2019 IEEE PES/IAS PowerAfrica

Electric Energy Production from Cotton Residues Using Stirling Engine

V. Zogbochi, P. K. Chetangny, S. Houndedako, A. Vianou
Polytechnic School of Abomey-Calavi
University of Abomey-Calavi
Abomey-Calavi, Benin
victor.zogbochi@imsp-uac.org
Chetangny@yahoo.com
hounde2003@yahoo.fr
avianou@yahoo.fr

D. Chamagne
FEMTO-ST - UMR CNRS 6174
University of Bourgogne Belfort, Franche-Comte, France
didier.chamagne@univ-fcomte.fr

G. Barbier
Laboratoire de Physique et Mécanique Textiles (LPMT)
Université de Haute Alsace
Mulhouse, France
gerald.barbier@uha.fr

***Abstract*— This work designs and simulate a system based on free-piston Stirling engine and a brushless doubly fed induction generator to adapt it to local electrical energy production by using cotton waste. The thermal model of the Stirling machine is based on the polytropic expansion / compression process of the working gas to include a number of parameters and to facilitate numerical simulation. A special emphasis was made on the thermal model of the generator to evaluate the impact of heat on the hot part of the block on its performance. The heat source is a synthesis gas obtained from the processing of cotton residues with a gasification rate of 70%.**

Experimental and simulation results have shown that this machine consuming 0.7 ton of gas i.e. 1 ton of cotton waste is capable of producing a maximum power of 1.5 kW.

Keywords— electrical energy, gasification, solid waste, polytropic process, Stirling engine.

I. INTRODUCTION

Access to energy in sufficient quantity and quality is one of the major development challenges as the Sustainable Development Goals (SDG 7) rightly stipulates: to ensure access to energy that is affordable, reliable, durable and modern for all. This objective, to be met in developing countries in Africa, requires a research policy to adapt available resources for energy production to open up areas with difficult access to electricity. The ECOWAS[1] countries have understood the challenge by initiating a regional interconnection project that will create a common electricity grid for each of the five zones of the sub-region. But the major challenge is the amount of energy to inject into the network to ensure its effectiveness and stability. Another difficulty arises with respect to the accessibility of rural areas far away from the main network because of the high cost of their connection. The solution to these problems lies in decentralized production, based on clean energies that will not only open up electricity but also the socio-economic development of these environments.

To contribute to this, this research work proposes a solution adaptable to all regions regardless of the degree of difficulty related to the extension of the main network. This solution involves the analysis, design and simulation of a generator set consisting of a Stirling engine (SE) and a Brushless Doubly-Feed Induction Generator (BDFIG) that is movable and can be adapted to all hot sources including those from biomass agricultural. The adaptation of biomass to the Stirling engine for rural energy production was the subject of a study conducted by Podeser Erich [1], [2] which proposes an α-type Stirling engine with a 25% (heat / mechanical power). To improve the design and performance of a Stirling engine adapted to biomass, a mathematical model based on fluid dynamics has been proposed by Mahkamov [3]. The transformation of biomass into gas has considerably improved the mechanical efficiency [4] - [8]. Since cotton is the main source of export for the majority of ECOWAS countries, its culture is experiencing considerable growth, leaving behind tons of waste consisting of stalks, stems, shells and linter which are generally abandoned and burned each season. Studies have demonstrated that the Higher Heating Value (HHV) of cotton stems is estimated at 17.54 MJ / kg [9] and its electric potential at 4.76 MWh /ton [10]. Four thermochemical conversion processes are proposed in the literature to transform this raw energy into usable formats namely: combustion, liquefaction, gasification and pyrolysis. Studies have demonstrated that gasification has the best efficiency, ie 75% conversion into gas [11].

We analyse in this work how to recover this energy in the form of gas and burn it as a hot source of Stirling engine. Each stage of the process of transforming cotton residues into electricity is modeled and simulated.

