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**Research Article**

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# The Conventional Regulation Application on the Stability's Hydroelectric Generators: Case of Imboulou Power Plant Generators in the Republic of Congo

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**Abstract** We present with the modeling of the different constituent parts of an electrical network, namely: The synchronous machine (alternators), transmission electrical lines, transformers and loads.

We then present the studied network. A three-phase short circuit on a two-dull line is simulated, it is eliminated by opening the end circuit breakers of the line. The behavior of the system is first studied, when the electrical network is not regulated, and subsequently, the case where the electrical network is regulated, is examined.

**Keywords** Conventional Regulation, Transient Stability, Hydroelectric Generators, CONGO

## 1. Introduction/Background

The transient stability of an electrical network is its ability to regain a position of equilibrium, when it has been removed from its stable operating position by a large amplitude disturbance (short-circuit, loss of a structure, etc.) [1].

## 2. Modeling of electrical networks components

The constituent elements of the electrical network to be modeled consist essentially of the synchronous machine, power transmission lines, power transformers; loads and speed regulators.

### 2.1 Modeling of the sychronous generator

The synoptic diagram of a phase of the synchronous machine, as well as its phase diagram are shown in figure 1.a and figure 1.b, below:

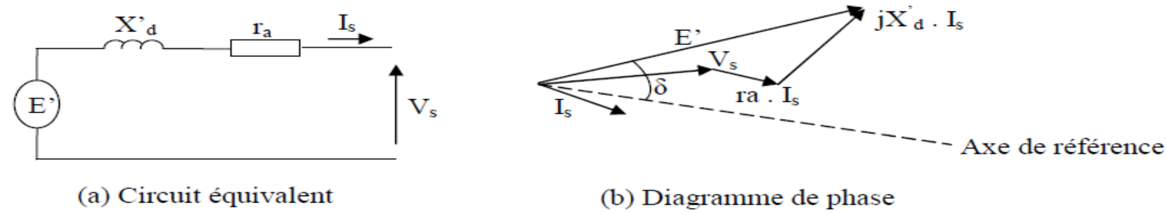



*Figure 1: Simplified representation of a synchronous machine [2],*

From figure 1, the expression of the synchronous machine voltage is given by the following relation:

$$E^{'} = V_s + r_a \cdot I_s + jX'_{d'} \cdot I_s \quad (2.1)$$

E': Transient f.e.m of the synchronous machine.

$V_s$: Generator output Voltages.

$I_s$: Generator output curent.

$r_a$: Generator stator resistance.

$X'_d$: Generator transient reactance

Along the d-q axes, the synchronous generator output Voltages data Vs, are given by the following equations:

$$V_d = E'_{d'} - rI_d - X'_{q'}I_q$$
$$V_q = E'_{q'} - rI_q + X'_{d'}I_d \quad (2.2)$$

The model of the machine used to carry out our study is that obtained from the transformation of PARK, representing the voltage transient variations along the d-q axis [2]. :

$$\frac{dE'_d}{dt} = \frac{[-E'_d - (X_q - X'_{q'}) \cdot I_q]}{T'_{q\circ}} \quad (2.3)$$

$$\frac{dE'_q}{dt} = \frac{[E_{fd} - E'_q + (X_d - X'_d) \cdot I_d]}{T'_{d\circ}} \quad (2.4)$$

With:

Efd: the excitation voltage.

T'do et T'qo: are respectively the open circuit time constants in transient state along the d-q axis.

In our study, we neglect the variation of the transient f.e.m along the d axis. Thus, the synchronous machine will be represented by a simplified model described by an equation, characterizing the variation of the flux on the q axis of the PARK model, and taking into account equation 3.4.

**Mechanical equation of the synchronous generator**

The appearance of a fault in the electrical network causes a break between production and consumption. Two cases can arise:

- The disturbance is small in amplitude and slow.
- The disturbance is of great amplitude.

We will not consider the effect of sub-transient versus rotor oscillation, so we can use the classic generator model [1]. Let's go back to the dynamics equation below:

$$M\frac{d^2\delta}{dt^2} = P_m - P_e - P_d = P_{pacc} \quad (2.5)$$

We notice:

$$M = \frac{j\omega}{S_n}$$

Where:

J: the moment of inertia.

Sn: the nominal apparent power of the generator.

