VOL. 11, NO. 6, MARCH 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

HARMONIC FILTER DESIGN USING INTELLIGENT METHOD FOR MITIGATION OF DISTRIBUTION SYSTEM DISTORTION

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ABSTRACT

Distribution system is a part of electrical system that suffering from a number of problems, such as load variation, voltage fluctuation, and harmonic distortion. Harmonic distortion is one of the concerns recently taking more attention since it may cause losses amplification, rms voltage increment, and, the most dangerous effect is, equipment destruction if resonance frequency occurs. The extensive use of devices generating harmonic frequencies is the main reason of the problem. The nonlinear v-i characteristic of the devices may result in distortion of system voltage that should be prevented not to spread and further deteriorate the system. For this purpose, harmonic filter is commonly installed in the system. Distribution system normally includes a number of shunt capacitors for voltage improvement and losses minimization. However, the capacitors may also amplify the distortion. In this paper, the location and size of harmonic filters is determined using Genetic Algorithm. The aims are to improve the voltage and minimize the losses while mitigating the distortion. The implementation on the IEEE 18-bus system indicates simultaneous system enhancements including voltage improvement, losses reduction, and harmonic mitigation with minimum system modification and cost requirement.

Keywords: decoupled approach, genetic algorithm, harmonic filter, system enhancement, voltage distortion.

INTRODUCTION

A modern electrical system includes a number of components and devices that behaves differently with those previously known and used by people. These devices draw sinusoidal voltage from the utility but may inject non-sinusoidal current to the system. Therefore these components and devices are normally called as nonlinear loads since the relation between the voltage and current is nonlinear. The presence of higher order frequencies cannot be detected by protection relay causing the relay fails to work and, as a result, some important devices may be damaged. The other effects of using nonlinear loads are amplification of voltage and addition of losses. On the other hand, the use of the devices tends to increase recently ranging from low power scale single-phase system to medium-power scale three-phase system.

In low-power single-phase system a number of nonlinear loads are normally used. These may be found in house and office including: oven, air conditioner, fluorescent light, television, battery charger, power supply, computer, printer and copiers. Some other nonlinear loads can still be identified but not all of them can be listed here.

In industry, for the purpose of speed control of electrical machine, drive system is normally employed. Drive systems that mainly consist of power electronic components are nonlinear devices with non-sinusoidal waveforms injecting low order harmonic currents into distribution system. The operation of variable frequency and PWM drives may lead to prominent power quality problems due to their power ratings. DC Drives use controlled rectifiers to enable variable dc voltage while AC drives usually employ PWM inverters with variable voltage and variable frequency technology. In an AC drive, a capacitor is usually installed between the rectifier and PWM inverter. The capacitor is used to suppress ripple of dc voltage. However, the capacitor may amplify line harmonics affecting power quality problems. Harmonic distortion of AC drives under light load conditions becomes more severe. Meanwhile, DC drives are directly connected to DC motor without capacitor resulting in less harmonic distortion compared to AC drives. The nonlinear v-i relation of drive systems may cause some problems, such as triplen harmonic currents, neutral current, additional losses, transformer overheating, incorrect operation of fuses, circuit breakers and relays etc [1].

Three-phase system is also highly polluted by a number of small rating to reasonable harmonic generating devices such as adjustable speed drives and HVDC transmission system in high power rating. Massive single-phase nonlinear loads distributed along three-phase four wire distribution system also contribute distortion in the system.

Some distribution systems are also equipped with a number of shunt capacitors for power factor correction, voltage control and losses minimization [2]–[9]. Since capacitors may magnify system harmonic, some analyses for capacitor placement and sizing were carried out by taking harmonic into account [10]–[12]. Some strategies were also proposed to not only consider harmonic, but also minimize harmonic distortion [13]. By carefully allocating and sizing the capacitors taking into account the presence of harmonics, the purpose of capacitor installation can be achieved while the effect of harmonic amplification can be avoided.

