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Study of the reliability of autonomous Wind turbine - diesel asynchronous generator-system

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***Abstract*— In this article , we study the reliability of a hybrid energy system consisting of two sources of production of wind electricity self - diesel asynchronous generator .This study reliability us to determine the different technological solutions to better ensure continuity of electricity production and this whatever the peak daily consumption or weather conditions that affect energy production in isolated sites .**

***Keywords*— Reliability, Self-excited induction Generator, Diesel generator, Wind turbine, Renewable energy.**

I. INTRODUCTION

In most isolated sites, the diesel generator is the main source of electric energy. For these sites, the extension price of the electrical grid proves prohibitive and the cost of the fuel supply increases completely with isolation, this opened the door to alternatives based on renewable energy.

The continuing decline in prices of the generators based on renewable energy and the increasing reliability of these systems led to greater use of decentralized energy sources, namely electric hybrid systems of energy generation in isolated sites.

The combination of several sources of energy especially renewable optimizes maximum power generation systems, both from a technical and an economical point of view. The new technological solutions offered by hybrid generators, present by against a considerable evident interest by their unbeatable flexibility, their flexibility of functioning and their cost.

Currently, hybrid energy systems (HES) combine at least two complementary technologies: one or more conventional energy sources usually diesel generators, and at least one renewable energy source [1] .The Renewable energy sources, do not deliver a constant power. Their combination with conventional sources provides a continuous electrical output.

A hybrid system must:

Ensure at all times the sufficient energy required by the load, and if possible, to produce the maximum energy from renewable energy sources

Rely on an automated management of system components in order to ensure the stability of the system at all times.

For isolated sites, the solution to retain is certainly the coupling between multiple sources , such as wind turbines, photovoltaic panels and diesel generators.

However these installations requires a study of their reliability to determine the different technological solutions to better ensure the continuity of the electricity production and this regardless the daily consumption peaks or the weather conditions that affect the energy production and master both fundamental constraints of operating a power grid:

1. The voltage level at every point of the network, remain near its nominal value.

2. The frequency of the voltage wave must be stable and close to its nominal value.

In this context, the work presented in this article is a contribution to the study of the reliability of bodies representing an autonomous hybrid power system-wind turbine- diesel asynchronous generator to define an ideal operation of the system to ensure its stability at all times, including in the transitions between the different modes of the system operation (single wind, single diesel and wind- diesel). From a technological point of view, the reliability is not just a matter of compliance to the electricity supply, but also the maintenance and the dependability of the system, often including the particular conditions of isolated sites [2] .

II. THE COMPONENTS OF THE HYBRID SYSTEM ARE:

Components of the hybrid system in autonomous operation are:

- A fuel pump to power the diesel from the fuel
- Diesel actuators for driving the generators.
- Battery capacitors for the supply of generators by reactive energy.
- Generators to convert mechanical energy into electrical energy.
- Wind turbine for capturing the kinetic energy of the wind and converts it into a torque that rotates the rotor blades of the asynchronous generator
- A high speed multiplier for the speed of rotation
- Autonomous asynchronous generator

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- Battery capacitors for the supply of generators by reactive energy.
- A common load supplied by the two generators (electric power consumption)

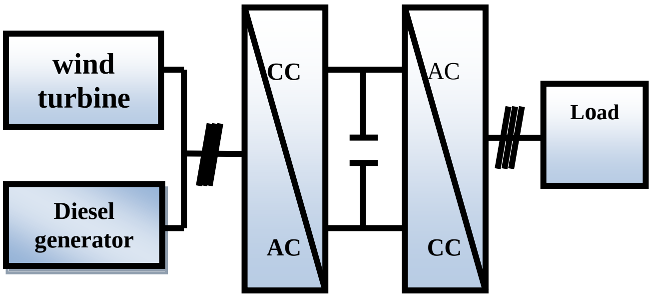

Fig 1: Architecture of the hybrid system wind turbine - diesel generator

III. ISOLATED WIND TURBINE MODELLING SYSTEM

The global system studied consists of a wind turbine including 3 blades of length R , leading to an asynchronous generator through a speed gain of multiplier M [3].

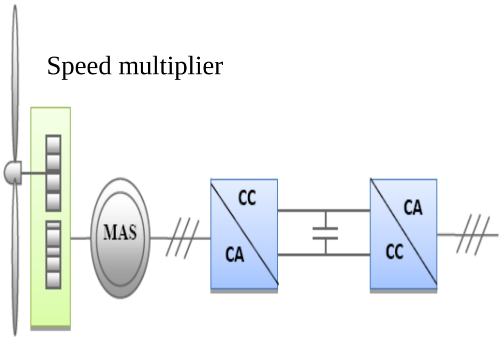

Fig 2: Wind turbine system architecture

A. Wind Turbine Modelling System

the wind power is defined by the :

$$P_V = \frac{\rho.\pi.R^2.V^3}{2} \qquad (1)$$

With ρ the density area, R the length of the blade and v, wind speed.

