Harmonic Estimation in Radial Distribution Feeders Based on Particle Swarm Optimization

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***Abstract*—This paper presents a method based on the particle swarm optimization algorithm applied to estimate harmonic components in radial distribution feeders. It is important to mention that this method is not applied as harmonic state estimator, neither to estimate the total harmonic distortion at the substation. So, the proposed method can be employed to estimate the harmonic components in specific points of common coupling between the harmonic source and the feeder. In this sense, some case studies were prepared in order to validate the method. The point of common coupling where the harmonic source is located were obtained by means of expert knowledge. Nevertheless, the specialist/engineer should be induced to err the exact position of the harmonic source due to the presence of other harmonic sources with lower levels of distortion. Thus, the precision rate of this method was evaluated in accordance with the uncertainty that can be generated by the expert knowledge. These analysis are crucial to verify the performance of the proposed method, mainly, in the utility's point of view.**

Keywords—harmonic components, harmonic estimation, particle swarm optimization, power quality.

I. INTRODUCTION

Nowadays, the utilities have the concern for the electricity delivered to the consumers. Moreover, we have the energy efficiency, where some linear loads had been replaced by nonlinear loads. Thus, it is possible to observe the increment of current and/or voltage harmonic distortions in the distribution feeders. Given these high level of distortions, it becomes clear the poor power quality which mainly affect the consumers.

In conformity with these premises, some research have been developed with the intuit to reach a precisely harmonic power flow to radial and/or weakly meshed distribution feeders [1-3].

However, in order to employ the above mentioned research, it is necessary a prior knowledge about the harmonic components of each Point of Common Coupling (PCC). Hence, this information is very difficult to obtain due to the absence of power quality monitors installed at these points or smart meters installed at the consumers.

Due to the difficult to determine the harmonic power flow, the research in this area were directed to harmonic state estimation [4-5] and nonlinear load identification [6-7]. It is important to highlight that state estimators need some measurements to determine the harmonic components at each bus.

Among the methods previously cited, we can highlight the research developed by [7], where the authors use the IEEE 34-bus with unbalanced voltages and light loading conditions. So, the proposed method was designated to determine the precise location of harmonic sources based on harmonic power flow calculation. However, this method needs a total of 26 meters located at the feeder. Thus, this kind of method is impractical owing to the high cost for purchase harmonic analyzers.

In [5], a Bayesian method was proposed to estimate the state of the IEEE 13-bus. It is important to say that the authors use pseudo-measurements and the IEEE 13-bus was modified to be a balanced feeder, but this condition is improbable in distribution feeders. Moreover, this method needs 5 harmonic analyzers to realize the state estimation.

Following the context above cited, this paper proposes a method that is capable to determine the harmonic components at a specific PCC. Hence, this technique must be employed to obtain the load with the higher harmonic distortion based on the expert knowledge.

This paper was divided in five sections, where in Section I was given the introduction, Section II presents the characteristics of the distribution feeder modeled and simulated. In the Section III we describe the harmonic estimator aspects. Finally, the Sections IV and V are, respectively, designated to show the results of each case study and the research conclusions.

II. DISTRIBUTION FEEDER MODELED AND SIMULATED

The simulated radial distribution feeder contain 20 buses and consists in a modification of the IEEE 13-bus [8]. Therefore, some characteristics such as transformers, loads, and overhead lines are similar to IEEE 13-bus. Figure 1 shows the 20-bus distribution feeder proposed to evaluate the methodology.

In order to model and simulate the 20-bus distribution feeder, we use the ATP (Alternative Transient Program) software [9]. Despite of this software be employed to transient analysis, in this case it is used to steady-state.

Other features concerning to the 20-bus distribution feeder are described in Table I, where were discriminated: source, transformers, capacitor bank and meters (voltage and current).

The Figure 1 shows the 20-bus line diagram where two power quality meters were allocated (one of them between the buses 10 and P1 and the another one between the buses 50 and P2).