The abovementioned strategy will be further improved by combining reactor with shunt capacitor to be a passive filter. As suggested in [1], a reactor may be inserted in the existing shunt capacitor to suppress the harmonics. A number of filter locations will be selected

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based on the level of harmonic distortion and the filter size will be determined. The filter locations are selected using harmonic power flow analysis and the size of the filters is determined using Genetic Algorithm. The objective is to simultaneously control the voltage, minimize the loss and mitigate the harmonic distortion. The proposed strategy is expected to be effective with minimum investment cost. The scheme is implemented on IEEE 18-bus system with a nonlinear load. The type of nonlinear load is changed during the simulations and the obtained system improvement and harmonic mitigation are analyzed.

METHODOLOGY

For filter design, analyses of harmonic distortion for the existing system will be carried out using decoupled harmonic power flow. The total harmonic distortion of voltage (THDv) for every bus will be given and this value will be used to determine the location of the filters. The number of filters will be determined in advance. With the locations in hand, the value of reactor and capacitor will be calculated using Genetic Algorithm. The combination of shunt capacitor and reactor will act as a harmonic filter and the evaluation of system will again be carried out in terms of harmonic mitigation, voltage improvement and losses minimization.

Decouple harmonic power flow

Power flow is the backbone of power system analysis and design. The calculation provides results normally required for further calculations of system analysis and design. The calculation is initially carried out by formulating network equation. System representation in the form of node-voltage is commonly used and the solution for simultaneous nonlinear equations normally employs an iterative method, such as Gauss-Seidel and Newton-Raphson.

The aforementioned calculation is typically carried out for fundamental frequency. The applications of nonlinear loads result in the existence of higher components other than that of fundamental frequency, called harmonics. The nonlinear v-i characteristic of the loads results in harmonic currents propagating through the system and produces potentially dangerous harmonic voltages. Therefore the presence of harmonic components of nonlinear loads must be included in the calculations to predict their effects and to avoid possible severe damages.

At fundamental frequency, the system is modeled using conventional approach where the admittance of line section between bus i and bus i+1 is expressed as follows.

$$y_{i,i+1} = \frac{1}{R_{i,i+1} + jX_{i,i+1}} \tag{1}$$

Where $R_{i,i+1}$ and $X_{i,i+1}$ are the respective resistance and inductance of line section between bus i and $i+1$. The magnitude and phase angle of bus voltage are then calculated using the following mismatch equations [14]

$$P_i - \sum_{j=i-1}^{i+1} \left|Y_{ji}^1\right|\left|V_j^1\right|\left|V_i^1\right| \cos(\delta_i^1 - \delta_j^1 - \theta_{ji}^1) = 0 \tag{2}$$

$$Q_i - \sum_{j=i-1}^{i+1} \left|Y_{ji}^1\right|\left|V_j^1\right|\left|V_i^1\right| \sin(\delta_i^1 - \delta_j^1 - \theta_{ji}^1) = 0 \tag{3}$$

Where

$$Y_{ji}^1 = \left|Y_{ji}^1\right| \angle \theta_{ji}^1 = \begin{cases} -y_{ji}^1, & if\ j \neq i \\ y_{i-1,i}^1 + y_{i+1,i}^1 + y_{ci}^1, & if\ j = i \end{cases} \tag{4}$$

V_i^1 and y_{ci}^1 are the respective fundamental voltage and shunt capacitor admittance at bus i, and P_i and Q_i are the respective total (linear and nonlinear) active and reactive powers at bus i. Power loss in the line section between bus i and $i+1$ is calculated by the following equation.

$$P_{loss(i,i+1)}^1 = R_{i,i+1}\left(\left|V_{i,i+1}^1 - V_i^1\right|\left|y_{i,i+1}^1\right|\right)^2 \tag{5}$$

At harmonic frequencies, power system is modeled as a combination of passive elements and current sources [15]. The system can be considered as a passive element with harmonic injection currents. The linear load is modeled as a resistance in parallel with an inductance representing active and reactive loads at fundamental frequency. Nonlinear loads, in general, are considered as ideal harmonic current sources injected to the system [16]. The admittance-matrix-based harmonic power flow is the most widely used method as it is based on the frequency-scan process [17]. In this approach, system admittance will vary with the harmonic order. Since skin effect is ignored at higher frequencies, the resulting admittance at h^{th} harmonic frequency for load, shunt capacitor and feeder are respectively given by the following equations [11] [14].

