

Dimensioning a hybrid electrification system (PV / WT / DG + battery) using a dynamic simulation

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Abstract—*The aim of this paper is to demonstrate that a dynamic simulator, taking into account temporal data of renewable sources and using energy on one year, is able to sizing each element composing the electric generation system and the storage system. The electrical system includes photovoltaic panels (PV), a wind turbine (WT), a diesel generator (DG) and a storage battery. To illustrate the sizing capability of the dynamic simulator, we have fixed the surfaces of the PV and wind turbine as well as the battery. We are looking to obtain 100% supply by whole generation system. The study is limited to the power minimization of the diesel generator and to elaboration a strategy of starting and stopping the DG according to the SOC of the battery. I.e. with minimum power of DG, minimize the number of start-up and minimize the amount of excess energy. The simulation results for several sizing of DG illustrate the possibility to choose the power DG and the SOC thresholds of the battery to starting or stopping the DG.*

Keywords—*dynamic simulator; sizing; diesel generator; energy management; renewable energy*

I. INTRODUCTION

During these last decades, autonomous hybrid power systems have experienced widespread use in most sectors. The installation of such a system requires the study of its components configuration and management. Several authors have been interested in to these studies especially in hybrid system design optimization.

In [1], authors have developed a design methodology based on the developed interface called HOGA (Hybrid Optimization by Genetic Algorithms). The main idea of sizing is based on optimizing a cost function that includes the different costs of hybrid system equipments (PV/ Wind/ diesel + storage systems).

In [2], authors have used genetic algorithms to optimize the size of the hybrid system. This includes solar panels, wind turbines and storage batteries (PV/ Wind/ battery storage). Optimization have been made using Matlab environment.

In [3], authors propose a method to design a hybrid power system composed of a renewable generator associated to a storage component. Design aims to minimize both system economic cost and dissatisfaction rate of demand (or Loss of Power Supply Probability (LPSP)). So, a Graphic User Interface (GUI) has been developed using Matlab as programming environment. Method has been applied to the design of hybrid wind/PV system with batteries and hydrogen storage. In [4], the authors have used the direct algorithm for optimizing the size of a hybrid system composed of PV generator, wind turbine, batteries and diesel generator.

Notes that all the studies cited above just minimize the design economic cost expressed in € or \$.

In [5], authors propose a new approach for sizing hybrid systems, based on system Life Cycle Analysis in terms of Embodied Energy (EE: energy required by all the activities associated to a production process expressed on MJ or kWh). Optimization tries to find the best configuration of wind turbine rotor area, PV generator installed surface and batteries capacity that minimizes both EE and LPSP. It has been carried out using a dynamic model and applying two different algorithms for single and multi-objective optimization.

As a continuation in this study we propose, in this paper, a dynamic simulation based method of a hybrid system (pv / wt / battery) including a DG.

The organization of this work is given by the following key points:

- Representation of generator models;
- Description of the adopted hybrid configuration;
- Simulation and evaluation of the considered hybrid system.

II. REPRESENTATION OF A HYBRID SYSTEM MODEL

According to the study of the hybrid system constitution, it is necessary to define the specific power model of each subsystem. We distinguish below the solar generator model (*pv*), wind generator model (*wt*), the DG model and storage model.

II.1 SOLAR GENERATOR MODEL

Solar generator model is given by the following expression [3] [5]:

$$P_{pv}[W/m^2] = \eta_G A_{pv} I_r \quad (1)$$

With :

η_G : The total efficiency of the generator, which is expressed by the following equation:

$$\eta_G = \eta_r \eta_{pv} [1 - \beta_t(T_c - T_{NOCT})] \quad (2)$$

Where

η_r : is the efficiency reference of the solar generator, which is the ratio between the generated power and the power of the irradiation received by the generator. This efficiency varies according to the used technology, for the polycrystalline technology, this efficiency is equal to 13% [5].

η_{pv} : represents the degradation factor of the solar generator according to during its life time. This factor is equal to the value of 0.9 with an ideal maximum power tracker [5].

β_t : represents the influence coefficient of the temperature of the photovoltaic cells on the efficiency of the generator, which varies between 0,004 and 0,006 / ° C.