Only the power quality meter at the end of the feeder was randomly allocated. This location was chosen in order to better cover the feeder.

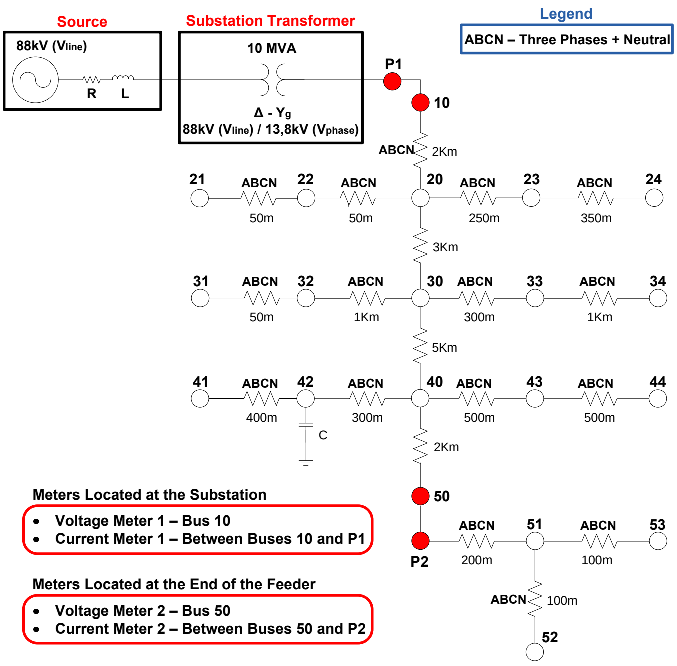

Fig. 1. Line diagram of the 20-bus radial distribution feeder.

Due to this research is focused on the identification of harmonic sources, a 6-pulses rectifier was modeled to supply RC and RL loads. Thus, six case studies were created based on the 20-bus distribution feeder and the 6-pulses rectifier. This case studies will be presented in the Section IV.

III. Harmonic Estimation at the PCC

The harmonic estimator proposed in this paper was addressed to determine a mean harmonic distortion at the PCC. In this sense, the expert knowledge is responsible to define a possible bus where the predominant harmonic source is located. However, it is possible that the expert knowledge is uncertain. So, the harmonic estimator attempts to minimize this uncertainty.

Bearing in mind this pre-determined bus, the estimator follow the procedures shown in Figure 2. These procedures must be done to obtain the mean value of harmonic components at the PCC.

Analyzing the Figure 2, it is possible to note that the harmonic estimator needs the acquisition of actual (measures obtained after entry of the harmonic source) and historical measurements (before the entry of the harmonic source). The historical and actual data are obtained from current and voltage meters allocated at the points highlighted in Figure 1 (P1, 10, P2, 50).

Based on these measurements, the Discrete Fourier Transform (DFT) is applied to obtain the frequency spectrum for each current and voltage acquired. So, the results of the DFT are presented to the power quality engineer in order to support the decision, i.e., the determination of the bus where the harmonic source is probably located.

TABLE I. 20-Bus Radial Distribution Feeder: Meters, Transformers and Source Characteristics.

Source	
Nominal Line-to-Line Voltage (kV)	88.0
Resistance - Zero Sequence (Ω)	20.805
Resistance - Positive Sequence (Ω)	4.062
Inductance - Zero Sequence (mH)	203.721
Inductance - Positive Sequence (mH)	52.540
Nominal Frequency (Hz)	60
Substation Transformer	
Connection	Δ-Yg
Primary Winding - Line-to-Line Voltage (kV)	88.0
Secondary - Winding Line-to-Neutral Voltage (kV)	13.8
Primary Winding - Resistance (Ω)	0.055
Secondary Winding - Resistance (Ω)	0.794
Primary Winding - Inductance (mH)	1.628
Secoundary Winding - Inductance (mH)	23.626
Apparent Power (MVA)	10.0
Capacitor Bank	
Connection	Δ-Yg
Capacitance (μF)	5.965
Voltage and Current Meters	
Sample per Cycle	256
Sampling Rate (Hz)	15360

