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Optimization of Harmonic Identification Methods in the Kinshasa Distribution Power Grid

Mathangila Kimeya, Lidinga Mobonda Flory, Okemba Rodrgue Armel Patrick, Nsongo Timothée, Bandekela Kazadi André, Omboua Alphonse

Abstract— **in this paper, we present various mathematical methods for the identification of harmonic in the electrical energy distribution network. The developed equations addressed the harmonic problem in the distribution transformer.**

Index Terms— **Optimization of methods, Harmonic identification, Grid, Distribution**

I. INTRODUCTION

In recent years, there has been a large increase in non-linear loads connected to the electricity network: computers, fax machines, discharge lamps, arc furnaces, battery chargers, inverters, electronic power supplies, electronic ballasts, are examples of which the Operating principle uses electronic power components: diodes, thyristors, transistors, triacs etc. These components are in general, the cause of electrical disturbances and in particular harmonics. Harmonics in electrical installations began to gain importance in the 1990s, as the proportion of electronic charges became comparable to that of traditional electrical equipment. Usually users turn to electric power providers when quality issues appear on the distribution and yet in most cases they are caused by the equipment that the subscriber implements on his own facility.

The consequences for the power supply system become worrying because of the increasing use of this equipment, but also the application of electronics to almost all electrical loads. Indeed, a nonlinear load calls from the network a large current, deformed, decomposable into harmonics. Harmonic currents have negative effects on almost all components of the electrical system, creating new dielectric, thermal and / or mechanical stresses.

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Mathangila Kimeya, diploma from Engineering 1978 UNIKIN in D.R of Congo

Dr.Ir Flory Lidinga Mobonda, Phd In Engineering Sciences, Dept. Of Electricity, University Of Brazzaville-Congo. Directeur du Centre de Recherche et d'Encadrement en Sciences de l'ingénieur (CRESI-Kin/RD Congo)

Rodrigue Armel Patrick Okemba Diploma from Engineering 2011 of the University of Brazzaville-Congo,

Prof. NSONGO Timothée is presently lecturer at the University of Brazzaville-Congo, Dept.physics.

Prof. André Bandekela Kazadi lecturer at the ISTA-Kinshasa of Congo, Dept. of electricity. Directeur de la SNEL electricity. He is expert of rural electrification (decentralized) using photovoltaicsystems.

Prof. Alphonse Omboua Is an electrical engineer, he received his PhD, from the University of Liege (Belgium) s. He is presently lecturer at the University of Brazzaville-Congo, Dept *of electricity. He is expert of rural electrification (decentralized) using photovoltaicsystems.*

A. Harmonics Of Odd Or Even Ranks

The curve above shows the original signal, fundamental at 50 Hz, as well as its harmonic of rank 2 at 100 Hz. Thus the frequency of the harmonic of rank 3 will be equal to 3 times the frequency of the fundamental, it is to say equal to 150 Hz.

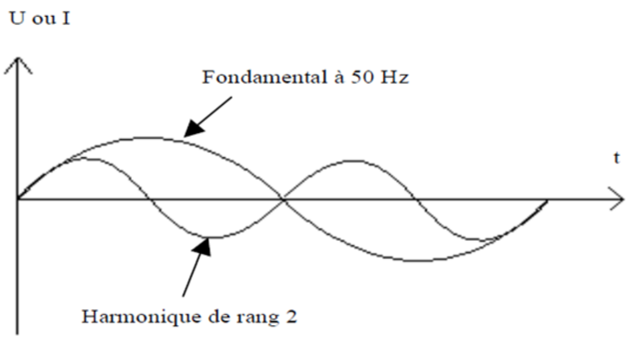

Fig. 1 The original signal, fundamental at 50 Hz

The harmonics are distinguished by their rank, even or odd type. Harmonics of even rank (2, 4, 6,8 ...), very often negligible in an industrial environment, cancel out due to the symmetry of the signal. They exist only in the presence of a continuous component. On the other hand, harmonics of odd rank (3, 5, 7.9 ...) are frequently encountered on the electrical network. Harmonics above rank 25 are in most cases negligible.

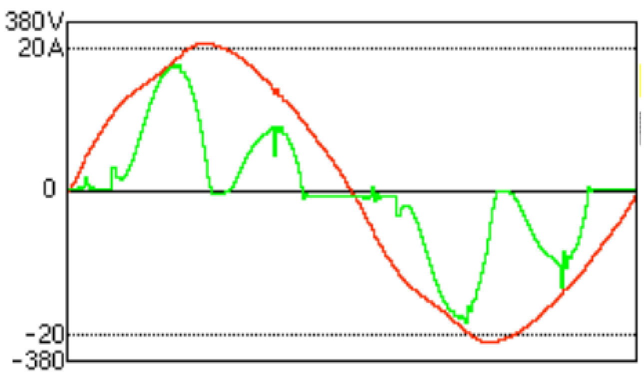

Fig. 2 The sum of the harmonics present

On the screen above, the green curve is the sum of the harmonics present. The red curve shows a distorted signal of the mains voltage. It is clearly visible that when the harmonic signal reaches high amplitudes, this causes a voltage drop. It can be seen in the table that harmonics of even and odd rank exist.

Odd harmonics are present in electrical, industrial and commercial buildings.