T_c : is the temperature in (°C) of the photovoltaic panel cell. It depends on irradiance (I_r) and ambient temperature (T_a) as follows:

$$T_c = 30 + 0.075(300 - I_r) + 1.14(T_a - 25) \quad (3)$$

T_{NOCT} : is the Nominal Operating Cell Temperature. It is calculated when the cells operate under standard operating conditions: irradiance of $800 W/m^2$, $25^\circ C$ ambient temperature, average wind speed of 1 m/s, module in an electrically open-circuit state, wind oriented parallel to array's plane and all sides of the array fully exposed to wind [5].

I_r : symbolizes the irradiance expressed on $[W/m^2]$.

II.2 WIND GENERATOR MODEL

The power model of the wind generator as given by [5] is expressed by the following equations:

$$P_{wg} = \frac{1}{2} C_p \eta_{gb} \eta_g \rho A_{wt} w_s^3 \quad (4)$$

$$P_{wg} = \frac{1}{2} \eta_G \rho A_{wt} w_s^3 \quad (5)$$

Where

C_p : the Turbine efficiency;

η_{gb} : the gearbox efficiency ;

η_g : the generator efficiency ;

The wind turbines are generally evaluated by the overall efficiency η_G which varies according to the used technology. For three-bladed horizontal turbines this efficiency is equal to 35%.

$A_{wt} [m^2]$: the wind turbine swept area;

$w_s [m/s]$: the wind speed ;

$\rho [kg/m^3]$: the air density.

With

$$\rho = (353.049/T_a). \exp(-0.034(Z/T_a)) \quad (6)$$

$Z[m]$: is the elevation and T_a is the ambient temperature.

Notice that wind turbine generator model given by the expression (5), suppose that rated power and generator efficiency are varying linearly as a function of rotor surface. This supposition is valid for low power wind which can operate without saturation in the range of wind speed between 0 and 25 m / s. In our case the wind generator used provides the power when the wind speed reaches the value of 3.5 m / s.

II.3 DIESEL GENERATOR MODEL

The use of a diesel generator for an electrification hybrid system requires knowledge of its energy model. This last will link the variation of DG energy and the amount of the fuel it consumes [6]. In this study we have considered diesel generator manufactured by Caterpillar [7]. Table I shows their main characteristics.

TABLE I. CHARACTERISTICS OF DIESEL GENERATORS [7].

Size of diesel generator	Capacity (rated power) (KW)	Fuel consumed (L/h)			
		Load 50%	Load 75%	Load 100%	Load 110%
GD1	7.6	1.5	2.0	2.5	2.8
GD2	11.0	2.0	2.7	3.6	4.0
GD3	14.4	2.6	3.4	4.4	4.8
GD4	17.6	2.9	3.9	5.3	5.9
GD5	26.4	3.8	5.2	6.9	7.6
GD6	39.8	5.6	7.9	10.6	11.8
GD7	44.0	4.8	8.0	11.7	13.3

The objective here is to determine a general model for diesel generator power measurement. Firstly, from the data

listed in the previous table and fuel consumption data (L/h) specific to the generators, we worked on the extraction of a model, which allows us to measure the fuel consumption of a generators according to the power generated for one hour. Figure 1 shows the fuel consumption (L/h) for different generators depending on load percentage.

The consumption of the diesel generators shown in Figure 1 is obtained from four points of each diesel consumption. These points are a load of 50%, 75%, 100% and 110%. Thus, from all informations shown above and using the approximation techniques we can find the general consumption model of diesel generator. The general model of consumption of diesels in (L/h) is given in Figure 2.

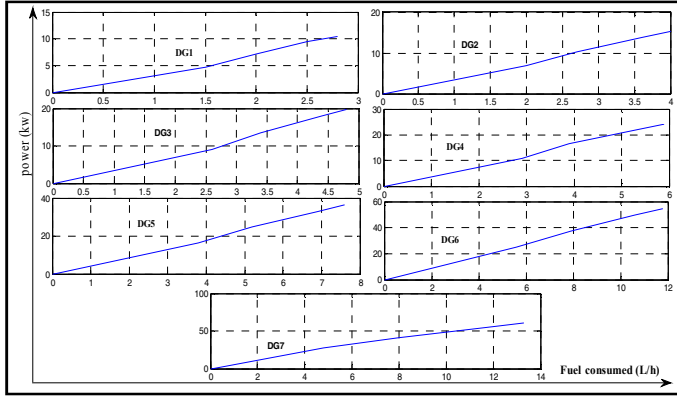


Figure 1 : Fuel consumption (L/h) of diesel generator according to percentage of load

