Analysis of Harmonic Mitigation Techniques in 14 Bus IEEE Power System Using Passive Filters

D. Marrugo[1]
V.M. Garrido-Arévalo[2*]
O.D. Montoya[2]

1. Maestría en Ingeniería. Universidad Tecnológica de Bolívar, Colombia.
2. Laboratorio Inteligente de Energía. Universidad Tecnológica de Bolívar, Colombia.

* **dumarrugo@utb.edu.co**

Abstract: This article presents a brief definition of harmonic distortion in power systems, the damage they cause, and the importance of solving this problem. Likewise, the 14-bar system of the IEEE, suitable for conducting harmonic distortion studies is also simulated in the Power Factory DigSilent software. Additionally, the results of power flow and harmonic distortion are presented before and after applying each mitigation technique, which is made up of passive filters in parallel to the bars and filters in series between bars. Finally, a comparative analysis of the results of both techniques implemented in the electrical network is carried out, it is observed that each of these techniques has its advantages, however, it is evident that shunt filters have a better performance in high harmonic distortions, thus reducing the total harmonic distortion (THD) from 19.28 % to 2.15 % being within the limits allowed by the IEEE 519 standard, while series filters achieve better performance in low harmonic distortions (less than 5 %) reaching 3.16 %, this series technique uses smaller amounts of filter to reach the allowed limit, thus generating lower costs.

1. Introduction

The increase in reactive energy in the network is a product of the various components used in energy distribution and transport systems, which cause deformations in the voltage and current wave. These leads, among other things, to an impact on the energy bill, therefore it is necessary to use techniques that allow eliminating or reducing the problems caused by them. One of the techniques proposed in the literature is the use of filters. This article presents the comparison of different types of filters and their response in reducing harmonics in a given power system. First, the procedure for comparing power flow in the network will be constructed as mentioned by the author of the article [1] that compares the behavior of power flow in cases with and without distortion in a public transport system, but does not present technique mitigation of harmonics in power systems. There are different techniques and different filter designs to use, as we see in [2] and in [3] that share procedure, the latter proposes the design of two different passive filters for the currents harmonics and compares simulation results between a system with filters installed and the same system without filters. Distortion occurs primarily in multiples of the carrier frequency (50 or 60 Hz) that are known as harmonics. For example, the 3rd harmonic on a line operating at a carrier frequency of 60 Hz will be 180 Hz, while the 7th will be 420 Hz. THD is the cumulative percentage of distortion for all types of harmonics relative to the total power (See Fig.1)

2. State of art

The use of passive filters is presented in [4], in this document, a supply system was proposed to affect the public electricity grid and a control scheme of the passive filters installed in the system substation. The simulation results show that the designed passive filters have an effective suppression in the characteristic harmonics and harmonic resonance. In addition, it is appreciated that the voltage and current can meet the requirements of the respective national standard. To know what data to analyze in the calculation of power flow, articles [5] and [6] were a good guide, the first shows how to perform the power flow analysis in a system with harmonic distortion and how to determine if said system complies with the norm for harmonic distortion limits and voltage fluctuations. This article does not show ways to mitigate the harmonics of the studied network, but it does give a good approach to the parameters to be taken into account when designing a power system. And second, it focuses on the analysis of power flows in micro-networks of renewable energies installed by consumers of the conventional electrical system. The selected techniques consisted in the use of passive shunt filters or parallel to the load, similar to that presented in [7]. This article that, although it deals with active power filters as a harmonic mitigation method, also gives the central idea to the parallel arrangement, to locate the bank of filters in the network, such that they divert a large part of the harmonic currents of the network , to the filters. The technique of passive filters in series, used in [8], where it is implied that the best method to mitigate harmonics is through the use of filters. The passive series filter is suitable for mitigating voltage harmonics, interconnected in series from bus to bus of the network being studied. This article discusses passive filter control strategies that mitigate harmonics and maintain the sine waveform. The utility that is expected of these 2 techniques, in addition to trying to improve the quality of energy, is to be within the permitted levels of harmonics that regulate in power systems, as mentioned in [7], maintain limits of quality proposed by IEEE-519 standards to protect sensitive loads.