II. RESEARCH METHODOLOGY

A. Technique of gasification of cotton residues

The gasifier adopted for this work is the stratified downdraft gasifier which is very convenient for the transformation of agricultural biomass into gas (confer fig. 1.). The synthetic gas produced is composed of Carbone monoxide (CO), Carbone dioxide (CO_2), hydrogen (H_2), methane (CH_4) and Nitrogen (N_2). It is a clean gas with low tar concentration. The composition of cotton synthetic gas is presented in table 1 [9]. Moreover, the elementary analysis of cotton stack presents the following results [13] :

C : 41,73% ; H : 5,82% ; O : 52,05% ; N : 0,1%

[1] Economic Community of West African States

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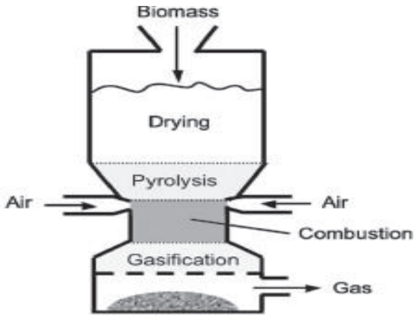

Fig. 1. Downdraft gasifier for cotton residue

TABLE I. COMPOSITION OF THE GAS PRODUCED FROM COTTON RESIDUE

Entities	CO	CO_2	H_2	CH_4	N_2
Percentage	11.1	10.5	9.45	0.9	68.5

Supposing the initial debit of cotton biomass is constant, the debit of energy production is:

$$\dot{E}_s = LHV * \dot{m}_s \quad (1)$$

Where LHV is the Low Heating Value which is calculated with the **Dulong** formula [14]:

$$LHV = 338.3\, C + 1442\left(H + \frac{O}{8}\right)\frac{J}{kg} \quad (2)$$

$\dot{m}_s$ is the mass flow rate related to the geometry of the gasifier and defined as follow:

$$\dot{m}_s = \rho C \sqrt{\frac{2\Delta C}{\rho}} \frac{A_0}{\sqrt{((\frac{A_0}{A_1})^2 - 1)}} \quad (3)$$

ρ=massic volume

C=coefficient of discharge

P=pressure

A_0=large section area

A_1= narrow section area

B. Stirling Engine modelling

The transformation of the synthetic gas energy into mechanical energy is done by using an external combustion engine invented by Robert Stirling in 1816. The choice of the engine is based on the fact that it can be adapted to any area for electricity production and can use all types of heat sources available.

The first model Stirling engine has begun with Doctor **Schmidt** in 1871. Since then, many analytical models are trying to improve the performances of engine by taking into account different types of losses in the generator. The works of **Martin** [15] classify these models into three categories depending on the complexity of their analysis: first order which uses experimental results to predict the engine performances, the second order models consider the engine divided into several volumes and suppose the compression/expansion volume to be isothermal, adiabatic or polytropic and the third order models combine many losses in the machine's process and compute them in the same unit. Recent work of **Babaelahi et al** [16] has shown another aspect of the polytropic process in Stirling engine. In fact, like in other models, the machine is divided into five compartments as in fig. 2. In each compartment, the compression and expansion of the working gas contain a polytropic heat transfer coefficient that allows us to simplify the model and eliminate some hypothesis

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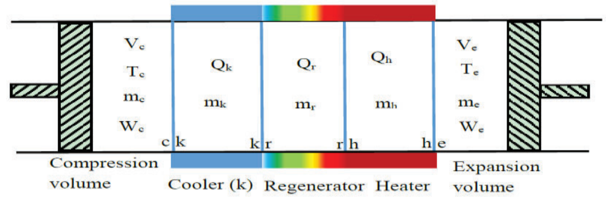

Fig. 2. Compartments of Stirling engine

By definition, a polytropic process is a quasi-static process in which heat and work transfers take place. It is the process suitable to model the compression and expansion of a working gas in the stirling engine [17]. The relationship between the pressure p and the density ρ going from initial state i (i=c,k,r,h,e) to the final state f (f is the next index following i) is defined by:

$$\frac{p_i}{\rho_i^n} = \frac{p_f}{\rho_f^n} \quad (4)$$

n is the polytropic index.

