OPTIMAL HARMONICS COMPENSATION IN A SEA WATER DESALINATION PLANT

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ABSTRACT: A centralized compensator is presented in this paper as an effective harmonic suppression technique based on active power line conditioners (APLCs). The basic concept is to correct the grid distortion caused by power electronics-based loads. The APLCs will mitigate the distorted current by injecting anti-harmonic currents at particular network buses. The network performance is observed and the optimal corrective signals are generated through the centralized compensator considering all buses rather than the local situations to get quasi-sinusoidal voltages with minimum APLCs actions. An approach is investigated to solve the APLCs allocation and sizing problem (AAS) based on genetic algorithm under full load conditions for a sea water desalination plant as a practical case study. The online implementation of the optimal settings is achieved using Artificial Neural Network (ANN).
KEYWORDS: Active power line conditioners, Centralized compensators, Genetic algorithm, Harmonic compensation, Artificial neural network.

1. INTRODUCTION

Nowadays, active power line conditioner is one of the most common harmonic suppression tools. Basically, the extraction of the unwanted line current harmonic components is the basic concept of APLCs. They will generate and inject similar components but with opposite sign into the line in such a way to produce a partial or total cancellation of the unwelcome harmonic components. Either series or parallel connection can be used for the active filter with the power system and hence, it can operate as either voltage source or current source [1]. A negative harmonic current is injected to the utility system using the shunt active power filter so that the nonlinear load harmonic currents can be cancelled. A distorted-voltage waveform is inserted to the system by the series active power filter to maintain a sinusoidal load voltage at its rated magnitude [2-4]. Thus, active power filters “APFs” offer exceptional ability to clean the network from harmonics and compensate load unbalances at the same time.

Corrections in the time domain or in frequency domain are the two fundamental approaches for mitigating power harmonics with APLCs, which are presented in many publications [5-12]. One of the two previous methodologies can be used in conjunction with voltage-type or current-type converters. The exact chopped waveform that is required to correct a distorted voltage or current waveform is produced using an inverter and a dc source involved in the APLCs. The dc source is alternately and rapidly connected, positively or negatively, or disconnected to absorb or supply power as system requirements [13].

The voltage-type APLCs have many advantages since they can eliminate higher order harmonics without increasing individual converter switching rates. In addition, they are cheaper and lighter than current-type APLCs. However, they have more complex control system since several converters connected in parallel are required. In addition, current types are simpler and more reliable than voltage-type APLCs. Generally, voltage-type APLCs are used for wide compensation and electric utility interest. Conversely, current-type APLCs are popular for single-node distortion problems [13].

The utilization of APFs has been reported in various topologies since 1980 [11-17]. A discussion of several control techniques is presented in [5] to ensure their expected implementation. Conversely, a proposed APF using a switched capacitor topology has been illustrated as an alternative solution [5-6]. This strategy enables the implementation at low frequency switching and reduces the component items and capacitor ratings. The solution of allocation and sizing problem of APFs is normally solved based on optimization process, where various objective functions have been proposed [14-18]. Handling the harmonics can be accomplished by minimizing the voltage distortion or the APLCs injected currents. The former reduces the unwanted effects of harmonic distortions on the network, while the later minimizes the total cost and just achieves harmonic standards.

Genetic algorithms (GAs) have been used in many optimization applications [15]. In [16], GA is applied to find worst voltage harmonic conditions on a distribution feeder with distributed variable harmonic sources, variable loads, and switchable capacitor banks at different locations. A genetic-based algorithm was presented in [17] to solve the allocation and sizing problem of Active Power Filter using two algorithms. This is accomplished by reducing the voltage distortion in the network and the sizes of APLCs, while meeting the harmonic standard levels. Therefore, a four-part comprehensive multi-objective function is introduced.

Actually, one APLC may not be adequate under some circumstances, such as when the APLC has a relatively small current rating, or when the power system has sever harmonic pollution. The theory and solution methods developed to handle multiple APLC problems are presented in [17-18].

