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Self-Regulation of an Alternator in an Electrical Isolated Network

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ABSTRACT: We present in this article, an approach to the self-regulation (the automatic regulator) of the frequency and the module of the voltage fromthe terminalsof the alternator of a hydroelectric power station.To get a regulation which can keepconstant the voltage whatever the functioning regime of the alternator,It is necessary to use the automatic regulators according to the time of thequick or slow action and we shall take as the digital application, the case of the project from great Inga (hydroelectric power station in the D.R.C :Democratic Republic of Congo).

KEYWORDS: GreatInga, Alternator, Regulation, automatic, isolated Network.

I. INTRODUCTION

Whatever the device used, the electromotive force (ei) of the alternator is always adjusted by the speed and the excitation from electricity.The exploitation of alternators in a power station is subjected to many problems, among which the phenomena of magnetic reaction from the armature of the rotor which cause the dispersionofits flux and the variation of the inductive flux; it can consequently come to the variation of the voltage at the terminals of the alternator that can lead to the overtaking of the fixed limits. That is why, it is useful to adjust the voltageon the terminals of the alternator in the order to keep it in the regulation limits. The regulation of the voltage also allows protectingthe guarantee of the reactive power in various areas from the system.

If dealing with the voltage, we have said that it is essentially a local problem (compensation). We must indeed limit (restrict) the reagent transits in the network (we accept variation changes from 5 to 10 % according to the voltagelevel and thekind of customer). On thecontrarythe frequency bound related to the alternators rotation speed is an interesting issue for the associated electric global network.

All imbalancesbetween the production and the consumption results in the speed variation (imbalance between engines torque provided by the turbine and the hard wearing torque corresponding to the electric charge of the network) and the frequency is therefore brought to the risks of instability described above.The frequency must be hold in a range of ± 1HZ (otherwise there are risks for pumps, losses of transformers, synchronization clocks, stability of machines, etc.). Any time the conditions of coupling must be realized;this supposes on the on hand, a certain constant the frequency. On the other Hand, the electrical power generated by an alternator, can vary according to the energy neededand that power is got from the training organ on the basis of a mechanical power.

II. PATTERN OF ELECTRICAL POWER CONTROL REGULATIONS

This adjustment aims to keep (maintain) the energetic system (electrical network) in a position as closed as possible to the instructions in spite of the disturbances made up by the variation from loads and the possible modifications from the topology of the network. They totallyespace the will of the exploiter. The variables of command [U] are for example the command of the valving of a turbine and that of the excitatrice from an alternator. They allow acting on the system. The main characteristics of these models are reminded as follows.

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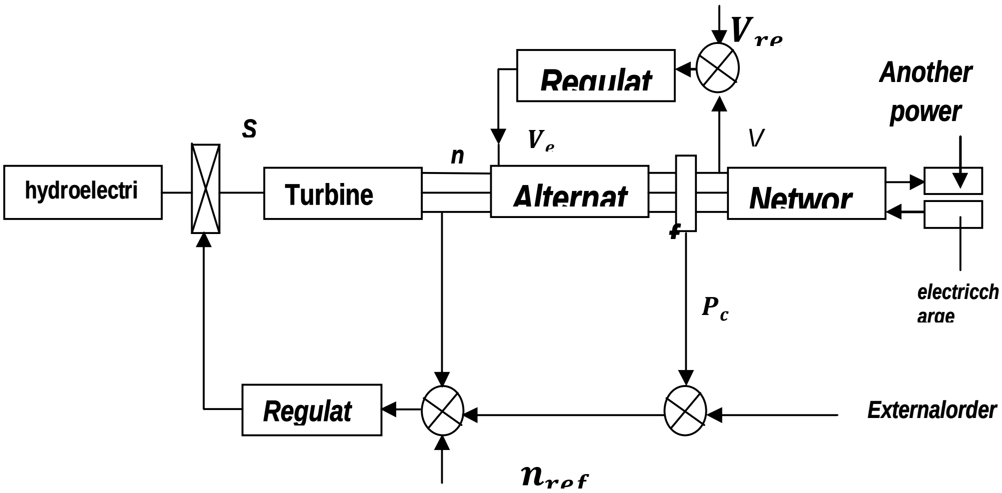

