

Simplified Method for Single Line to Ground-Fault Location in Electrical Power Distribution Systems

M. Zahri*, Y. Menchafou **, H. El Markhi **, M. Habibi*

* Laboratory of Telecommunication and Engineering Decision Systems, Ibn Tofail University, Kenitra, Morocco

** Laboratory of Signals, Systems and components, Sidi Mohamed Ben Abdellah University, Fez, Morocco

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ABSTRACT

Power distribution systems play important roles in modern society. When distribution system outages occur, speedy and precise fault location is crucial in accelerating system restoration, reducing outage time and significantly improving system reliability, and then improves the quality of services and customer satisfaction. In this paper, we propose a reduced algorithm utilizing the sum of sending-end currents of the three phases to calculate the fault current, and therefore, avoid the iterative aspect of the classic algorithm for single line to ground fault location and reduce its computational charge. The test results are obtained from the numerical simulation using the data of a distribution line recognized in the literature.

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Corresponding Author:

Mustapha Zahri,

Laboratory of Telecommunication and Engineering Decision Systems,

Ibn Tofail University,

Kenitra, Morocco,

Email: mustapha.zahri@gmail.com

1. INTRODUCTION

Distribution networks are dispersed in each urban and rural region, and are crossed from each alley and street. Each distribution feeder has many laterals, sub-laterals, load taps, balanced and unbalanced load and different types of conductors [1]. Power distribution systems (PDSs) are subjected to fault conditions caused by various sources such as load abrupt changes, adverse weather conditions, equipments failure and external object contacts. The faults statistics can orientate the strategic choices of companies and researchers to guide their work towards the single phase to ground faults that cause the majority of power disturbance.

Owing to the expansion of distribution network, to the radial topology, the existence of short and heterogeneous lines and also a lower degree of instrumentation it is very difficult and complicated to locate the fault in these networks.

Currently the only technique used for locating faults in distribution systems of electric power is the visual inspection of FPI (Fault Passage Indicators) which imposes an important time of restoration [2].

In recent years, many techniques have been proposed for automated FL (Fault Location) in the distribution systems, these methods can be divided into three main categories:

- Traveling wave-based methods: in these methods, high frequency components of voltage and/or current measured at substation are applied [3], [4]. The disadvantage of these methods is the need of high-sampling frequency; consequently, applying these methods is very expensive.
- Artificial intelligence and statistical Analysis or hybrid methods can help operator or engineers to do much laborious work, to reduce the time factor and to avoid the human mistakes [5]-[8].

- Impedance-based methods, in which the fundamental frequency component of voltage and current measured at substation, are used [9]-[13]. These methods generally can be easily applied and they are cheaper than the others.

However, individually they do not fully consider the characteristics of distribution systems (unbalanced operation, presence of intermediate loads, laterals, and time-varying load profile), which significantly affect their performance and hinders their practical implementation.

Furthermore, from the fault statistics, it can be noted that the single phase to ground faults are the most frequent, thus, the strategic choices of companies and researchers works can be orientated towards the single phase to ground fault location [14]. This led us to work on improving fault location algorithms in terms of accuracy, simplicity and computational charge, since the practical use of those algorithms requires the implementation on programmable electronic devices.

The main objective of the proposed methodology is to use the sum of sending-end currents of the three phases to calculate the fault current used to determinate the fault location, in order to reduce the computational charge of the classic algorithm for single line to ground fault location and to avoid its iterative aspect. The proposed method was validated using real under-ground distribution feeder data and Matlab as an analysis tool.

The remainder of this paper is organized as follows: The classical iterative and the reduced algorithms are presented in sections 2 and 3 respectively, the test results are shown in Section 4, whereas the conclusions of this work are presented in Section 5.

2. ITERATIVE FAULT LOCATION ALGORITHM

After the detection and the classification of the faults, the FL process is initialized. First, the system is divided into n branches, where n is the number of possible paths (end nodes). For each branch, the fault distance is estimated, using an impedance-based method [15]-[18].

