Experimental Investigation of the Power Quality of Diesel Engines Operating With Straight *Jatropha Curcas* Oil

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Abstract- Local vegetable oils have become alternative fuels for diesel engines in rural areas of sub-Saharan Africa countries. Many studies have been published on this issue and showed the potential and merits of these renewable fuels. However, most of these studies were mainly focused on energy efficiency, socio-economic and environmental aspects without any allusion to the power quality of engines running with vegetable oils. This paper examines the power quality of diesel engines operating with straight *jatropha curcas* oil which is one of the main vegetable oils produced in Burkina Faso and mostly used to feed diesel engines in rural electrification. Experimentations have been conducted on a diesel engine of nominal power of 9.2 kW. The diesel engine was equipped with a dual fueling system to operate both with straight *jatropha curcas* oil and diesel oil. The Power quality parameters of the system under studied namely grid's voltage and frequency as well as the total voltage harmonic distortions have been investigated and discussed in accordance with the standard EN 50160. The results obtained indicate that straight *jatropha curcas* oil offers globally a better performance in terms of power quality than diesel oil and could consequently substitute validly this later in diesel engines for the electricity generation.

Keywords Power quality, voltage; frequency, harmonic distortion, diesel engine, *Jatropha curcas* oil.

1. Introduction

The high costs of electricity in most of the African countries can be attributed to strong dependence on centralized energy systems which operate mostly with fossil fuels. Besides, those systems require huge investments for establishing transmission and distribution grids that can reach remote regions [1]. The major drawback of this situation is that many countries (79%) within the continent are net oil importers which has a great impact on their energy sector and consequently on their economy [2]. Furthermore, the fossil fuel combustion results in the emission of obnoxious gases, rising concerns about the climate change and other health hazards.

In this context, it is urgent to develop alternative energy fuels such as biofuels that could offer to these countries the prospect of a sustainable development by especially alleviating the region's dependence on fossil-based fuels and improving the access to energy services to the populations [3].

Indeed, biofuel production is a major opportunity, particularly where large arable land areas are available and a large share of the population is involved in agriculture, such as in West Africa [4]. The production of straight vegetable oil (SVO) for direct use as fuel in diesel engines is one of the main branches in the biofuel sector in West Africa.

Using vegetable oils as fuel is not new and dates back to the end of the 19th century with the inventor of the diesel engine [5,6]. For example, in the Port of Abidjan (Ivory Coast, West Africa), where it was becoming difficult to supply conventional fuels, the port construction company powered its 50–800 hp engines with palm oil [7].

There has been renewed interest in this activity in recent years, for stationary applications in the fields of agriculture, industry and power generation [8-13]. *Jatropha Curcas* oil is the biofuel on what most of the investigations have been conducted to substitute diesel oil in West Africa [9,14].

In Burkina Faso, 70,000 trees of jatropha were planted in 2009 and the government has been collaborating with the European Union Biofuel Directive since 2003 to boost this sector in the country [15]. Biofuel development projects such as the "Fondation Faso Biocarburant" (FFB) were established, and financed by Dutch investors [16].

In Mali, there are many biofuel projects that are currently underway; one of which includes a local non-governmental organization (NGO) namely Mali-Folke Center Nyetaa and offers assistance to local farmers to grow jatropha seeds [17]. Communities living near this NGO are provided with electricity generated from diesel engines that use jatropha seeds oil. The project aims to generate 300 KW of electricity to more than 10,000 rural residents. It is expected that more than 100 hectares of jatropha plantation will be established and used as feedstock for the production plants [17].

In Ghana, the government introduced in 2010 a bioenergy policy which was launched to substitute the country's petroleum oil with 10% biofuels by 2020 and 20% by 2030, respectively [18]. The country introduced this policy with the intention to valorize the potential of biomass resources that is abundant for the generation of transport fuels and electricity. Jatropha seeds oil has been identified as one of the most promised oils that can been used [18].