$$y_{li}^h = \frac{P_{li}}{\left|V_i^1\right|^2} - j\frac{Q_{li}}{h\left|V_i^1\right|^2} \tag{6}$$

$$y_{ci}^h = h y_{ci}^1 \tag{7}$$

$$y_{i,i+1}^h = \frac{1}{R_{i,i+1} + jhX_{i,i+1}} \tag{8}$$

Where P_{li} and Q_{li} are the respective active and reactive linear loads at bus i. The nonlinear load is treated as harmonic current sources and the h^{th} harmonic current injected at bus i introduced by the nonlinear load with real power P_n and reactive power Q_n is derived as follows:

$$I_i^1 = [(P_{ni} + jQ_{ni})/V_i^1]^* \tag{9}$$

$$I_i^h = C(h) I_i^1 \tag{10}$$

Where I_i^1 is the fundamental current and I_i^h is

VOL. 11, NO. 6, MARCH 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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the h^{th} harmonic current determined by *C(h)*, the ratio of the h^{th} harmonic to the fundamental current. *C(h)* can be obtained by field test and Fourier analysis for all customers along the distribution feeder [16].

For decoupled harmonic power flow, loop equations may be written for every harmonic frequency considered. Each loop is formed including the source nodes. After modifying admittance matrix and the associated harmonic currents, the harmonic load flow can then be calculated using the following equation [14].

$$Y^h V^h = I^h \tag{11}$$

At any bus i, the rms voltage is defined as:

$$|V_i| = \left(\sum_{h=1}^{H} \left| V_i^h \right|^2 \right)^{1/2} \tag{12}$$

Where H is the maximum harmonic orders considered. After solving load flow for different harmonic orders, the distortion of voltage indicated by total harmonic distortion at bus i (THD_{vi}) is expressed by the following equation.

$$THD_{vi}(\%) = \left[\frac{\left(\sum_{n \neq 1}^{H} \left| V_i^h \right|^2 \right)^{1/2}}{\left| V_i^1 \right|} \right] \times 100\% \tag{13}$$

At the h^{th} harmonic frequency, real power loss in the line sections between buses i and $i+1$ is given by [16]:

$$P_{loss(i,i+1)}^h = R_{i,i+1} \left(\left| V_{i,i+1}^h - V_i^h \right| \left| y_{i,i+1}^h \right| \right)^2 \tag{14}$$

The total power loss including the loss at fundamental frequency is given by:

$$P_{loss}^h = \sum_{h=1}^{H} \left(\sum_{i=1}^{m} P_{loss(i,i+1)}^h \right) \tag{15}$$

Where m is number of bus. For the problem in hand, decoupled harmonic power flow (DHPF) is repeatedly run to evaluate the possible solutions. Therefore the accuracy of DHPF is quite crucial. The developed DHPF has been evaluated by comparing the generated results with those given by commercial packages [18], [19]. The comparisons indicate that the results provided by the developed DHPF are sufficiently accurate. This convinces the applications of the DHPF for filter design will lead to the correct results.

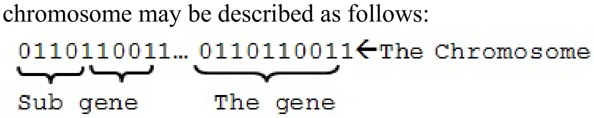
Implementation of genetic algorithm

Using decoupled harmonic power flow, the buses are selected as candidates for filter locations. The selection is based on the level THD_v. The number of filters to install is firstly decided. The next step is filter sizing using Genetic Algorithm (GA).

Genetic Algorithm is a robust method which able to find near global optimal solution as they perform a multi-directional search. It belongs to the class of probability, but different from random algorithms as it combines elements of directed search by maintaining a population of potential solution. The algorithm is classified as intelligent method due to its capability to solve the complicated numerical problem where the other methods encounter difficulty to get through. The disadvantage of this technique is the high processing time associated.