Tableau I.1 harmonics Rank

Rang	1	2	2	4	5	6	7	8	9
F (Hz)	50	100	150	200	250	300	350	400	450
Sens	+	-	0	+	-	0	+	-	0

Even-order harmonics only exist if the signal is asymmetric in the presence of a DC component. The meaning can be positive, negative or nil.
In the case of a three-phase asynchronous motor with hardwired neutral, the positive-order harmonics create a pulsating torque with the same meaning as that created by the fundamental. This results in an overcurrent in the motor, a source of overheating which reduces its life and which may reduce the insulation level of the motor windings with risk of failure
In all cases they are the cause of overheating in cables, motors, transformers etc. Negative harmonics create a pulsating torque in the opposite direction to that created by the fundamental, thus slowing down the machine and causing overheating. Harmonics in zero sense called homopolar have no effect on the rotation of the machines but add up in the neutral conductor. The neutral conductor will be traversed by 3 times more current on rank 3, 6, 9 than each of the live conductors. They generate heating in conductors, degradation of equipment and destruction of capacitor banks.

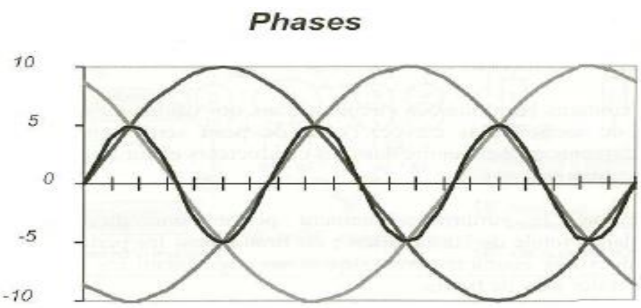

Fig. 3: Harmonic of rank 3

B. Spectral representation of harmonics

The harmonic spectrum is the harmonic decomposition of a signal in its representation in the form of a bar-graft. Each bar represents a harmonic, with its frequency, its effective value, its contribution and its phase term. The spectral representation of the harmonics is possible thanks to a Fourier series decomposition. The harmonic spectrum above represents the set of harmonics, from rank 1 to rank 25.

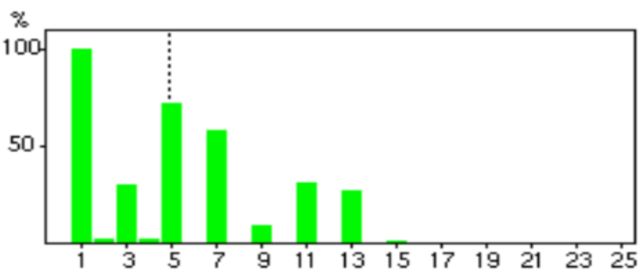

Fig. 4: Harmonic spectrum

C. Symptoms and consequences of harmonics

The presence of harmonics disturbs other loads, even linear, connected to the terminals of the same voltage source. Indeed, these charges may no longer be powered under conditions satisfying the voltage references required. Other possible consequences are:

- Warming up of the neutral cable: the harmonic currents of rank 3 and multiples of 3 lie in the neutral conductor; the neutral current frequently being 120 to 130% of the phase currents; ¬ Main untimely disruptions, due to overcurrent;
- Untimely differential disruptions due to harmonic frequencies, associated with the parasitic capacitances of the network;
- values of the effective currents higher than those required for the energy requirements of the load;
- Overheating of the installations (transformer, cables ...) by film effect;
- Voltage resonance on a system composed of capacitors designed to measure the displacement factor.

II. MATHEMATICAL MODELING

A. Presence of harmonics or not

Harmonic currents flowing through the impedances of the electrical system because harmonic voltage drops, observed in the form of harmonic distortion in voltage. One of the solutions to detect the presence of harmonics is the calculation of the THD, harmonic distortion rate. There are two types: voltage (appears at the source) or current (due to the loads). When the THD is zero, we can conclude that there are no harmonics on the network
This harmonic distortion ratio corresponds to the ratio between the real rms value of a signal (U or I) and its rms value (Ieff1 in the example below).
For example, for a harmonic of rank N, the rate of individual distortion, by harmonic, in current is calculated as follows:

$$\tau_N = \frac{I_{effN}}{I_{eff1}} \qquad 2.1$$

To know the global deformation of this signal, it is necessary to take into account all the harmonics present. There are two measurement methods: THD_f (total harmonic distortion with respect to the fundamental) or THD_r (total harmonic distortion with respect to the true rms value of the signal).
The total harmonic distortion can exceed 100%, it means that on this installation, at this point of measurement, the harmonic contribution will be greater than the fundamental one. In the absence of harmonic, the THD is zero. In practice, a THD of less than 10-15% is a good reference.

The following expressions define these two THD values:

$$THD_F = \frac{\sqrt{\left(I_2^{\,2} + I_3^{\,2} + \cdots + I_n^{\,2}\right)}}{I_1} \qquad 2.2$$

$$THD_R = \frac{\sqrt{(I_0^2 + I_2^2 + \cdots + I_n^2)}}{\sqrt{(I_0^2 + I_1^2 + \cdots + I_n^2)}} \quad 2.3$$

Both formulas can be used interchangeably. One of the features for identifying a distorted signal is its peak factor (Fc). In the case of an undeformed sinusoidal signal, this peak factor corresponds to:

$$F_C = \frac{I_{max}}{I_{eff}} = \sqrt{2} = 1{,}414 \quad 2.4$$

When the current is deformed, the peak factor is greater than this value.

