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Electrical Network Stability and Performances Improvement Using Biomass Energy: Case of Kalale in Benin

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Abstract— **The power sector in Benin faces many problems, mainly power instability, low domestic power generation and emission of Carbone dioxide because of the use of fossil energy. The use of renewable energies, including biomass is a possible solution given the availability of this one. We design and built a downdraft gasifier suitable for gasifying the cotton biomass. The gas produced is burned in an internal combustion engine to produce electricity. The electrical network stability is ensure by choosing a very convenient node using Voltage Sensitivity Index method. The produced energy is injected in the network to enhance the capacity of the network and guarantee its optimal function. We made an experiment for a region in Benin and the results show the gasification efficiency of about 85% against gas to electric power efficiency of 35%. The network performances have been increase for 30 % after the suitable node have been chosen.**

Keywords— ***biomass, cotton stems/capsules, network stability, gasification, power injection.***

I. INTRODUCTION

The power sector in Benin faces many problems. By the end of 2017, more than 3.8 million Beninese still do not have access to electrical service. In 10 years and regardless of network extensions, there will still be 2.3 million "off-grid" people [1] .The authorities at all level show concern about this issue and a policy named 'Off Grid Electrification' is made. The challenge of this new policy is to bring quality off-grid electricity service to the populations not having access to [2]. This will be accomplished by valuating the resources locally available especially the renewable one. Many projects aiming at the electrical recovery of waste have been undertaken. The WAEMU[1] in 2008 has commissioned the feasibility study of a gasifier operating either at 250kVA or at 400kVA to supply a mini-grid in the Bouka district (Kalalé town). For this study, the installation cost, payback time, and selling price of electricity to the SBEE[2] network were determined [3], [4]. In addition, installation of a 40kVA (32kW) mixed gasifier using wood and agricultural waste is carried out at the Songhai centre in Porto-Novo in 2012. This gasifier operating 8 hours a day was to supply electricity to the plant production of plastic bags of said centre. It is functioning up till day and the centre's technicians have accumulated a experiences in operating and maintaining the plant [5], [6].

Behind these projects, there are many researches trying to analyse the scientific background of biomass valorisation. Many of them emphasize on gasification as alternative to transform biomass into electric energy for isolated areas [7],[8],[9]. For the produced energy to reach end users, there is need of distribution network. The contrast of power availability and demand causes severe instability problem and reduces the network performances. To contribute to the stability of the network, **Murari Krishna** [10] analyse the optimal placement and sizing of the DG unit by minimizing power losses and voltage deviation using Sensitivity based Methods. **Baker Alaa Abdulwahhab Azeez et *al*** [11] study the location of Small hydropower plant at a distribution

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[1] West African Economic Monetary Union

[2] Beninese society of electrical energy

network to enhance its performances by using Voltage Sensitive Index (VSI). As this method is applied to small hydro power plant, the economic realization sometimes is a problem because of the distance between the very sensitive node detected and the power plant [12].

Using biomass based electric energy to stabilize and enhance the technical performance of a distribution network is a new challenge that this work is facing. This study overcome the technical realization problem mentioned above because biomass power plant can be located in place where the produced energy cans easily be injected in main network without problem. We analyse the potential of cotton waste in kalalé town and design a downdraft gasifier to transform this energy into gas and use it as a fuel for an internal combustion generator. We use the Voltage Sensitivity Index (VSI) to determine the most sensitive node and then inject the produced energy into the main distribution network. Each step of the process was modelled and simulation where carried out using Newton-Raphson based software.

II. RESEARCH METHODOLOGY

A. Study of the availability of waste

The study of available agricultural waste for our projet consists of:

- The evaluation of the total waste produced after harvests,
- Determination of competing utilisation of the same waste other than electricity production
- The calculation of the average of the waste over ten (10) years.

The gross production of waste in the fields is determined using the following expressions:

$$M_{waste/i} = (M_{prod/i} * r_{stems}) + (M_{prod/i} * r_{cap}) \qquad (1)$$

With $M_{waste/i}$ the mass of waste available in year i, $M_{prod/i}$ the mass of cotton produced in year i, r_{stems} and r_{cap} the product / waste ratios of the stems and capsules.

Concerning the competing uses of cotton waste, the surveys conducted in July 2018 for the project "Biomass-Electricity", reveals that the residue of cotton after harvest are gathered and burned in the farm. At present, cotton residues are therefore burned without any other form of recovery (compost/natural fertilizer). Thus, a 100% availability of cotton residues is observed in area of study [13].