Pm: the mechanical power.

The power of the synchronous generator damper is given by the following equation:

$$P_d = D\frac{d\delta}{dt}$$

Which:

D: is the generator damping coefficient.

Pacc: is the acceleration power of the generator.

The reduced electrical power (Pe), at the output of the synchronous generator, is represented by:

$$P_e = P_E(\delta)\Big|X'_d \cong X'_q \cong \frac{E' V_s}{X'_d}\sin(\delta) \quad (2.6)$$

When:

Vs: the output generator voltage.

E ': the generator f.e.m during the transient regime.

X'd: the reactance between E 'and Vs during the transient state.

After the modeling of the synchronous generator, we present the modeling of the other components of the electrical power grid. The following assumptions are taken into account:

- The electrical power grid frequency is constant,
- The three-phase network is balanced. It is therefore possible to use its single-phase representation.

### 2.2 Modeling of the power transmission line

The transmission line between the two nodes "k" and "m" is represented by the model in □, presented in figure 2, below:

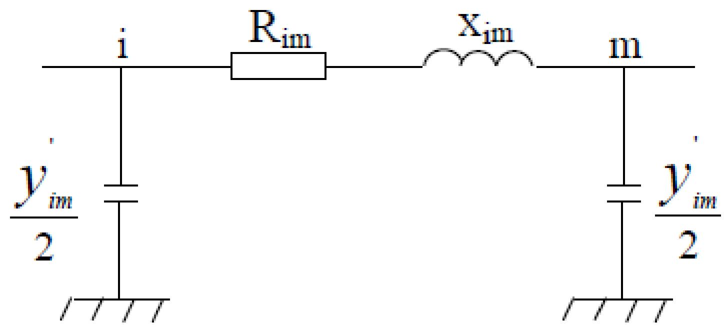



*Figure 2: Simplified diagram of a line in □ [2],*

The line shunt admittance is given by the following equation:

$$Y_{im} = \frac{1}{(r_{im} + JX_{im})m} + Jb_{im} \quad (2.7)$$

Where:

$r_{im}$: line resistance

$X_{im}$: line reactance

$Y_{im}$ /2: line shunt admittance half.

### 2.3 Modeling of the power transformer

As for the line, the model of the transformer adopted is that in □ , represented by figure 3.

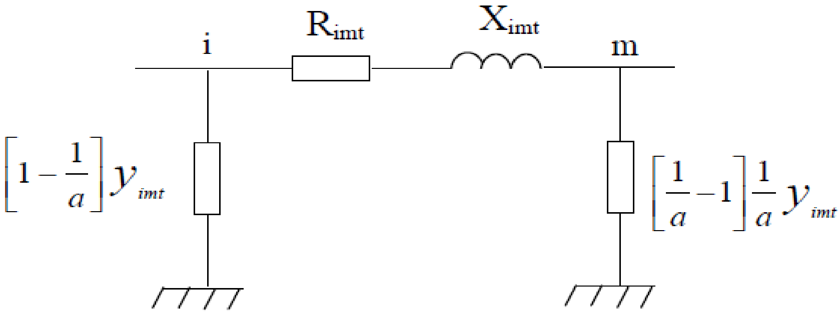



*Figure 3: The □ transformer model[1].*

The transformer admittance expression is given by:

$$Y_{imt} = \frac{1}{r_{imt} + JX_{imt}} \quad (2.8)$$

With:

a:the transformation ratio.

$r_{imt}$: the transformer resistance placed between i and m.

$x_{imt}$: the transformer reactance placed between nodes i and m.

By neglecting the losses caused during its operation, the transformer can be represented by its reactance ximt.

### 2.4 Modeling of the load

Network loads are represented by passive admittances (or impedances) connected to earth. They are obtained from the following relation:

$$Y_{ck} = \frac{P_{ck} - JQ_{ck}}{|V_k|^2} \quad (2.9)$$

Where:

$Y_{ck}$: admittance of the load at node i.

$P_{ck}$: active power injected at node i.

$Q_{ck}$: reactive power injected at node i.
$V_{ck}$: voltage modulus at node i.
The values of $P_{ck}$, $Q_{ck}$ and $V_{ck}$ are obtained by studying the laod flow in steady state.

### 2.5 Modeling of the speed controller

We will model two types of regulators: mechanical speed regulators and PI speed regulators.