The procedure of GA starts with randomly generating an initial population in the form of chromosomes. These chromosomes represent candidate of solutions. These initial chromosomes will then be refined using a cycle of three stages: evaluation of chromosomes using fitness function, selection of chromosomes for reproduction, and genetic manipulation including crossover and mutation. Completing this cycle means that one generation has occurred and new population is available and ready for the next three-cycle. After some number of generations, the iteration converges and the best individual is assumed to be the solution for the problem in hand. In this paper, GA is employed to determine the optimal size of filters for the selected buses.

The chromosome of initial population is constructed using binary digit. The chromosome consists of genes, where every gene indicates the value of a filter. In this paper, the length of gene is 10 bits divided into two sub-genes of 5 bits, indicating the value of capacitor and reactor, respectively. The length of chromosome therefore depends on the number of filter. For n filters to install, the length of chromosome is n x 10 bits. The construction of chromosome may be described as follows:



The chromosome is then represented to be the value of filters where each consists of capacitor and reactor value. One chromosome denotes some filters. The number of chromosome in one generation depends on the population size. The bigger the population size, the more the chromosome that also means the more possible solution considered.

The combination of filters given by every chromosome is then evaluated by running the harmonic power flow for the system with filters installed. The parameter of evaluation should represent the aims of suppressing the THD*v*, improving the voltage and minimizing system real power loss. However, the importance of every objective must be determined comparatively to the other objective(s). To enable this purpose, weighting factor is applied for every objective in constructing the fitness function as given by the following equation.

$$F = Max\left[F_{\max} - \left(wpP_{loss} + wv\sum_{i=1}^{m}\Delta V_i + wt\sum_{i=1}^{m}\Delta THD_i\right)\right] \quad (16)$$

Where P_{loss} is the per-unit real power loss, ΔV_i is the per-unit *rms* voltage violation at bus *i*, and ΔTHD_i is the per-unit THD violation at bus *i*. While *wp*, *wv* and *wt* respectively denote the weighting coefficient of real power loss, *rms* voltage violation, and THD violation. F_{max} is the normalization constant that enables conversion the minimized objectives to a proper value for comparative assessment. The result of chromosome evaluation is a fitness function for every chromosome. Assessment of a single chromosome requires running decoupled harmonic power flow. The number of decoupled harmonic power flow to run therefore depends on the size of population.

The chromosome evaluation resulting in fitness value will then be followed by selection procedure. The selection is based on chromosome fitness values using tournament method [20]. The next procedure is crossover. The method for crossover is one point crossover where each paired chromosomes exchanges a part of bits to their partner. The part of bits to exchange is determined randomly. As in the natural process that some individual may change genetically due to mutation, the obtained chromosomes may also experience the same process. A number of bits in any chromosome may get change from 0 to 1 or from 1 to 0. Since the occurrence of mutation should not to be very often, the probability rate of mutation must be low. After completing the aforementioned procedures, the new population is now available for fitness evaluation in the next generation. The flowchart of GA for filter design is shown in Figure-1.

Evolutionary Strategy of the Developed GA

For the problem of filter allocation and design, the size of population and the number of generation are fix and determined before calculation. The best chromosome is preserved and directly transferred to the next generation. It is protected from being rejected under the selection process and from genetic modification i.e. crossover and mutation. However, this best individual should also compete with others in the next assessment. The better individual may identified and the new best chromosome may then be appointed. This scheme is normally called as elitism [20].

The weighting factors are fixed during the evolutionary process and may be changed according to the level of importance. The iteration is limited to the maximum number of generation. However, the algorithm is also equipped with a procedure to detect the occurrence of premature convergence. If the fitness iteration progress does not improve in the three successive generations, then the iteration is stopped. It may then be checked if a number of chromosomes become uniform and, therefore, no chromosome modification taking place resulting in no improvement of solution that may be obtained.