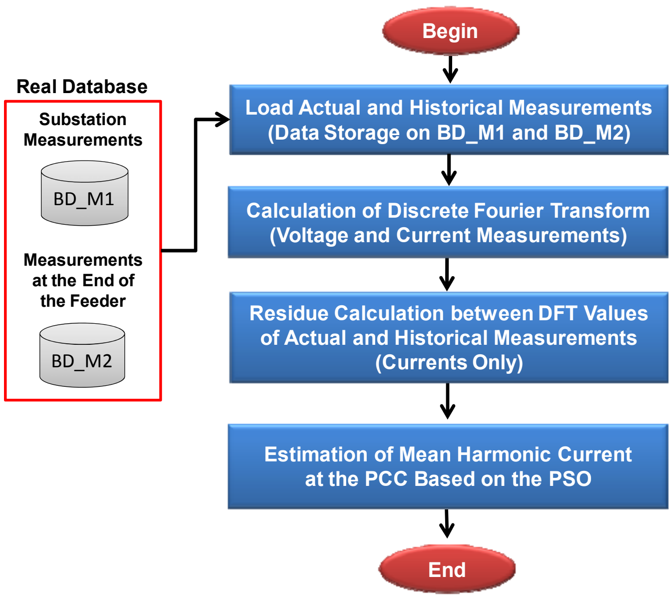

Fig. 2. General procedures of the proposed method.

In the next step, the algorithm performs the residue calculation between the values obtained after the DFT (actual and historical data).

After the procedures above mentioned, the harmonic estimator runs based on the procedures shown in Figure 3.

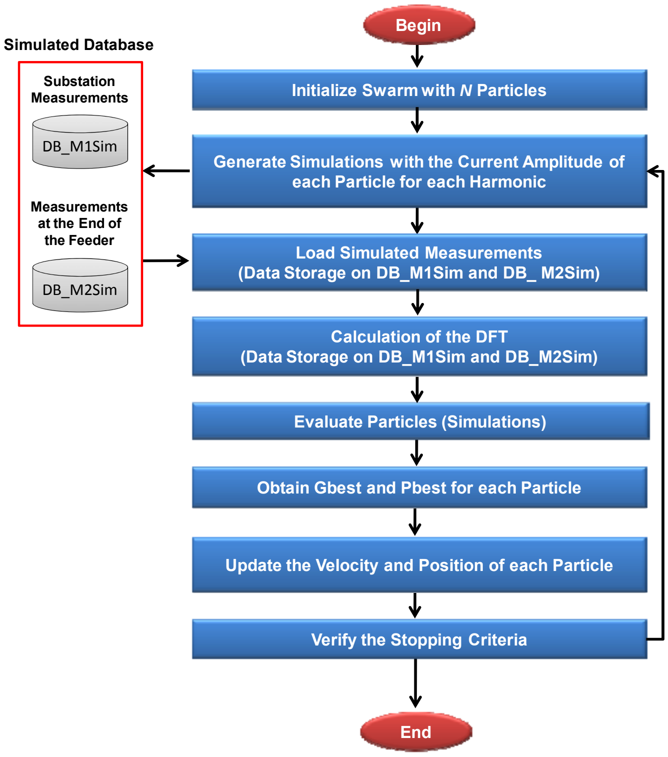

Fig. 3. Flowchart of the harmonic estimator based on particle swarm optimization.