#### 2.5.1 Mechanical speed controller

The input of the mechanical speed controller is the speed error and its output is the directional position. The operation of the mechanical governor is based on the use of mechanics and hydraulics.
The elements of the model are the pilot valve represented by a first order transfer function, the servomechanism represented by an integrator, the damper represented by a first order transfer function with zero at the origin and the droop which is a step in the form of a gain between the output (directional position) and the input (speed error). The functional diagram of the speed controller is shown in Figure 4 [1].

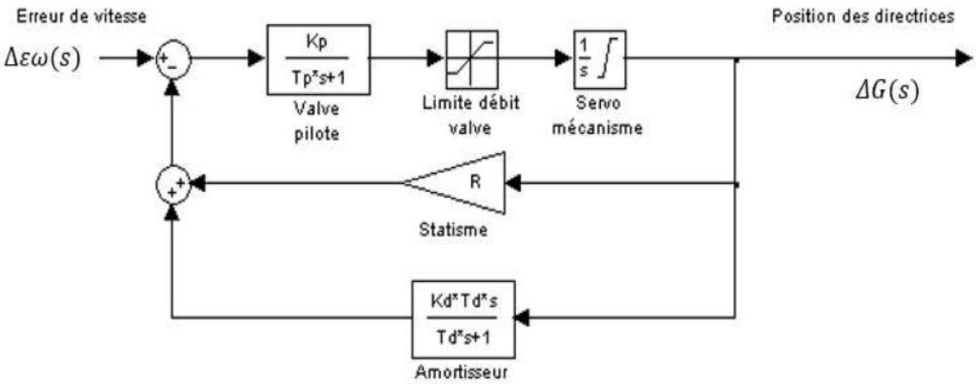



*Figure 4: Mechanical speed controller functional diagram [1]*

It follows from this graph that the transfer function, in the complex plane, of the closed-loop mechanical regulator is given [3]:

$$G(s)_{cmec} = \frac{{}^{1}/_{R}(T_d s+1)}{\frac{T_d T_P}{K_P R}s^3+\left[\frac{T_P}{K_P R}+\frac{T_d}{K_P R}\right]s^2+\left[\frac{1}{K_P R}+\frac{K_d T_d}{R}+T_d\right]s+1} \quad (2.10)$$

$Kp$ is the gain of the pilot valve (s-1), Kd the gain of the damper (without units), $R$ the droop (without units), $Td$ the time constant of the damper (s) and, $Tp$ the time constant of the pilot valve (s).
The parameters imposed in the regulator are the gain and the time constant of the pilot valve. The maximum opening speed of the guiding lines is adjusted according to the penstock's capacity to accept overpressures and the droop setting is a parameter common to all the regulators in a network.
Adjustments are made to the gain and time constant of the damper [3]. The proposed settings relate to the constants $Kd$ and $Td$. With our data, their expressions are then:

$$K_d = |2.3 - (T_w - 1)0.15|\frac{T_w}{T_m} \quad (2.11)$$

$$T_d = |5 - (T_w - 1)0.5|T_w \quad (2.12)$$

### 2.3 Presentation the test power grid

The network used is a single machine network, that of the Imboulou-Ngo section in the Republic of Congo and shown diagrammatically in figure 5. The connection of the alternator to the infinite power network is provided by a transformer and a double-ended line made up of two sections: the first between points A and B, 200 km long and the second between points B and C, 300 km long. The sections are separated by node B made up of a busbar.