The work done by the expansion of the gas i.e the variation of a volume inside a cylinder is computed as:

$$W_b = \frac{\frac{p_f}{\rho_f} - \frac{p_i}{\rho_i}}{1 - n} \quad (5)$$

The heat transfer is calculated using the following formula:

$$Q = \frac{\gamma - n}{\gamma - 1} W_b \quad (6)$$

Where $\gamma = \frac{C_p}{C_v}$ is Laplace coefficient

The specific shaft work is modeled as:

$$W_s = \frac{n}{1 - n}\left(\frac{p_f}{\rho_f} - \frac{p_i}{\rho_i}\right) \quad (7)$$

The cycle efficiency is defined as [18]:

$$\eta = \frac{Q}{W_s} \quad (8)$$

C. Generator model

The conversion of mechanical energy into electrical energy is made possible by using a brushless doubly fed induction generator (BDFIG). The BDFIG shares the same advantages as the commonly applied DFIG, but has some additional advantages:

- The reliability is improved by eliminating brushes and slip rings. The regular maintenance cost will decrease.
- The BDFIG is a medium-speed generator so that a two-stage gearbox can be used. The capital cost will reduce, and a higher reliability can be achieved.

- The BDFIG has a better grid fault ride-through capability.

Typically, the machine has two stator windings which are of different frequencies, one a fixed frequency connected to the grid, and the other a variable frequency derived from a power electronic frequency converter. Stator winding which is connected directly to the grid is called the Power Winding (PW), and the other connected to a variable voltage, variable frequency converter is called the Control Winding (CW) [19],[20].

C-1. The park model of BDFIG

Using electrical machine analysis theory, dynamic model of BDFIG can be obtained in dq reference frame. Voltage equations for two stator windings and one rotor winding in dq frame are given by the following equations

$$V_{dp} = R_p i_{dp} + \frac{d\phi_{pq}}{dt} - \omega_p \phi_{pq} \quad (9)$$

$$V_{qp} = R_p i_{qp} + \frac{d\phi_{pq}}{dt} + \omega_p \phi_{dq} \quad (10)$$

$$V_{dc} = R_c i_{dc} + \frac{d\phi_{dc}}{dt} - (\omega_p - (P_p + P_c)\omega_r)\phi_{qc} \quad (11)$$

$$V_{qc} = R_c i_{qc} + \frac{d\phi_{qc}}{dt} + (\omega_p - (P_p + P_c)\omega_r)\phi_{dc} \quad (12)$$

$$V_{dr} = R_r i_{dr} + \frac{d\phi_{dr}}{dt} - (\omega_p - (P_p + P_c\omega_r)\phi_{qr} \quad (13)$$

$$V_{qr} = R_r i_{qr} + \frac{d\phi_{qr}}{dt} + (\omega_p - (P_p + P_c\omega_r)\phi_{dr} \quad (14)$$

.

Indexes d, q, p, c and r refer to direct axe, quadratic axe,Power Winding (PW) , Control Winding (CW) and rotor respectively. ω_r is the synchronous speed of the machine defined as:

$$\omega_r = \frac{\omega_p \mp \omega_c}{P_p + P_c} \quad (15)$$

Where ω_p and ω_c are angular frequency of Pw and CWwhile P_p and P_c are their pole pair number

C-2. Thermal model of BDFIG

Heat is always generated when solid parts are working very close to each other. For that reason, the design of electric machine must take into account the thermal losses in such a way to maximize the power output and limit the temperature to the minimum. In addition, adequate heat removal is ensured by convection in air and conduction through the fastening surfaces of the machine and radiation to ambient. The rising of temperature in the machine causes powers losses listed below [22]:

- resistive losses in stator and rotor conductors known as Joule losses ;
- iron losses in the magnetic circuit;
- additional losses;mechanical losses.

Fig. 3 represents the simplified equivalent circuit and table II describe the elements of the circuit. P_{js}, P_{jr} and P_f are stator losses, rotor losses and iron losses respectively.

