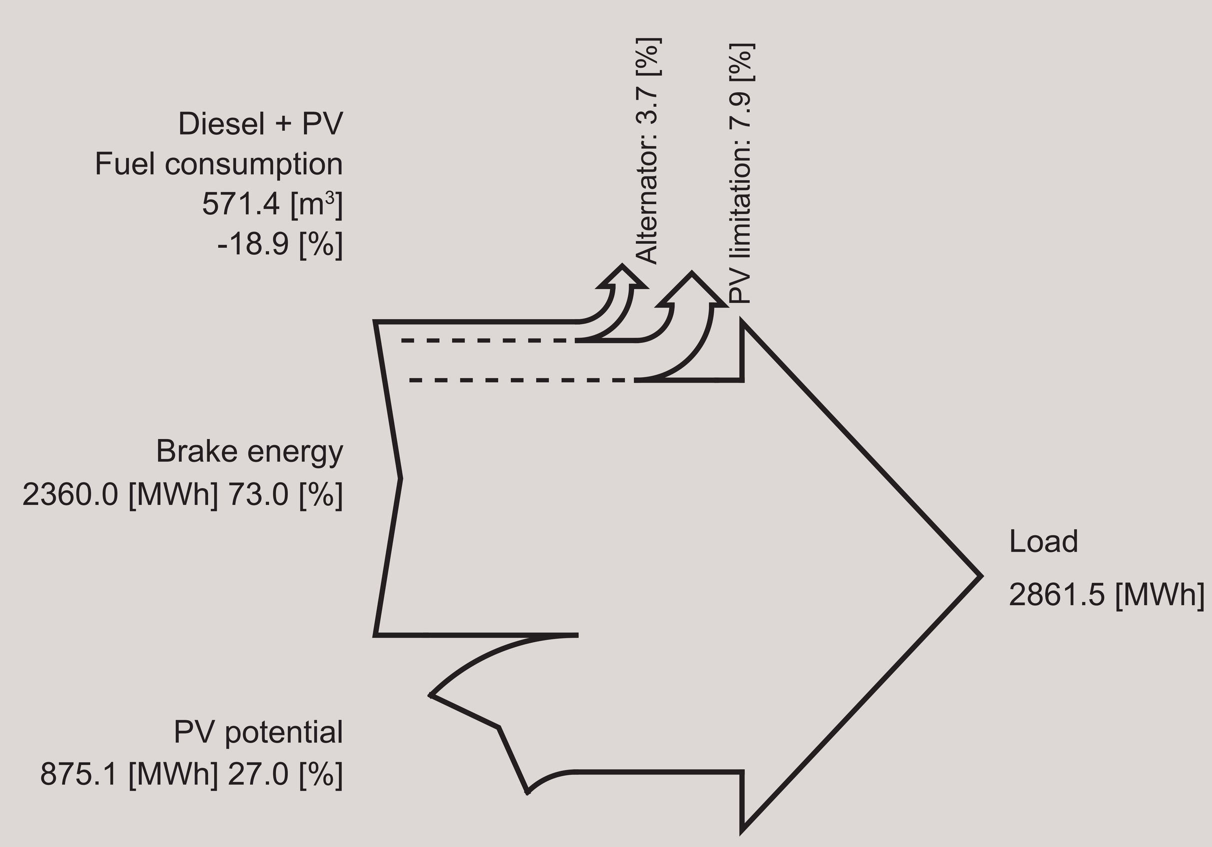


Real load profile (remote petrol exploitation field)

Yearly fuel savings as a function of the installed PV power, using the minimum genset power, PMIN, as parameter



Yearly Sankey diagram of the PV-diesel hybrid system (PV power= 300kWp and PMIN=30%)



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