Most of the previous studies about the usage of vegetable oils as substitute of diesel oil are focused on energy efficiency, socio-economic, quality of oil and environmental aspects, and have shown a great interest to use straight jatropha curcas oil (SJO) as substitute of diesel oil (DO) in diesel engines. However, the issue of power quality (PQ) has not been investigated in those studies. Sidibe et al. [11] made a review of the state of the art for straight vegetable oils (SVO) use as fuel in diesel engines. They examined the influence of the type and quality of vegetable oils used as fuel in diesel engines. Blin et al. [19] studied the characteristics of SVO for use as fuel in stationary diesel engines. They proposed a quality standard with a set of specifications (parameters, test method, limit value), which vegetable oils must comply with in order to be used as fuel in stationary diesel engines without causing breakdowns or serious lifetime reductions. Tatsidjodoung et al.[16] on their study focused on the potential and strategies for sustainable energy policies about the biofuel development in Burkina Faso. They showed that the biofuel production strategy in Burkina Faso is mainly based on Jatropha curcas. Ofori-Boateng et al.[10] made a techno-economic feasibility of the use of jatropha oil as fuel in diesel engines. This study showed that jatropha oil is the best 'candidate' for 'green kerosene' and biodiesel in diesel engines. Hanf et al.[21] discussed the opportunity for substituting fossil fuels with biofuels in Burkina Faso and showed that biofuels projects need to be mindful of food security and economic incentives and should be part of national strategies. Tesfa et al.[22] studied the combustion characteristics of diesel engines running with biodiesel blends. They found that the engine running with biodiesel has produced slightly higher incylinder pressure and peak heat release rate than the engine running with normal diesel oil at all operating conditions. They also showed that the brake specific fuel consumption values for the engine running with biodiesel are higher than the engine running with normal diesel by a maximum of 14%.

Srinidhi and Madhusudhan [23] investigated on the Diesel engine performance fuelled with Nickel Oxide Nano Fuel-methyl Ester. Performance investigations were conducted on a single cylinder tangential Vertical-I VCR engine which was fuelled with blends of palm oil methyl ester and conventional diesel in volumetric proportions of 10%, 20 % and 30% naming B10, B20 and B30. This study showed that B20 blend with Nickel Oxide nanofuels with dosing level of 40ppm proved a better alternative to conventional fuel for diesel engine in term of thermal efficiency and specific fuel consumption.

As one can notice, the issue of power quality (PQ) of a generator in relation to the type of fuel has not been well investigated in the scientific literature. The only study we found about this issue is the one of Patinol et al. [24] who assessed the power quality of internal combustion (IC) engines operating with different fuels. They presented a case study of engine using biogas and gasoline to generate electricity and their results showed that electricity generation was of poorer quality with biogas comparatively to gasoline and regarding the frequency and voltage fluctuations.

The power quality problem refers to any power problem manifested in voltage, current, or frequency deviations that results in failure or missed operation of utility or end user equipments [25]. It is nowadays a worldwide issue and it is gaining importance because new equipments are more sensitives to power quality variations [26]. Many recent studies were focused on this issue [27-31] but its correlation with the type of fuel used to run a generator has been weakly investigated as stated previously.

It appears then, the necessity to strengthen the study about the power quality issue of a generator depending on the type of fuels used. The present study is a contribution to overcome this shortcoming by studying the power quality of a diesel engine running with straight Jatropha curcas oil (SJO). SJO is the main vegetable oil used in diesel engines in West Africa for different applications [16, 21]. A comparative analysis was made with diesel oil. Electrical parameters related to PQ issue namely grid's voltage and frequency, and total harmonic voltage distortion (THDV) were assessed based on experimental investigations.

2. Methods

2.1. Usage of straight vegetable oil in indirect-injection diesel engines

There are two types of diesel engines: direct-injection and indirect- injection diesel engines and both of them could be used for electricity generation. In the present study, a direct-injection diesel engine is used. It is the technology widely used for electricity production and other rural applications in West Africa [11]. However, before using straight vegetable oils in direct-injection diesel engines, it is necessary to adapt the engine for operation in "dual fueling" system [32].

Dual-fuelling consists in starting up the engine with diesel oil, then only injecting vegetable oil into the circuit once the engine load is sufficient to give a high temperature in the combustion chamber (500 °C in average), enabling total oil combustion [7]. This procedure is then used in the present study. Table 1 presents the specifications of the engine used.

Table 1. Diesel generator characteristics

Parameters	Specifications
Type	T 12 K
Nominal Power (kWe/kVA)	9.2/11.5
Velocity (rpm)	1500
Voltage (V)	400/230
Maximum current (A)	17

Our diesel generator was then equipped with a dual-fuelling system so that it could operate both with straight jatropha curcas oil (SJO) and diesel oil (DO).

2.2. Power Quality Assesment

The purpose of power quality (PQ) standards is to protect utility and end-user equipment from failing or mis-operation when the voltage, current or frequency deviates from normal values. PQ standards provide this protection by setting measurable limits on how the voltage, current or frequency can deviate from normal values.