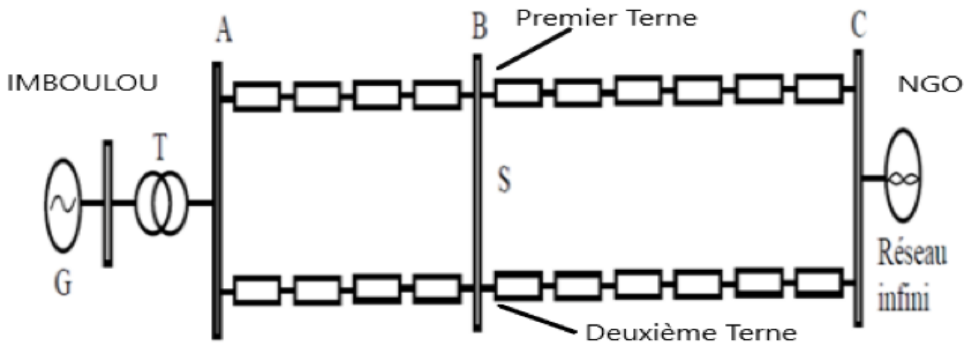



*Figure 5: Fault located at a point of a short-circuited line [8]*

The values of the generator electrical and magnetic parameter examined are those of the generators of the Imboulou hydroelectric power station in the Republic of Congo, and are grouped together in Tables 1, 2, and 3. The optimum setting of the parameters of the regulators is obtained by the Ziegler and Nichols method [1].

**Table 1:** Generator electrical and magnetic parameter value [5]

| **Generator Parameter** | **Symbol** | **Value** |
|---|---|---|
| Rotor permanent reactance (p.u) | Xd | 1.896 |
| Rotor transient reactance(p.u) | Xd’ | 0.32 |
| Rotor subtransient reactance (p.u) | Xd’’ | 0.213 |
| Permanent quadrature reactance (p.u) | Xq | 1.896 |
| Quadrature transient reactance (p.u) | Xq’ | 0.32 |
| Quadrature transient reactance (p.u) | Xq’’ | 0.213 |
| Rotary zero-sequence transient time constant (s) | T’do | 1.083 |
| Quadrature-zero sequence transient time constant (s) | T’qo | 1.1 |
| Rotoric transient time constant (s) | T’’d | 0.135 |
| Subtransient time constant (s) | T’’q | 0.135 |
| Three-phase rated output power (MVA) | Sn | 1000 |
| Rotational inertia (kg m2) | J | 100.000 |
| Stator resistance (p.u.) | Ra | 0.00242 |

The transmission line used is of the "CURLEW" type. The magnitudes of its diagram in π are grouped together in Table 2.

**Table 2:** Line parameter values [5]

| **Parameter** | **Symbol** | **Value** |
|---|---|---|
| Line resistance (Ω/Km) | Rij | 0.739 |
| Line inductance (mH /Km) | Lij | 1.035 |
| Line capacitance (µF/Km) | Cij | 0.11 |

The transformer used is a star-coupled 2-winding transformer. These electrical and magnetic characteristics are grouped together in Table 3.

**Table 3:** Transformer electrical and magnetic data [5]

| **Parameter** | **Symbol** | **Value** |
|---|---|---|
| Leakage inductance % | Xcc | 12.8 |
| Ratio of transformer | U1/U2 | 15.7/220 |
| Apparent power (MVA) | Snom | 45 |
| Primary winding resistance (m Ω) | R1 | 0.739 |
| Secondary winding resistance (m Ω) | R2 | 0.48 |
| Primary winding inductance (mH) | L1 | 0.0502 |
| Secondary winding inductance (mH) | L2 | 32.6 |

After having defined the electrical and magnetic parameters of the lines, transformers and generators, constituting the section of the single machine electrical network to be examined; it is necessary to know the maximum fault elimination time called critical times (tcr), representing the time during which the generators maintain their stability despite the presence of the fault in the network. This is a very crucial element in the analysis and assessment of generator stability. This is the purpose of the following paragraph.

## 3. Results & Discussion

After having defined the electrical and magnetic parameters of the lines, transformers and generators, constituting the section of the single machine electrical network to be examined; it is necessary to know the maximum fault elimination time called critical times (tcr), representing the time during which the generators maintain their stability despite the presence of the fault in the network. This is a very crucial element in the analysis and assessment of generator stability [6]. This is the purpose of the following paragraph.

### 3.1. Determination critical time as a function of the fault position

We simulated the defect first on a dull one (curve in red) then on the two dull ones (curve in blue) using the MATLAB 8 Simulink software.