The aerodynamic power appearing at the rotor of the turbine is given by:

$$P_{aer} = C_p(\lambda)\frac{\rho.\pi.R^2.V^3}{2} \qquad (2)$$

Such as Pc representing the aerodynamic efficiency of the wind turbine .The speed ratio λ is the ratio of the linear speed of the blades and the wind speed.

$$\lambda = \frac{\Omega_{turbine}.R}{V} \qquad (3)$$

With Ω the mechanical speed of rotation of the turbine .for the turbine used in this study, the power coefficient Cp is approximated by the following formula.

$$C_p(\lambda) \approx \frac{G.\lambda.(\lambda_0-\lambda)}{a^2-(\lambda_0-\lambda)^2} \qquad (4)$$

Using the above equation we deduce the aerodynamic torque according to the equation:

$$C = \frac{P_{aer}}{\Omega_{turbine}} = C_p(\lambda).\frac{\rho.s.V^3}{2}.\frac{1}{\Omega_{turbine}} \qquad (5)$$

1) Multiplier model

Using the above equation we deduce the aerodynamic torque according to the equation (7):

$$G_g = \frac{C_{aer}}{M} \qquad (6)$$

$$\Omega_{turbine} = \frac{\Omega_{mec}}{M} \qquad (7)$$

With the M multiplication ratio

2) Dynamic Equation of the tree

Equation (8) represents the total inertia that appears on the generator rotor.

$$J = \frac{J_{turbine}}{M^2} + J_g \qquad (8)$$

$$J\frac{d\Omega_{mec}}{dt} = C_{mec} \qquad (9)$$

$$C_{mec} = C_g + C_{em} + C_{vis} \qquad (10)$$

$$C_{vis} = f.d\Omega_{mec} \qquad (11)$$

With, C_{MEC}, mechanical torque C_{em} , the electromagnetic torque produced by the generator and CVIS , the viscous friction torque.

The diagram of the model of the mechanical equation is given in figure 2.

B. Model of the self-excited asynchronous generator (SEIG)

The classic model of the asynchronous machine in the landmark Park, adopted in this study is:

$$\left.\begin{aligned} v_{sd} &= R_s.i_{s\alpha} + \frac{d\varphi_{s\alpha}}{dt} - \omega_s.\varphi_{s\beta} \\ v_{s\beta} &= R_s.i_{s\beta} + \frac{d\varphi_{s\beta}}{dt} - \omega_s.\varphi_{s\alpha} \\ v_{r\alpha} &= R_r.i_{r\alpha} + \frac{d\varphi_{r\alpha}}{dt} - (\omega_s-\omega).\varphi_{r\beta} \\ v_{r\beta} &= R_r.i_{r\beta} + \frac{d\varphi_{r\beta}}{dt} - (\omega_s-\omega).\varphi_{r\alpha} \end{aligned}\right\} \qquad (12)$$

Such as, $v_{s\alpha}$, $v_{s\beta}$, vrα , $v_{r\beta}$, $i_{s\alpha}$, $i_{s\beta}$, $i_{r\alpha}$, $i_{r\beta}$ are respectively the voltages and currents at the generator output in the model park.

Ra , Rs , Ls and Lr are respectively the resistance stlkes stator and rotor inductances Lm and the magnetizing inductance .

$$\omega = p.\Omega_{mec} \qquad (13)$$

Where p is the number of pole pairs

$$\left.\begin{aligned} \varphi_{s\alpha} &= L_s.i_{s\alpha} + L_m.i_{r\alpha} \\ \varphi_{s\beta} &= L_s.i_{s\beta} + L_m.i_{r\beta} \\ \varphi_{r\alpha} &= L_r.i_{r\alpha} + L_m.i_{s\alpha} \\ \varphi_{r\beta} &= L_r.i_{r\beta} + L_m.i_{s\beta} \end{aligned}\right\} \qquad (14)$$

The electromagnetic torque is given by the formula :

$$C_{em} = p.(\varphi_{s\alpha}.i_{s\beta} - \varphi_{s\beta}.i_{s\alpha}) \qquad (15)$$

C. Mathematical model of the excitation circuit

The voltages of the excitation capacitor can be represented by the system of differential eqs (16):

Differentiating both sides of the equation is obtained:

$$\left.\begin{aligned}\frac{dv_{s\alpha}}{dt} &= \frac{1}{C}.i_{s\alpha}\\ \frac{dv_{s\beta}}{dt} &= \frac{1}{C}.i_{s\beta}\end{aligned}\right\} \qquad (16)$$

Where: C is Capacity of the excitation capacitor bank.