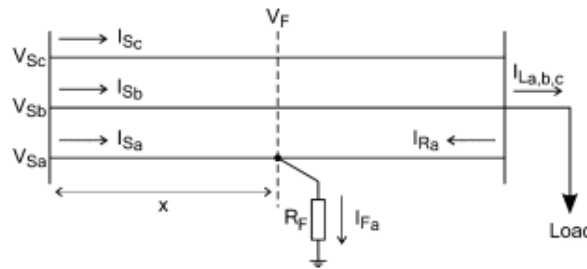


Figure 1. Single-phase-to-ground fault modeling

2.1. Mathematical development

The system illustrated in Figure 1, contains a local bus, a generic faulted distribution line with constant fault resistance (R_F), and an equivalent load.

It is possible to show that for a single phase-to-ground fault in phase *m*:

$$\begin{bmatrix} x \\ R_F \end{bmatrix} = \frac{1}{M_{1m} \cdot I_{Fmi} - M_{2m} \cdot I_{Fmr}} \begin{bmatrix} I_{Fmi} & -I_{Fmr} \\ -M_{2m} & M_{1m} \end{bmatrix} \begin{bmatrix} V_{Smr} \\ V_{Smi} \end{bmatrix} \quad (1)$$

Where the subscript indices r and i represent, respectively, the variables real and imaginary parts, the variables are as follows:

- V_{sm} phase *m* sending –end voltages (in volts);
- V_{Fm} phase *m* fault-point phase voltages (in volts);
- x fault point to local bus distance (in kilometers);
- I_{Fm} fault current (in amperes).

Also, M_{1m} and M_{2m} are defined in (2) and (3)

$$M_{1m} = \sum_k (Z_{mkr} I_{Skr} - Z_{mki} I_{Ski}) \quad (2)$$

$$M_{2m} = \sum_k (Z_{mkr} I_{Ski} - Z_{mki} I_{Skr}) \quad (3)$$

Where

k phases a, b and c ;
 Z_{mk} impedance between phase m and k [Ω/km];
 I_{Sk} phase k sending-end current (in amperes).

The fault distance is estimated by (4):

$$x = \frac{I_{Fmi} \cdot V_{Smr} - I_{Fmr} \cdot V_{Smi}}{M_{1m} \cdot I_{Fmi} - M_{2m} \cdot I_{Fmr}} \quad (4)$$

From (4) it is possible to obtain the fault distance from the parameters of the system: the fault current and the sending-end voltages. Since voltages are already known, an iterative procedure that updates the fault current is used to estimate the fault distance.

2.2. Fault Current Estimation Procedure

In equation (4) the only unknown parameter is the fault current I_{Fmr} , i. All other variables are system parameters or measured variables.

Referring to Figure 1, the fault current can be obtained by (5):

$$I_{Fa} = I_{Sa} + I_{Ra} = I_{Sa} - I_{La} \quad (5)$$

Where I_{La} is the phase a load current.

Nevertheless, the load current during the fault period is different from the pre-fault load current, due to voltage drops and systems dynamics during the fault. For this reason, an iterative technique used to estimate the load current during the fault, is described as follow:

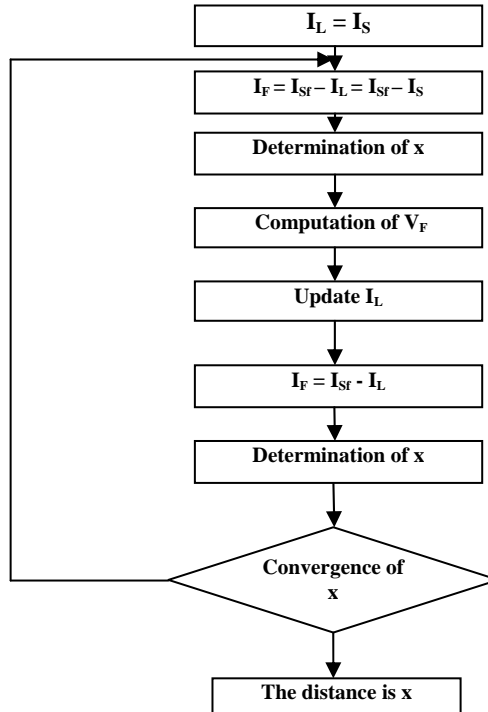


Figure 2. Conventional iterative Algorithm

- 1) Load current during the fault I_{La} is assumed to be the same as the pre-fault load current.
- 2) The fault current is calculated using (5)