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B. FOURIER SERIES DECOMPOSITION

Any periodic signal whatever its form may be decomposed into a sum of sinusoidal signals whose respective frequency is an integer multiple of the fundamental frequency. The fundamental frequency is the frequency of the original signal (50 Hz).

$$S(t) = \sum_{1} \left(A_0 + A_1.\sin(2\Pi.2f_1) + A_2.\sin(2\Pi.3f_1) + \cdots + A_n \sin(2\Pi.nf_1)\right) \quad 2.5$$

This mathematical expression makes it possible to break down any signal into sum of sinusoidal signals, where f1 is the frequency of the fundamental component and A0, A1, A2, ... An are the respective amplitudes of each sinusoid. These amplitudes are calculated by applying relations defined by the Fourrier series. We can therefore define harmonics as multiple sinusoidal oscillations of the fundamental. As a result, harmonics are components whose frequency is greater than that of the fundamental.

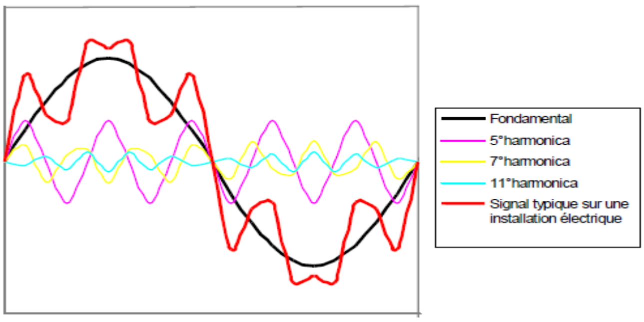

Fig. 5: sinusoidal oscillations harmonics

C. Discret Fourier Transform Analysis (DFT)

A stationary discrete periodic signal of periods N, its frequency content can be extracted by the discrete Fourier transform (DFT). Let the sequence x (n), by applying the DFT, we have:

$$X(t) = \sum_{n=1}^{N} x(n).e^{\frac{-j2\pi(k-1)(n-1)}{N}} \quad 2.6$$

Avec : $1 \le k \le N$

Where

k : frequency index

The reverse DFT is therefore determined from the relationship:

$$X(n) = \sum_{K=1}^{N} X(n).e^{\frac{j2\pi(k-1)(n-1)}{N}} \quad 2.7$$

With : $1 \le n \le N$

This expression can decompose in the form:

$$X(n) = a_0 + \sum_{k=1} a_k.\cos\left(\frac{2\pi k.t(n)}{N\Delta t}\right) + b_k.\sin\left(\frac{2\pi k.t(n)}{N\Delta t}\right) \quad 2.8$$

With:

$$a_0 = \frac{N(1)}{N} \quad 2.9$$

$$a_k = 2.R_c\left(\frac{x(k+1)}{N}\right) \quad 2.10$$

$$b_k = 2.I_m\left(\frac{x(k+1)}{N}\right) \quad 2.11$$

Where:

x: being a signal of size N, sampled during the time t of step Δt.

a_k and b_k, are the Fourier coefficients.

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D. RECURSIVE DISCRETE FOURIER TRANSFER (TFDR)

The DFT of the harmonic of rank m corresponding to the time step (k-1), of a discrete signal $\{x_n\}$ can be expressed by:

$$X_m(k-1) = \sum_{n=0}^{N-1} x_n.e^{j\beta_m{}^{n-j\varphi_m{}^{(k-1)}}} \quad 2.12$$

$$X_m(k-1) = e^{-j\varphi_m{}^{(k-1)}} \sum_{n=0}^{N-1} x_n.e^{j\beta_m{}^{n}} \quad 2.13$$

With:

j : the complex number, such that $j^2 = -1$;

$\beta_m = \frac{2\pi m}{N}$, and for m=0 to N-1(N odd integer number)

φ_m : represents the change of the phase of the reference signal.

If a data appears at the instant associated with the time step k, the new DFT becomes, with the new data:

$$X_m(k) = \sum_{n=0}^{N-1} x_n.e^{j\beta_m{}^{(n-1)-j\varphi_m{}^{(k)}}} \quad 2.14$$

$$X_m(k) = e^{j\beta_m{}^{-j\varphi_m{}^{(k)}}} \sum_{n=0}^{N-1} x_n.e^{-j\beta_m{}^{n}} \quad 2.15$$

The coefficients X_N and X_0 are respectively replaced by x (K) and x (K-N) to standardize the discrete model. And we have:

$$X_m(k) = e^{j\beta_m}.e^{-j\varphi_m{}^{(k)}}\left(e^{j\varphi_m{}^{(k-1)}}.X_m{}^{(k-1)} + x(k) - x(k-N)\right) \quad 2.16$$

The relation $\varphi_m(k) = \varphi_m(k-1) + \beta_m$ gives a simple recursive solution for the harmonic signal of rank m, as follows:

$$X_m(k) = X_m(k-1) + e^{-j\varphi_m{}^{(k-1)}}.\left(x(k) - x(k-N)\right) \qquad 2.17$$

The inverse DFT of equation 3-12 gives the harmonic component of rank m of x (k) for values of m ranging from 0 to N / 2 and n ranging from 1 to N:

$$X_m(n) = \text{r}(m) R_c e^{j\beta_m} e^{j\varphi_m{}^{(k-1)}} \qquad 2.18$$

The factor r is defined by:

$$\text{r}(n) = \begin{cases} N^{-1}, for\ m = 0, N/2 \\ 2N^{-1}, \text{otherwise} \end{cases} \qquad 2.19$$

The response of the TFDR filter at time instant k, $X_m(k)$ is obtained by equation 3-13 for n = N.