In this paper, a centralized controller is developed based on APLCs to minimize the harmonic distortion in the network. The target is to observe all buses and define the minimum APLCs currents to handle the harmonics everywhere in the network rather than local harmonic suppression. The GA is used as an optimization tool due to its capabilities to handle optimal allocation and sizing problems [18-20]. For realistic results and conclusions, as a main objective of this research, the investigated system is a real sea water desalination plant in Algiers, Algeria. The obtained results ensure the effectiveness of the centralized controller to handle the harmonic problem at all buses with minimum APLCs currents.

2. GENERAL APPROACH

The centralized controller is responsible for defining the required compensating currents at all buses based on the actual harmonic contents. Thus, the power system will sustain its voltage with high quality. So, it is obligatory to use an optimization technique to define the best number, locations and sizes of APLCs. Secondly, the optimal APLC currents will be defined for a large number of various loading conditions to build a database. A training process will be carried out based on the database in the offline mode to generalize the optimization process. Consequently, the central controller will define the optimal current magnitudes that should be injected by the APLCs under any loading conditions in the online mode. The centralized controller needs to operate within smart grid environment to utilize bidirectional communication systems, smart meters and fully automated arrangements [19-21]. Hence, the smart grid environment will help to implement such successful centralized controllers. Figure 1 shows the schematic diagram of centralized controller.

3. THE SYSTEM CONFIGURATION

The power system under study consists of a large number of induction motor-driven water pumps. These loads contain variable speed drives (nonlinear loads), soft-start controllers, and uninterruptible power supplies, which are considered as sources of harmonics. The power-electronic-based loads in the water treatment distribution system cause severely distorted voltage waveforms at the point of common coupling (PCC). Other linear loads connected at the same PCC will incorporate a distorted supply voltage, which may lead to various unwanted effects. The overheating of motors, transformers and cables, malfunction of some protection devices, and resonance with capacitors are some of these effects.

The details of the water desalination plant are given in Appendix A. After simulating all system components on the ETAP® program, a power flow is performed for the plant. Then, the harmonic analysis study is accomplished to show the effect of nonlinear loads on the system under consideration.

According to the IEEE Standard 519-1992 [22], maximum allowable voltage total harmonic distortion (THD) is 5% and voltage individual harmonic distortion (IHD) is 3% for distribution network below 69kV. Since the system under study has maximum voltage of 60kV, the application of these standard limits will be acceptable.

4. PROBLEM FORMULATION

4.1 APLCs mathematical model

The commonly used and simplest model of APLC is a current source that injects harmonics to the point of common coupling (PCC) in power systems [16-18]. With the assumption that the APLC current has a certain amplitude and phase angle, the phasor model given by (1) is used.

$$I_{Fm}^{h} = I_{Fm}^{hr} + jI_{Fm}^{hi} \quad (1)$$

where: I_{Fm}^{h} is the APLC current at bus m for harmonic order h and I_{Fm}^{hr} and I_{Fm}^{hi} are its real and imaginary parts. The indices r and i represent the real and imaginary parts of the APLC current, respectively.