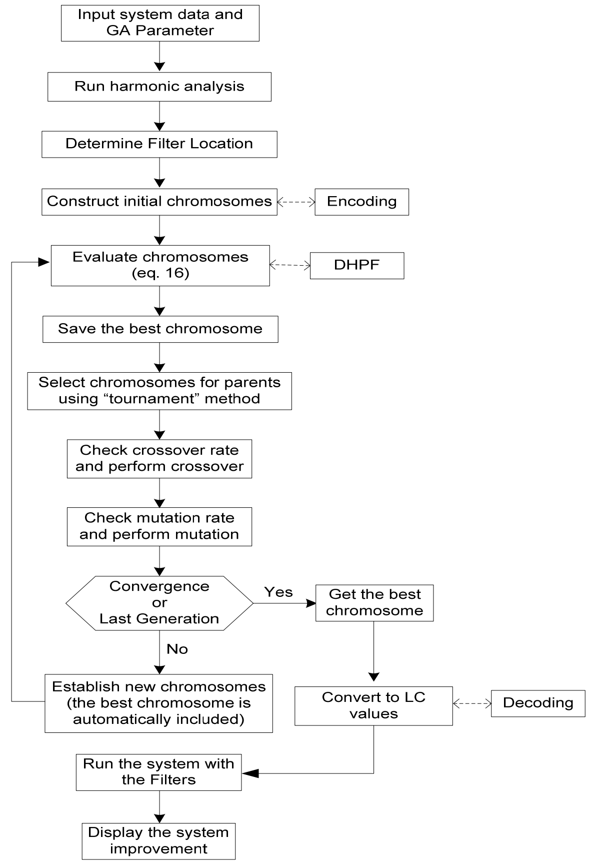


Figure-1.GA flowchart for harmonic filter design.

RESULT AND DISCUSSION

System data

The IEEE 18-bus distribution system as shown in Figure-2 is used for implementations of the proposed GA to determine the best harmonic filters [18]. This system includes a 3 MW converter as the nonlinear load connected to bus 5. There are two type of converter that are used in this study, IEEE 6-pulse rectifier and Rockwell 6 pulse Variable Frequency Drive. The nonlinear load is modeled as current sources. The harmonic contents are given in Table-1 and the non-sinusoidal current waveform is shown in Figure-3.

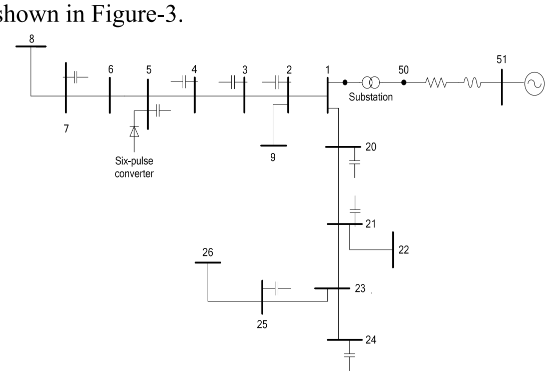


Figure-2. The IEEE 18-bus distribution system.

VOL. 11, NO. 6, MARCH 2016 ISSN 1819-6608
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Table-1. The harmonic spectrum of nonlinear load.

Order	IEEE 6-pulse rectifier		Rockwell 6-pulse VFD	
	Magnitude (%)	Angle	Magnitude (%)	Angle
1	100	0	100	0
5	20	0	23.52	111
7	14.3	0	6.08	109
11	9.1	0	4.57	-158
13	7.7	0	4.2	-178
17	5.9	0	1.8	-94
19	5.3	0	1.37	-92
23	4.3	0	0.75	-70
25	4	0	0.56	-70
29	3.4	0	0.49	-20
31	3.2	0	0.54	7
35	2.8	0	0	0
37	2.7	0	0	0
41	2.4	0	0	0
43	2.3	0	0	0
47	2.1	0	0	0
49	2	0	0	0