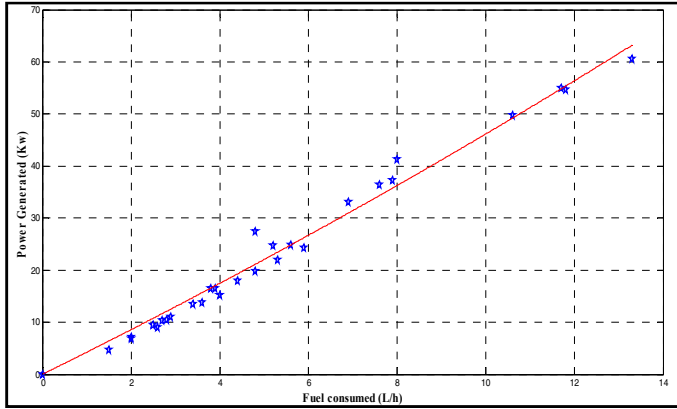


Figure 2. Power model of diesel generators

From figure 2 we can extract the power model of diesel generator. The expression (7) gives its mathematical model.

$$P_{GD} = 0.04155 Q_{fuel}^2 + 4.2 Q_{fuel} \quad (7)$$

Where

P_{GD} : is the power delivered by the diesel generator (kW).

Q_{fuel} : is the amount of fuel consumed (L).

II.4 BATTERY BANK MODEL

Among the most commonly used batteries in hybrid systems are lead-acid batteries. The expression of their charge-discharge is given by the following equations [1], [2] and [5]:

$$SOC(t) = SOC(t-1) + \left(P_G(t) - \frac{P_{load}(t)}{\eta_{dcac} \eta_{wr}} \right) \frac{\eta_{Bat}}{V_{bus}} \Delta t \quad (8)$$

With :

$$P_G(t) = P_{re}(t) + P_{fo}(t) \quad (9)$$

$$P_G(t) = P_{pv}(t) \eta_{dcac} + P_{wt}(t) \eta_{acdc} + P_{DG} \eta_{acdc} \quad (10)$$

Where:

P_{re} : is the Power of renewable generators;

P_{fo} : is the power of fossil generators;

$P_{load}(t)$: Power required by the load at t time;

η_{Bat} : Battery Charge-discharge efficiency, equal to 1 during the discharge and equal to 0.8 - 0.85 during the discharge [2] and [5].

η_{dcac} , η_{dcac} and η_{acdc} : are respectively the efficiency of DC/DC, DC/AC and AC/DC converters;

η_{wr} : wire losses;

V_{bus} : DC bus voltage;

SOC : State Of Charge of battery bank;

Δt : simulation time step;

For battery longevity, the state of charge $SOC(t)$ must be bounded by two different thresholds, an upper threshold noted SOC_{max} which represents the nominal capacity of the battery bank C_n and a lower threshold called SOC_{min} .

So that $SOC_{min} \leq SOC(t) \leq SOC_{max}$.

Obtaining a battery bank requires the knowledge of the relation between the number of battery units and battery capacity [2] [4] and [5]. This relation is given by the following equation:

$$C_n = \left(\frac{N_{Bat}}{N_{Bats}} \right) C_{Bat} = N_{Batp} C_{Bat} \quad (11)$$

Where

N_{Bat} : the total number of batteries;

N_{Bats} : the number of batteries connected in series;

N_{Batp} : Number of batteries connected in parallel;

C_{Bat} [Ah]: Capacity of a battery unit.

The relation between maximum and minimum state of charge is given by the following formula:

:

$$SOC_{min} = (1 - DOD) SOC_{max} \quad (12)$$

With

DOD : represents the Depth Of Discharge, which generally equal 80% of the nominal capacity [2] [5].