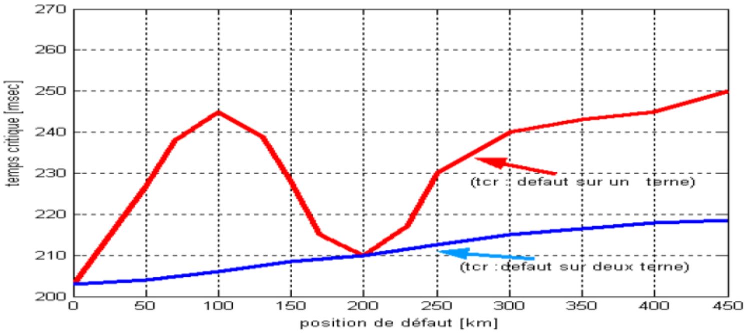



*Figure 6: Curve critical time as a function of the fault position [8]*

The critical time is determined as a function of the position of the defect with respect to node A. As soon as the defect appears on a single circuit, we observe an increase in the critical time exponentially, until reaching the value of (tcr = 0.245 (msec)) for a fault located at a distance of less than 100Km, then gradually decreases (tcr = 210 (msec)) until the fault is eliminated, for one of the fault located at a distance between 100Km and 200Km. We have shown that the critical fault elimination time after application, for a fault located at this point, is 245 ms. We chose this fault location because it is quite close to the alternator and therefore restrictive.

We observe the behavior of the network for two fault elimination times (te): a time less than the critical time that we will take equal to 235 ms and a time equal to the critical time equal to 245 ms.

We see a predictable result, namely reduction of the critical time if the two dulls are affected by the fault and therefore greater stress on the network. Furthermore, the critical time increases as the incident (fault) moves away from node A connected to the generator [8].

### 3.2. Generator electrical power as a function of the fault position

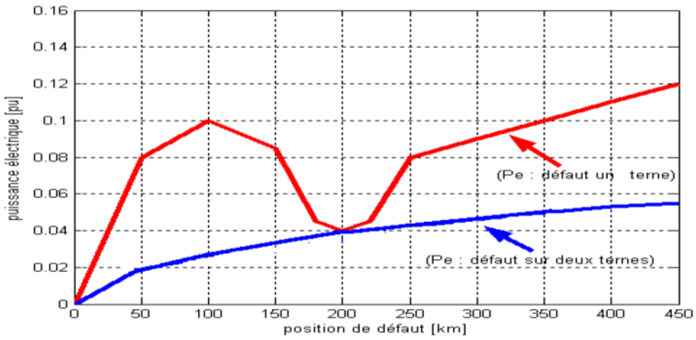



*Figure 7: Curve Generator electrical power as a function of the fault position [8].*

Fig. 7 illustrates the curves of the generator electrical power as a function of the fault position. They are drawn from relation (2.6), previously developed.

We observe a similarity between the shapes of the curves in Figures 6 and 7. As soon as the fault appears on a single circuit, we observe an exponential increase in the electrical power in the network, until reaching the maximum power of the generator (Pe = 0.1 (pu)) for a fault located at a distance of less than 100 km, then gradually decreases (Pe = 0.04 (pu)) until the fault is eliminated, for one of the fault located at a distance of between 100 km and 200 Km.

On the other hand, when the fault appears on the two dulls, the reactances of the two dulls placed in parallel systematically eliminate the effects of the fault on the line, thus allowing the generator to be less affected by the effects of the fault. Hence the slow increase in power in the network (Pe = 0.04 (pu)) up to a distance of 200 km.

### 3.3. Performance Analysis of Unregulated and Regulated Electrical Systems

This paragraph presents the impact of conventional regulation on the behavior of the operating characteristic quantities of the alternator of a hydroelectric power station when a fault occurs during its operation.

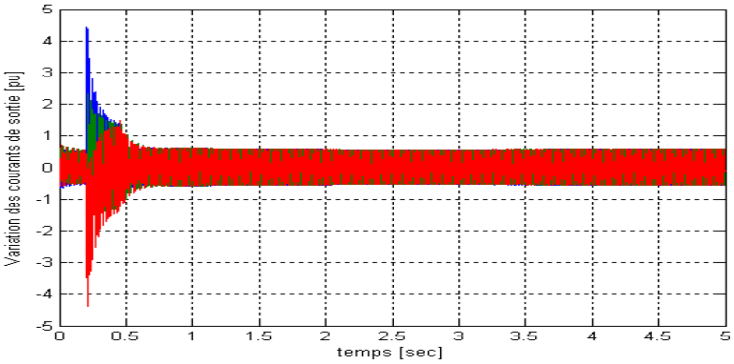
The network used is a single machine network, that of the Imboulou-Ngo section of the Republic of Congo, shown schematically in figure 5, which was the subject of the fault analysis in the previous section.