Table 2. EN 50160 standard limits

Electrical parameters	Limits
Voltage	▪ The voltage rms value must be in the range Unominal ± 10% (230 V± 10%) for 99% of the measurements ▪ The voltage rms value must be in the range Unominal +10% /-15% (230 V+10% /-15%) for the total 100% of the measurements
Frequency	▪ 50 Hz ± 2 % (ie 49 Hz to 51 Hz) for 95 % of the measurements ▪ 50 Hz ± 15 % (ie 42.5 to 57.5 Hz) for the total 100 % of the measurements
Total voltage harmonic distorsions (THDV)	▪ THDVshould be less than 8% for all the measurements

At present, a number of standards are available for defining limits to various PQ parameters. International communities such as the International Electrotechnical Commission (IEC), the Institute of Electrical and Electronics Engineers (IEEE), the Council of European Energy Regulators (CEER) and the American National Standards Institute (ANSI) have created a set of standards for defining different PQ parameters.

The standard EN50160 set by CEER describes the voltage characteristics of the electricity supplied by a network operator in Europe and most of the African countries at a customer's installation. This standard was harmonized with the IEC standards for definition, monitoring and measurement purposes. In 2010, the latest version of the EN50160 standard was published [33, 34]. As the EN 50160 is the standard currently in force in many African countries, the analysis of the results obtained in the present study was mainly based on it.

The most important parameters defined by the EN 50160 standard are grid's voltage, grid's frequency and total voltage harmonic distortions [35]. The limits of these parameters for low voltage systems (*U*nominal ≤ 1 kV) without any connection to an interconnected grid as the one under consideration in the present study according to the standard EN 50160 are gathered in Table 2.

Figure 1 shows the diagram of the electrical system under study. As explained in the previous section, the diesel engine (DG) is equipped with a dual fueling system so that it could run both with diesel oil and straight vegetable oil (Jatropha curcas oil in the present study).

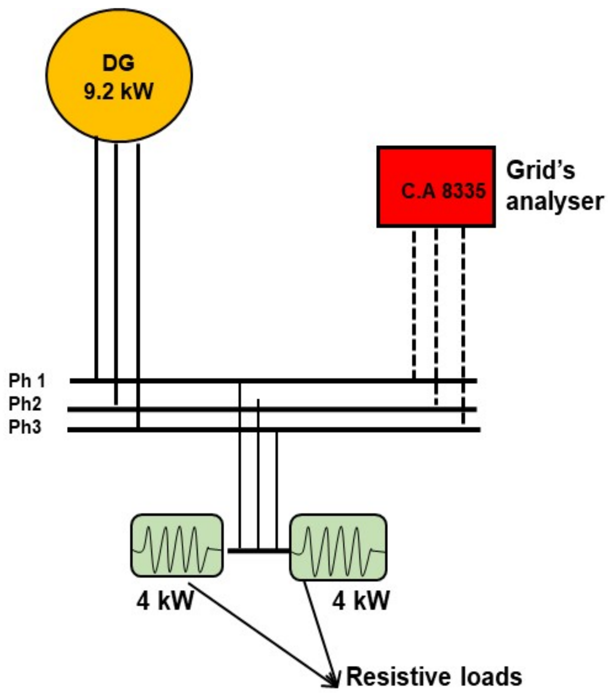

Figure. 1. Diagram of the electrical system under study

Two resistive load benches of 4 kW each were used to simulate the load demand. Resistive loads have been used because they are of linear type and consequently could not cause any harmonic currents in the power system [36]. By doing that, we could then focus only on the harmonic voltage distorsions (THDV) which are from the responsibility of the power operator.

The analyzer C.A 8335 from Chauvin Arnoux was used to measure and record electrical data that have been used for PQ analysis [37].

3. Results and discussion

In this section, the experimental results concerning voltage fluctuations, grid's frequency and voltage harmonic distortions of the diesel engine fueling with straight *jatrophas curcas* oil (SJO) and diesel oil (DO) are displayed and discussed. Figure 2 shows the total power generated and the power on each phase of the three-phase grid formed by the diesel engine during the experimentations.