The expression of the DC bus voltage depending on the voltage of a battery can be written as follows:

$$V_{bus} = \sum_{i=1}^{N_{Bats}} V_{bati} \quad (13)$$

With V_{Bati} : is the voltage of a single battery . In our case the DC bus voltage $V_{bus} = 48 V$.

III. HYBRID POWER SYSTEM SIMULATION AND SIZING

After power sources modeling, we proceed to the establishment of dynamic simulator of the hybrid system.

Initially, we start with hybrid configuration using multi objective optimization techniques in [5]. In this last work the authors have determined an optimal hybrid system comprising the solar generators, the wind generators and storage batteries. The issues addressed by the authors are:

- Study and analysis life cycle of the renewable hybrid system in term of Embodied Energy over long life.
- Determination of an optimal area of PV generator and wind turbine rotor to satisfy the energy needs of an isolated site.
- Obtaining an optimal capacity of battery bank sufficient for storage and power management.
- Minimizing the conception cost of the global hybrid system.
- Minimization of the losses of energy in the hybrid system.

Thus, based on all the points analyzed by [5] we begin our study. In our case the hybrid system that we want to study

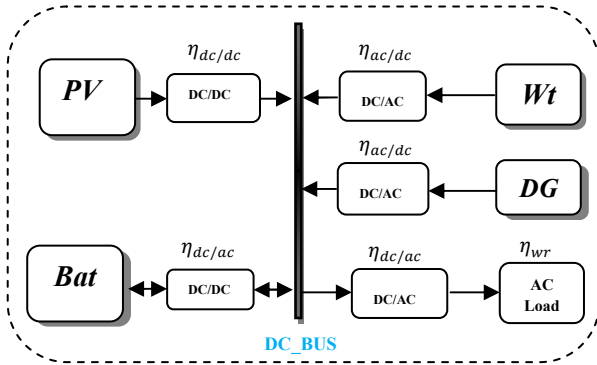


Figure 3. Hybrid system in parallel configuration consists of two different energy sources. The first source is a combination between solar and wind energy, the second source is a fossil energy provided by a diesel generator (DG). During the first stage we present the structure of the hybrid configuration used for electrification, the configuration chosen is illustrated in Figure 3.

The different values of adaptation blocks are:

$$\eta_{acdc}(\%) = \eta_{dcac}(\%) = \eta_{dcac}(\%) = 95, \quad \eta_{wr}(\%) = 98,$$

III.1 DYNAMIC SIMULATION OF HYBRID SYSTEM

The simulation step of the hybrid system is the phase that allows us to calculate the shared energy with the battery by difference between the renewable energy source and the consuming energy. The development of a dynamic simulation model adequate to the real process requires the description of the hybrid system operation.

In the configuration represented in Figure 3, the energy produced by the diesel generator and the wind turbine is rectified and converted into AC to be supplied the load. When the energy generated by the solar generator, the wind turbine and the energy stored is sufficient to meet the needs of the load, the diesel is stopped.

Here the role of the diesel generator is to remove the lack or insufficient of energy which can be produced by renewable energy source.

The deficit of energy produced by the hybrid system is measured by the reliability function [3] and [5]. The mathematical formula for this function is given by the following expression:

$$LPSP = \sum_{t=1}^T \left(\frac{E_g(t) - E_{Load}(t) / \eta_{dcac}}{\sum_{t=1}^T E_{Load}(t)} \right) \quad (14)$$

With

$LPSP$: Loss of Power supply Probability.

$E_g(t)$: Energy generated by the energy system at time t .

$E_{Load}(t)$: Energy consumed by the load at time t .

$$E_g(t) = E_{pv}(t)\eta_{dcac} + E_{wt}(t)\eta_{acdc} + E_{DG}(t)\eta_{acdc} \quad (15)$$

Where

$E_{pv}(t)$: Energy delivered by the solar field for the current time t .

$E_{wt}(t)$: Energy delivered by the aero-generator at t time.

$E_{DG}(t)$: Energy delivered by the diesel generator at the instant t .

η_{dcac} : Efficiency of the adapter DC-DC converter.

η_{acac} : Efficiency of the converter DC-AC converter.