The behavior of the hydroelectric power station will be examined taking into account that it is equipped with conventional voltage and speed regulators. We will first examine the hydroelectric power station not equipped with a regulator, and secondly, the case of the power station equipped with conventional voltage and speed regulators.

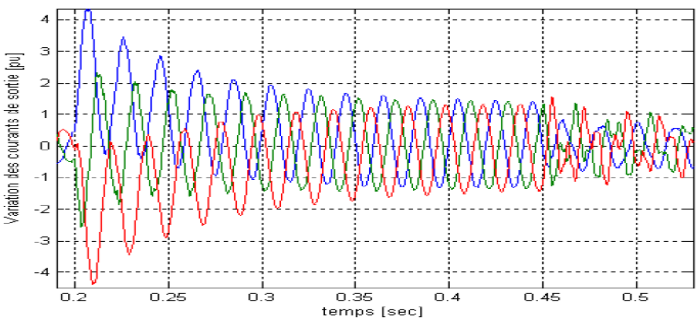
Figures 8 to 12 show the behavior of the characteristic quantities of the alternator (generator), when a fault appears at time t = 0.2 seconds for a fault elimination time equal to te = 245 ms let t = 2.5 seconds [8].

### 3.4. Generator Output Current Variation

Figures 8a, 8b and 8c, represent the curves of output current variation Generator hydroelectric power plant examined previously taking into account figure 5., and the electrical and magnetic characteristics grouped in Tables 1, 2, and 3.




(a)




(b)

*Figure 8: Generator output current variation [8].*

(a) generator output current variation of the hydroelectric power plant for the unregulated system

(b) enlargement of figure 8 a.

(c) generator output current variation of the hydroelectric power plant for the regulated system.

For the unregulated system, the control unit has no regulator, as soon as the fault appears at time t = 0.2 seconds, an exaggerated increase in the amplitude of the current is observed, four to five times the nominal value (5 pu)

followed by oscillations of the signal throughout the rest of the operating period, and until the complete elimination of the fault in the network (Figure 8b).
For the regulated system case, the control unit has a conventional regulator, as soon as the fault appears at the instant t = 0.2 seconds, a slight increase in the maximum value of the current is observed from 0.5 p.u to 1 p.u. Thanks to the corrective action of the regulator, the current is kept constant (0.5 pu) throughout the rest of the operating period despite the presence of the fault, and until its complete elimination in the network (Figure 8c).

### 3.5. Generator Output Voltage Variation

As in the case of currents, we analyze the cases of regulated and unregulated generator.
In Figure 9, we have represented the variation of the Generator output voltage variation as a function of time.

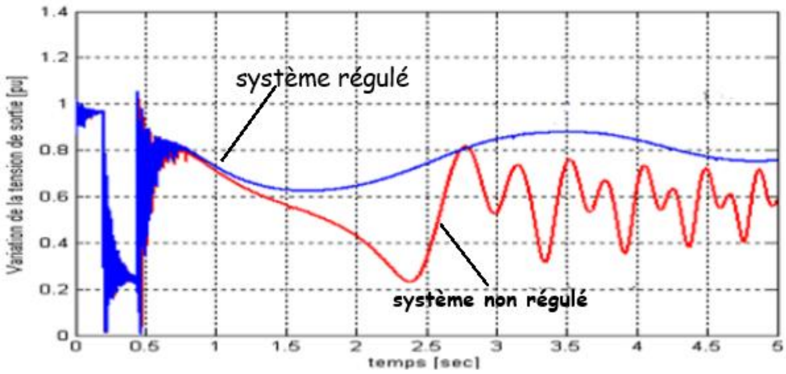



*Figure 9: Generator output voltage variation [8]*

For the unregulated system, when the fault appears at time t = 0.2second, the voltage is crushed from 1 pu to 0.2 pu in the interval 0.2 S≤ t ≤0.5 S. The control unit has no voltage regulator, there is a crushing of the voltage of 0.8 pu until the minimum value of 0.25 pu is reached at the instant te = 2.5 seconds (red curve Figure 9), corresponding to the time of fault elimination until oscillation for the remainder of half of the signal period.
The control unit has a voltage regulator (conventional) as stated above. The system is regulated, the appearance of the fault at the instant t = 0.2second, blue curve in Figure 9 shows the crushing of the voltage from 1 pu to 0.2 pu in the interval 0.2 S ≤ t ≤0.5 S, as in the first case. We subsequently see a peak in the signal of 1.15 p.u at the instant t = 0.5s. Thanks to the corrective action of the voltage regulator, the signal stabilizes, and resumes its sinusoidal shape from the instant t = 0.5s, until an amplitude of 0.85 p.u. [8].
After the current and the voltage, we are interested in the generator electrical power variation.