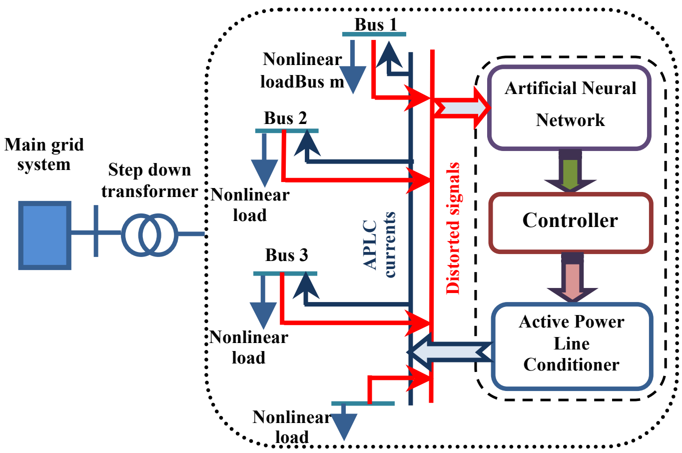

Figure 1. Schematic diagram of the centralized controller

4.2 Power system modeling

Considering an M-bus power system that contains nonlinear loads, N-APLCs are used to compensate the harmonic voltages throughout the network. The APLCs are located at buses m_1, $m_2 \ldots m_N$. The value of the harmonic transfer impedances between any two buses and the harmonic voltages at any bus before placing the APLCs are assumed to be known. In addition, it is assumed that there is no coupling between harmonics [18].

The harmonic voltages and their active and reactive components at bus m for harmonic h without APLCs are [18]:

$$Vbus^{h}_{mwout} = Vbus^{hr}_{mwout} + jVbus^{hi}_{mwout} \quad (2)$$

where: $Vbus^{h}_{mwout}$ is the voltage phasor for harmonic h at bus m without installing the APLC.

The harmonic transfer impedance and its active and reactive components between any two buses are given as [18]:

$$Z^{h}_{mk} = Z^{hr}_{mk} + jZ^{hi}_{mk} \quad (3)$$

The voltage phasor for harmonic h at bus m with APLC and its active and reactive components are given as [18]:

$$Vbus^{h}_{m} = Vbus^{h}_{mwout} + \Delta Vbus^{h} \quad (4)$$

The term $\Delta Vbus^{h}_{m}$ can be determined as follows [18]:

$$\Delta Vbus^{h}_{m} = \sum_{m=1}^{M} Z^{h}_{m,k}\, I^{h}_{m} \quad (5)$$

As can be recognized from equations (4) and (5), the bus voltages for each harmonic $Vbus^{h}_{m}$ are affected by a number of variables. These variables are the bus voltage for each harmonic before APLC installation $Vbus^{h}_{mwout}$, the impedance for each harmonic and the injected currents of APLCs. All these variables are considered as decision-making variables.

4.3 Objective function and constraints

Various objective functions have been proposed for allocation and sizing of APLCs problem [16-21]. Generally, there are two types of constraints that can be observed: the constraints related to the maximum current produced by APLC, namely APLC size, and those related to the IEEE-519 standard [22]. These standard limits are used to evaluate the individual and the total harmonic distortions level for all buses.

The objective function is formulated taking into account the multi-bus, multi-harmonic (MBMH) problem. In this paper, an algorithm is introduced based on the considered constraints. The target is to minimize the total objective function considering the standard total harmonic distortion as a fundamental constraint. The total APLC injected currents will be added as another constraint based on the non-linear load current value to limit the ratings of the used APLCs.

The most important objectives of placement and sizing of APLCs in a power system are to reduce the total harmonic distortion (THDt), motor load losses (MLLt), total harmonic transmission line losses (HTLLt) and the total APLCs injected currents (IFt). The mentioned parts will be lumped into the following multi-objective function:

$$OF = W_1 \cdot THD_t + W_2 \cdot MLL_t + W_3 \cdot HTLL_t + W_4 \cdot IF_t \quad (6)$$

where: W_1, W_2, W_3 and W_4 are the weight coefficients for THD, MLL, HTLL and total APLCs current respectively.

From (6), the objective function is composed of four parts: the summation of total harmonic distortions at all buses “THDt”, the summation of motor load losses at all buses “MLLt”, the summation of harmonic transmission-line losses at all buses “HTLLt” and the summation of APLCs current at all buses “IFt”. Each part is formulated as follows:

Total harmonic distortion part (THDt) [18]

$$THD_t = \sum_{m=1}^{M} THD_m , \; m=1, 2, \ldots, M \quad (7)$$

$$THD_m = \frac{\sqrt{\sum_{h=2}^{H} \left|Vbus^{h}_{m}\right|^2}}{\left|Vbus^{1}_{m}\right|} , \; h=2, 3, 4, \ldots, H \quad (8)$$

where: H is the maximum considered harmonic order; THD_m is the value of THD at bus m and $Vbus^{h}_{m}$ and $Vbus^{1}_{m}$ are the voltage at bus m for harmonic order h and the fundamental component respectively.