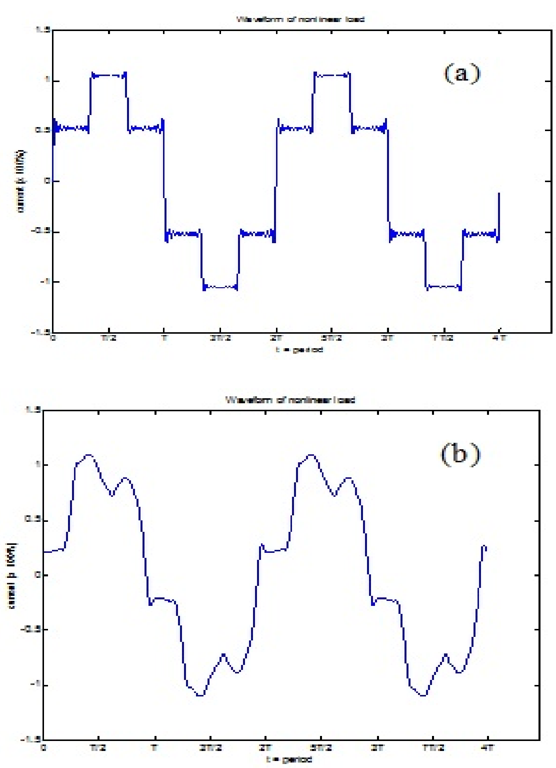

Figure-3. Non-sinusoidal current waveform of (a) IEEE 6-pulse Rectifier and (b) Rockwell 6-pulse VFD.

For optimization using GA, the parameters of optimization are specified. The population size is 75, the maximum generation number is 150, and the probability rates of crossover and mutation is 60% and 1%, respectively. The weighting factors for voltage improvement, real power loss minimization and THDv mitigation is 25%, 25% and 50%, respectively. In this study, 4 locations will be selected where the filters will be installed. The size of inductor and reactor are optimized using GA.

Case 1: IEEE 6-pulse rectifier

In this case, the nonlinear load used is IEEE 6-pulse rectifier. From the calculation, the locations and filter sizes are given in Table-2 and the voltage improvement and THD reduction are indicated in Table-3.

Table-2. Filter locations and sizes of case 1.

Bus Number	Inductor (H)	Capacitor (µF)
5	0.763	36.669
7	1.315	12.223
24	124.547	30.558
25	38.773	18.335

Table-3. The voltage regulation improvement and THD reduction of case1.

Bus Number	Volt reg Improve (%)	THD*v* Reduce (%)
1	2.099	-0.266
2	2.171	0.030
3	2.273	0.620
4	2.315	0.590
5	2.460	1.268
6	2.443	1.780
7	2.368	1.715
8	2.367	1.716
9	2.171	0.030
20	2.995	-0.785
21	3.715	-0.569
22	3.714	-0.568
23	5.027	0.154
24	5.686	1.456
25	4.440	0.867
26	4.363	0.867
50	0.100	-0.020
51	-0.000	-0.019

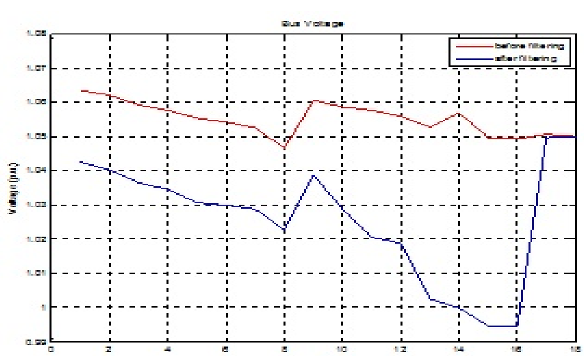

Figure-4. Bus voltage of the system.

It may be seen that, in general, bus voltage is improved and THDv is reduced. The average voltage regulation improvement is 2.817 % and the average THDv reduction 0.492 %, respectively. The highest distortion is 4.999 % at bus 26, which still complies with the maximum permitted distortion of 5%. Without filters, the maximum distortion can be more than 6%, exceeding the maximum distortion limit. The bus voltage and the related regulation improvement are shown in Figures-4 and 5, respectively, while the bus THDv is shown in Figure-6. The installation of filters also enables saving of real power of 28.699 kW. This highlights that the filters does not only control the harmonic distortion but also improves the voltage and minimizes the system power loss.