For the case φ_m (k) = fφ_m (k-1) = 0, we have stationary reference waveforms. In this case, equations 3.38 and 3.39 become:

$$X_m(k) = e^{-j\beta_m}.\left(X_m(k-1) + \Delta x(k)\right) \qquad 2.20$$

$$X_m(n) = \text{r}(m).R_c\left(X_m(k).e^{j\beta_m{}^{(n-1)}}\right) \qquad 2.21$$

For values of n ranging from 1 to N.

We note in the principle of the TFDR filter that it gives the harmonic waveform. The answer is quick to inspect the harmonics evolving over time. Which means that this theory can follow the event in real time.

E. STATE VARIABLE

The state variable can be represented as:

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}_{k+1} = \begin{pmatrix} cos(\omega\Delta t) & -sin(\omega\Delta t) \\ sin(\omega\Delta t) & cos(\omega\Delta t) \end{pmatrix}.\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}_k + \begin{bmatrix} \omega_1 \\ \omega_2 \end{bmatrix}_k \qquad 2.22$$

And the equation associated with the measurement is:

$$Z_k = (1 \quad 0).\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}_k + V_k \qquad 2.23$$

The representation of the state variable of a signal of n frequencies, that is to say the fundamental with (n-1) harmonics is:

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ \vdots \\ x_{2n-1} \\ x_{2n} \end{bmatrix}_{k+1} = \begin{pmatrix} M_1 & \cdot & \cdot & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & \cdot & \cdot & M_n \end{pmatrix}.\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ \vdots \\ x_{2n-1} \\ x_{2n} \end{bmatrix}_k + \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \vdots \\ \alpha_{2n-1} \\ \alpha_{2n} \end{bmatrix}.\text{w}_k \qquad 2.24$$

Where sub-matrices M_i so are given by:

$$\text{M}_\text{i} = \begin{pmatrix} \cos(\text{i}\omega\Delta t) & -\sin(\text{i}\omega\Delta t) \\ \sin(\text{i}\omega\Delta t) & \cos(\text{i}\omega\Delta t) \end{pmatrix} \qquad 2.25$$

Sub-matrix M_i is of dimension 2 so the matrix matrix M is of dimension 2n, hence the index varies from 1 to 2n. And the measurement equation is in the form of equation 3-36. A stationary reference is considered in the models given by equations 3-34 and 3-36. This gives the components, in phase and in phase quadrature, respectively represent the instantaneous values of the cosine and sinusoidal waveforms.

$$\text{Z}_\text{k} = (1 \quad 0 \quad . \quad . \quad . \quad . \quad 1 \quad 0).\begin{bmatrix} \text{x}_1 \\ \text{x}_2 \\ \vdots \\ \vdots \\ \text{x}_{2n-1} \\ \text{x}_{2n} \end{bmatrix}_\text{k} + \text{V}_\text{k} \qquad 2.26$$

III. HARMONIC MODELING AND SIMULATIONS

The purpose of the study of the harmonic [10] is to quantify the rate of distortion in voltage and current at different points of a distribution network. The result is very useful for evaluating the correction measure and the damage generated by the harmonic components. Studies related to harmonics can determine the dangerous resonance conditions and also verify compliance with acceptable limits.

The need for harmonic study may be indicated by excessive measurement of the distortion rate in existing systems or by installation of equipment producing harmonics.

The study has three stages:

- Definition of the equipment producing the harmonics and determination of the representation model;
- Determination of models to represent the other components in the system to be studied with the external network;
- Simulation of the system with different cases. Currently, many models have been proposed to represent harmonic sources as well as linear components. It is the same for the algorithms for extracting the harmonic components.

A. Modeling harmonic sources

The most common model of harmonic sources is in the form of harmonic currents, characterized by its effective value and its phase shift. The phase shift is often defined with respect to the fundamental component of the basic voltage. These data can be obtained by idealizing a theoretical model or by updated measurements. In many cases, the measured waveforms provide more real representations of harmonic sources to model. This is especially true if the system is unbalanced or there are interharmonic quantities.

if the system only contains a dominant harmonic source, the phase spectrum is not important. However, phase angles must be represented when multiple sources are present. The most common method is to modify the phase spectrum according to the phase angle of the fundamental frequency of the voltage seen by the load. It's not too bad to also ignore the phase angle.

Non-linear voltage or current sources: the most known sources are transformers because of the non-linearity of the magnetic device, fluorescent or gas tubes, arc furnaces. Non-linear relationships exist between voltage and current. The harmonic components generated by these devices are very significant. It is best to represent these devices according to their harmonic characteristics of voltage or current instead of using a simple harmonic voltage source.