Motor load loss part (MLLt) [18]

$$MLL_t = \sum_{m=1}^{M} MLL_m , \; m = 1, 2, 3, \ldots, M \quad (9)$$

$$MLL_m = \frac{\sqrt{\sum_{h=2}^{H} \frac{\left|Vbus^{h}_{m}\right|^2}{h}}}{\left|Vbus^{1}_{m}\right|} , \; h = 2, 3, \ldots, H \quad (10)$$

where: MLLm is the value of MLL at bus m.

Harmonic transmission line loss part (HTLLt) [18]:

$$HTLL_t = \sum_{h=2}^{H} \left[\sum_{m_1=1}^{M} \sum_{m_2=1}^{M} \frac{R_{m_1,m_2}}{Z^{2}_{m_1,m_2}} \left|Vbus^{h}_{m_1} - Vbus^{h}_{m_2}\right|^2 \right] \quad (11)$$

$m_1, m_2 = 1, 2, 3, \ldots, M, \qquad m_2 > m_1$

where: R_{m_1,m_2} and Z_{m_1,m_2} are the line resistance and impedance between buses m_1 and m_2 for harmonic order h.

APLCs current part (IFt) [18]

$$IF_t = \sum_{m=1}^{M} \sqrt{\sum_{h=2}^{H} \left| I_{F,m}^{h} \right|^2} \qquad (12)$$

where: $\left| I_{F,m}^{h} \right|$ is the amplitude of APLC current at bus m for harmonic order h.

4.4 Optimization Algorithm

In this algorithm, two types of constraints are considered. The first type belongs to the voltage harmonic distortion, which must be decreased below the harmonic standard levels. The second one refers to the APLCs size, which depends upon the total maximum allowable APLCs injected currents. The optimization problem described by:

$$\text{Min } OF = W_1 \, THD_t + W_2 \, MLL_t + W_3 \, HTLL_t + W_4 \, IF_t \qquad (13)$$

Such that

$$THD_m \le \overline{THD}_m, \; m = 1, 2, \ldots, M \qquad (14)$$

$$\text{and } \sum_{k=1}^{K} \overline{I_k} \le \bar{I}_{F\,max}, \; k = 1, 2, \ldots, K \qquad (15)$$

where: THD_m is the total harmonic distortion at bus m, $\overline{THD}_m$ is the maximum total harmonic distortion at bus m imposed by harmonic standards and $\bar{I}_k$ is the size of APLCs at the candidate bus k.

The decision making problem variables are the real and imaginary parts of the APLC current at bus m for harmonic orders h $I_{F,m}^{h,r}$ and $I_{F,m}^{h,i}$. The voltage phasor for harmonic h at bus m $Vbus_m^h$ is a nonlinear function of both of them.

5. GENETIC ALGORITHM IMPLEMENTATION FOR AAS

The Genetic Algorithm (GA) is one of the most powerful optimization techniques. According to this technique, the population with the better fitness has higher opportunity to survive [23]. Therefore, GA is implemented to solve the APLC allocation and sizing problem. To evaluate the applicability of the proposed technique, the algorithm is applied to a water treatment plant, which supplies clean drinking water for more than one million people in Algiers, Algeria. It consists of a large number of variable-speed induction motors with soft-start controllers, and uninterruptible power supplies, which are main harmonic sources [23]. All the essential harmonic data, as well as transmission impedances, voltage magnitude and their angles are calculated using MATLAB 2010 software. These data are used as inputs for the proposed algorithms.