D. Simulation of autonomous Wind system

The global model previously established will allow to establish a performance review and the limits of use of the autonomous wind system. For this, the generator is driven by the wind turbine. The self-excitation capacities are fixed. The self-priming is then stimulated.

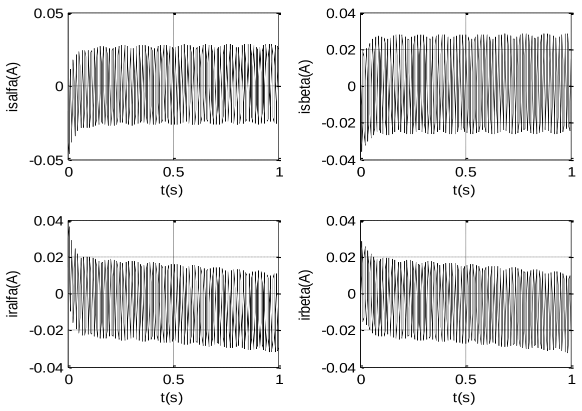

Fig 3: The rotor and stator currents when starting the self excited asynchronous generator driven by the turbine.

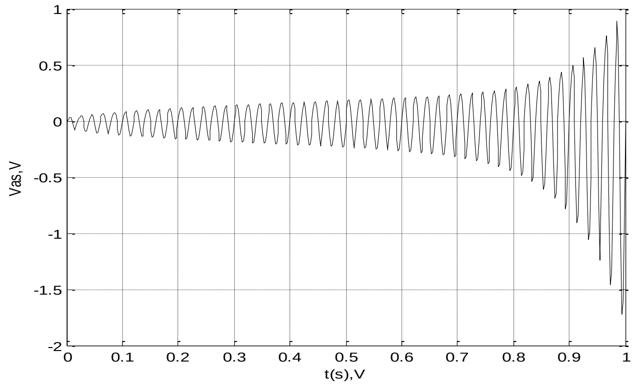

Fig 4 : The stator voltage when starting the self excited asynchronous generator driven by the turbine.

We notice that the initial voltage stator before the priming process is different and weak. and then stabilizes after the self priming of the generator.

IV. ASYNCHRONOUS GENERATOR DIESEL MODELLING SYSTEM

The dynamic regime of the Self-excited induction generator is determined by the mutual influence of the physical processes that take place in the diesel actuator, the generators and the loads [4],[5].This is why the mathematical model of this regime takes into consideration the description of the autonomous subsystems (diesel actuator, asynchronous machine, the capacitor bank and load) and their characteristic relations as presented on Fig. 5.

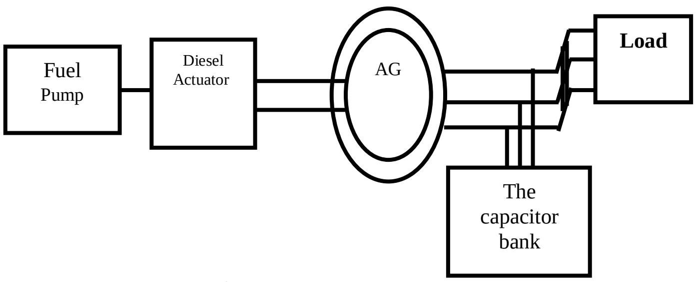

Fig 5: Self-Excited Induction Generator Bloc Diagram.

A. Diesel mathematical model

The variation of the diesel actuator rotational speed is determined by the following equation:

$$\frac{dw_d}{dt} = \frac{1}{j\left(C_i - C_r.C_{em} - C_m\right)} \qquad (17)$$

The link between the diesel actuator and the fuel pump is determined by the form shown in eq. (18) :

$$w_h = U_w.w_d \qquad (18)$$

B. Mathematical model of the Asynchronous Generator

It is necessary to perform a conversion of the machine variables so as to get those of the primitive machine. This conversion implies the transformation of the original generator coils to an electrically and magnetically equivalent coil set in d and q axis. This transformation is a particular case of the park transformation [6] ,[7] ,[8].

$$\left.\begin{aligned}-u_{sd} &= \frac{d\psi_{sd}}{dt} + r_s.i_{sd}\\ -u_{sq} &= \frac{d\psi_{sq}}{dt} + r_s.i_{sq}\\ 0 &= \frac{d\psi_{rd}}{dt} + r_r.i_{rd} - w_r.\psi_{rq}\\ 0 &= \frac{d\psi_{rq}}{dt} + r_r.i_{rq} - wr.\psi_{rd}\end{aligned}\right\} \qquad (19)$$