- 3) Fault distance is estimated using (1), (2), and (3).
 4) Fault-point voltages are estimated using (6)

$$\begin{bmatrix} V_{Fa} \\ V_{Fb} \\ V_{Fc} \end{bmatrix} = \begin{bmatrix} V_{Sa} \\ V_{Sb} \\ V_{Sc} \end{bmatrix} - x \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix} \begin{bmatrix} I_{Fa} \\ I_{Fb} \\ I_{Fc} \end{bmatrix} \quad (6)$$

- 5) Load current I_{La} is updated using the fault-point voltages in (7) and (8):

$$I_{La} = [Y_{aa} \quad Y_{ab} \quad Y_{ac}] [V_{Fa} \quad V_{Fb} \quad V_{Fc}]^T \quad (7)$$

$$Y_{pq} = [(l-x)Z_{pq} + Z_{Lpq}]^{-1} \quad (8)$$

Where

Z_{pq} is the line impedance (mutual or self) between phase p and q ;
 Z_{Lpq} is the load impedance (mutual or self) between phase p and q ;
 l is the total line length.

- 6) Check if x has converged, using (9)

$$|x(\alpha) - x(\alpha - 1)| < \delta \quad (9)$$

Where δ is a previously defined threshold value and α is the iteration number.

- 7) If x has converged, stop the procedure; otherwise, go back to step 2).

3. PROPOSED ALGORITHM

In the case of a balanced symmetrical operation, analysis of three-phase systems is similar to that of an equivalent single-phase system, characterized by voltages, phase currents and phase impedances of the power system. Once a significant asymmetry appears in the configuration or operation of the power system, it is no longer possible to establish electrical equations using cyclic impedances. This is the case of distribution networks where the load is fundamentally unbalanced due to the large number of unequal single phase loads. An additional asymmetry is introduced by the uneven spacing of the conductors of three-phase lines and underground cables. Neutral of generators and power transformers can be grounded in different ways depending on the protection needs, power supply system and the characteristics of loads supplied. Generally, an impedance is placed between the neutral of the transformer and the earth to enable relay to detect single line to ground faults [19].

Power Distribution system can thus be modeled by three voltage generators with a common point N supplying balanced three sinusoidal voltages V_1 , V_2 and V_3 . They are connected to three load impedances, via three lines numbered 1, 2, and 3. A simplified modeling of an electrical distribution network is shown in Figure 3.

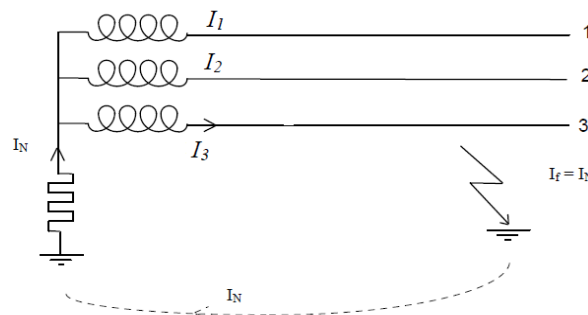


Figure 3. Simplified modeling of an electrical distribution network

I_1 , I_2 and I_3 , the currents through three load impedances, thus, the neutral current is zero.

$$I_N = I_1 + I_2 + I_3 = \frac{V_1}{Z} + \frac{V_2}{Z} + \frac{V_3}{Z} = 0 \quad (10)$$

However, if a fault occurs on one phase (Single phase to ground fault), the fault current is, then, transmitted to the neutral via the earth, and the relation (10) becomes:

$$\begin{aligned} I_N &= I_1 + I_2 + I_3 = V_1 \left(\frac{1}{Z} + \frac{1}{R_f} \right) + \frac{V_2}{Z} + \frac{V_3}{Z} \neq 0 \\ I_N &= I_1 + I_2 + I_3 = \frac{V_1}{Z} + \frac{V_2}{Z} + \frac{V_3}{Z} + \frac{V_1}{R_f} \neq 0 \\ I_N &= I_1 + I_2 + I_3 = \frac{V_1}{R_f} = I_f \neq 0 \\ I_N &= I_f = I_1 + I_2 + I_3 \neq 0 \end{aligned} \quad (11)$$

Using (11), we can calculate the fault distance without having to go through the iterative method of the classical algorithm; the reduced algorithm is then illustrated in Figure 4:

- 1) Acquisition of the sending-end currents and voltages of each phase;
- 2) Fault current can be calculated using (11);
- 3) Fault distance is so obtained using the equations (1), (2) and (3).