6. RESULTS OF THE OPTIMIZATION PROCESS

In this algorithm, two constraints are considered: the first is the total rms current value of the APLCs, while the second belongs to the total harmonic distortion. The former limits the APLCs current to the total nonlinear currents in the system, i.e., 0.715 pu, while the later ensures meeting the IEEE standard limits. In this approach, all buses are considered as candidate buses for APLCs installation simultaneously. The optimal APLC compensation currents are calculated to minimize the harmonic effect at all buses with minimum possible cost. The minimum cost is achieved by selecting the minimum number of APLCs with minimum rating subject to all given constraints. This process is repeated for several loading conditions.

The calculated total harmonic distortion at each bus for different APLCs states at full load are shown in Table 1 Only five states are illustrated since the sixth state necessitates very high currents. It is clear also that the THD in the first and second states violated the constraints since low number of APLCs is not enough to compensate the harmonics with reasonable currents.

Table 2 illustrates the summation of APLCs current (IFt), the average total harmonic distortion (THDav), the average motor load loss (MLLav) and the total objective function (OF) indices obtained from the simulation of the system for the three feasible states. It is obvious from the two tables that state 3 provides the minimum total objective function and satisfies all constraints. In other words, installing 8 APLCs at buses 5, 6, 7, 8, 11, 12, 13 and 14 can be considered as the optimal solution because it minimizes the total objective function, while satisfying all constraints. Figure 2 illustrates the total harmonic distortion with and without APLCs at each bus for the different feasible states.

The above results consider the full load only as the worst condition. The success of the optimization process to define the optimal allocation and size of the APLCs for this condition ensures the possibility of defining the output compensating currents under other loading conditions. It is, thus, possible to define the optimal compensating currents under different loading conditions in the offline mode. Thus, a database can be built in the offline mode and used in a further training process to enable optimal decision making in the online mode. An ANN can be used in the training process due to its nonlinear and generalization capabilities. Consequently, a centralized controller can be used to optimally regulate the performance of APLCs to decide for the APLCs current at each bus instantaneously according to the distortion levels.

Table 1. The full load percentage calculated total harmonic distortion for each bus for different APLCs placement states

Bus No	State Number				
	State1	State2	State3	State4	State5
1	2.27	2.27	2.27	2.27	2.27
2	2.06	2.06	2.06	2.06	2.06
3	2.28	2.28	4.50	4.50	✓4.50
4	2.06	2.06	4.22	4.50	✓4.50
5	9.31	9.07	✓4.50	✓4.51	✓4.50
6	8.35	9.01	✓4.50	✓4.51	✓4.50
7	✓2.00	✓6.93	✓2.69	✓2.69	✓3.26
8	✓2.00	✓6.70	✓2.81	✓4.51	✓3.53
9	9.36	3.80	4.49	✓4.51	✓4.50
10	8.32	3.53	4.49	✓4.50	✓4.49
11	0.56	✓4.53	✓4.48	✓4.49	✓4.52
12	0.81	✓4.52	✓4.46	✓4.49	✓4.53
13	✓0.08	✓6.44	✓4.50	✓4.50	✓4.48
14	✓0.07	✓6.47	✓4.50	✓4.50	✓4.49

Table 2. Results of system analysis for the second case at full load condition

State No.	State3	State4	State5	Without
IF_t	0.7150	0.7027	0.7189	0
$\%THD_{av}$	3.87	4.04	4.01	14.28
MLL_{av}	0.0125	0.0132	0.0131	0.04688
OF	0.767	1.9037	2.025	