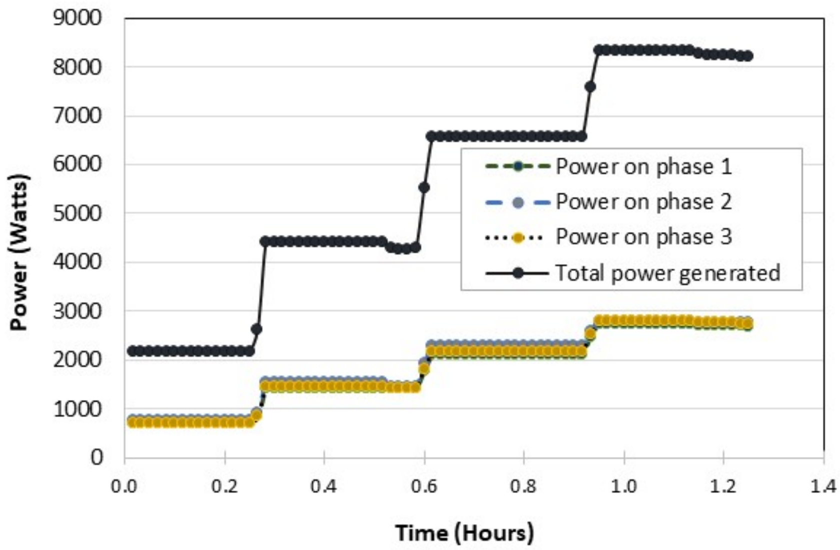

Figure 2. Electricity generation on the grid

One can confirm the symmetric nature of the resistive loads used as the loads on the different phase are quite equivalents.

3.1. Grid's voltage

The EN 50160 standard states that voltage values must be ranged from $U_{nominal}$ to $U_{nominal} \pm 10\%$ for 99% of the measurements.

Figures 3-5 display the voltage of the grid and the voltage rise or drop (ΔV) (in relation to the nominal voltage required by the standard) on the phase 1, 2 and 3 respectively, and for the two scenarios studied (i.e. diesel engine running with SJO and DO). For the two scenarios, one can observe that the amplitude of each phase voltage is not quite equal to the nominal voltage value in low voltage (LV) distribution line (230 V) required by the EN 50160 standard.

Indeed, it can be seen from Fig. 3 that for the phase 1, the values of voltage range from 223.9 to 229.6 V with SJO and from 224.4 to 229 V with DO. Consequently, the voltage drop is between 0.17 and 2.65%, and between 0.43 and 2.43% with SJO and DO respectively. The mean voltage during experimentations has the same value (227.4 V) for the two scenarios. Thus, for the phase 1, one can conclude that whatever the type of fuel is (SJO or DO), the values of voltage are in line with what is required by the norm. As one can see in Fig. 4, for the phase 2, the values of voltage range from 231.4 to 240.2 V with SJO and from 232 to 242.2 V with DO. Consequently, the voltage drop is between 0.60 and 4.34%, and between 0.87 and 5.30% for SJO and DO respectively. The mean voltage has the values 233.67 V (or a voltage rise of 1.59%) and 240.64 V (or a voltage rise of 4.54%) respectively for SJO and DO. Thus, one can notice that for the phase 2, the grid's voltage is inline with the standard whatever the type of fuel is. Furthermore, with SJO, PQ's parameters are even more respective of the norm compared to DO.