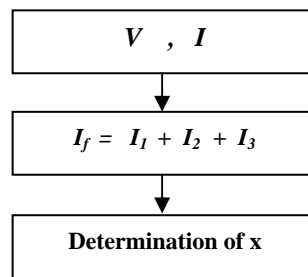


Figure 4. Fault Location reduced algorithm.

4. TESTS AND RESULTS

4.1. Tests

To verify performances of this algorithm, we have conducted several simulations using data from a distribution system recognized in literature [20].

The system that we have studied is a part of the underground distribution network, it is a line from 20 KV distribution network of total length 22.5 Km, composed of 6 sections of different lengths, simulated using distributed parameter line model as shown in Table 1.

Using Matlab [21] as simulation tool, 26 fault cases are simulated at different FL between 0-100%, for fault resistance $R_f=10 \Omega$ and for different load distributions as explained in Table 2.

- Balanced loads;
- Load at the left end;
- Load at the right end.

The fault distance is calculated for each case using the currents and voltages at the input of the line, and using the two algorithms (classical and reduced).

Table 1. Studied Sections of lines Parameters

Input voltages [KV]	$V_s=11.547, U=20$
Rf [Ohms]	10
Line impedance [Ohms/Km]	$Z_1=0.56+j0.831, Z_0=0.845+j2.742$
Line section length[Km]	$l_1=2.4 ; l_2=4 ; l_3=4 ; l_4=4 ; l_5=4.1 ; l_6=4 ;$

Table 2. Different load distributions

balanced loads			
Bus	Load (KVA)	Bus	Load (KVA)
1	15	4	15
2	15	5	15
3	15	6	15
load at the left end			
Bus	Load (KVA)	Bus	Load (KVA)
1	89,5	4	0,1
2	0,1	5	0,1
3	0,1	6	0,1
load at the right end			
Bus	Load (KVA)	Bus	Load (KVA)
1	0,1	4	0,1
2	0,1	5	0,1
3	0,1	6	89,5

4.2. Results

4.2.1. Performances Comparison

The proposed algorithm is extensively tested in comparison with the conventional iterative algorithm to verify the effect of the fault location (near or far from the entrance section), the fault resistance and load distribution on the performance of this method.

The performances of fault location algorithm are usually measured by the errors on the fault distance:

$$err(\%) = \left| \frac{x(actual) - x(estimated)}{l} \right| \quad (12)$$

Where

$x(estimated)$: estimated fault distance (in meters);
 $x(actual)$: real fault distance (in meters);
 l : total line length (in meters).

Figures 5, 6 and 7 illustrate some obtained test results, for Single Line to Ground fault with $R_f = 10\Omega$. The obtained results show a comparison between two curves, the first presents the errors on the fault distance using the classical iterative algorithm. The second tracks the errors on fault distance using the new reduced algorithm (without iterations).

From Figure 5, it can be observed that for the load distribution at the left end, the curves are, approximately, the same, which means both algorithms have the same performances.

As seen on Figure 6 and 7, the errors obtained by the proposed algorithm are better than those obtained using the conventional one.