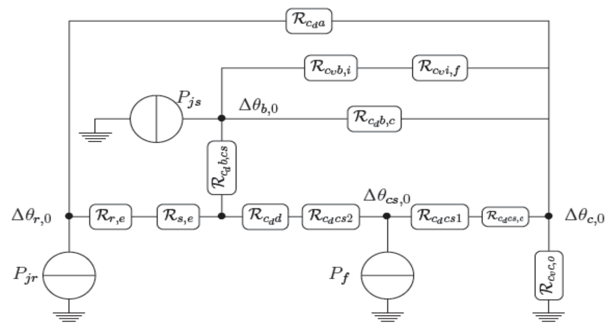

Fig. 3. Simplified thermal equivalent circuit of BDFIG [21]

TABLE II. THERMAL EQUIVALENT CIRCUIT ELEMENTS SIGNIFICATION

Elements	Designation
R*cvca,0*	Convection thermal resistance between external frame and ambient
R*cvi,f*	Convection thermal resistance between internal air and flanges
R*cvb,i*	Convection thermal resistance between coil heads and internal air
R*s,e*	Thermal resistance between stator and rotor
R*cdf,c*	Conduction thermal resistance between flanges and crankcase
R*cda*	Axial conduction thermal resistance in the shaft
Rcdr,f	Conduction thermal resistance between bearings and flanges
R*cdcs*1, R*cdcs*2	Axial conduction thermal resistance of cylinder head
$\Delta\boldsymbol{\theta}_{b,o}$	Core temperature variation
$\Delta\boldsymbol{\theta}_{c,o}$	Motor's carcass temperature variation
$\Delta\boldsymbol{\theta}_{r,o}$	Rotor temperature variation

D. Energy system

The entire electrical energy production consist of the gasifier which transforms the cotton residue into gas that serve as heating agent of the Stirling engine to produced mechanical power for the BDFIG. Fig. 3. depict the overall energy production system. The specifications of each black of the system are given in tables III, IV and V

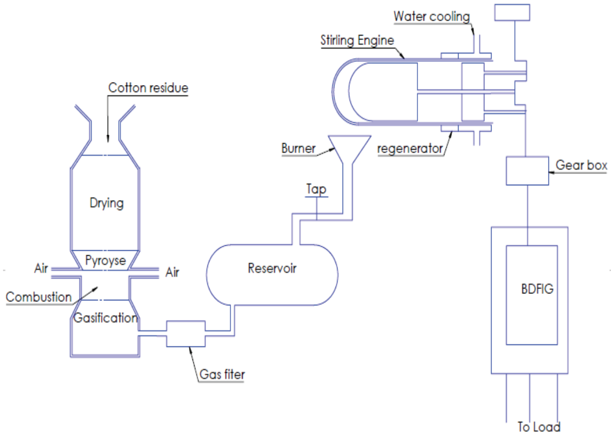

Fig. 4. Overall energy production system

TABLE III. CHARACTERISTICS OF DOWNDRAFT GASIFIER

Designation	**Parameter**	**Value**
Large section area [mm^2]	A_0	125600
Narrow section area [mm^2]	A_1	45216
Density [Kg/dm^3]	ρ	189

TABLE IV. CHARACTERISTICS OF STIRLING ENGINE

Designation	**Parameter**	**Value**
compression clearance volume [mm^3]	V_c	214200
Expansion clearance volume [mm^3]	V_e	214200
swept vols [mm^3]	S_v	870600
Expansion phase angle advance [degree]	Φ_e	90
Regenerator length [mm]	L_r	34
Cooler length [mm]	L_c	87
Working gas	air	

TABLE V. CHARACTERISTICS OF BDFIG

Description	**Parameter**	**Value**
Axial length [mm]	L	240
Air-gap length [mm]	g	1
Stator outer radius [mm]	R_{so}	135
Stator inner radius [mm]	R_{si}	85
Rotor inner radius [mm]	R_{ri}	35
Number of phases	N_{ph}	3
Number of pole-pairs	P_p	4
Rated frequency [Hz]	F_p	50
Number of stator slots	N_{ss}	72
Number of rotor nests	P_r	5
Number of loops per nest	Q_r	4

III. RESULTS

A. Gasifier efficiency

The gasifier performances are summarized in table VI

TABLE VI. COTTON WASTE GASIFICATION PERFORMANCES

Gas efficiency (%)	70
Thermal to mechanical efficency (%)	41.23
High Heating Value (MJ/ kg)	17.2

B. Stirling Engine performances

Based on the characteristics of the engine referenced in table 4, we conduct simulations in Matlab and the results of the performance parameters considered as displayed in table VII.