Fig1 Model(pattern)linking to an electrical power control regulation

Where*:*
S: control Servomotor
N: rotation speed of training
Nrg : adjusted speed
Nref: reference speed
V_e: excitation voltage
V: voltage
Vrg : adjusted voltage
f : frequency
g: statism
f_N: nominal frequency
P_c : instruction of power
P_N :nominal power
P_0: power carried
C_e : excitation power current
C_m: shaft torque

III. MODELLING OF THE PARAMETERS ADJUSTMET SYSTEM REGULATION

A. MATHEMATICAL MODELS (PATTERNS)

The mathematical pattern (model), is a set of differential equations generally the nonlinear ones. We can add the power and the frequency of adjustment in closed-loop to the previous figure. We are going to show (ΔPM) as an independent value with the speed regulator. (ΔPM)will depend on (Δω) and(ΔPc) because(ω) is the angular speed of the turbine shaft(Δω = Δδ) ; Δδ is the output speed available to the controland we can now add the turbine. At the same time we include (P_{ss}) in the previous figure.
We have:$\omega = \omega_o + \delta$(1)

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B. ACTIVE POWER REGULATOR OF THE DIFFERENT TYPES OF ELECTRIC CHARGES

The powerfrom regulation loop is held to make significantly the transitory regime, in this commoncasewith the acceptable approximation. We can put ΔPM = 0 and ignore the power control loop of powercontrol (control loop of the power). Let us note therigorous justification from the reduced model is studied by the method of particular disturbance. It is easy to determine the stability of the power loop.

We write:fe=fi-δ(P_c/P_N)f(2)

$\delta = \frac{\Delta f/f_N}{\Delta P/P_N}$(3)

C. FREQUENCY RELATIVE VARIATION BY POWER RELATIVE VARIATION

If the network calls a power P, the instruction frequency will return (yield) $f < f_1$; for an isolated machine, it seems logical to impose f = f1 = constant. But, we show that the statism of generatorsallows a stable distribution of the power called between the generators. In this case, we can replace the previous relation (3) by the following relationship:

$P_c = P_o - \frac{1}{g}\frac{P_N}{f_N}(f - f_N)$(4)

D. 4 EQUATIONS OF THE ROTOR MOVEMENT (ROTOR MOVEMENT EQUATIONS)

Both differential equations (5) and (6) express the Newton's law applied to the movement of the rotor (therotor movement). The conversion of mechanical energy into electrical energy realized(done) by the alternator is based on theelectromagnetic inductionphenomenongoverned by Faraday’s and Lenz’s laws. Acircuit submittedto a varying magnetic induction is the (head quarter) seat of electromotive force (e.m.f) given by:

$\varepsilon = -\frac{d\psi}{dt}$(5)

Here (ψ)is the flow of magnetic flux (flow) embraced by the circuit. If the circuit is closed andconductive, it is the seat of an induction current.

The alternator used in a hydroelectric power station is a three-phase synchronous generator, in established regime, the rotor is shaftedby the turbine and turns in the angular speed (Ω_N)called synchronous speed. The magnetic field created by the rotor turns with the same speed and, according to the Faraday's law, it creates in each statoric winding an alternative electromotive force (e.m.f) of the form:

$\varepsilon = \sqrt{2}E\cos(\omega nt + \theta)$(6)

The rotor receives a mechanical couple (T_m) from the turbine whereas the interactions between the currents circulating in the windings develop a reminder torque called « electromagnetic torque Te ». The equations of movement from the rotor will be:

$\frac{d\delta}{dt} = \Omega - \Omega_N$(7)