### 3.6. Generator electrical power variation

We have represented the generator electrical power variation as a function of time in figure 10. As in the previous cases, we analyze the cases of regulated and unregulated generators.

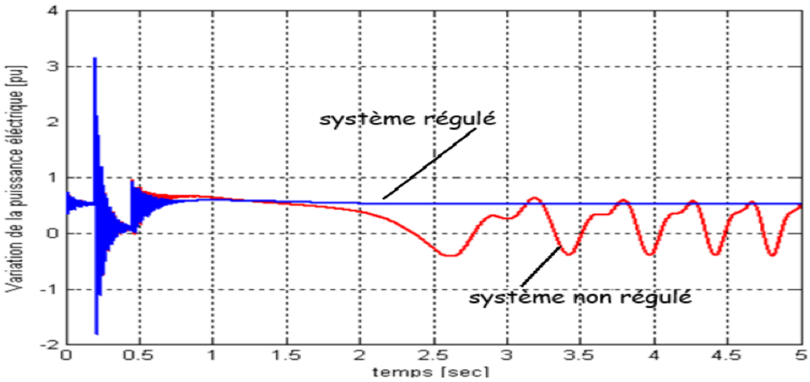



*Figure 10: Generator electrical power variation [8]*

No regulator in the control unit, the system is not regulated and appearance of the fault at the instant t = 0.2second, we see a rapid increase in the power in the network from 0.5pu to 3 pu, then it decreases to is cancelled at time t = 0.5seconds. In the interval 0.5 S≤t≤2.5 S, the power is crushed by 0.5 pu until the minimum value of -0.25 pu corresponding to the consumption of power by the power plant alternators is reached, followed by power oscillations (red curve Figure 10).

The control unit has a conventional regulator, the system is regulated and the appearance of the fault at the instant t = 0.2 seconds, Figure 10 (blue curve) shows a rapid increase in power in the network from 0.5 pu to 3 could Thanks to the corrective action of conventional regulators, the power is kept constant (0.5 p.u) throughout the rest of the operating period despite the appearance of the fault in the network [8].

After the current, the voltage and the power, we dealt with the generator speed variation in the case of an unregulated and regulated system.

### 3.7. Generator speed variation

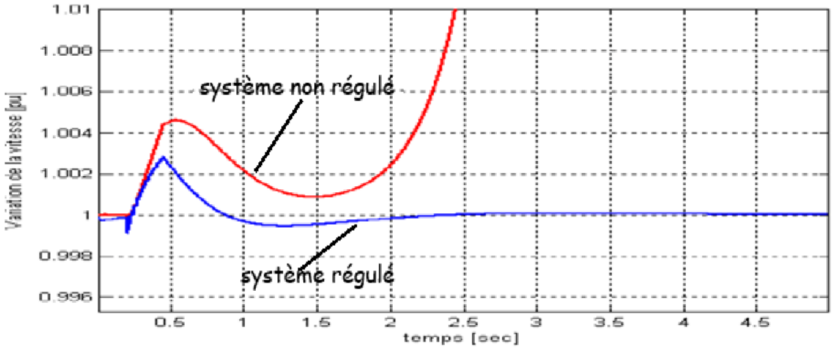



*Figure 11: Generator speed variation [8]*

As in the previous cases, we analyze the cases of regulated and unregulated generators. Fig. 11 represents the generator rotation speed variation as a function of time.