Non-integer harmonic sources (inter-harmonics): There are several power electronics devices that produce distortion (where the components are harmonics). Also, there are a number of devices that generate the inter-harmonic components where its associated frequency values lie between two harmonics. It is the same for the infra-harmonics, frequencies lower than that of the fundamental one. These two categories are often due to periodic and random variations in the power absorbed by certain machines such as, for example, machines controlled by a train of waves.

B. *Classic modeling of a power grid*

The modeling is often simplified by a voltage source superimposed with another harmonic source due to the injection of harmonic currents by the disturbing load. Other loads that do not pollute are modeled by linear elements such as capacitor, inductance, or resistance.

The network is characterized by its power of short circuit, by its reactance in series with a resistance, often negligible compared to the reactance mentioned at the point of connection (point where the user connects). The value of the reactance is given by:

$$X = \frac{V_n^{\,2}}{S_{cc}} h \qquad 3.1$$

The resistive value can often be omitted depending on the network case: medium or low voltage. But, taking into account the skin effect, its value is close to:

$$R = R_1\sqrt{h} \qquad 3.2$$

C. *Harmonic modeling of a transformer*

In harmonic regime, a transformer is modeled by a reactance X_T in parallel with a resistance R_p, and all in series with a resistance R_s. This value is finally reduced to secondary:

$$X_T = \frac{u_{cc}}{100}\frac{V_{n2}^{\,2}}{S_n} h \qquad 3.3$$

$$R_p = 20\frac{V_{n2}^{\,2}}{S_n} \qquad 3.4$$

$$R_s = \frac{1}{100}\frac{V_{n2}^{\,2}}{S_n} \qquad 3.5$$

D. *Skin effect equations*

The skin effect, which is less significant at the fundamental frequency, appears important when a high rank frequency is present.

X_T : here represents the leakage reactance of the line transformer.

The line (or cable) is represented by the configuration in n.

Depending on the characteristic of the cable used, the values of the transverse capacitances can be neglected. The load is divided according to its category: linear or non-linear. The first is represented by a resistance in parallel with an inductor according to the following expressions:

$$R_{ch} = \frac{V_n^{\,2}}{P_U} \qquad 3.6$$

$$X_{ch} = h\frac{R_{ch}}{\tan\varphi} \qquad 3.7$$

The angle φ is the phase shift generated by the load

.

The capacitor bank can be modeled by its reactance X_c, and its value is:

$$X_c = \frac{V_n^{\,2}}{h.Q_c} \qquad 3.8$$

E. *Modeling of the resonant filter*

Considering all these values, the modeling of a resonant filter is determined from the values of the components (R, L and C) according to its reactive power and its quality factor:

$$C_F = \frac{Q_c}{\omega h.U_n^{\,2}} \qquad 3.9$$

$$L = \frac{1}{2\pi.f_0^{\,2}.C} \qquad 3.10$$

$$R = \frac{2\pi.f_0^{\,2}.L}{F} \qquad 3.11$$

In general, the linear passive charges have particular effects on the power grid according to the frequency domain mainly close to the resonant frequency.

F. *GENERAL MODELING*

The basic model of the load is shown in Figure 2-3. To characterize this model, it is necessary to know the composition of the typical load. Usually data are not available. Model A, R_{Ch} resistance in parallel with L_{Ch} inductance.

Where:

$$R_{ch} = \frac{V_n^{\,2}}{P_U} \qquad 3.12$$

$$L_{ch} = \frac{V^2}{2.\pi.f.Q} \qquad 3.13$$

Model B assumes that the total reactive load is provided by inductance because most of the reactive power comes from induction motors. This model can not be recommended.

$$R_{ch} = \frac{V_n^{\,2}}{k.P_u} \qquad 3.14$$

$$L_{ch} = \frac{V_n^{\,2}}{2.\pi.f.k.Q} \qquad 3.15$$

With k=0.1h+0.9

The model C, a resistor R_{ch} parallel with an inductance L_{ch} and in series with an inductance transformer L_T, where :

$$L_{ch} = \frac{h.R_{ch}}{2.\pi.f.\frac{6.7Q}{P_U} - 0.74} \qquad 3.16$$

$$L_T = 0.073h.R_{ch}$$

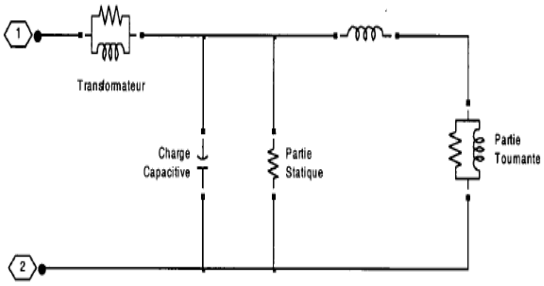

Fig. 6: Basic model of the load

As previously mentioned, to simplify the calculation, we can represent the harmonic current source, unlinear load side, by a harmonic voltage source brought back to the main source (this is only a representation). This does not affect the overall representation of the power grid studied.