These survey results make it possible to deduce that all the cotton waste from the municipality of Kalalé could be used for the production of electricity. However, any losses due to collection and transport should be considered. As part of this study, we assume that these losses could be estimated on average between 10 and 30% of the gross quantity available on the fields. Thus, the quantity of waste that can actually be recovered per year is determined as follows:

$$M_{val/i} = \alpha * M_{waste/i} \qquad (2)$$

With $M_{val/i}$ the mass of cotton stalk that can be recovered in year i and α the coefficient of losses.

The average waste over ten (10) years is calculated from the expression:

$$\bar{M} = \frac{\sum_{i=1}^{10} M_{val/i}}{10} \qquad (3)$$

B. Characteristics of cotton stems

The characteristics of the cotton stems used in this article have been gathered from the results of studies carried out on this type of agricultural waste from the "Biomass-Electricity" project [13].

TABLE I. PHYSICO-CHEMICAL CHARACTERISTICS OF COTTON STEMS

Characteristics of cotton stems	Values
Granulometry	>100mm
Humidity	On gross : 5.4% ; On sec : 5.71%
Lower heating value	17.2MJ/kg is 4100kcal/kg
Ash content	4.7%

C. Choice of valuation technology

There are three biomass recovery processes that are dry (combustion, gasification and pyrolysis), wet (anaerobic digestion) and chemical transformation (biofuel production).

The choice of the upgrading technology depends not only on the type and quantity of biomass available but also on the desired final energy form. Since the desired form of energy for this study is electrical energy, only dry process technologies is examined.

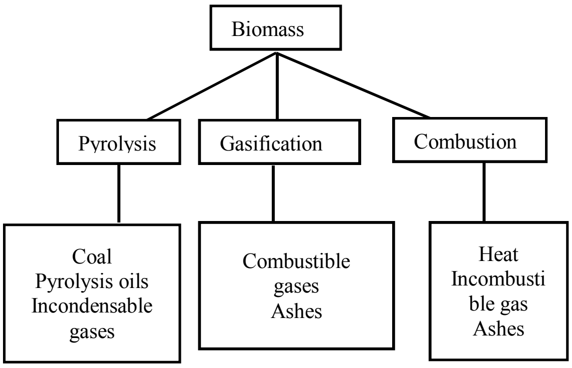


Fig. 1. Thermochemical conversion pathways for biomass and products obtained [14]

Pyrolysis produces coal, pyrolysis oils and incondensable gases. Electricity will be produced in this case, either by burning the coal produced in a boiler (combustion) or by gasifying this coal. This process will therefore have a relatively low efficiency compared to gasification and combustion processes that can directly produce electricity using either gas in a gas engine or steam in a steam turbine. Thus, the comparison will be between the combustion and gasification processes.

TABLE II. COMPARISON OF COMBUSTION AND GASIFICATION TECHNOLOGIES [8]

Processes	Electrical efficiency	Power range
Combustion associated with the Rankine Combined Cycle	10 à 20 %	5 kWe à 3 MWe
Combustion associated with a steam turbine	20 à 30 %	>1 MWe
Gasification associated with a gas engine	20 à 25 %	5 kWe à 5 MWe

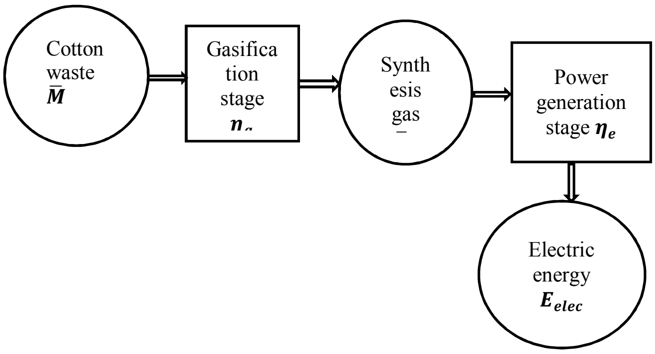
Gasification associated with a pile Solid Oxyd Fuel Cell	40 % à 45 %	5 kWe à 10 MWe

Usually, for a medium power range, gasification and combustion technologies associated with the Rankine combined cycle are used. In addition, the gasification technology associated with a SOFC (Solid Oxyd Fuel Cell) is currently a technology under development [8]. Thus, because of its better performance compared to the combustion technology associated with the Rankine cycle, the gasification technology associated with a gas engine will be retained for the rest of the study. Gasification comprises two major processes: fixed bed processes (co-current and counter current) and fluidized bed processes (dense, circulating and driven). These are economic only for a minimum size of 20 MWe [15]; they are not suitable for this study. Since the fixed-bed process against the current is not suitable for the production of electricity, the process that will be used is the co-current fixed-bed process.