$\frac{1}{\Omega_N}\frac{d\Omega}{dt} = \frac{\Omega_N}{2H}(T_m - T_e)$(8)

Where:

Ω_N: Angular speed called synchronous

Ω : Angular speed

E. MODEL OF THE TURBINE

The supplied mechanical power is fixed by the openingdegree of thewater admission valve in the conduct. When we modify the opening degree of valves, the water flow in the conduct does not immediately reach its new value of balance because the weight of water becomesslow. The differential equation which translates this dynamic variation is:

$\frac{1}{\Omega_N}\frac{dQ}{dt} = \frac{1}{T_w}\left(1-\left(\frac{Q}{Z}\right)^2\right)$(9)

Where:

T_m: mechanical constant of time

T_w: hydraulicconstant of time

Q: the water flow in the pipe

As previouslyindicated in this equation; Q, Z and Tw are additional. The mechanical power is given by:

$P_m = \frac{Q-Q_V}{1-Q_V}\left(\frac{Q}{Z}\right)^2$(10)

The mechanical power collected by the turbine is indeed lower than the total power given up by the water. A part of that water is lost when we refer to the water inside the conduct and the turbine. We deduct themechanical torque, in a dimensional variable, and withdraw:

$T_m = \frac{\Omega_N}{\Omega}\left(\frac{Q}{Z}\right)^2\left(\frac{Q-Q_V}{1-Q_V}\right)$(11)

F. ELECTROMAGNETIC PATTERN

The alternator delivers an alternative voltage and current in the network terminals to which it is connected. These greatnesses depend not only on flows of magnetic flux densities existing in the stator and the rotor of the alternator but also on the parameters of the network, the high voltage line and the transformeron the one hand. On the other hand, the circuit modeling the excitation winding settled on the rotor is given by the relation between these greatnesses:

$V_f = R_f . i_f + \frac{1}{\Omega_N}\frac{d\psi_f}{dt}$(12)

The electromagnetic torque can be expressed according to variables, (δ,ψ_f)and (ψ_{q1}); the electric power delivered by the power station is given up by:

$P_e = \frac{\Omega}{\Omega_N} T_e$(13)

Where:

Ω_N: Angular speed called synchronous

Ω : Angular speed

P_e : Electric power

T_e :Constant of hydraulic inertia

G. VOLTAGE REGULATOR

For not damaging or perturbing various components of the network, it is important to maintain the amplitude of the voltage (V) in acceptable ranges. That is why the synchronous machines areequipped with a voltage regulator. This one acts on the power supply voltage of the excitation winding (Vf)in order to maintain the amplitude of the voltage delivered (V) close to an instructionvalue (V_0). The functioning of such a system is governed by the following differential equation:

$\frac{1}{\Omega_N}\frac{dV_f}{dt} = -\frac{V_f}{T} + \frac{G(V_0-V)}{T}$(14)

Here the constant of time (T) and the gain G characterize the performances of the voltage regulator. The voltage V, expressed according to ,ψ_f andψ_{q1} is written:

$$V = \left[\left(\frac{X_d{}' . V_r Vr \cos\delta + X_e . \psi_f / T_{d0}{}'}{X_e + X_d}\right)^2 + \left(\frac{X_q{}' . V_r \sin\delta + X_e . \psi_f / T_{q0}{}'}{X_e + X_q{}'}\right)^2\right]^{1/2} \quad (15)$$

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IV. MODELING OF THE GENERATOR OF THE PROJECT GREAT ING

A. TYPICAL VALUES OF THE PARAMETERS FROM THE HYDROELECTRIC POWER PLANT

The criteria of generators design generally give rise to values of parameters which are close to the power plant one another. The values of constant (Tm) are generally situated between 4 and 8seconds. The report of the mechanical constant of time on the hydraulic constant of time (Tm/Tw) is situated between 3 and 7. The amortization of the load varies between 0 and 3. The constant of time of the experimental valve is generally considered equal at 0,05 seconds or neglected. The gain of the experimental valve is generally equal to 5 for the mechanical regulators of Woodward brand.