TABLE VII. STIRLING ENGINE PERFORMANCES

Performance parameters	**Value**
Heat transferred to the cooler[W]	-142494.98
Heat transferred to the heater [W]	345865.41
Net heat transferred to the regenerator: [W]	320.40
Total power output: [W]	2037928.2
Thermal efficiency : [%]	58.9

The total output work and the pressure of the working gas of the engine as a function of crank angle is depicted in fig. 5 and Fig. 6. Under pressure of 150 bar, this machine can produce a work of 16kJ and a torque of 6.5 N.m. The maximum speed of the machine is 2050 rpm.

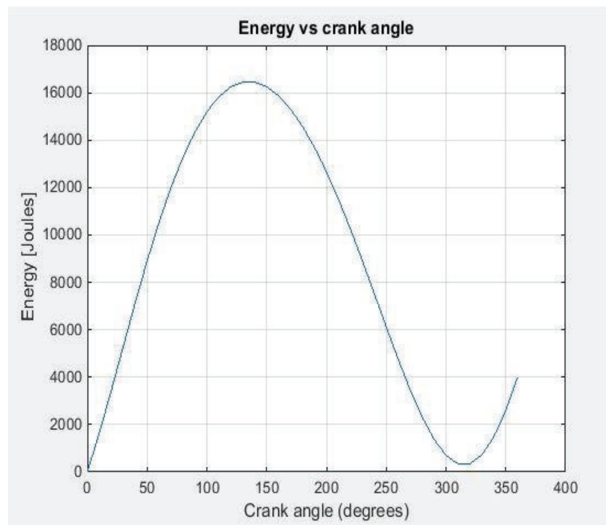

Fig. 5. Stirling engine energy curves

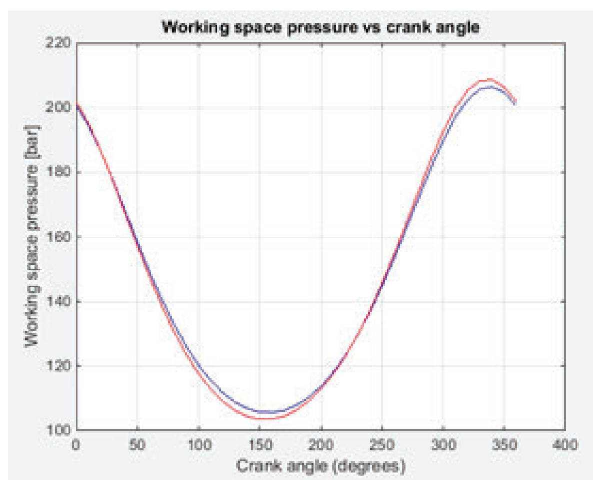

Fig. 6. Working space gas pressure versus shaft angle

C. BDFIG simulation results

The BDFIG described in table V is used for the simulation and the results are shown in Fig. 7 and Fig. 8. The generator's three phases output voltage over time are represented in Fig. 7. According to this figure, the transient regime lasted for about 0.27 second before the value of the voltage stabilized at 250 volts.