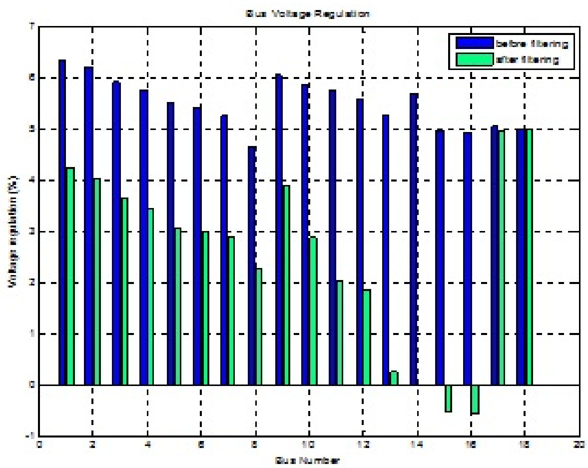

Figure-5. Bus voltage regulation of the system

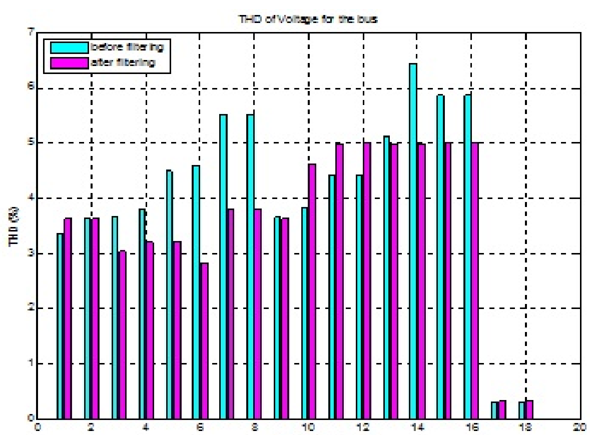

Figure-6. THDv of system bus.

Case 2: Rockwell 6-pulse VFD

To demonstrate the ability of the proposed algorithm dealing with different types of nonlinear load, the current nonlinear load is replaced with another type. The Rockwell 6-pulse VFD is now installed on the system as nonlinear load. The spectrum of harmonic and the nonlinear current waveform are indicated in Table 1 and Figure-3(b). The result generated by GA for filter locations and sizes are indicated in Table-4.

Detail inspection of Table-2 confirms that the location of filters is different with that of the nonlinear IEEE 6-pulse rectifier load. The system enhancement including improvement of system voltage regulation and harmonic distortion are indicated in Table-5.

Table-4. Filter locations and sizes of case 2.

Bus Number	Inductor (H)	Capacitor (μF)
7	1.559	12.223
21	1.072	24.446
24	1.451	30.558
25	1.892	18.335

Table-5. Voltage regulation improvement and THD reduction of case 2.

Bus Number	Volt reg Improve (%)	THD*v* Reduce (%)
1	1.49	-0.779
2	1.498	-0.523
3	1.513	0.06
4	1.522	0.473
5	1.555	1.803
6	1.55	1.831
7	1.539	1.891
8	1.539	1.891
9	1.498	-0.523
20	2.278	-0.657
21	2.908	-0.127
22	2.908	-0.126
23	3.823	0.848
24	4.299	1.581
25	4.109	1.225
26	4.109	1.225
50	0.072	-0.067
51	0	-0.067

The average voltage regulation improvement is 2.123% and the average THD improvement is 0.553%. While the real power loss can be reduced as big as 38.988 kW. This again confirms that installation of filters may not only present distortion minimization but also voltage improvement and real losses minimization. The most distorted bus is bus 26 with THDv of 5% which complies with the standard of maximum harmonic distortion. For the system without filters, the distortion can be more than 6%.

The bus voltage and the related voltage regulation are indicated in Figures-7 and 8, respectively. The mitigation of harmonic distortion indicated by minimization of THDv is shown in Figure-9. The figures confirm that installation of filters in the distribution system may improve system performance. It does not only suppresses the distortion, but also improves the voltage and minimize the real power loss

Discussion

Figures-4 and 7 show that installation of filters enables the system voltage can be maintained as close as 1 p.u. The closer the voltage to nominal value of 1 p.u., the better the system condition is. The maximum voltage deviation is 5%. It may be observed in the figures that without harmonic filters the bus voltage may exceed the limits.