B. VALUES OF THE PARAMETERS FROM THE GENERATOR GREAT INGA

For the case of Inga's hydroelectric power plants; the values of the parameters stemming from the ministry and from the national committee of energy are included here:

(BoardIV.1 Parameters of the power plant of the project greatInga)

parameter	Symbol	Unit	CHE.I_1	CHE.I_2	CHE.I_3	CHE.I_G
Moment of gyration	PD^2	J	360	360	360	360
Length of the conduct	L	m	86	105	110	135
Acceleration of gravity	g	m/s^2	9,81	9,81	9,81	9,81
Height of the clear fall	H_o	m	52,50	56,20	61,20	155
Power ofgenerator	P_G	MW	60	178	270	750
Voltage ofgenerator	V_G	kV	11	16	16	16
Speed of the generator	N_G	tr/m	136	107	375	375
Constant of time of the experimental valve	T_p	s	0.05	0.05	0.05	0.05
Statism	R	p.u	0.05	0.05	0.05	0.05
Synchronizer torque of the network	K_s	p.u	0,66	0,66	0,66	0,66
Gain of the valve	K_p	p.u	0,44	0,44	0,44	0,44

Where:
CHE I_1: Inga 1 hydroelectric power plant
CHE I_2: Inga 2 hydroelectric power plant
CHE I_3: Inga 3 hydroelectric power plant
CHE I_g: Great Inga hydroelectric Power plant

C. FUNCTION OF TRANSFER OF VACUOUS GENERATOR

$$G_o(s) = \frac{f(s)}{p(s)} = \frac{1+2T_e.S}{1+0,5\,T_e.S} = \frac{1}{T_m S} \qquad (16)$$

$$G_o(s) = \frac{(1+1,68\,s)}{(1+0,42\,s)} = \frac{1}{185\,s} \quad H(s) = 1,5$$

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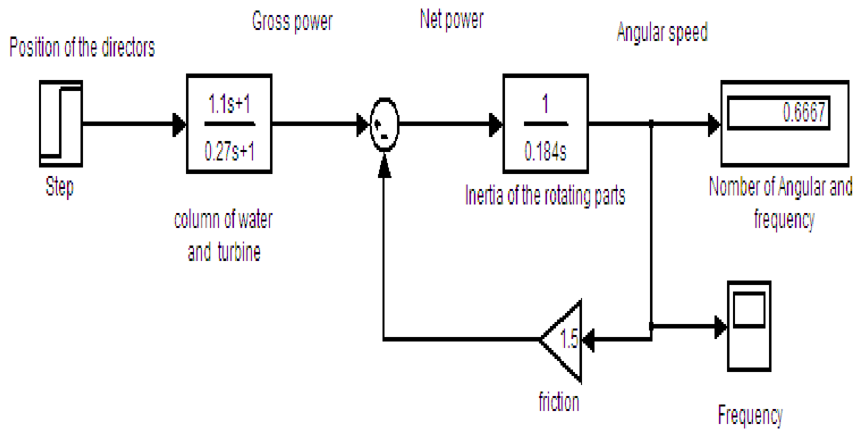

Fig 2. Functional diagram of vacuous generator

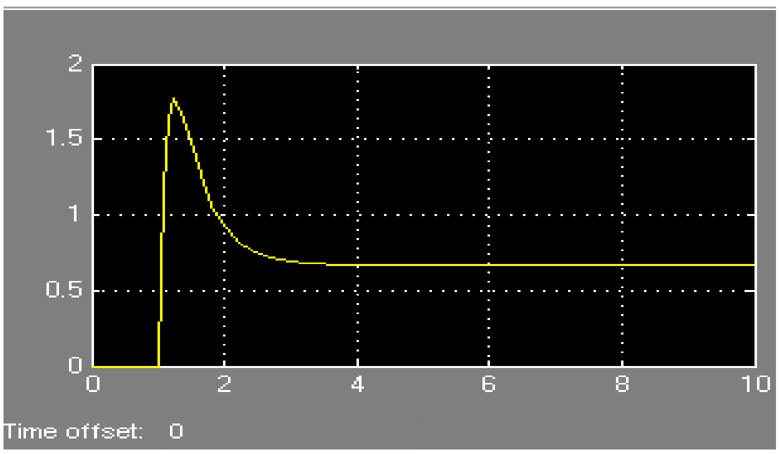

Fig 3. Curve of the stability of the frequencyfrom vacuous generator according to the time