IV. EXPERIMENTAL RESULTS

Consider the simplified diagram of a power grid with passive filters and inverter, shown in the figure below,

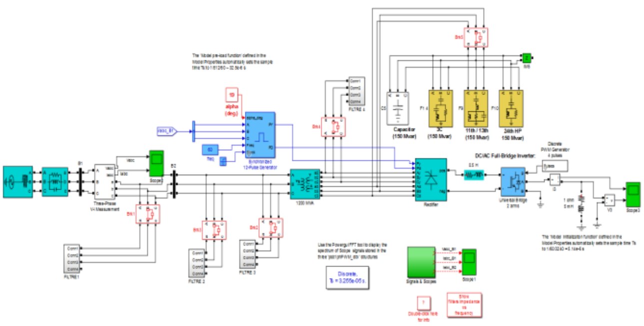

Fig. 7: Three-phase diagram power grid's with passive filters and an inverter

The table below shows the values of the parameters of the selected standard network.

Table 1: Three-phase power grid parameters

V_s	L_s	L_L	R_L
3θ-60Hz-500KV	98.03mH	$76\mu H$	5Ω
$Z_h = \frac{V_s^2}{S_b} = \frac{500^2}{20e^3}$. $Z_s = 4\%$ et $Z_L = 1\%$			

Table 2: Parallel Passive Filters Parameters

tuning frequency of filter	L (mH)	C (μF)	R (Ω)	Fq
5h	0.89	304.38	0.085	19.76
7h	2.55	56.22	0.34	
High Pass	0.11	537.12	0.46	