From these analyses, it appears that the cotton waste used for this study will be valued using the co-current fixed-bed gasification technology associated with a gas engine.

D. *Determination of the amount of energy produced by the plant*

The determination of the energy that will be produced by the plant is made from the yields of each stage of transformation. The energy conversion efficiency of the gasifier (gasification stage) is of the order of 70%. The efficiency of the engine-generator set (power generation stage) is of the order of 20 to 30% [15].



The energy of the gas at the exit of the gasifier:

$$\eta_g = \frac{E_g}{\bar{M}} \quad so \quad E_g = \eta_g * \bar{M} \tag{4}$$

With $\bar{M}$ he average mass of recoverable cotton waste per year (in tep).

The quantity of electricity at the output of the engine-generator group:

$$\eta_e = \frac{E_{elec}}{E_g} \quad so \quad E_{elec} = \eta_e * E_g \tag{5}$$

By replacing (4) in (5) we obtain the annual electrical energy produced by the plant:

$$E_{elec} = \eta_e * \eta_g * \bar{M} \tag{6}$$

The electric power is given by the expression:

$$P_{elec} = \frac{E_{elec}}{t_f} \tag{7}$$

By replacing (6) in (7) the produced electric power is expressed as follows:

$$P_{elec} = \frac{\eta_e * \eta_g * \bar{M}}{t_f} \tag{8}$$

TABLE III. SIZING PARAMETERS OF THE PLANT

Parameters	Values
Conversion rate	1 ton of waste → 0,29 tep 1 tep → 11630 kWh
Efficiencies	η_g = 85 % η_e = 30 %

E. *Sizing of the waste storage room*

The storage room of the raw material is dimensioned taking into account the volume of waste and air outlets needed for packaging. The waste is conditioned by balls of weight P_b with dimensions (length, width, height) very precise.

The dimensions of the storage room will therefore be determined by calculating the total number of bales and the area they will occupy. The total number of balls can be determined from the following expression:

$$N_b = \frac{\bar{M}}{W_b} \tag{9}$$

With N_b the total number of balls

$\bar{M}$ the average annual amount of waste collected

P_b the weight of a ball

The building area will be determined by fixing the height of the building and determining the number of stacks of bales to be made according to this height. By thus fixing the height of the building, the number of balls which can constitute a pile with the expression below is determined:

$$N_{b/stack} = \frac{H}{H_b} \tag{10}$$

Avec $N_{b/stack}$ the number of bales per stack

$\bar{H}$ the height of the building

H_b the height of a ball

Make sure that the last bullet in the stack is not too close to the roof of the building.

Next, determine the number of balls that will occupy the area using the following expression:

$$\text{Total number of stacks} = \frac{N_b}{N_{b/stack}} \tag{11}$$

The area of the premises will be determined from the following expression:

$$S = S_b * Total\ number\ of\ stacks \tag{12}$$

Avec S the area of the premises and $S_b$the area occupied by a waste ball.

The dimensions of the room are fixed considering a margin for the circulation (for example 5% of the surface)

F. Choice of elements of the gasification and power generation system of the plant

The choice of the gasification system is based on the feed rate D_a of the reactor which is expressed as follows:

$$D_a = \frac{\bar{M}}{t_f} \tag{13}$$

The brand of the gasification system, the generator set and the transformer is chosen according to the type of waste and the control of the various technologies in the country of implantation.

G. Injecting the produced power into the main network

The injection of the power produced by a decentralized generator (in the case of the biomass power plant as part of this work), can be done by determining the most sensitive node of the network from the calculation of the voltage sensitivity index. (VSI). The main goal of the Voltage Sensitivity Index (VSI) search is to find the most sensitive node in the network from the point of view of voltage sensitivity. It provides a digital solution that allows the operator to monitor the system and initiate corrective measures as needed to prevent network collapse.

The stages of the power injection are as follows [10]:

Step 1: Run load flow for base case.