The function of transfer from vacuous generator is:

$$G_v(s) = \frac{\frac{1}{f}(1-T_w.s)}{\left(\frac{T_w}{2}s+1\right)\left(\frac{T_m}{f}s+1\right)} \quad (17)$$

With $T_w(s) = 2.T_e s$ and f= D+ y

Where:
D: damping coefficient of the load: 0 to 3
Y:difference of height between the low and high levels of water: 1,5
$G_v(s)$: is the function of transfer of the vacuous generator
f : is the coefficient of appropriate amortization of the generator by friction (p.u)
s : is the operator of Laplace
T_m : is the mechanical constant of time
T_w:is the hydraulic constant of time

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$$G_v(s) = \frac{(0{,}66 + 1.1088\,s)}{(0.42\,s + 1)(123{,}33\,s + 1)}$$

D. FUNCTION OF TRANSFER IN COMMUNITY POLICING ON A NORMAL LOAD

The configuration of the generator on community policing load involves that it feeds only the load and that the visible power of the load is lower than that of the generator. The functional diagram of the generator connected with a local load is presented to the figure below.

$$G_i(s) = \frac{(1-T_w.S)}{\left(\frac{T_w}{2}S+1\right)(T_m.S+(D+f))} \quad (18)$$

Where:
G_i(s):isthe function of transfer of the generator in community policing
D : is the amortization of the load (*p.u.* active power / *p.u.* frequency)
f: is the coefficient of appropriate amortization of the generator by friction (*p.u*)
S : is the operator of Laplace
T_m : is the mechanical constant of time
T_w : is the hydraulic constant of time

$$G_i(s) = \frac{(0{,}22 + 1{,}1088\,s)}{(0.42\,s + 1)\,(41{,}11\,s + 1)}$$

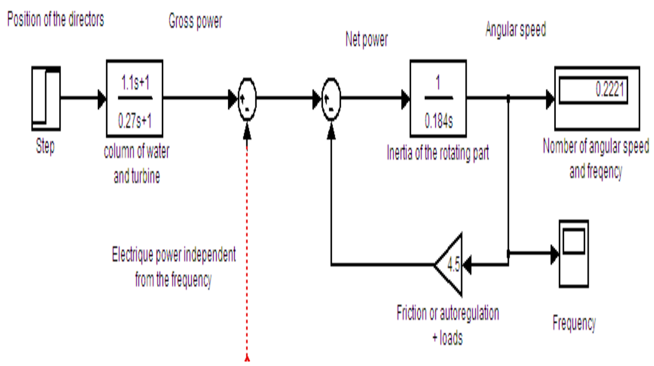

Fig 4. Functional diagram of the generator connected with a load

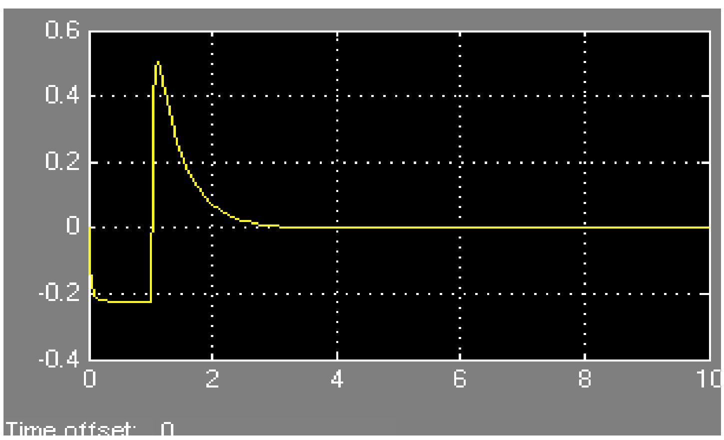

Fig 5. Curve of the stability of the frequency from vacuous generator connected with a load according to the time.