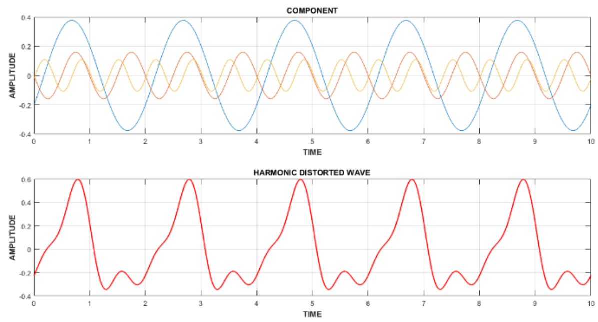

Fig. 1. Fundamental sine wave (Blue), 3rd harmonic sine wave (Yellow), and harmonic distorted wave (Red)

3. Metodology

This section describes the process of selecting the network to be used for the calculation and study of power flow, then the harmonic distortion analysis to solve the problem of noncompliance with the permissible levels in the network, the network chosen to work was that of 14 IEEE buses (See Fig. 2), which is very suitable for harmonic analysis, as we can see in [12] “The simulations to test the proposal are made in the standard test system of 14 IEEE buses for analysis of harmonics”.

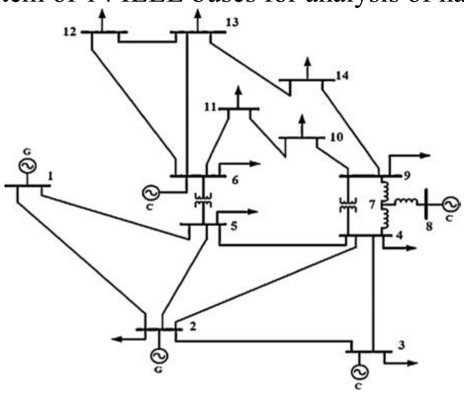

Fig. 2. IEEE 14 Bus System

For the design of the filter it is necessary to know the nominal voltage and the reactive power at which it is going to work. How to find the reactance of the filter is described in [9]

$$\mathcal{X}_{filtro} = \frac{(V_{nominal})^2}{var} \qquad (1)$$

The value in (1) is obtained to find (2) that corresponds to the capacitive reactance

$$\mathcal{X}_{Cap} = \frac{(h^2)}{h^2 - 1}\mathcal{X}_{filtro} \quad (2)$$

After obtaining the capacitive reactance (2), we proceed to calculate the value in farads of the capacitor (3) to be used in the filter

$$\mathcal{C}_{faradios} = \frac{(1)}{w * X_{Cap}} \quad (3)$$

The process is repeated to find inductive reactance (4) and inductance in Henries (5)

$$\mathcal{X}_L = \frac{\mathcal{X}_{Cap}}{h^2} \quad (4)$$

$$\mathcal{L}_{henrios} = \frac{\mathcal{X}_L}{w} \quad (5)$$

Harmonic Distortion (HD) is a term used to determine the effect of harmonics on power systems. According to IEEE519 [14]; Total Harmonic Distortion (THD) is:

$$\mathcal{THD} = \sqrt{\frac{\sum_{h=2}^{hmax} h^2}{h_f}} \quad (6)$$

The square root of the squared sum of each harmonic order is found, divided by the fundamental magnitude.

3.1. Test cases

Two cases of simulation are proposed for the development of this work:

- Case 1: In this scenario the system is presented without implementing mitigation techniques.
- Case 2: For this scenario, the filter arrangement is implemented according to the technique to be used. Additionally, there are some considerations that must be considered:
    - Harmonic distortion calculations will be made for resonance frequencies of 300 Hz (5th harmonic).
    - The analysis is centered on bus 6, for conclusions of results. Since, it is the most critical because it connects with other 4 buses, it has a compensator, a transformer and its load injects currents of 4 different harmonics and even, it is the second bus with more system surge.

3.2. Test techniques

Organize buses from lowest to highest, according to the power factor, considering as possible options those that have the lowest values in the system.