A. SIMULATIONS RESULTS WITHOUT FILTERS

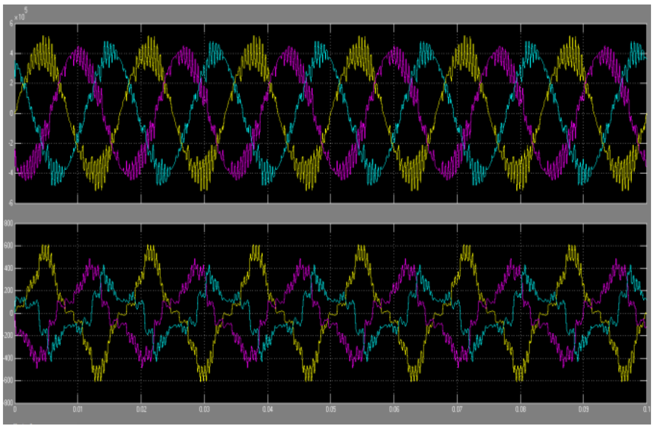

Fig. 8: Source Voltage and Current waves without Filters

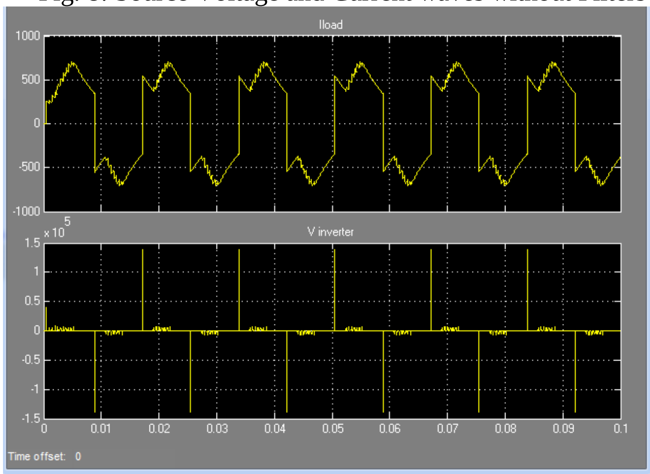

Fig 9. : Load Voltage and Current waves without Filters

B. SIMULATIONS RESULTS WITH FILTER 1 IN SERVICE

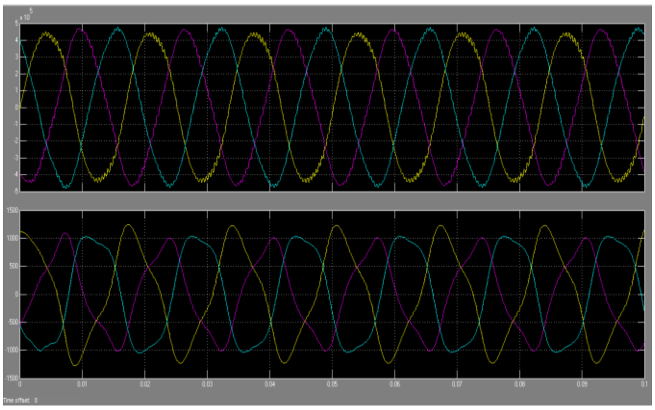

Fig 10. : Source Voltage and Current waves with Filter 1

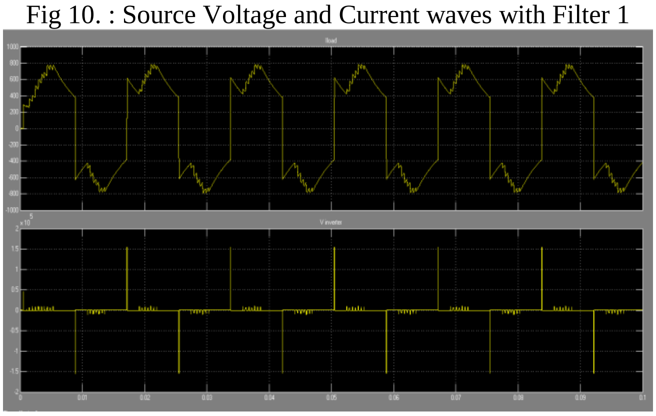

Fig 11. : Load Voltage and Current waves with Filter 1

C. SIMULATIONS RESULTS WITH FILTER 1-2-3-4-5 IN SERVICE

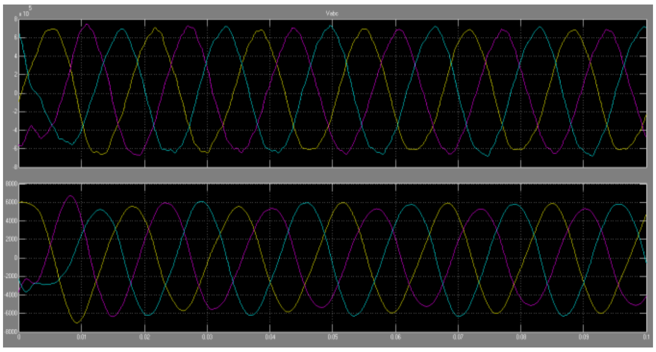

Fig 12. : Source Voltage and Current waves with Filters 1-2-3-4-5

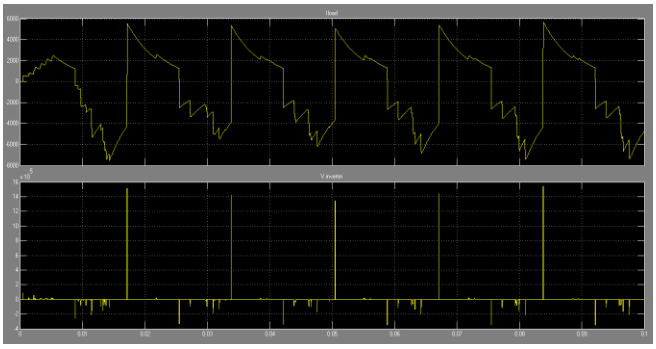

Fig 13.. : Load Voltage and Current waves with Filter 1-2-3-4-5

D. SPECTRAL ANALYSIS OF CURRENT AND VOLTAGE WAVES WITH FILTERS 1-2-3-4-5

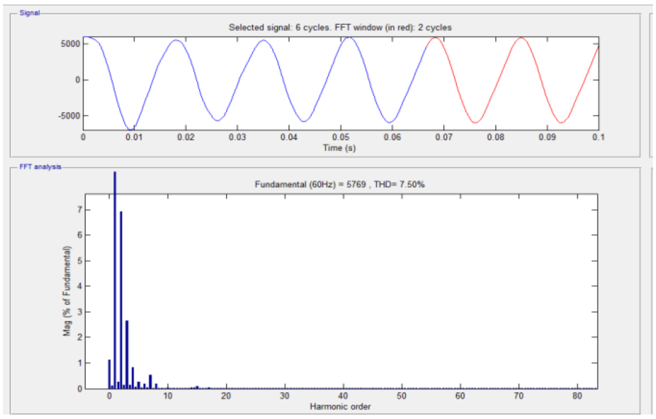

Fig 14. : Spectral Analysis of Signal Source Output Current Phase A with 1-2-3-4-5 Filters

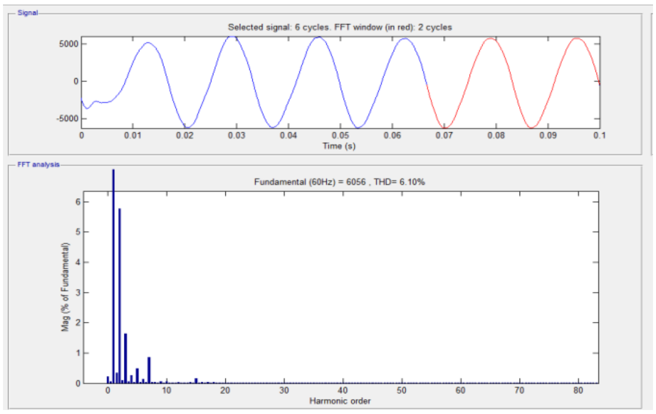

Fig 16. : Spectral Analysis of Signal Source Output Current Phase C with 1-2-3-4-5 Filters

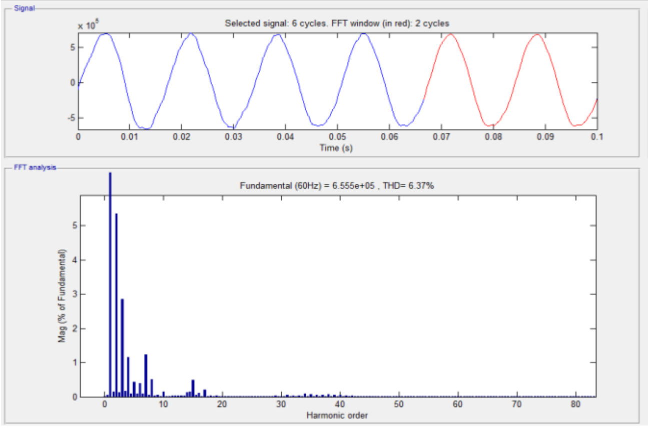

Fig 17: Spectral Analysis of Signal Source Output Voltage Phase A with 1-2-3-4-5 Filters