We define the probability of energy excess by the following expression:

:

$$PE = P(E_g(t) \geq E_{load} \text{ and } SOC(t) \geq SOC_{max}) \quad (16)$$

For implementing the hybrid system using the programming environment MATLAB / SIMULINK, we initially define the metrological profiles, consumption profile and the necessary parameters of the hybrid system. The block diagram of hybrid dynamic simulator in the SIMULINK environment is given in Figure 4.

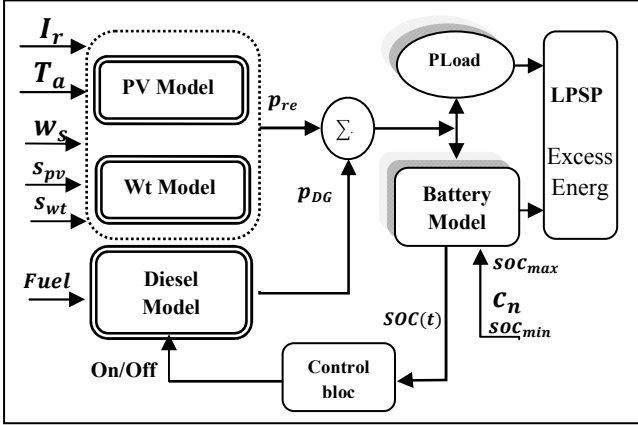


Figure 4. Block diagram of the hybrid simulator

The hybrid simulator shown in Figure 4 includes all hybrid system components: renewable generators, DG, storage system and load. Necessary inputs to carry on hybrid system simulation are climate data of the site, the diesel fuel model of converters.

In this study, data comes from the National wind Technology center in Colorado (defined by Latitude: 39° N, Longitude: 105 °West, Altitude: 1855 meters) [8]. The load profile is obtained from [10], which represents the profile of a residential habitat.

III.2 HYBRID POWER SYSTEM SIMULATION RESULTS AND DISCUSSION

In the simulation model shown in Figure 4, the satisfaction of the load is ensured by the renewable sources ($p_v + w_t$) and fossil source (DG) using a battery bank for energy storage. Our goal here is to evaluate the some performance of hybrid system after the integration of a new source of energy (GD). For this reason we adopted this work at the optimal configuration presented by [10]. For a load profile is 2193Kwh/year, the authors found the following optimal vector:

- Area of the solar field equal to 14.67 m^2 ;
- Area swept by the wind field equal to 3.46 m^2 for a wind turbine provided 800 w ;
- Storage bank consists of 4 battery 12V 200 Ah;
- LPSP = 4.5%

In the continuation of this work we keep the same areas and the same nominal capacity of the battery. The role of the diesel generator DG is to eliminate of the energy lack in the load and to obtain a value of LPSP equal to zero. So, for achieving this goal, the GD works in start-stop mode. It starts for avoid the energy lack to the load and stops to avoid excess

energy in the battery. But for maximizing the lifetime of the GD, it is necessary to limit the number of starts. And for minimizing the embodied energy, it is necessary to choice the minimal power of the GD.

The control of DG is realized using a control block, this block is in relation with the SOC of the battery. Thus, the DG start and stop are linked to the state of charge SOC of the battery. The starting of the DG if $\text{SOC}(t) < \text{SOC}_{Dmin}$ and its stopping if $\text{SOC}(t) > \text{SOC}_{Dmax}$.

Simulation tests are illustrated in the tables II, III and IV.

TABLE II. SIMULATION FOR $\text{SOC}_{Dmin} = 35\%$ et $\text{SOC}_{Dmax} = 70\%$

Power of GD (kw)	Excess of energy (Kwh/year)	LPSP(%)	Number On / Off Of DG/year
0.4204	1403	0.08425	36
0.5467	1413	0	33
0.6309	1414	0	32
0.8417	1413	0	34

TABLE III. SIMULATION FOR $\text{SOC}_{Dmin} = 40\%$ et $\text{SOC}_{Dmax} = 70\%$

Power of GD (kw)	Excess of energy (Kwh/year)	LPSP(%)	Number On / Off Of DG/year
0.4204	1414	0.03919	41
0.5467	1426	0	38
0.6309	1428	0	40
0.8417	1422	0	40

TABLE IV. SIMULATION FOR $\text{SOC}_{Dmin} = 40\%$ et $\text{SOC}_{Dmax} = 60\%$

Power of GD (kw)	Excess of energy (Kwh/year)	LPSP(%)	Number On / Off Of DG/year
0.4204	1405	0.07151	42
0.5467	1402	0	43
0.6309	1397	0	43
0.8417	1398	0	49

In these results of simulation we have supposed that, the diesel generator is used to meet energy needs by charging the batteries bank. The starting and stopping of the generator is conditioned by the lower threshold SOC_{Dmin} and the upper threshold SOC_{Dmax} . These thresholds are obtained by adjustment to obtain a hybrid configuration adequate to the profile of consumption.