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E. FUNCTION OF TRANSFER FROM THE GENERATOR IN NETWORK

The function of transfer of the speedfrom generator according to the position of the directors is:

$$G_r(s) = \frac{\frac{S}{K_S\Omega_0}\,(1-T_W.S)}{\left(\frac{T_W}{2}.S+1\right)\left(\frac{T_m}{K_S\Omega_0}.S^2+\frac{K_D}{K_S\Omega_0}.S+1\right)} \quad (19)$$

Where:
G_r (s) : is the function of transfer of the generator in network
KD :is the coefficient of amortization of the shock absorbers of the generator (*p.u*)
Ks :is the synchronizer torque (*p.u*)
S : is the operator of Laplace
T_m : is the mechanical constant of time
T_w : is the hydraulic constant of time
Ωo : is the nominal angular speed (rad/s)
We obtain

$$G_r(s) = \frac{0{,}01\, s\,(1 + 1{,}68\, s)}{(1 + 0{,}42\, s)(7{,}1\, s^2 + 0{,}025\, s + 1)}$$

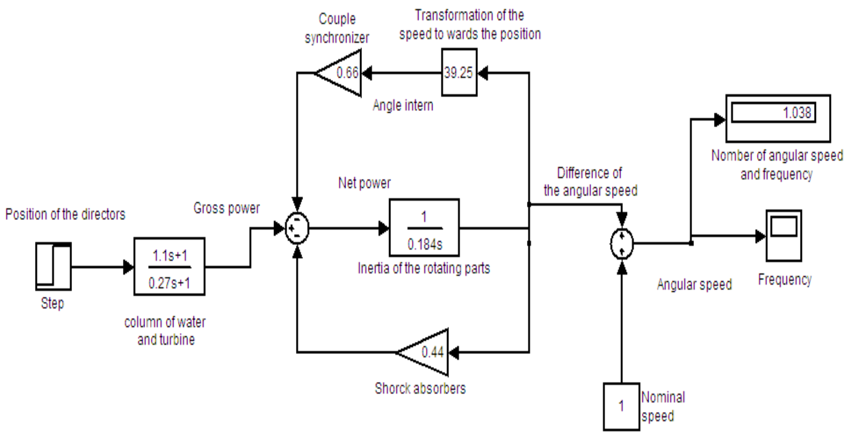

Fig 6. The functional diagram from the generator in network

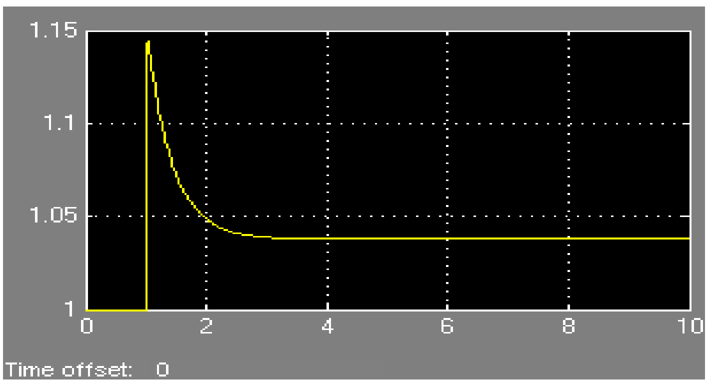

Fig 7. Curve of the stability of the frequency from the generator in network according to the time

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V. SIMULATIONS AND RESULTS

A. DIGITAL APPLICATIONS TO THE PROJECT GREAT INGA

In titular experimental, the regulation of parameters from the power plant (alternator) is a function of the power from the network. The data of experiments of the isolated electrical network are in the board below.