In this paper, as previously mentioned, the estimator is based on Particle Swarm Optimization (PSO). Thereby, the PSO is initialized with N particles (these particles have random values of position and its velocities are equal to zero). So, in the next step, each particle is evaluated related to the objective function which furnish the best particle (g_{best}) and the better positions obtained until the moment for each particle (p_{best}). Consequently, the velocity of each particle is updated in accordance with (1):

$$v_i(t+1) = v_i(t) + \varphi_1 \times (p_{best} - x_i(t)) + \varphi_2 \times (g_{best} - x_i(t)) \quad (1)$$

where:

- φ_1 and φ_2 are respectively the cognitive and social parameters;
- v_i and x_i are the velocity and position of the i^{th} particle;
- t represents the actual state of the swarm.

Therefore, after the particles velocity update, its positions must also be updated in conformity with (2):

$$x_i(t+1) = x_i(t) + v_i(t+1). \quad (2)$$

All the procedures presented must be repeated until the algorithm reach the stopping criteria. This PSO algorithm was implemented based on the foundations proposed by [10-11]. It should be mentioned that was used a swarm with 15 particles.

IV. Casy Studies

As previously mentioned, a 20-bus distribution feeder was modeled and simulated in order to validate this research. Thus, six case studies were created and its peculiarities will be properly treated in the sequence. Mentioning that for each case study, some nonlinear loads (6-pulses rectifier) were allocated in the feeder.

Before the presentation of each case study, it is important to highlight the buses determined by the expert knowledge and the comparison with the exact position of the harmonic source.

TABLE II. Buses Pre-Determined by Expert Knowledge

Case Study	Buses		Error [m]
	Exact	Estimated	
#1	21	20	100
#2	30	30	0
#3	34	30	1300
#4	53	50	300
#5	52	50	300
#6	42	40	300

A. *Case Study #1*

In order to obtain the actual measures, a 6-pulse rectifier feeding a inductive load (600 Ω e 200 mH) was allocated on bus 21. Its harmonic current signature can be viewed in the Table III. This is an ideal case study, because the historical measures do not present harmonic distortions (uncommon condition).

TABLE III. RL Load (600 Ω e 200 mH) allocated on bus 21

Harmonic Order	Peak Current [A]		
	Phase A	Phase B	Phase C
1	59.935	60.165	59.922
3	0.148	0.268	0.121
5	13.332	13.183	13.316
7	6.896	7.117	6.799
9	0.155	0.244	0.122
11	5.314	5.225	5.275
13	4.055	4.260	3.918

Analyzing the actual signals of voltage and current, it is noted a Total Harmonic Distortion (THD) of voltage about: 1.71% (phase A), 1.91% (phase B) and 1.74% (phase C).

The mean value of exact and estimated harmonic currents obtained for this case can be visualized in the Table IV.

It is important to note that higher harmonic orders (11^{th} and 13^{th}) and those harmonic components with low amplitude presents considerable errors.

TABLE IV. RESULTS OBTAINED TO THE CASE STUDY #1

Harmonic Order	Mean Currents [A]	
	Exact	Estimated
1	60.007	64.464
3	0.179	0.014
5	13.277	13.387
7	6.937	7.172
9	0.174	0.056
11	5.271	0.863
13	4.078	0.932

B. *Case Study #2*

The second case study was generated to present the same historical data of case study #1. The actual state of this feeder has a 6-pulses rectifier allocated in bus 30. This rectifier feed a RL load (900 Ω and 900 mH). Thus, its harmonic currents were measured and can be visualized in the Table V.

TABLE V. RL LOAD (900 Ω E 900 MH) ALLOCATED ON BUS 30

Harmonic Order	Peak Current [A]		
	Phase A	Phase B	Phase C
1	40.183	40.495	40.276
3	0.262	0.340	0.078
5	8.426	8.158	8.356
7	5.220	5.530	5.266
9	0.260	0.337	0.088
11	3.717	3.478	3.643
13	2.892	3.221	2.953

Furthermore, the actual measurements has a voltage unbalance (-5% for the phase B and +10% in the phase C) when compared to historical measurements.