- *Shunt mitigation technique:* This technique is focused on reducing the harmonics of order 5th, 7th, 11th, 13thand 17th. As mentioned in [11], in the turbine generator or motor-load systems, large mechanical stresses are usually caused by the presence of odd harmonics (5th, 7th, 11th, and 13th especially). For this, it is necessary to design banks of different RLC filters parallel to the load, consequently, the greater amount of harmonic current flowing into the power system is reduced. These filters together will attack the entire group of harmonics proposed to mitigate. For this technique, the arrangement of shunt filters is implemented according to the harmonic currents that are injected into each bus. In that sense, 14th harmonic currents are injected into the system of different orders in different buses and to drain them a filter is installed for each current injected.
- *Mitigation Technique Series:* For this technique the same harmonic distortion of the previous case study is used, initially 14 filters were placed with the same design values of the shunt filters, interconnected from bar to bar. But it was noted that, instead of mitigating harmonic distortion, we were injecting harmonics into the system, therefore, we proceeded to reduce filter by filter until obtaining considerable mitigation results, thus it was until we reduced to 5 interconnected filters between the bars with more overvoltage of the system.

4. Results

The power flow of the network is performed, and the harmonic distortion of the system is calculated for the different test cases and mitigation techniques. As mentioned, the analysis is centered on bus 6 in order to provide a more understandable presentation of the results.

4.1. First test case without filters.

This simulation is performed to verify that the transformers and lines are not overloaded and that the bars have acceptable voltages. The results of the flow can be seen in Table 1. The power flow is executed in order to identify the behavior of the voltage variables in p.u and power factor in all the buses in the system.

Table 1. Power flow of bus 6 without implementing filters.

Bus 6 V=123.05kV	P[kW]	Q[kvar]	U[pu]	PF	Load
Load 6	11.20	7.50	0.83	0.06	----
Gen/Comp	00.00	13.77	0.00	0.06	55.08
L6-12	7.84	2.72	0.94	0.04	3.89
L6-13	17.77	8.00	0.91	0.09	9.15
L6-11	7.21	4.82	0.83	0.04	4.07
T 220-132kV	-44.02	-9.27	-0.98	0.21	45.11

In the same way, the calculation of the harmonic distortion of the system without filters is performed. The results can be seen in Table 2. THD refers to the total harmonic distortion on the bus and HD refers to the harmonic distortion of each multiple of the fundamental frequency, in this case the fifth harmonic (300 Hz). That is, on bus 6 there is 19.28 % total harmonic distortion. Where 10.52 % of 19.28 %, belongs only to distortion of the fifth harmonic.

Table 2. Harmonic distortion of buses 3 to 6 without implementing filters.

Bus	Rated voltage [kV]	HD Fn=300Hz	THD
3	230.00	24.05	30.29
4	230.00	24.66	32.11
5	230.00	27.10	34.15
6	115.00	10.52	19.28

4.2. Second test case with shunt filter

Now we proceed to execute the first technique, passive filters in parallel to the load or shunt. For this, we use the software harmonic distortion calculation option, which allows us to choose which harmonic we want to focus on for the results. In this case we work on the 5th harmonic. The results are presented in Table 3:

Table 3. Power flow of bus 6 with shunt filters implemented.

Bus 6 V=123.05kV	P[kW]	Q[kvar]	Q[kvar]	U[pu]	Load
Load 6	11.20	7.50	0.83	0.06	-----
Gen/Comp	00.00	4.48	0.00	0.02	17.90
L6-12	7.93	1.12	0.99	0.04	3.76
L6-13	17.58	6.19	0.94	0.09	8.74
L6-11	7.09	4.26	0.86	0.04	3.88
T 220-132kV	-43.80	-10.02	-0.97	0.21	45.05
Filter Har. 6	0.00	-1.14	0.00	0.01	-----
Filter Har. 7	0.00	-1.14	0.00	0.01	-----
Filter Har. 5	0.00	-1.14	0.00	0.01	-----
Filter Har. 13	0.00	-1.14	0.00	0.01	-----
Total compensation	----	-4.58	------	----	-----

When comparing these results with those presented in Table 1, significant variations are observed in some elements such as in the generator / compensator whose reactive power was reduced by 67.46 %; Likewise, its burden was reduced from 55.08 % to 17.90 %. In that same sense, the reactive power through the lines 6-12, 6-13 and 6-11 decreased by58.82 %, 22.625 % and 11.61 % respectively in relation to the values obtained in the simulation without filters.