(Board V.1 Estimated data of the isolated network to the project great Inga)

Parameters	**Symbol/unit**	**Net$_1$**	**Net$_2$**	**Net$_3$**	**Net$_4$**	**Net$_5$**
Vacuous speed	N_o (tr/min)	375	375	375	375	375
Vacuousfrequency	F_o (Hz)	50	50	50	50	50
Torque	C_m (MNm)	15,5	15,5	15,5	15,5	15,5
Vacuous voltage	V_o (kV)	16	16	16	16	16
Network power	P_r (MW)	250	500	750	1000	1250
Network voltage	U_r (kV)	500	500	500	500	500
Resistance of winding	R (MΩ)	0,25	0,25	0,25	0,25	0,25
Efficiency	H (%)	0,90	0,90	0,90	0,90	0,90

To note : Net = electric network

When the alternator is linked on the network, it produces a resisting torque on the turbine which slows down slightly its speed, as a result the frequency is slightly lower than 50 Hz, and theparameters of the generator vary.

B. RESULT OF THE SECOND ELECTRICAL NETWORK WITH NO REGULATION (NET$_2$)

To note: $\boldsymbol{\alpha} = \frac{P_r}{U.cos\varphi.\sqrt{3}}$ (20)

(Board V.2 Results of the second electrical network with no regulation (Net$_2$)

Parameter	**Formula**	**Obtainedresults**
Power supplied by the turbine	$P_{ft} = P_r + [(\alpha)^2 . R]$	590,172*MW*
Generatorefficiency	$\eta = \frac{\text{Pr}}{P_r + [(\alpha)^2 . R]}$	84,6 *%*
Angular speed	$\Omega = \frac{P_r + [(\alpha)^2 . R]}{C_m}$	38,07 *rad/s*
Generatorrevolution per minute	$N = \frac{60}{2\pi}\left[\frac{P_r + (\alpha)^2 . R}{C_m}\right]$	363,59 *tr/min*
Frequency of the supplied currents	$f_r = p.\frac{1}{2\pi}.\left[\frac{P_r + (\alpha)^2 . R}{C_m}\right]$	48,47 *Hz*
Pulsation of these currents which deducts with the frequency	$\omega_r = p.\left[\frac{P_r + (\alpha)^2 . R}{C_m}\right]$	304,6 *rad/s*

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C. GRAPHIC SIMULATION OF THE POWER PLANT TO THE ISOLATED NETWORK

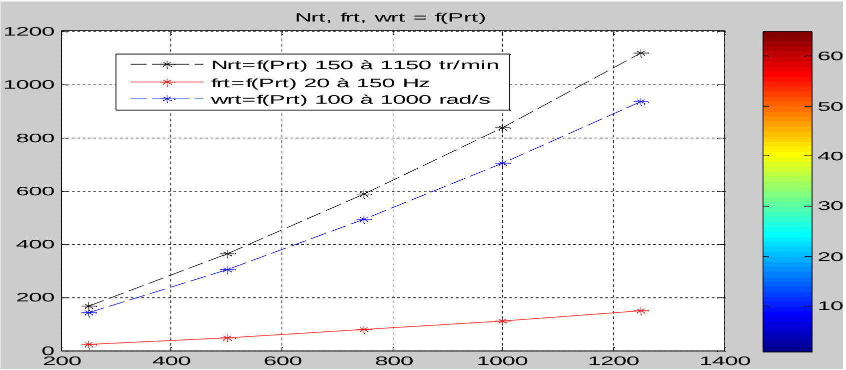

Fig 8.Graphic simulation of the variation of the speed, frequency and pulsation according to the power from the isolated network.

In titular experiment, the stability of the network is linked to the frequency regulation from the value of instruction which is close to the nominal value. The data of experiments of the isolated electrical network are in the board below.