It is important to mention that the percentage of voltage unbalance were randomly generated.

In this case study, it was found THD of voltage at the substation about: 1.36% (phase A), 1.54% (phase B) and 1.39% (phase C). Thus, after perfom the harmonic estimator , it was possible to obtain the exact and estimated mean harmonic currents (Table VI).

TABLE VI. RESULTS OBTAINED TO THE CASE STUDY #2

Harmonic Order	Mean Currents [A]	
	Exact	Estimated
1	40.318	43.750
3	0.227	1.001
5	8.313	8.284
7	5.339	6.018
9	0.228	1.008
11	3.613	1.795
13	3.022	0.123

Analyzing these results, we can see that the harmonic estimator presents the same pattern response shown in the case study #1.

C. *Case Study #3*

This third case study, as well as case studies #1 and #2, was generated to has historical data without harmonic distortion. However, the capacitor bank previously allocated in bus 42 was out of operation.

The simulation that represents the actual state has a 6-pulses rectifier allocated in bus 34. This rectifier has been allocated in the feeder in order to feed a RL load (1300 Ω and 200 mH). Thus, the harmonic signature observed at this PCC can be viewed through the Table VII.

TABLE VII. RL LOAD (1300 Ω E 200 MH) ALLOCATED ON BUS 34

Harmonic Order	Peak Current [A]		
	Phase A	Phase B	Phase C
1	27.922	28.085	27.960
3	0.084	0.175	0.094
5	6.273	6.166	6.290
7	3.005	3.177	3.054
9	0.094	0.182	0.091
11	2.511	2.416	2.564
13	1.686	1.869	1.753

Furthermore, in the actual state of the feeder some RL loads had their impedances changed in order to generate variations in feeder loading. It is worth mentioning that only the resistive part of these RL loads was changed in a randomly way.

The voltage THD for this third case study were calculated at the substation: 0.92% (phase A), 1.11% (phase B) e 0.99% (phase C).

The results obtained by the harmonic estimator based on PSO were those shown in Table VIII.

TABLE VIII. RESULTS OBTAINED TO THE CASE STUDY #3

Harmonic Order	Mean Currents [A]	
	Exact	Estimated
1	27.989	27.354
3	0.118	0.026
5	6.243	6.225
7	3.079	3.103
9	0.122	0.025
11	2.497	2.431
13	1.770	1.658

In this case study, only the estimation pattern related to the harmonic components of low amplitude was maintained.

D. *Case Study #4*

This case study was created to use the same profile of historical measurements presented at this moment (without distortions).

Briefly, it can be said that the actual state of the feeder includes voltage unbalance about: -7% (phase A), 7% (phase B) and -4% (phase C). In addition, variations on the RL loads distributed over the feeder were done and also a 6-pulse rectifier feeding a RC load (800 Ω and 1000 μF) was allocated on bus 53. The harmonic distortions observed at the PCC for this case study can be viewed by means of Table IX.

It was found for this case study voltage THD at the substation about: 1.90% (phase A), 2.46% (phase B) and 1.46% (phase C).

TABLE IX. RC LOAD (800 Ω E 1000 μF) ALLOCATED ON BUS 53

Harmonic Order	Peak Current [A]		
	Phase A	Phase B	Phase C
1	44.446	45.610	44.898
3	0.359	0.444	0.795
5	21.303	21.523	21.765
7	10.675	10.304	10.400
9	0.437	0.149	0.455
11	3.609	3.704	3.840
13	2.481	2.442	2.457

After the estimation of harmonic components (Table X), the proposed method showed a high error to estimate the fundamental component and for those with low amplitude.