Step 2: Find the Bus voltage sensitivity indices at each node using VSI equation by penetrating the 20 % of DG value at respective node and rank the sensitivities of all nodes in ascending order to form priority list.

$$VSI_i = \sqrt{\frac{\sum_{k=1}^{n}(1-V_k)^2}{n}} \tag{14}$$

With $\boldsymbol{VSI_i}$ the VSI calculated at the injection node $\boldsymbol{i}$, $\boldsymbol{V_k}$ the voltage at the node k at p.u and n the number of nodes of the network

Step 3: Select the bus with lowest priority and place DG at that bus.

Step 4: Change the size of DG in small steps and calculate power loss for each by running load flow.

Step 5: Store the size of DG that gives minimum loss.

Step 6: Compare the loss with the previous solution. If loss is less than previous solution, store this new solution and Discard previous solution.

Step 7: Repeat Step 4 to Step 6 for all buses in the priority list.

Step 8: End

The study of the power flow is an essential step preceding any electrical network analysis. It allows the calculation of the quantities of a steady-state and balanced network such as the voltages and their phases at all the nodes of the network, the currents in the lines, the active and reactive powers transited in the lines as well as the losses of powers in the lines. For ease of calculation, the quantities used are the magnitudes in the "per unit" system.

The determination of the admittance matrix is the starting point for calculating the "Load flow". For an electrical network of N nodes, the nodal voltages of the system are expressed by the relation:

$$I_{bus} = Y_{bus} * V_{bus} \tag{15}$$

With I_{bus} the vector of complex currents injected at each node

V_{bus} the vector of the complex voltage of each node

Y_{bus} nodal admittance matrix of the system

When the above relation is explained, we obtain the following matrix relation:

$$\begin{bmatrix} \overline{I_1} \\ \vdots \\ \overline{I_N} \end{bmatrix} = \begin{bmatrix} \overline{Y_{11}} & \cdots & \overline{Y_{1N}} \\ \vdots & \ddots & \vdots \\ \overline{Y_{N1}} & \cdots & \overline{Y_{NN}} \end{bmatrix} \begin{bmatrix} \overline{V_1} \\ \vdots \\ \overline{V_N} \end{bmatrix} \tag{16}$$

The admittance matrix is a square matrix ***N*N*** formed from the elements composing the circuit; each element of the circuit being connected to two nodes $\boldsymbol{i}$ et $\boldsymbol{k}$ or to a node $\boldsymbol{i}$ and to the reference node. The elements of the admittance matrix are obtained by applying the following method:

The elements $\boldsymbol{\overline{Y_{ii}}}$ of the diagonal are obtained by summing the admittances of the branches connected to the node $\boldsymbol{i}$. Is :

$$\overline{Y_{ii}} = \sum_{\substack{k=0 \\ k\neq i}}^{N} \overline{y_{ik}} \tag{17}$$

The elements $\boldsymbol{\overline{Y_{ik}}}$ are obtained by making the negative sum of the admittance of the branch connected between the nodes $\boldsymbol{i}$ and $\boldsymbol{k}$. Is :

$$\overline{Y_{ik}} = -\sum_{k\neq 1} \overline{y_{ik}} \quad \text{where } i = 1,2,\ldots,N \tag{18}$$

The relation (16) makes it possible to write the relation below:

$$\overline{I_i} = \sum_{k=1}^{N} \overline{Y_{ik}} * \overline{V_k} \tag{19}$$

The complex quantities $\boldsymbol{\overline{Y_{ik}}}$ and $\boldsymbol{\overline{V_k}}$ can be represented in their polar form from the following expressions:

$$\overline{V_k} = V_k cos\ \delta_k + jV_k sin\ \delta_k \tag{20}$$

$$\overline{Y_{ik}} = Y_{ik} cos\ \theta_{ik} + jY_{ik} sin\ \theta_{ik} \tag{21}$$

The apparent power injected at node i is given by the following relation:

$$\overline{S_i} = P_i + jQ_i = \overline{V_i} \sum_{k=1}^{N} \overline{Y_{ik}}^{*}\, \overline{V_k}^{*} \tag{22}$$

By replacing the expressions (20) and (21) in relation (22) we obtain:

$$\overline{S_i} = \sum_{k=1}^{N} V_i Y_{ik} V_k cos(\delta_i - \delta_k - \theta_{ik}) + jV_i Y_{ik} V_k sin(\delta_i - \delta_k - \theta_{ik}) \tag{23}$$