(Board V.3 Data of the isolated network by imposition of the frequency)

Parameter	**Symbol**	**Unit**	**Net$_1$**	**Net$_2$**	**Net$_3$**	**Net$_4$**	**Net$_5$**
Frequency in load	f_r	Hz	49.5	49.5	49.5	49.5	49.5
Vacuous voltage	V_0	kV	16	16	16	16	16
Network voltage	U_r	kV	500	500	500	500	500
Network power	P_r	MW	250	500	750	1000	1250
Resistance of the winding	R	MΩ	0,25	0,25	0,25	0,25	0,25

When we impose the frequency in an energy system, the rotation speed, the angular speed and the pulsation, all these parameters stay constant even if there is the variation of the electrodynamics' parameters from the network. In this condition, the alternator produces in the network, a stable voltage and frequency, but the power supplied by the turbine will give a variable engine torque. Thus, inside an important electrical network, the engine torque, the frequency and the power are bound by a following mathematical relationship:

$C_{mr} = \frac{P_r+\Delta P}{\omega_r}.p$(21)

Where:
p:number of pairs of poles
ω_r :Pulsation of these currents which deducts with the frequency
C_{mr} :engine torque
P_r : Network power

5.5 Result of the second electrical network with the regulation (Net$_2$)

To note :$\beta = \frac{f_r}{p}$(22)

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(Board V.4 Result of the second electrical network with the regulation (Net_2)

Parameter	**Formula**	**Obtainedresults**
Pulsation of these currents which deducts with the frequency	$\omega_r = 2\pi . f_r$	311.0177 rad/s
Rotation speed of the generator	$N_r = 60.\boldsymbol{\beta}$	371.25 tr/min
Angular speed	$\Omega_r = \boldsymbol{\beta}.2.\pi$	38,85 rad/s
Engine torque	$C_{mr} = \frac{P_{ft}}{\boldsymbol{\beta}.2.\pi}$	15.1804 rad/s

F. GRAPHIC SIMULATION FROM A GENERATOR CONNECTED TO THE ISOLATED NETWORK IN SETTLED FREQUENCY

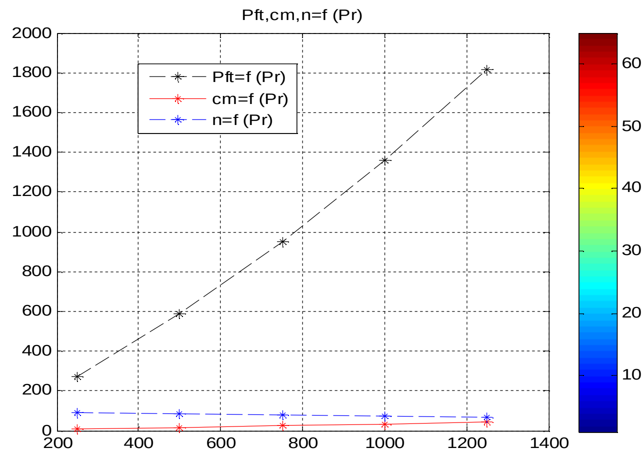

Fig 9. Graphic simulations of the power plants to the isolated network in settled frequency

VI. CONCLUSION

The approach presented in this survey deals with the systematic study of the self-regulation of the frequency and the module of the voltage from alternators. This study enabled us to point out the following parameters:

- ✓ Model connecting regulation elements of an electrical network;
- ✓ Self-regulation loop;
- ✓ Frequency and power regulation loops of turbo-alternator;
- ✓ Establishment of the function of transfer of quick regulator;
- ✓ Setting of network by the sensors retroacting system;
- ✓ Disposition of elements of regulation;
- ✓ Power and voltage regulation generator block diagram;
- ✓ Regulation of a simplified power system.

Besides we developed some equations connected to the functioning of isolated network, to the variation of speed linked to the power of electrical network, the interesting phenomena, the function of transfer and the equation of the frequency and power regulation of the alternator.

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