The hanging fluxes are related to the generator currents as follows:

$$\left.\begin{aligned}\psi_{sd} &= L_s.i_{sd} + L_m.i_{rd}\\ \psi_{sq} &= L_s.i_{sq} + L_m.i_{rq}\\ \psi_{rd} &= L_r.i_{rd} + L_m.i_{sd}\\ \psi_{rd} &= L_r.i_{rq} + L_m.i_{sq}\end{aligned}\right\} \qquad (20)$$

1. Mathematical model of the excitation circuit

The voltages of the excitation capacitor can be represented by the system of differential eqs (21):

$$\left.\begin{aligned} u_{sd} &= c\int i_{sd}dt + u_{sd0} \\ u_{sq} &= c\int i_{sq}dt + u_{sq0} \end{aligned}\right\} \qquad (21)$$

Where $u_{sq} = u_{sq0}|t=0$ et $u_{sd} = u_{sd0}|t=0$: The initial voltages.

The electromagnetic torque of the asynchronous generators is determined by:

$$C_{em} = \frac{3}{2}.p.L_m(I_{rd}.I_{sq} - I_{rq}.I_{sd}) \qquad (22)$$

The empty generator is driven by a diesel actuator and the necessary condition to create a voltage between its edges is the existence of a remaining field. In order to increase this relatively low voltage amplitude to its nominal value, enough reactive power by the capacitor bank magnetization should be supplied to the generator [9] shown in fig. 5.

2. Conditions of self-start up of the empty generator

The self-start up of the generators occurs when both the two following conditions are satisfied:

Total active power =0

Total reactive power =0

What means that the impedance equivalent to a stator phase of the machine is also null ?

$$(Z_G = a + bj = 0)$$

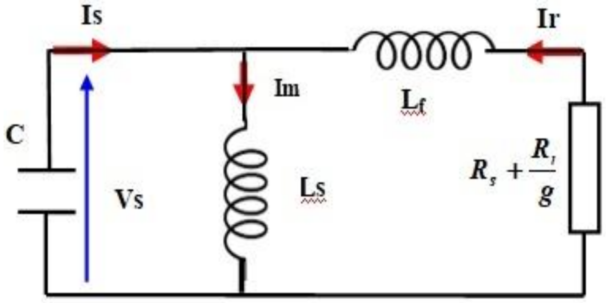

Fig 6: Simplified equivalent diagram of one phase of the generator brought back to the stator

The diagram of fig. 6 is equivalent to a generator producing on Z_c impedance (as shown on fig. 7).

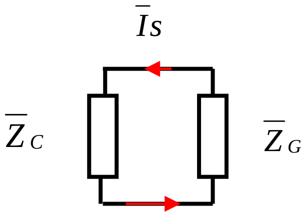

Fig. 7: Transformation of the equivalent diagram

We have:

$$\left(\frac{1}{\overline{Z}_C} + \frac{1}{\overline{Z}_G}\right).\overline{V}s = 0 \qquad (23)$$

Where:

$$\frac{1}{Z_C} = j.C.w \qquad (24)$$

Thus:

$$\frac{L_f.w}{\left(Rs + \frac{Rr}{g}\right)^2 + (L_f.w)^2} + \frac{1}{Ls.w} = C.w \qquad (25)$$

The self-start-up of the generator cannot occur unless its produced apparent power corresponds to its absorbed one. For the reactive power part, the following equation should be satisfied (for g.= 0).

$$\frac{1}{L_s.w} - C.w = 0 \qquad (26)$$

This condition shows that the minimal value leading up to the self-start-up is function of the cyclic stator inductance as well as the rotor pulsation and the sliding thereof [10]. The asynchronous generator does not receive any reactive energy except the one coming from the C capacity [11].

C. Simulation result

Finally for simulation, simply insert the models of the AAG, diesel actuator and the capacitor bank and implanting under the Matlab / Simulink environment.

The simulation model allowed us to obtain the results of self-priming vacuum:

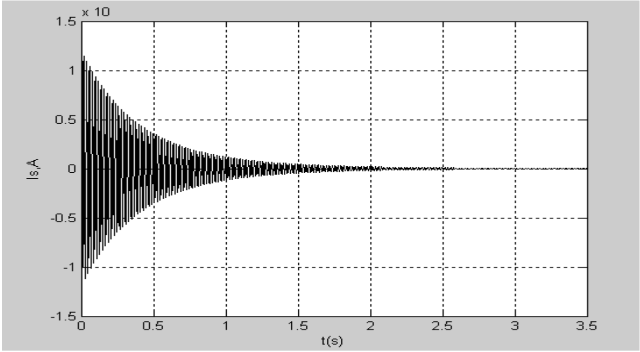

Fig 8 : The current generator with C < Cmi

If the capacitor value is $C < C_{min}$, the current of generator Figure (9) lowers to be canceled , so the self-priming is not possible .