The power station does not have regulators, the initial speed of the generator equal to 1 pu. The appearance of the fault at the instant t = 0.2 second, causes the speed to vary exponentially until the maximum value of 1,005 p.u is reached at t = 0.5 seconds (red curve in Figure 11). At the instant 0.5 S≤t≤2 S, the speed gradually decreases until it reaches the minimum value of 1.001 p.u. at the instant t≥2.5 Sec, the speed value increases instantaneously until the power plant is released. This time, the plant has a regulator. The appearance of the fault at the instant t = 0.2 second, causes the speed to vary exponentially until the maximum value of 1. 0023 p.u is reached at t = 0.5 seconds (blue curve Figure 11). At the instant 0.5 S≤t≤2 S, the speed gradually decreases until it reaches the minimum value of 0. 999 p.u. Thanks to the corrective action of the regulator, the system regains its stability at t = 2 seconds, and maintains a constant speed at 1 p.u, until the fault is completely eliminated [8].

### 3.8. Generator Laod Angle Variation

We have represented the generator laod angle variation as a function of time in Figure 12. As in the previous cases, we analyze the cases of regulated and unregulated generators.

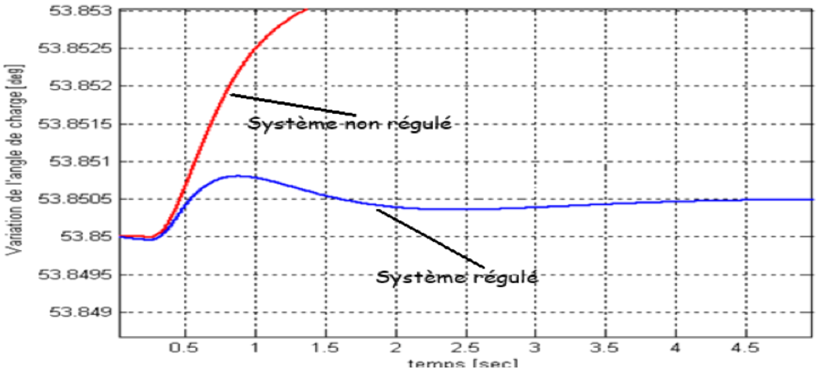



*Figure 12: Generator laod angle variation [8]*

As the plant does not have regulators, the initial value of the load angle is equal to 53.850 degrees. As soon as the fault appears at the instant t = 0.2 seconds, the load angle increases exponentially until it reaches the maximum value of 53.853 degrees (red curve in Figure 12). Attempting to clear the fault at the instant te = 2.5 seconds has no effect, the load angle value continues to increase until the power plant is stalled. The system is regulated, the appearance of the fault at the instant t = 0.2 second, the load angle increases exponentially until reaching the upper value of 53.8508 degrees at t = 0.7 seconds (figure 12 blue curve). Thanks to the corrective action of the regulator, the system regains its stability at t = 1.5s and until the fault is completely eliminated.

Table 4 below shows each characteristic and its initial and final values with the time after which stabilization is obtained. Examination of the results of all the characteristics shows that the system regains its stability after a time t = 2.5s after elimination of the fault [8].

**Table 4:** Initial and Final Characteristics of the Generator Examined

| **Characteristics** | | **Initial values** | **Final values** | **Difference** | **Times (Sec)** |
|---|---|---|---|---|---|
| output current | $i(pu)$ | 0.566 | 0.559 | -0.007 | 1.055 |
| output voltage | $vt(pu)$ | 0.97 | 0.9 | -0.007 | 1.555 |
| electrical power | $Pe(pu)$ | 0.5 | 0.52 | 0.02 | 1.555 |
| Speed | $\Omega(pu)$ | 0.9999 | 1 | 0.0001 | 2.055 |
| laod angle | $\delta(degré)$ | 53.85 | 53.8505 | 0.0005 | 2.055 |

## 4. Conclusion

The study of the different configurations taken by the generator made it possible to understand the variety of behaviors of a generator depending on the load connected to it. Understanding the behavior of the generator and its stability is facilitated by studying the resulting linear equations. The validation of the optimal settings is essential because they serve as a reference during fault detection. Examination of the results obtained for the disturbed network shows that conventional voltage and speed regulation is effective with an adequate choice of regulation parameters. The regulation has been tested for a critical fault elimination time, that is to say for a time that does not allow the network to regain its equilibrium if no regulation is installed [8].

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**Biography**

**Rodrigue Armel Patrick OKEMBA** PhD student in engineering sciences of Marien Ngouabi University, Brazzaville-Congo. He is an electrical Engineering Research laboratory; he is also an expert of rural electrification (decentralized) using photovoltaic systems.

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