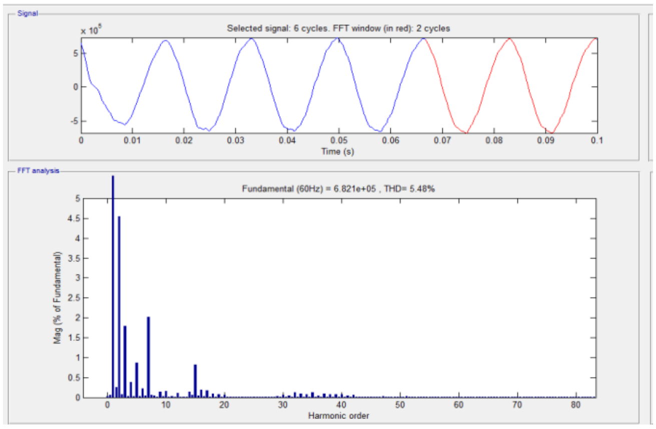

Fig 19: Spectral Analysis of Phase C Source Output Voltage Signal with 1-2-3-4-5 Filters

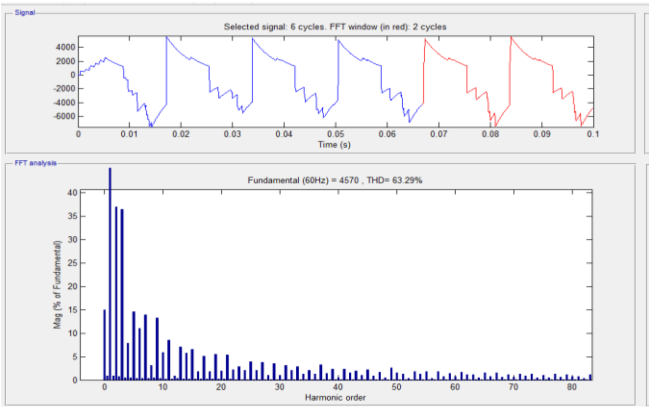

Fig 20: Spectral Analysis of Current at Load Level with 1-2-3-4-5 Filters

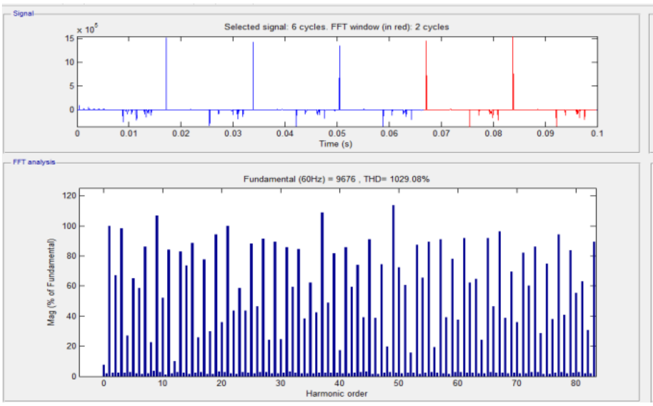

Fig 21: Spectral Analysis of Charge Level Voltage with 1-2-3-4-5 Filters

V. CONCLUSION

We have applied our algorithm on many images and found that it successfully detect the text region. Current harmonics can not be deleted: it is the load that generates them. It will therefore be necessary to confine them as close to the polluting loads to avoid that they go up on the whole network. The main methods used correspond to the installation of filtering or isolation systems (transformers).
This method will limit the degradation of the energy (dequalification of the source voltage) as well as their other harmful effects. Once the harmonics "mastered", the associated power losses disappear. All of the power provided by the network is then available for other loads. The power supplied by the network will therefore be optimized, leading to a reduction in energy costs.

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Mathangila Kimeya, *diploma from Engineering 1978 UNIKIN in D.R of Congo, Master degree 2004 of Electrical Engineering KUL of (Belgum)- and PhD student in engineering sciences of the University of Brazzaville-Congo.*


Dr.Ir Flory Lidinga Mobonda, *Phd In Engineering Sciences, Dept. Of Electricity, University Of Brazzaville-Congo. Directeur du Centre de Recherche et d'Encadrement en Sciences de l'ingénieur (CRESI-Kin/RD Congo) Master's degree 2014 University of Brazzaville-Congo and PhD student in engineering sciences of The University of Brazzaville-Congo; Graduate Diploma in Management of Energy Sector 2015 of the HEC Montréal (University de Montréal, Quebec, and Canada).*


Rodrigue Armel Patrick Okemba *Diploma from Engineering 2011 of the University of Brazzaville-Congo,*


Prof. NSONGO Timothée is presently lecturer at the University of Brazzaville-Congo, Dept.physics.


Prof. André Bandekela Kazadi, is an electrical engineer, he received his PhD, from the institute energétique of Moecou (Rusie) in 1984. He is presently lecturer at the ISTA-Kinshasa of Congo, Dept. of electricity. Directeur de la SNEL
of electricity. He is expert of rural electrification (decentralized) using photovoltaicsystems.


Prof. Alphonse Omboua Is an electrical engineer, he received his PhD, from the University of Liege (Belgium) s. He is presently lecturer at the University of Brazzaville-Congo, Dept of electricity. He is expert of rural electrification (decentralized) using photovoltaicsystems.

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