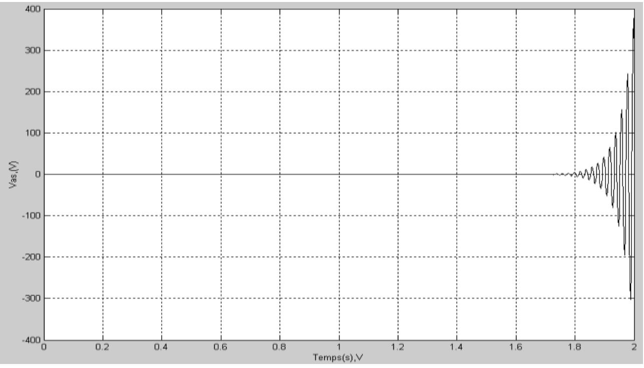

Fig 9: Voltage of the self startup of an empty generator

It can be noticed on this figure that the induced tension increases indefinitely, in an exponential way, due to the non saturation of the magnetic circuit of the machine

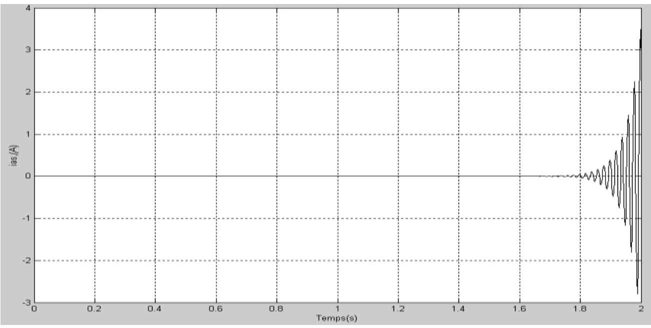

Fig 10: Stator induced current of the empty generator

The induced stator current reaches, in few seconds, a value that exceeds by several times the nominal value, what is very far from the reality.

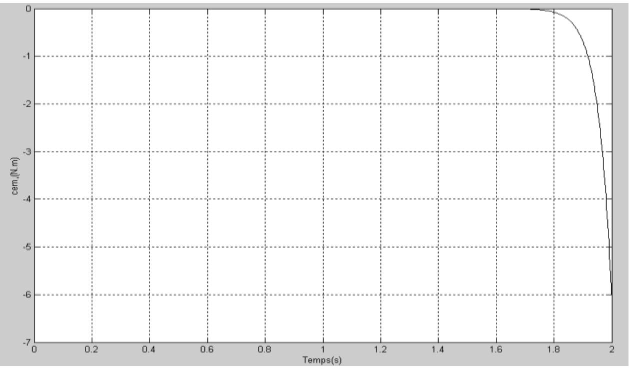

Fig. 11: Electromagnetic torque of the empty generator

When the generator starts itself, its electromagnetic torque rises indefinitely which will increase the active power.

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D. Consideration of the magnetic saturation phenomenon

In saturation regime, the fluxes and the currents are no longer proportional. The magnetization characteristic is composed in addition to the linear part, of a part of bend and another called of saturation. This last one will limit the generator magnitudes [12].

$$L_m = \frac{|\overline{\psi_m}|}{i_m} \tag{27}$$

Expression of the magnetizing current based on stator current and rotor is given by:

$$i_m = \sqrt{(i_{sd} + i_{rd})^2 + (i_{sq} + i_{rq})^2} \tag{28}$$

To take account of the saturation magnetic circuit of the machine, it is necessary to model the magnetization curve Fig. 12.

Several spline interpolation functions are used [13], however, there is no function that covers all points of the curve, and modeling remains approximate with minimal error.

For our raised magnetic characteristic, we adopt the approximation of the iron magnetization curve fig.12, by the LANGEVIN function $\left(L(x) = coth(x) - \frac{1}{x}\right)$. [14], [15].

The calculation of the asynchronous machine main magnetic circuit saturation is performed using the LANGEVIN function as an approximation of the iron magnetization curve.

$$L_m = \frac{1}{a.i_m}\left[\frac{1}{\coth(b.i_m)} - \frac{1}{b.i_m}\right] \tag{29}$$

Which value is obtained by the magnetization graph of the generator free regime test shown in fig. 12.

a, b: Coefficient calculating the approximation obtained by the magnetization curve ,fig.12.