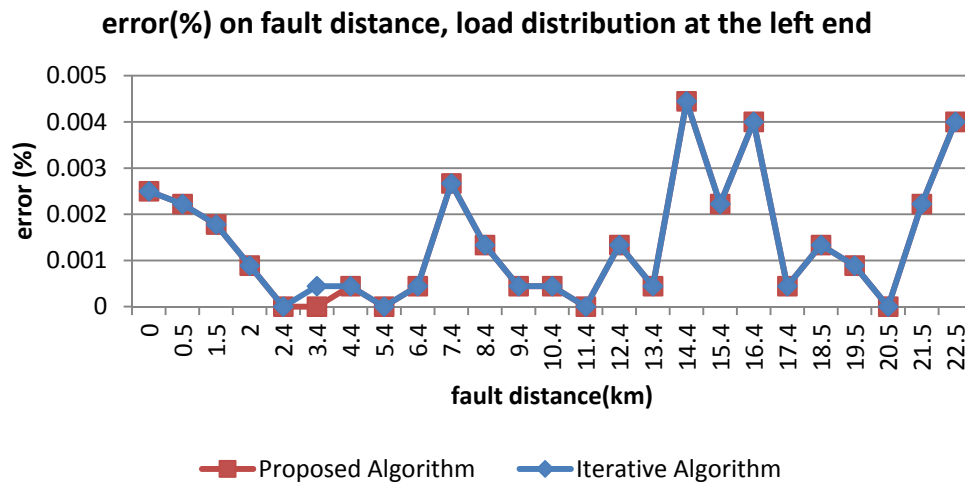


Figure 5. Error on fault distance for a load distribution at the left end

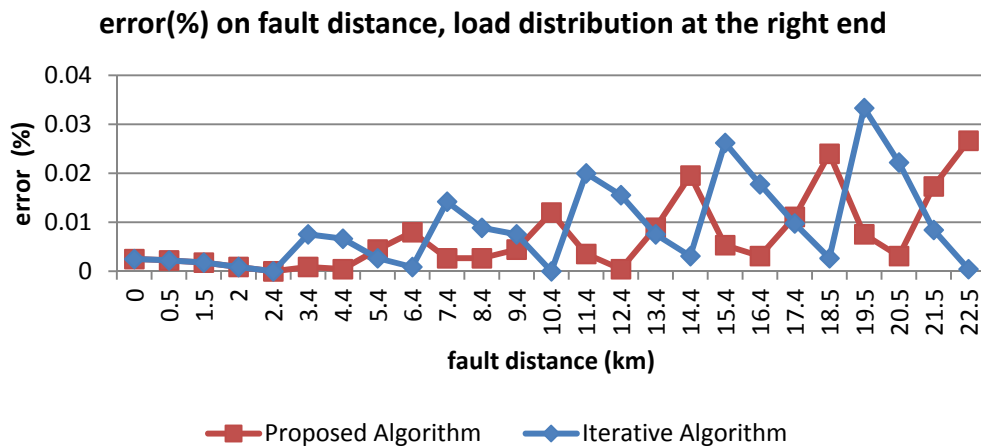


Figure 6. Error on fault distance for a load distribution at the right end

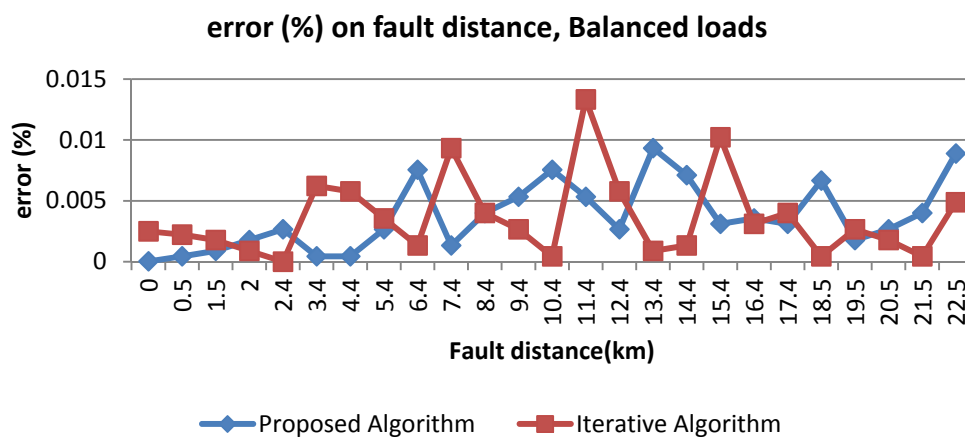


Figure 7. Error on fault distance for a Balanced loads

4.2.2. Computational Charge Comparison

In computer science, the analysis of algorithms is the determination of the amount of resources (such as time and storage) necessary to execute them. Both characteristics can be evaluated by examining the structure of the algorithm.

A given computer will take a discrete amount of time to execute each of the instructions involved with carrying out this algorithm. The specific amount of time to carry out a given instruction will vary depending on which instruction is being executed and which computer is executing it, but on a conventional computer, this amount will be deterministic. Say that the actions carried out in step 1 are considered to consume time T_1 , step 2 uses time T_2 , and so forth.