The charging and discharging of the battery bank is strictly related to the difference between the total energy provided by the hybrid renewable energies or/and the DG, and the energy consumed by the load denoted $\Delta P(t)$.

We distinguish two different cases:

- In the case where $\Delta P(t) \geq 0$, the remaining energy is used for charging the battery. The GD stops if $SOC(t) > SOC_{Dmax}$. If the state of charge exceeds the SOC_{max} an excess of energy counted.
- In the case where the difference of energy is negative, the load profile will be covered by the battery or/and the diesel generator. The GD starts if $SOC(t) < SOC_{Dmin}$. If the state of charge exceeds the soc_{min} a loss of power supply probability counted and the load is relieved.

By analyzing the three tables, we can see that the optimal configuration is not evident, because in table III, the better is the power 546,7W, without LPSP, with minimal power and minimal PE, but the minimal number of starting is for the third line. If the GD power is smaller, the LPSP is not equal to zero, and the increasing of the SOC_{Dmin} minimizes the LPSP but maximizes PE. It is evident that if the interval of the thresholds is small, the number of starting increases and if the SOC_{Dmax} is smaller, the PE is smaller.

Figure 5 shows the operation of diesel generator compared to the state of charge of the battery bank for $SOC_{Dmin} = 35\%$ et $SOC_{Dmax} = 70\%$, $P_{GD} = 0.6309kw$, $DOD\% = 80$.

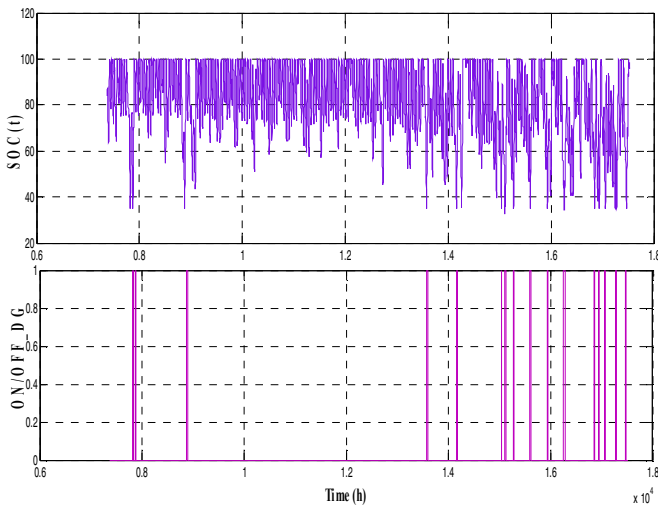


Figure 5. Operation of diesel generator depending on the state of charge of the battery bank

IV. CONCLUSION

In this paper, we presented a new tool that allows a dynamic simulation of hybrid electrification systems. Our contribution appears in the integration of a diesel generator within a solar-wind generator system connected to a storage battery. According to the tests of simulation carried out using the dynamic technique of simulation, it appeared that the

exploitation of temporal data for the sizing is very important. This importance can be summarized by the following points:

- It is possible to quantify the loss of power supply probability of the load,
- It is possible to quantify the energy excess that is not collected, for a specific design of the generation system (surface area of the PV, the surface area of the WT, the capacity of the Battery and the power of the GD).

The use of diesel generator in hybrid electrification systems is presents the advantage to improve reliability of the global system by the elimination of the energy lack.

In this work, the economic analysis and life cycle of the hybrid system are not treated. Starting from this study, many perspectives may be envisaged and summarized as follow:

- The economic analysis and the life cycle of the hybrid system,
- The use of multi-objective optimization approaches, for sizing the global generation system which minimizes the gray energy on a long life cycle.

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