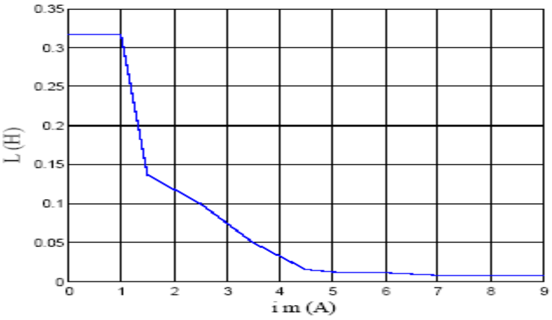

Fig 12: Variation of the magnetization inductance Lm according to Im

By resolving the equation system (19), and taking in consideration the eq. (29), the saturation of the machine, with a self-start-up voltage, will be obtained as presented on fig.13.

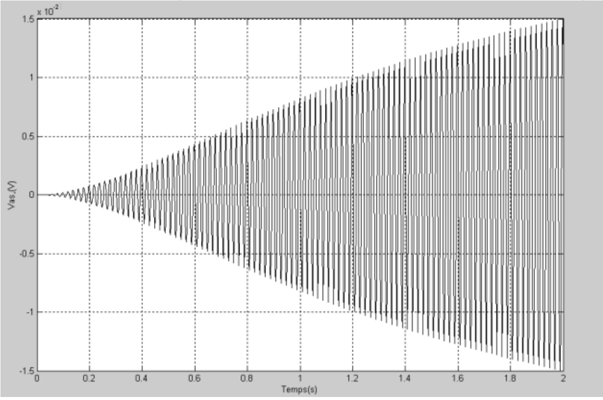

Fig 13: Self-start-up voltage of the generator at void in saturation regime

At the beginning of the start-up, the voltage increases in a way identical to the linear case, then converges toward a value that depends on the choice of the condenser and speed values.

E. Mathematical model of the Self-excited induction generator supplying an R-L load

This model is obtained by adding to the equations system (21) the following load equations:

$$\left.\begin{aligned} \frac{du_{sd}}{dt} &= \frac{1}{C}\left(i_{sd} - \frac{u_{sd}}{R} - i_{ld}\right) \\ \frac{du_{sq}}{dt} &= \frac{1}{C}\left(i_{sq} - \frac{u_{s\beta}}{R} - i_{lq}\right) \\ \frac{di_{ld}}{dt} &= \frac{1}{L}.u_{sd} \\ \frac{di_{lq}}{dt} &= \frac{1}{L}.u_{sq} \end{aligned}\right\} \quad (30)$$

The equation system (30) solution provides the results of simulation with a variable load speed

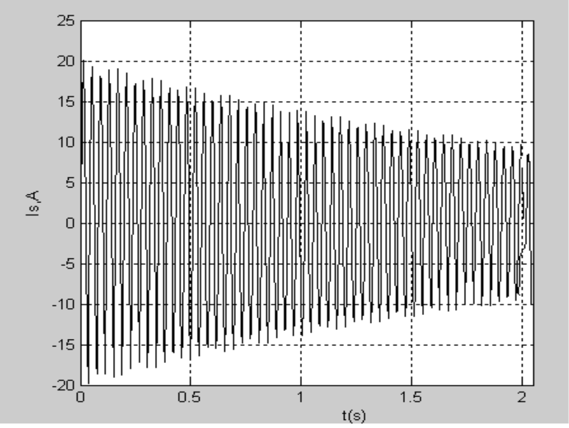

Fig. 14: Self startup voltage of the loaded generator for C=300 µF

It can be noticed on fig. 14 that, when a load is applied, the voltage decreases with a light variation of frequency which is due to the decrease of the speed .

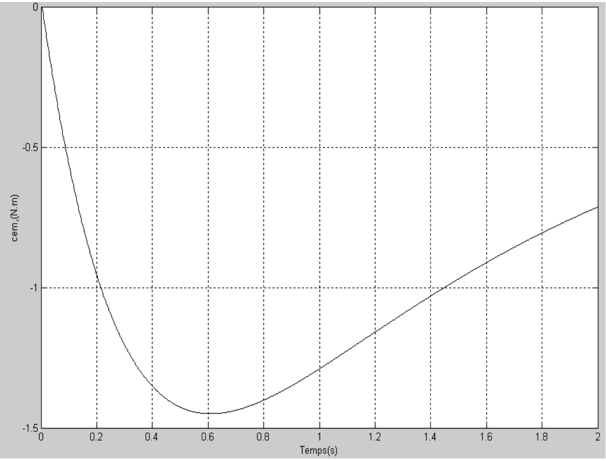

Fig 15: Electromagnetic Torque of the loaded Generator under loading

The electromagnetic torque passes from a steady state to another steady state defined by the load.