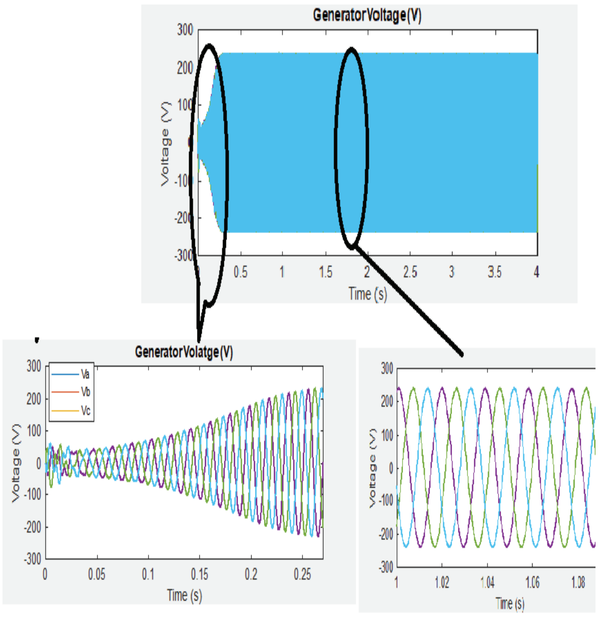

Fig. 7. Generator's 3-phases output voltage

The electromagnetic torque of the generator is depicted in Fig. 8.

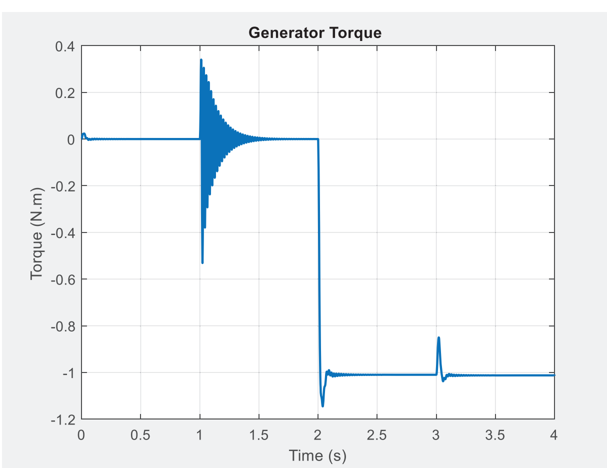

Fig. 8. Generator torque

D. Genrateur thermal analysis

In order to determine how the generator will behave when working in combination with thermal engine, we analyze the temperature rise inside its windings and case. Figure 9 shows the temperature curves for the time of 5000 seconds when the generator will be running at constant speed of 238 rpm. The case temperature reach the steady value at 430 K after 2000 second running time while the winding temperature reach 385 K after 1500 seconds. The machine's heating rate is low and maximum temperature is not so high.

However, as the machine is going to be placed in a confined area and form a compound with external combustion engine, it necessary to provide extra ventilation system in order to quickly dissipate additional heat that may rise from the heat engine.

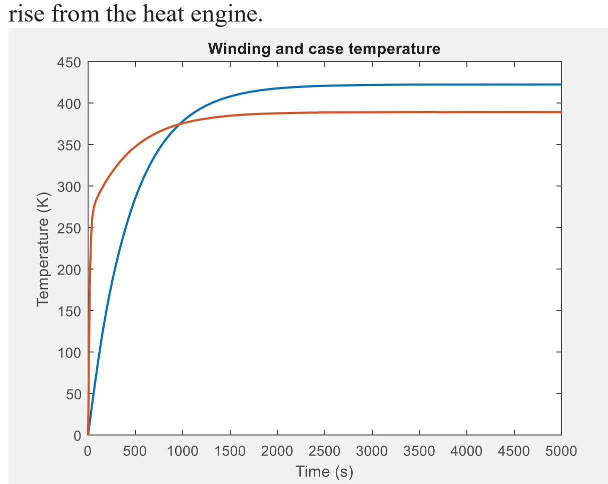

Fig. 9. Stator winding and case temperature evolution over time

IV. CONCLUSION

This work aims at producing electric energy out of the residue of cotton left behind each harvest by designing a block of system composed of downdraft gasifier, external combustion engine and brushless doubly fed induction generator. The designed model requires less maintenance and has proven to produce the energy needed for rural electrification. Each component of the system has been modeled and simulations are made using Matlab software. To optimize the mechanical output of the external combustion engine (Stirling engine) and conduct simulation that is very close to the reality, we use polytropic process to take into account various losses and adjust simulation parameter to the best output.

Our next challenge is to optimize the whole system for better performance and to reduce the energy losses during the mechanical process.

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