Which allows to write:

$$P_i = \sum_{k=1}^{N} V_i\, Y_{ik} V_k cos(\delta_i - \delta_k - \theta_{ik}) \tag{24}$$

$$Q_i = \sum_{k=1}^{N} V_i\, Y_{ik} V_k sin(\delta_i - \delta_k - \theta_{ik}) \tag{25}$$

This set of 2N nonlinear equations represents the polar form of the equations of the calculation of the power flow; they make it possible to find the active powers $\boldsymbol{P_i}$ and reactive $\boldsymbol{Q_i}$ injected at the node $\boldsymbol{i}$. Depending on the active and reactive powers generated $(\boldsymbol{P_{Gi}}$ and $\boldsymbol{Q_{Gi}})$ and the requested active and reactive powers $(\boldsymbol{P_{Di}}$ and $\boldsymbol{Q_{Di}})$ at node $\boldsymbol{i}$, we can write:

$$P_i = P_{Gi} - P_{Di} \tag{26}$$

$$Q_i = Q_{Gi} - Q_{Di} \tag{27}$$

By replacing the equations (24) and (25) respectively in the relations (26) and (27), we obtain the expressions of the powers generated hereafter:

$$P_{Gi} = P_{Di} + \sum_{k=1}^{N} V_i\, Y_{ik} V_k cos(\delta_i - \delta_k - \theta_{ik}) \tag{28}$$

$$Q_{Gi} = Q_{Di} + \sum_{k=1}^{N} V_i\, Y_{ik} V_k sin(\delta_i - \delta_k - \theta_{ik}) \tag{29}$$

The system of equations obtained is a system whose complexity of resolution increases as the number of nodes increases; the manual resolution of such systems is therefore only feasible for a network with very few nodes. More complex systems require digital resolution using graphical power grid simulation tools such as PowerWorld, NEPLAN, etc ... or iterative methods such as Newton-Raphson, Gauss-Seidel, etc. .... The method initially used was the Gauss-Seidel method which has the disadvantage of converging into a number of iterations proportional to the size of the network. Currently, the universally adopted method is the Newton-Raphson method or the fast decoupled method, whose number of iterations required to obtain a solution is independent of the size of the network.

As part of this work, the simulation under the MATPOWER software was done using the Newton-Raphson iterative method whose execution code is predefined in the software. The application was made on the Parakou HTA network which is a 20 kV network with 220 nodes.

III. INJECTION RESULTS

The results of the power flow on the Parakou HTA network are as follows:

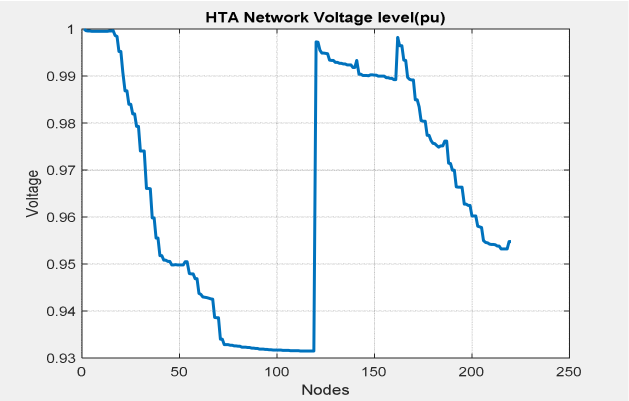


Fig. 2. Voltage level in the HTA Network of Parakou

The permissible voltage levels for MV networks must be between 95% and 105% of the nominal network voltage according to standard NF-EN-50160. Thus, the allowable voltages for the network under test with a nominal voltage of 20kV should be in the range [19kV; 21kV] or between [0,95; 1,05].

The voltage profiles at the nodes of the HTA network of the city of Parakou, show that the smallest voltage in p.u is below the fixed limit. It stands at 0.931 and is spotted at node 119. The active and reactive losses on the network are respectively 323 kW and 170 kVar.