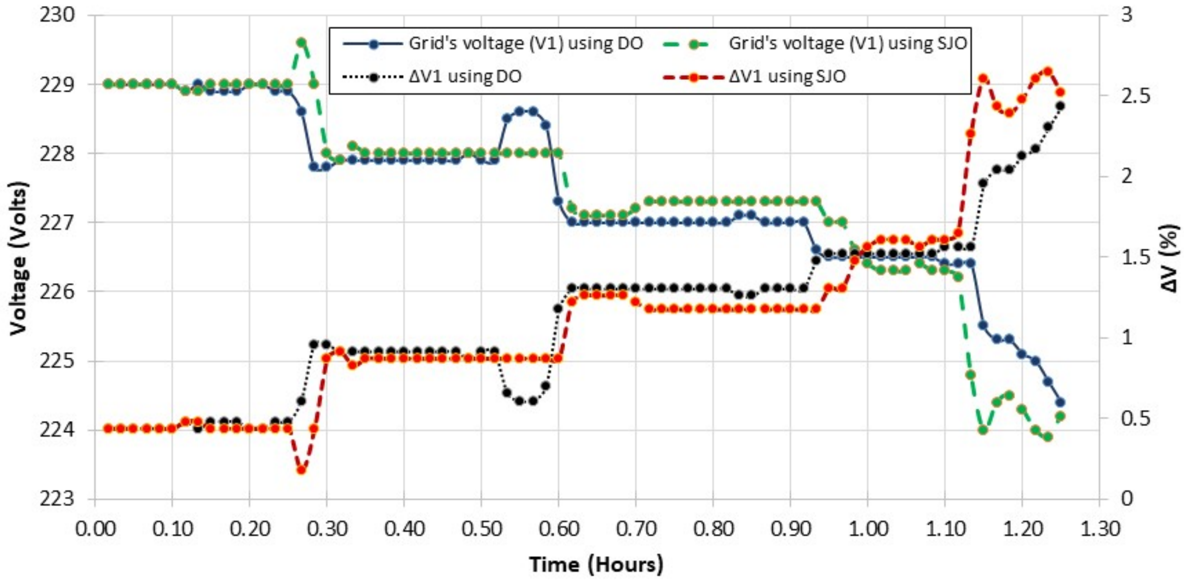

Figure 3. Voltage on the phase 1 of the grid

It can be seen that from Fig. 5 that for the phase 3, the voltage range from 226.7 to 232.7 V with a mean value of 229.98 V (or voltage drop of almost 0%) for the scenario with SJO and from 229.9 to 233.4 V with a mean value of 232.6 V (or voltage rise of 1.15%) for the scenario with DO. In that case also, the standard is fulfilled and the scenario with SJO has a mean value of voltage which is closer to the standard nominal voltage than the scenario with DO.

Thus, concerning the grid's voltage parameter, one can say that during all the experimentations and whatever the type of fuel is (SJO or DO), the voltage fluctuations in relation to the nominal value are no more than 10% ($U_{nominal}$ ±10%) which does not represent a problem in terms of power quality according to EN 50160 standard. It has been also noticed that the scenario with SJO is even more in line with the standard comparatively to the one with DO. So, contrary to the study of Patino et al. [24] which is focused on the electrical parameters surrounding the production of electricity using biogas in the engine of a gasoline generator and which showed that voltage flcutuations of electricity generated with biogas are more high than those with conventional fuel (gasoline), the present study shows a better performance in terme of voltage fluctuations of SJO compared to DO in a Diesel engine.