V. STUDY OF THE RELIABILITY OF AUTONOMOUS - WIND TURBINE - DIESEL GENERATOR-SYSTEM

For the modelling of the reliability of the autonomous system- Wind turbine- diesel generator using the method of the reliability diagram, this method allows to represent the system behaviour in a functional view [16].

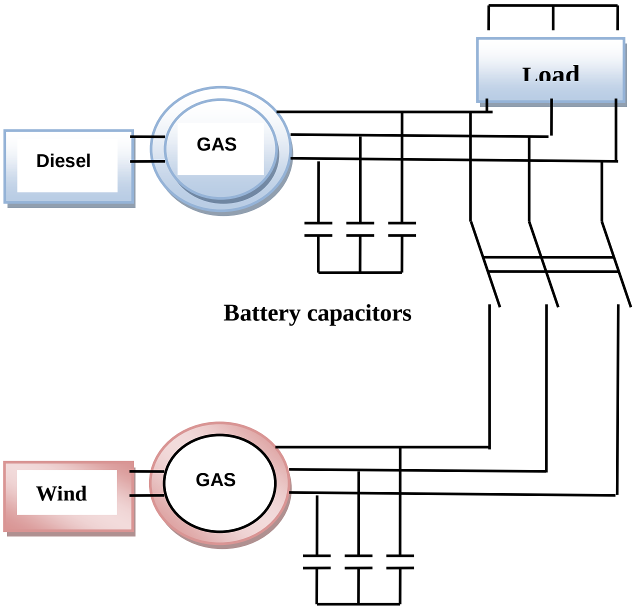

Fig 16: Block diagram of the connection of the autonomous system- Wind turbine- diesel generator

A. Modelling and construction of the reliability of the installation diagram

The modelling is based on the definition of the missions or functions of each component of the system. The reliability diagram describes the links between the components. The objective is to separate all operations to be mad to achieve the success of the mission system. Then, the reliability diagram gives a graphical representation that is easy to be interpreted and that allows reliability analyzes [17].

This method relies on the decomposition of the system into subsystems, each entity is modeled by Figure blocks (17) :

The Subsystems of the energetic installation in an autonomous operation are:

- A fuel pump (E11) to power the diesel from the fuel
- A diesel actuators (E12) for driving the generators.
- Battery capacitors (E14) for the supply of generators by reactive energy .
- Generators (E13) to convert mechanical energy into electrical energy.
- Wind turbine (E21) for capturing the kinetic energy of the wind and converts it into a torque that rotates the rotor blades of the asynchronous generator
- A high speed multiplier for the speed of rotation (E22)
- The autonomous asynchronous generator (E23)
- Battery capacitors (E24) for the supply of generators by reactive energy .
- A common load supplied by the two generators (electric power consumption) .

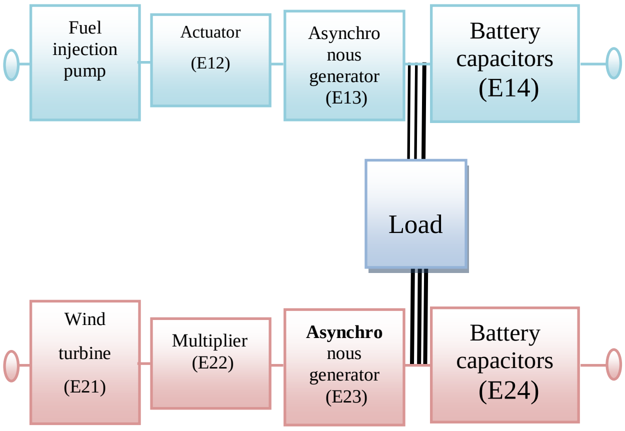

Fig 17: The reliability diagram of the autonomous system -Wind turbine - diesel generator

B. *Diagram of success*

Link or successful path is a set of entities whose operation ensures the success of the mission system.

Minimal success path is a smaller combination of entities which allow, when functioning, ensuring the required function for the system [18].