Table 4. Harmonic distortion of buses 3 to 6 implementing shunt filters

Bus	Rated voltage [kV]	HD Fn=300Hz	THD
3	230.00	0.30	0.30
4	230.00	0.29	0.29
5	230.00	0.35	0.35
6	115.00	1.60	2.15

The results of harmonics are presented in Table 4. When comparing these results with those obtained in Table 2, it can be seen that both the THD and the HD of the harmonic in question are reduced to levels allowed by the IEE519 standard. THD goes from 19.28 % to 2.15 % and HD goes from 10.52 % to 1.60 %. It should be noted that the percentages of distortion that remained in bars 3, 4 and5 are equal to HD and THD, this means that in those bars the harmonic distortion 7, 11, 13 and 17 was completely eliminated , since the remaining distortion belongs only to the 5th harmonic.

4.3. Second test case with serie filter

Now we proceed to execute the second technique, passive filters in series from bar to bar. The power flow is calculated when the filter is implemented. The results are shown in Table 5.

Table 5. Power flow when implementing serial filters.

Bus 6 V=123.05kV	P[kW]	Q[kvar]	U[pu]	PF	Load
Load 6	11.20	7.50	0.83	0.06	-----
Gen/Comp	00.00	29.13	0.00	0.14	116.50
L6-13	22.93	18.51	0.78	0.14	13.83
L6-11	3.02	6.56	0.42	0.03	3.39
T 220-132kV	-36.05	5.17	-0.99	0.17	36.52
Filter serie Bus 6-12	-1.10	-8.61	-0.13	0.04	4.07

Comparing the flow results in the 3 cases (Table 1, Table 3 and Table 5), it can be seen that the reactive power on bus 6 of the generator / compensator dropped with the shunt method and rose with the serial method, since the series filter caused the generator to compensate for more reactive power. We proceed to calculate the harmonic distortion of the system with filters in series and then make the comparison with the first technique and with the filters turned off. The results can be seen in Table 6.

Table 6. Harmonic distortion of buses 3 to 6 after implementing serial filters.

Bus	Rated voltage [kV]	HD Fn=300Hz	THD
3	230.00	24.05	30.29
4	230.00	6.80	12.78
5	230.00	7.02	13.17
6	115.00	8.13	16.12

In the comparison of these cases the THD of bus 6 went from 19.28 % to 16.12 %, it can be seen that the serial filter mitigates harmonic content but not enough to comply with IEEE 519 regulations, which only allows 2.5 % or less THD and 2 % HD [14].

Table 7. Comparison of THD values in each technique implemented.

Technique	Voltage [kV]	THD without filter	THD with filter
Filter serie	115	19.28	16.12
Filter shunt	115	19.28	2.15

Table 7 shows the comparison of the results of this work with similar ones. It is important to mention that the comparison will not be entirely accurate, since there are different factors in which other jobs change with respect to this, such as the operating voltage and the network itself. Even so, we agree that when using the method of passive shunt filters, very good mitigation results are obtained in THD, more importantly, it should be noted that only the one presented in this work complies with the provisions of the IEEE 519 standard in all the cases.

5. Conclusions

It is evident that the shunt filter has a higher performance than the serial filter, since the latter does not mitigate enough harmonic distortion, however, it was possible to reach considerable levels of mitigation, with few filters in series (5 filters were used). This means that in a case where the total harmonic distortion is low, of 5 %, it is preferable to implement 5 series filters that are responsible for mitigating to the limits allowed by the standard, since the series technique mitigated 3.16 % THD in the worst of our cases, than using 10 shunt filters. It is observed that the proposed objectives were met, since the shunt filter is the one that presents the best results by mitigating the harmonic distortion in the system, thus reducing the total harmonic distortion (THD) from 19.28 % to 2.15 % being within the limits allowed by IEEE 519 standard. It was observed that the bus voltage values are not affected when the filters are switched on or off. This means that the shunt method has correct voltage stability on the bars, for the series method, we can see that it does not affect the stability of the voltage and even alleviates the overvoltage.

References.

[1] GUO Min, JIN Qingren and CHEN Weidong. Analysis of the Harmonics Influence of Urban Rail Transport Load on Nanning Power Grid based on ETAP", 13th IEEE Conference on Industrial Electronics and Applications (ICIEA), 2018.