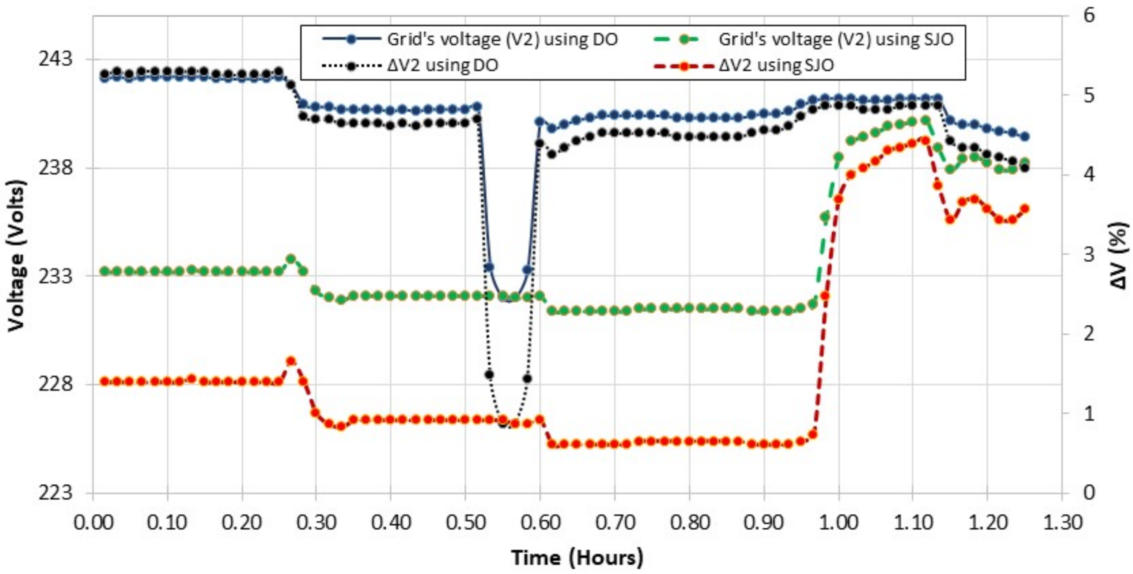

Figure 4. Voltage on the phase 2 of the grid

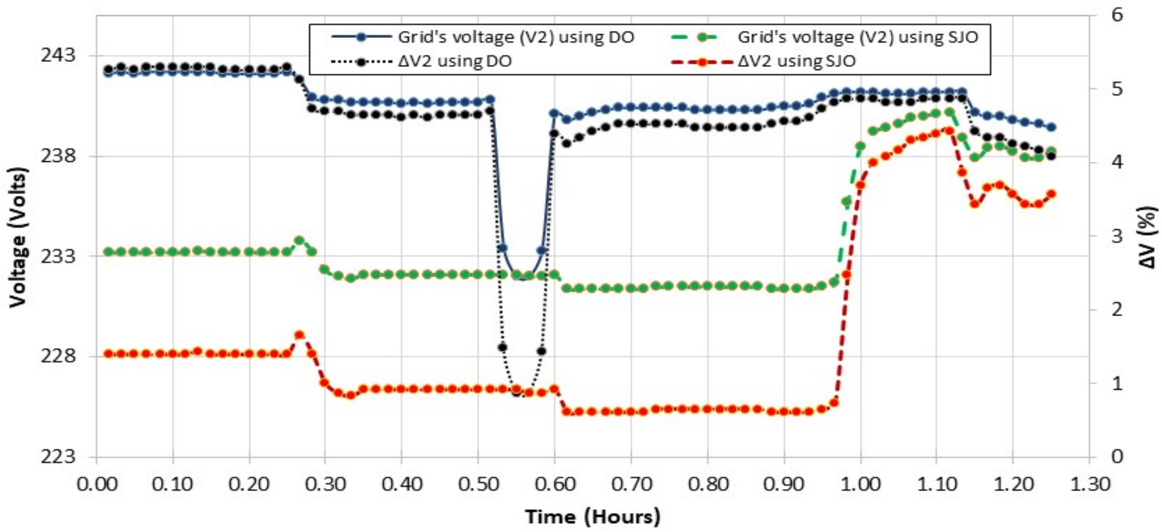

Figure 5. Voltage on the phase 3 of the grid

3.2. *Harmonic content of the voltage*

In accordance with EN 50160 standard, the THDV index should be less than 8% for all the measurements. Figures 6-8, show the voltage total harmonic distortions (THDV) on the phases 1, 2 and 3 of the three-phase grid formed by the diesel engine and for the two scenarios studied (engine running with SJO and with DO).

In Fig. 6, one can observe that THDV in the phase 1 for both of the scenario are less than 8% which is the maximum value allowed by the standard. Besides, for almost 100% of the measurements, the THDV index for the scenario with SJO are lower than the one for the scenario with DO. Indeed the THDV range from 1.2 to 3% with a mean value of 1.81% and from 1.5 to 2.8% with a mean value of 1.97% for the scenario with SJO and the one with DO respectively.