According to the figure (17) the diagram of the installation success is built by a representation series- parallel Figure (18) :

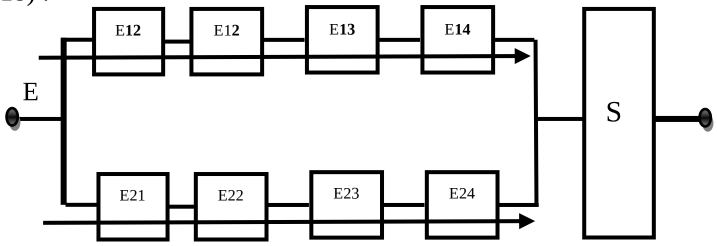

Fig 18: success diagram – Series- parallel installation

It is possible to assess the probability of the mission success knowing the probability of success of sub-missions constituents. This quantitative analysis aims, in particular, to define the probability of the right system operation.

The ways of success or minimal links of the installation:

- E12, E12,E13,E14
- E21, E22,E23,E24

The reliability R (t) of the installation by the calculation :

$$R(t) = 1 - \prod_{i=1}^{2}\left(1 - \prod_{j=1}^{4} R_{ij}(t)\right) \qquad (31)$$

$$R(t) = 1 - [(1 - R_{11}.R_{12}.R_{13}.R_{14}).(1 - R_{21}.R_{21}.R_{23}.R_{24})]$$

$$R(t) = [R_{11}.R_{12}.R_{13}.R_{14} + R_{21}.R_{21}.R_{23}.R_{24} - (R_{11}.R_{12}.R_{13}.R_{14}) \times (R_{21}.R_{21}.R_{23}.R_{24})] \qquad (32)$$

Knowing the laws followed by quads installation components are exponential , then:

$$R_{ij}(t) = e^{-\lambda_{ij}t}$$

$$R(t) = \left[e^{-(\lambda_{11}+\lambda_{12}+\lambda_{13}+\lambda_{14})t} + e^{-(\lambda_{21}+\lambda_{22}+\lambda_{23}+\lambda_{24})t} - \left(e^{-(\lambda_{11}+\lambda_{12}+\lambda_{13}+\lambda_{14})t}\right) \times \left(e^{-(\lambda_{21}+\lambda_{22}+\lambda_{23}+\lambda_{24})t}\right)\right] \qquad (33)$$

TABLE I : RELIABILITY CALCULATION R (T) OF THE INSTALLATION

The failure rate of plant components		Temps (h)	R(t)
$\lambda_{11} = \lambda_{21}$	10^{-4}	100	0,999568144
		500	0,990064709
$\lambda_{12} = \lambda_{22}$	10^{-4}	1000	0,964121365
		1500	0,926985356
$\lambda_{13} = \lambda_{23}$	10^{-5}	2000	0,882382215
		2500	0,833171772
$\lambda_{14} = \lambda_{24}$	10^{-9}	3000	0,781528082
		3500	0,729083686
		4000	0,677045108
		4500	0,626285194
		5000	0,577416795

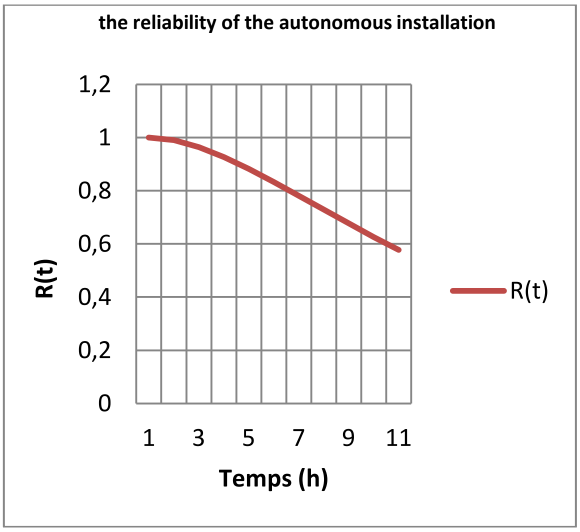

Fig 19 : Graph of the reliability of the autonomous installation - Wind turbine - diesel generator

Table (I) and Fig .19 shows the diagram of success method was offering a significant opportunity to quantify the reliability and evaluate the probability of failure of the complete system to control behavior are functional / dysfunctional.

VI. CONCLUSION

In this article, we presented different stages of the study of how a hybrid system a renewable energy source, by an autonomous regime for supplying the isolated sites. However these facilities requires a study of their reliability, with the objective to maintain a high level of reliability with a minimal cost thanks to an optimal dimensioning of hybrid systems to ensure the sufficient energy required by the load at all times, and to determine the various technological solutions to better ensure the continuity of the electricity production and regardless daily peaks of the consumption or the weather conditions that affect the energy production

and master the fundamental constraints of operating of an isolated electricity network, this leads us to conclude that the reliability of an hybrid system is not only a matter of respect of the norms for electricity supply, but also the maintenance and the safety of the system operating, often taking account of the specific conditions of the isolated sites.

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