TABLE X. RESULTS OBTAINED TO THE CASE STUDY #4

Harmonic Order	Mean Currents [A]	
	Exact	Estimated
1	44.985	79.752
3	0.533	1.437
5	21.530	20.629
7	10.460	9.631
9	0.347	0.140
11	3.718	4.031
13	2.460	2.398

E. Case Study #5

Different from the case studies previously reported, this case had historical data generated with harmonic distortions, i.e., it is assumed that the feeder already has nonlinear loads. Thus, the voltage DHT measured at the substation for the historical simulations were: 0.88% (phase A), 1.04% (phase B) and 0.88% (phase C). Moreover, the capacitor bank was maintained out of operation.

The simulation representing the actual state of the feeder has a 6-pulse rectifier feeding a RL load (1400 Ω e 600 mH) allocated on bus 52. In this way, the fundamental and harmonic components of this load was measured (Table XI).

TABLE XI. RL LOAD (1400 Ω E 600 MH) ALLOCATED ON BUS 52

Harmonic Order	Peak Current [A]		
	Phase A	Phase B	Phase C
1	25.762	25.801	25.852
3	0.085	0.022	0.087
5	5.559	5.562	5.518
7	2.866	2.951	2.990
9	0.077	0.066	0.086
11	2.152	2.176	2.150
13	1.541	1.647	1.685

In the actual state of this case, a voltage unbalance can be verified: +3% (phase A), -6% (phase B) and +9% (phase C); and a loading variation of the feeder.

During the actual state simulation were verified voltage THD at the substation about: 1.38% (phase A), 1.45% (phase B) and 1.28% (phase C). The results obtained for the case study #5 are summarized on the Table XII.

This results are very similar to those obtained for the case study #3.

TABLE XII. RESULTS OBTAINED TO THE CASE #5

Harmonic Order	Mean Currents [A]	
	Exact	Estimated
1	25.805	28.280
3	0.065	0.019
5	5.546	5.304
7	2.936	2.792
9	0.076	0.009
11	2.159	1.979
13	1.624	1.442

F. Case Study #6

Finally, the case study #6 is similar to the case study #5, but the capacitor is in operation and replaced to the bus 20. The historical data was obtained in the same way used to the case study #5. Thus, nonlinear loads were allocated on the feeder and a voltage THD at the substation was measured: 3.58% (phase A), 3.56% (phase B) e 3.49% (phase C).

The actual data was acquired allocating a 6-pulse rectifier on bus 42 to feed a RL load (1200 Ω e 400 mH). Its harmonic components are shown in Table XIII.

TABLE XIII. RL LOAD (1200 Ω E 400 MH) ALLOCATED ON BUS 42

Harmonic Order	Peak Current [A]		
	Phase A	Phase B	Phase C
1	29.650	30.029	29.710
3	0.277	0.437	0.162
5	6.549	6.269	6.489
7	2.974	3.332	2.961
9	0.225	0.355	0.162
11	2.279	2.127	2.263
13	1.438	1.692	1.356

The simulation to the actual scenario of the feeder presents loading variations, voltages unbalance about: +4% (phase A), +2% (phase B) and +2% (phase C), and voltage THD at the substation about: 4.24% (phase A), 4.20% (phase B) and 4.17% (phase C). For this last case study, the harmonic estimator shows high imprecision to determine harmonics with low amplitude and to estimate the fundamental current.

TABLE XIV. RESULTS OBTAINED TO THE CASE #6

Harmonic Order	Mean Currents [A]	
	Exact	Estimated
1	29.796	38.235
3	0.292	2.185
5	6.436	6.169
7	3.089	3.678
9	0.247	0.484
11	2.223	2.205
13	1.495	1.325

V. CONCLUSIONS

Analyzing the six case studies, we can be note that the proposed method is not effective to determine harmonics with low amplitude (less than 1 A). The cases #3 and #5 presents the better estimations, probably due to the absence of capacitor banks. So, the continuation of this research points to the definition of behavioral patterns based on the possible scenarios of load. Moreover, other optimization methods, such as ant colony, genetic algorithm and modified particle swarms must be adequate and tested envisioning results better than these presented on this paper.

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