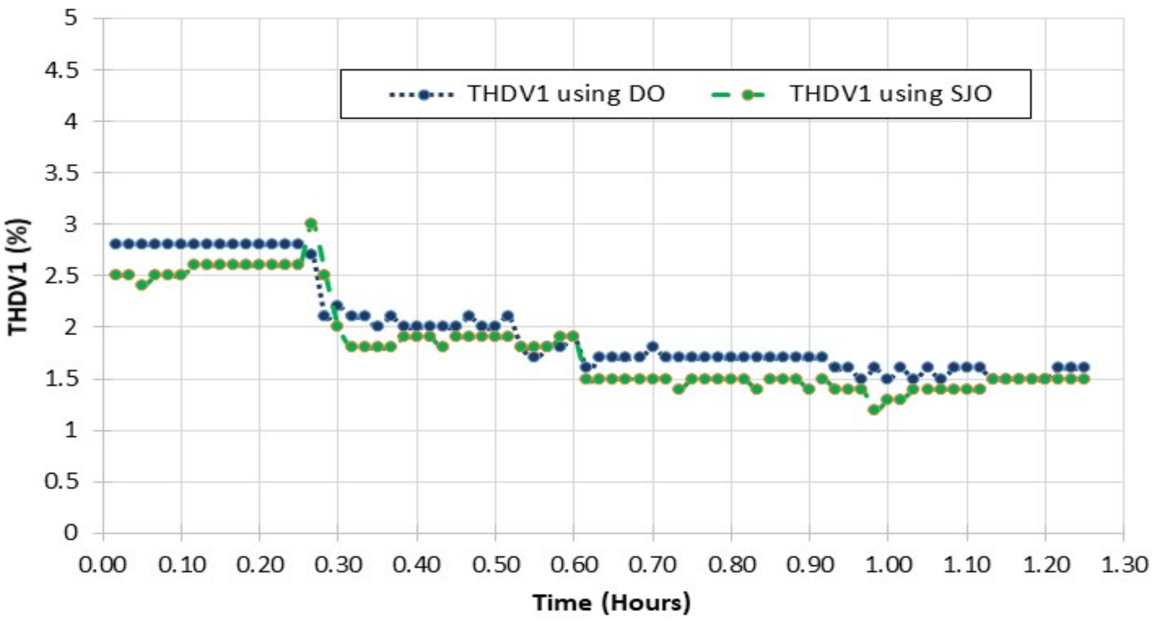

Figure 6. Total voltage harmonic distorsions on the phase 1 of the grid

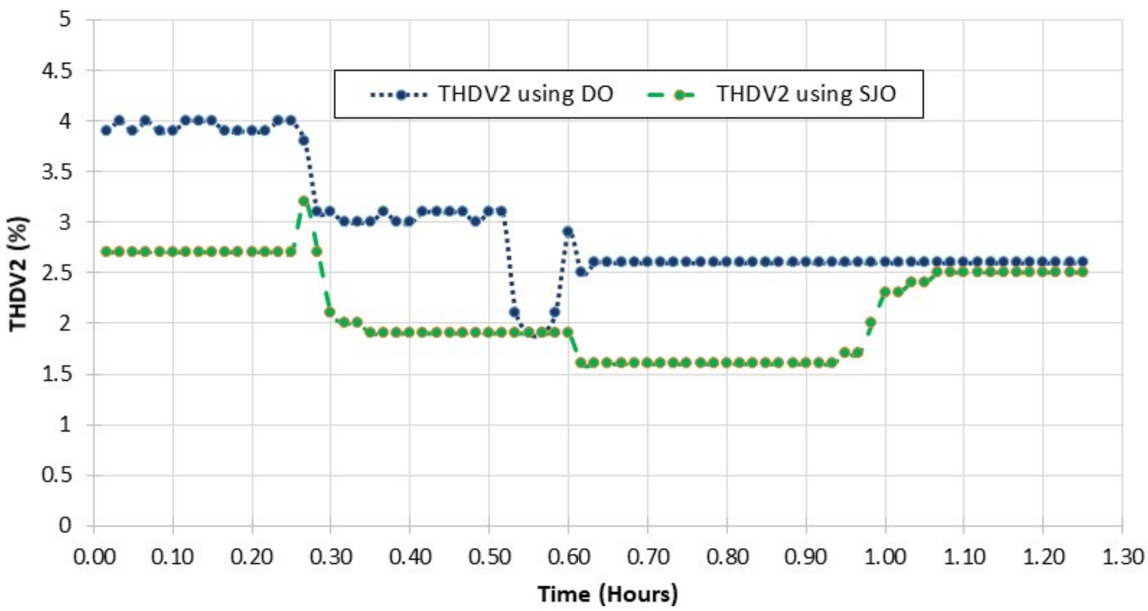

Figure 7. Total voltage harmonic distorsions on the phase 2 of the grid

In Fig. 7, one can see that the THDV values on the phase 2 for both of the scenarios are all less than 8% and consequently are in line with the EN 50160 standard. Indeed, the THDV values range from 1.6 to 3.2 % with a mean value of 2.12% and from 1.9 to 4% with a mean value of 2.94% for the scenario with SJO and the one with DO respectively. Here also, the THDV values for the scenario with SJO are less than those of the scenario with DO during the 100% of the measurements.

Figure 8 displays the THDV values on the phase 3 and for the two scenarios studied.

It can be seen that the THDV values range from 1.6 to 3.3 % with a mean value of 2.14% for the scenario with SJO and from 1.9 to 3.1% with a mean value of 2.47% for the scenario with DO. The standard is also fulfilled in this case with a better performance with the case of SJO which offers a lower THDV mean value comparatively to DO.