In the classical iterative algorithm above, steps 1 will only be run once and its may consume T_1 time.

The loop in steps 2, 3, 4, 5, 6 and 7 is trickier to evaluate. The inner instructions of the loop will execute n times for each instruction (with n is the number of iterations), where n varies between 1 and $i>1$ depending on the convergence of x , the time consumed in the loop is then:

$$n.(T_2 + T_3 + T_4 + T_5 + T_6 + T_7) \quad (13)$$

The test in step 8 consumes T_8 time, and the step 9 executes T_9 time. Altogether, the total time required to run the algorithm is:

$$T_{classical} = T_1 + n.(T_2 + T_3 + T_4 + T_5 + T_6 + T_7) + T_8 + T_9 \quad (14)$$

In the other hand, the simplified algorithm consumes 3 steps with T_1 , T_2 and T_3 times without any loops or tests, the total times of this algorithm is then:

$$T_{simplified} = T_1 + T_2 + T_3 \quad (15)$$

Table 3. Total excusion time comparison

Total time	iteratif algorithm	Proposed algorithm
Best scenario ($n=1$)	9 unit of time	3 unit of time
Worst scenario ($n=i>1$)	(3+6. i) unit of time	3 unit of time

In analyzing the complexity comparison in table3, It can be seen that, with a third computational complexity, the proposed algorithm allows not only to obtain the performances of the classical iterative algorithm of fault location but also to improve them for some load distributions.

5. CONCLUSION

This paper proposes and discusses a simplified method for single line to ground fault location, using the sending-end currents and voltages, and network parameters.

Furthermore, the proposed algorithm allows, with a low computational charge (with a non-iterative procedure), the fault location not only with the same performances of the conventional iterative algorithm, but also better for some distribution loads.

The performances of this algorithm are verified by several tests simulating 26 cases of single phase to ground faults for different load distributions, using real under-ground distribution feeder data and Matlab as an analysis tool.

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BIOGRAPHIES OF AUTHORS



Zahri Mustapha was born in Agadir, Morocco on August 1, 1969; He received the electrical engineering degree in 1993 from Superior National School of electricity and mechanics (ENSEM), Casablanca, Morocco. He is currently pursuing the Ph.D. degree in electrical engineering at the University Ibn Totail, Faculty des Sciences, Department of Physics, Kénitra, Morocco; and he is at the same time the head of the electricity department in the electricity and water distribution company in Kenitra (RAK).

His research interests include the detection and fault location, remote control systems and protection of electrical distribution networks



Menchafou Youssef was born in Skoura, Boulemane, Morocco, on April 6, 1990. He received the electronics and Telecommunication engineering degree in 2013, from the faculty of Sciences and Technics (FST), Sidi Mohamed Ibn Abdullah University, Fez, Morocco, where he is currently pursuing the Ph.D. degree in electrical engineering.

His research interests include fault detection and location, and distributed generation



Hassane El markhi was born in Morocco on 1971. He received the Engineer degree in electrical engineering from HassanIIUniversity, Casablanca in 1995. He received his Habilitation degree in signal processing for wireless communications from Sidi Mohamed Ben Abdellah University, Fez in 2007. He is currently a professor in the Department of Electrical Engineering with Science and Technical Faculty, Fez (Morocco). His main research interests include smart grid, fault location, and renewable energy systems.



Mohamed Habibi was born in 1957 in Khémisset in Morocco. He received his Thesis d'Université de 3^o Cycle (Electronics) from the Université of Sciences and Techniques, Lille Flandres Artois, France, in 1985 and the State doctoral thesis (Electronics) from the University Mohammed V, Ecole Mohammadia d'Ingénieurs, Rabat, Morocco, in 1993. He was member of the Laboratoire d'Electronique et Communications since 1989 at the 'Ecole Mohammadia d'Ingénieurs', Rabat. He was responsible of the Laboratoire d'Automatique et de Micro-ondes (LAMO) and presently he is member of the Laboratoire des Systèmes de Télécommunications et Ingénierie de la Décision (LASTID) since 2005. He is Professor of Electrical Engineering at the Université Ibn Totail, Faculté des Sciences, Département de Physique, Kénitra, Morocco since 1985. He is working on applications of microwaves.