Different distortion pattern requires different location and size of filters. Nonlinear load with different harmonic spectrum will imply different system distortion. The harmonic current injected by the load will flow through the whole system and harmonic analysis is required to figure the distortion at every bus. It may be observed that while the nonlinear load is connected to bus 5, the maximum distortion is at bus 26 which is far from the harmonic source. The relation between harmonic source location and system distortion may be accurately presented by harmonic power flow calculation.

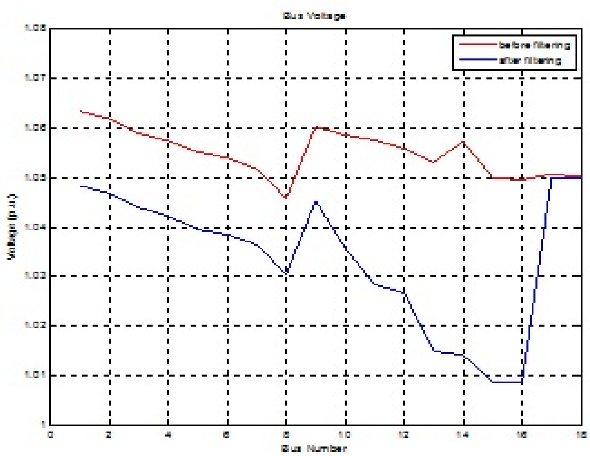

Figure-7. Bus voltage of the system.

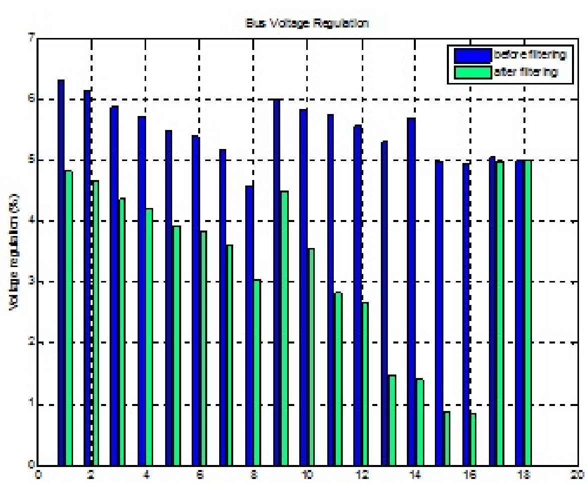

Figure-8. Bus voltage regulation of the system.

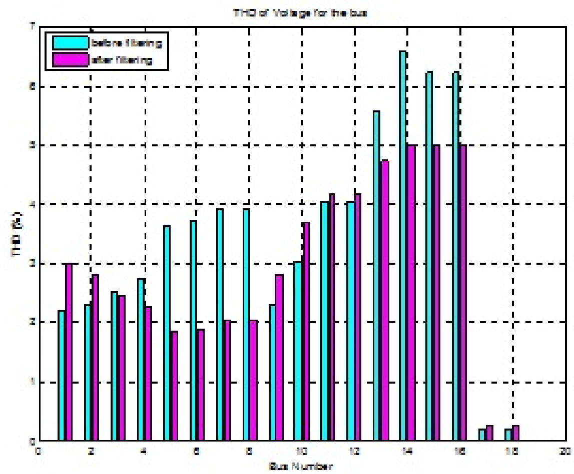

Figure-9. THDv of system bus.

CONCLUSIONS

The proposed Genetic Algorithm is employed to determine the locations and sizes of harmonic filters. The decoupled harmonic power flow is developed and used to be the part of assessment tools providing the value of bus THDv, bus voltage and system real power loss. The main conclusions are:

- The accuracy of decoupled harmonic power flow is essential for harmonic filter design using GA,
- The installation of filters enable system improvements including better voltage regulation, less harmonic distortion and lower real power loss,
- Different type nonlinear load cause different system distortion leading to different locations and sizes of filters,
- Proper selection of optimization parameters (weighting functions, number of initial solution and iteration) may improve the solution without increasing the computation charge,
- This study may be improved by selecting the commercially available filter components.

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