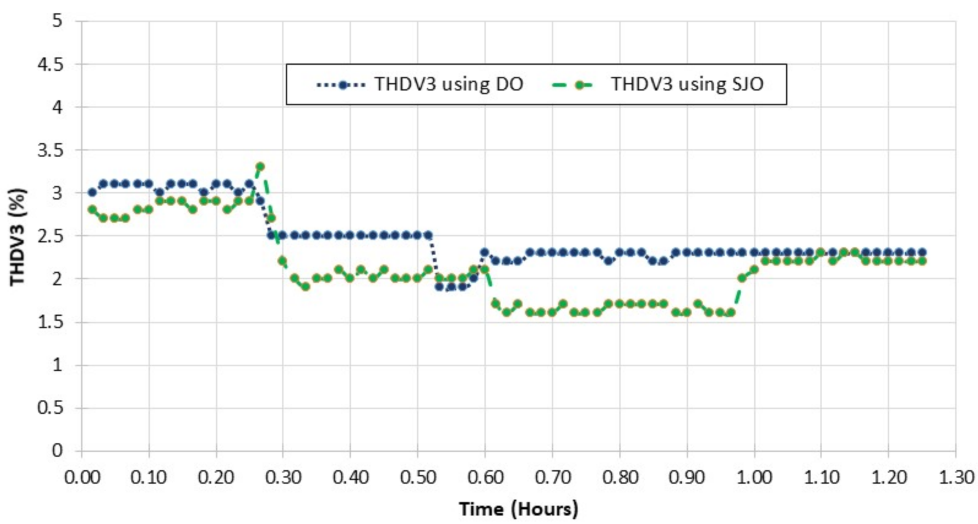

Figure 8. Total voltage harmonic distorsions on the phase 3 of the grid

3.3. Grid's frequency

In accordance with standard EN50160, the frequency ranges must be between 50±2% for 15% of the measurements or between 50 ± 15% Hz for the total (100%) of the measurements. Figure 9 displays the frequency of the grid for the two scenarios.

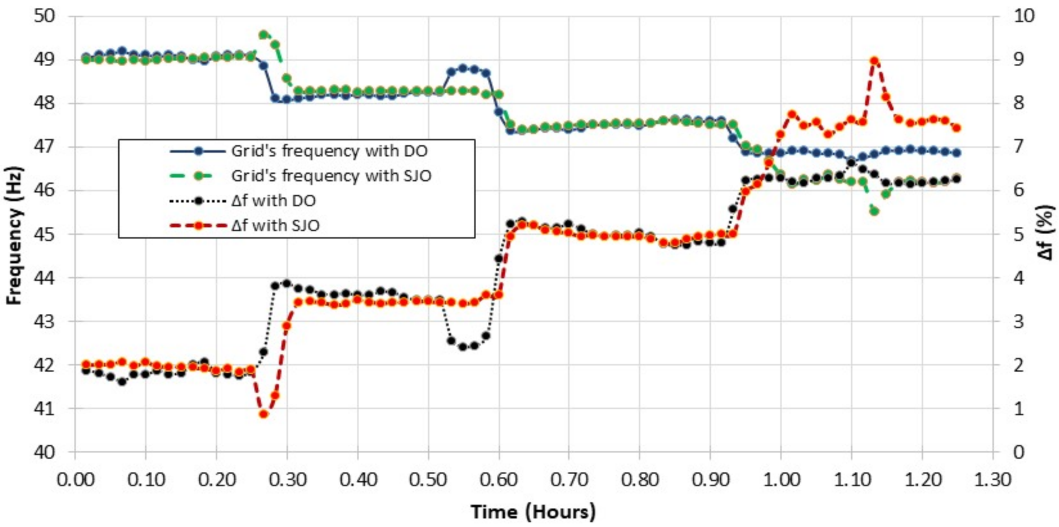

Figure 9. Grid's frequency

One can notice that the frequency of the grid ranges from 45.51 to 49.57 Hz for the case with SJO and from 46.69 to 49.19 Hz for the case with DO with a mean value of about 47.8 Hz (or drop of 4.4% in relation to the required frequency) for the two cases. The network frequency was then within the limits required by the standard for both scenarios. So, in terms of grid's frequency, one can conclude that SJO do not create more frequency fluctuations comparatively to DO, contrary to the study of patino et al [24] which showed a poorer quality of electricity generated with biogaz comparatively to gasoline concerning the frequency fluctuations.

4. Conclusion

Prior to the present work, no fundamental investigation was made about the power quality of diesel engines operating with vegetable oils. The purpose of the present work was to study the power quality of diesel engines running with straight jatropha curcas oil (SJO). Electrical parameters related to power quality namely grid's voltage and frequency, and total voltage harmonic distrortion have been investigated. Experimentations have been conducted for a diesel engine equipped with a dual fueling system that allows it to run with SJO and with diesel oil (DO). The analysis of the results was based on the EN50160 standard which is in force in European and many African countries.

The results obtained have shown that the electrical parameters of the mini-grid formed by the diesel engine were within the limits of the standard whatever the type of fuel (SJO or DO) used to run the diesel engine was. Furthermore, the comparison of the results indicates that SJO globally has a good potential in terms of power quality than DO and could then validly substitute this latter commonly used to fuel diesel engines for rural electrification in sub-Saharan Africa. Then, with a good energy efficiency, socio-economic and environmental potential as shown by many previous studies, the present work demonstrates that SJO also has a good performance regarding the power quality.

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