[2] Zia Hameed, Muhammad Rafay Khan Sial, Adnan Yousaf and Muham-mad Usman Hashmi, "Harmonics in Electrical Power Systems and how to remove them by using filters in ETAP", Conference Paper·February2016, https://www.researchgate.net/publication/313129662.

[3] Zubair Ahmed Menom, Mohammad Aslam Uquaili and MukhtiarAli Unar "Harmonics Mitigation of Industrial Power System Using Passive Filters", Mehran University Research Journal of Engineering Technology, Volume 31, No. 2, April 2012 [ISSN 0254-7821].

[4] Jinhao Wang, Min Zhang, Shengwen Li, Tingdong Zhou and HuijieDu, "Passive Filter Design with Considering Characteristic Harmonics and Harmonic Resonance of electrified Railway", 8th International Conference on Mechanical and Intelligent Manufacturing Technologies (ICMIMT) IEEE, 2017.

[5] Tengfei Li, Ke Mi, Yue Li, Liming Wang and Pengfei Shen, "Load Harmonic and Voltage Fluctuation Analysis Based on the ETAP Simulation", First International Conference on Advanced Algorithms and Control Engineering, 2018.

[6] Sneha Kulkarni and Sunil Sontakke, "Power System Analysis of a Microgrid using ETAP", International Journal of Innovative Science and Modern Engineering (IJISME) ISSN: 2319-6386, Volume-X, Issue-X,2017.

[7] D. C. Bhonsle and R. B. Kelkar, "Design and Simulation of Single-Phase Shunt Active Power Filter using MATLAB", International Con-ference on Recent Advancements in Electrical, Electronics and Control Engineering, IEEE 2011.

[8] R. N. K. Amol Anandrao Patil, Harmonic mitigation using Passive Filter, IJETI, 2017.

[9] R. E. Tique Rojas and J. S. Molano Aguas, "Diseño y construcción de un kit de filtros pasivos para la mitigación de corrientes armónicas", Universidad de la Salle Facultad de ingeneiria Bogota, 2013.

[10] A. Ambadar, "Procesamiento de señales analogicas y digitales,"1999.

[11] G. N. Méndez. Análisis de armónicos en las unidades de generación de las centrales hidroeléctricas illuchi 1 e illuchi 2 de elepco S.A",2013.

[12] C. Z. a. G. Rattá, A. Romero and G. Suvire, "Possibilistic Harmonic Load Flow for Electric Power Systems with Wind Farms", Medellin: IEEE, 2013.

[13] J. A. Boudreaux, Design, Simulation, and Construction of an IEEE14- Bus Power System, Louisiana: LSU Master's Theses. 4801., 2018.

[14] ÏEEE Recommended Practice and Requirements for Harmonic Controlling Electric Power Systems,"2014.

[15] G. P. Pravat Kumar Ray, Real time harmonics estimation of distorted power system signal,"2015.

[16] Remus N. Beres, Xiongfei Wang, Frede Blaabjerg, Marco Liserre and Claus Leth Bak,. Optimal Design of High Order Passive-Damped Filters for Grid-Connected Applications", IEEE, 2015.
[17] Arun Kumar Verma, Chinmay Jain and Bhim Singh, Adaptive noise cancellation based harmonic elimination in grid integrated photovoltaic system", IET journals, 2016.
[18] A. F. C. Castro, "Design Methodology to harmonic mitigation using Phase Multiplication for Distribution Networks", Bogota: IEEE, 2915.
[19] Y. X. Yan Pang. Analysis and Treatment of Harmonie in Power Network with Railway based on ETAP Software", 2016.
[20] R. V. Srihari Mandava. Analysis of Power System Harmonics Using PSNR Metric,"2018.
[21] G. Z. Xiaran Chen, "Harmonic Analysis of AC-DC Hybrid Microgrid Based on ETAP,"2016.
[22] P. S. P. G. P. Pravat Kumar Ray, Real time harmonics estimation of distorted power system signal,"2015.
[23] Santosh Kumar Singh, Robust estimation of power system harmonics using a hybrid firefly based recursive least square algorithm,"2016.
[24] IEEE, Recommended practices and requirements for harmonics controlling electrical power systems," 1992