Considering a plant that produces 1500 kW, after the injection of 20% of this power produced or 300kW on the different nodes of the network successively and computing the index of sensitivity of each node, we obtain the following VSI:

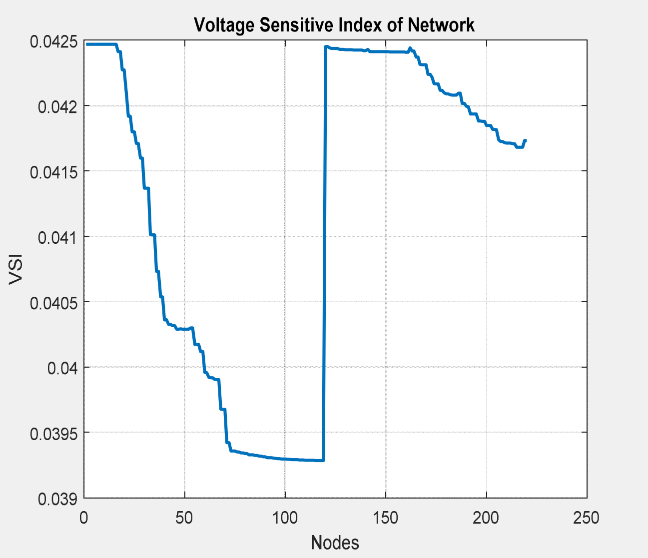


Fig. 3. Voltage Sensitivity Index of Parakou Network

The smallest value of VSI is 0.039 and corresponds to the VSI of node 119 of the network. It is therefore this node which represents the optimal node of injection of the power. It is now necessary to determine by progressive injection at this node the power of the plant which will have to be injected on the network without causing degradation of its performances.

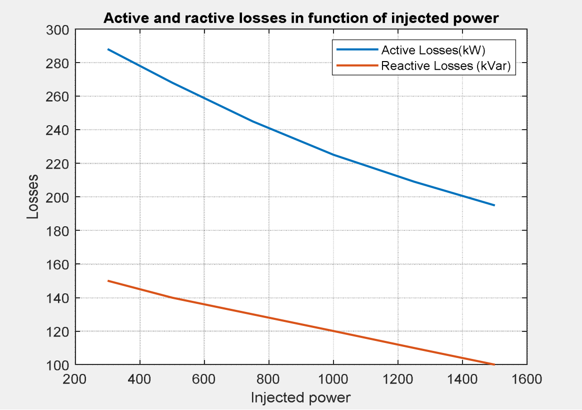


Fig. 4. Active and reactive power losses as function of injected power

The analysis of the figure above shows that as the injected power increases, the active and reactive losses decrease. Thus, it can be seen that after total injection of the power produced by the biomass power station (1500kW) the active losses went from 323 kW to 195 kW while the reactive ones went from 170 kVar to 100 kVar, ie reductions of 39 , 63% and 41.18%.

In conclusion, an active power of 1.5MW or 1500kW can be injected at node 119 of the HTA network of Parakou.

After this injection, the voltage profile in the network is as follows:

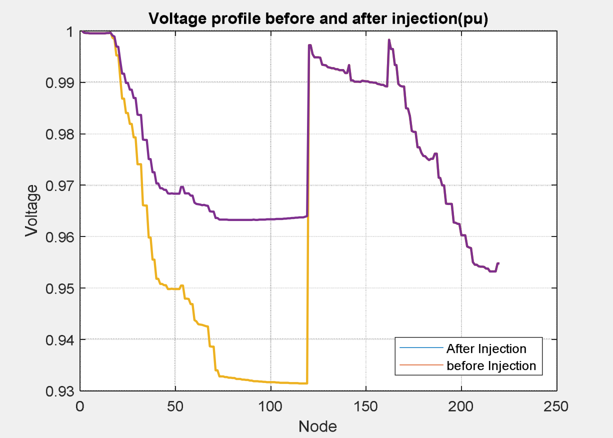


Fig. 5. Voltage levels before and after the injection of power produced by biomass generator

The graph above shows a clear improvement in the voltage profile of the Parakou network. The voltages of all the nodes obtained are within the allowable range of MV network voltages with a minimum voltage in the ratio of 0.931 (node 119) to 0.953 (node 218). This represent 30% performance of the network after injection of power.

IV. CONCLUSION

The main objective of this work is the study of the production of electrical energy from biomass and the injection of the power produced on a distribution network in order to improve the technical performances of this one. We therefore study the sizing the power plant from the cotton stems and capsules. With an amount of waste that can be recovered on average at 17,225 tons per year and the use of co-current fixed-bed gasification technology, the power plant can produce an annual energy of 12,200 MWh and a power of 1,500 kW in the event that it worked all year. This study was also devoted to the study of the distribution network HTA Parakou to identify its technical problems and the best point where will be injected he power produced by the biomass plant. The results of this study revealed the injection point which is identified on the single-line diagram of the network by the node bearing the number 119. This injection made it possible to improve the technical performances of this network notably the level of tension, active and reactive losses.

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