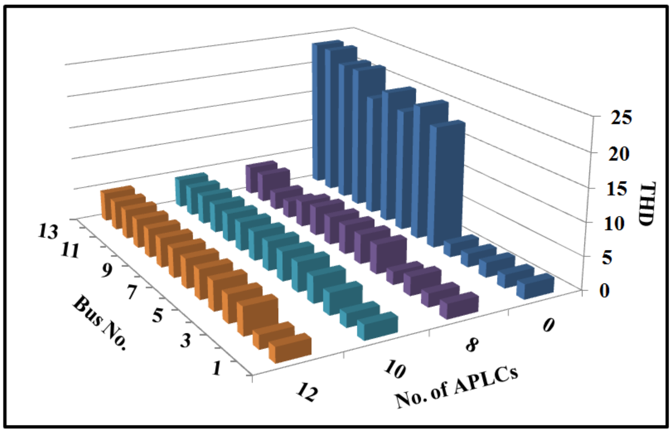

Figure 2. The THD with and without APLCs at each bus in different states

7. ONLINE IMPLEMENTATION OF THE CENTRALIZED CONTROLLER

Lately, ANN is used as a common technique that is used to generalize the onsite problems because of its great ability of simplifying such nonlinear complicated problems [19-21] and [24]. So, it will be used to generalize the results obtained from the GA optimization technique. Once well trained, ANN will be ready for implementation to define the outputs from APLCs in the online mode. A simple hardware can be developed based on the structure and parameters of the ANN to define the optimal or quasi-optimal APLCs outputs.

7.1 ANN Structure

Different ANNs are constructed to define the optimal APLC currents for different harmonic orders. All ANNs have only a single hidden layer with different number of neurons varying from 25 up to 50 neurons. The nodes in the input layer receive 216 inputs, while eight outputs are obtained at the output layer. The voltage harmonic contents are used as inputs to the ANN, which is used to generalize the results. The structured neural network is divided into 16 parallel networks eight of them for the real APLC current components, for various harmonic orders, and the rest for the imaginary ones. The sixteen circuits have the same inputs and the same ANN structure as mentioned previously as shown in Fig. 3.

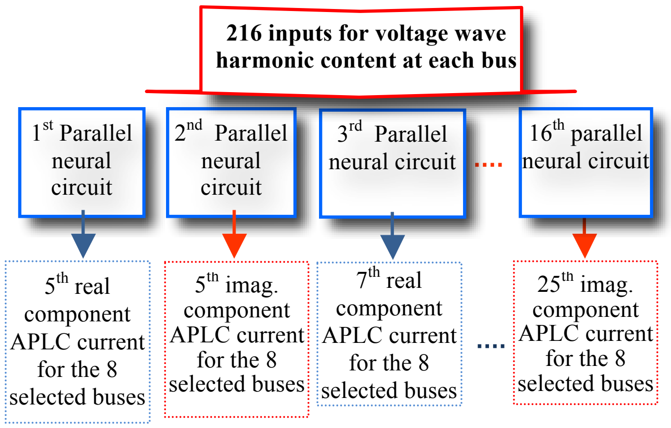

Figure 3. The ANN multiple parallel networks

7.2 Training the neural network

A database is constructed by applying GA optimization technique to 120 various loading conditions. This database can be used in neural network training. Results corresponding to 112 various loading conditions are used in the training process, while results regarding the rest of the loading conditions are reserved for testing the trained network. The training is carried out for more than 1000 epochs to ensure high accuracy in the training process.

To evaluate the effectiveness of the training process, Figs. 4 and 5 illustrate two selected comparisons between the optimal target and the ANN-based settings for the real and imaginary harmonic content as an example for the obtained training results.

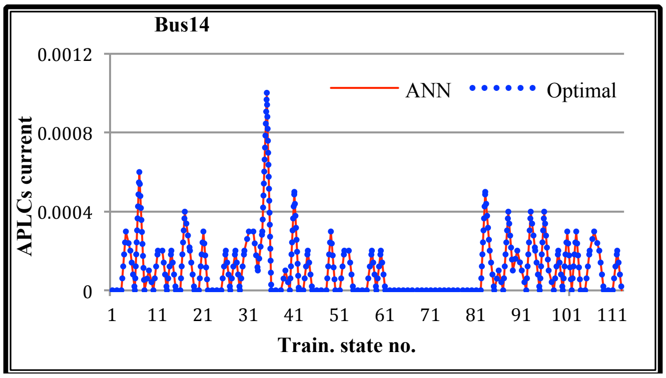

Figure 4. Comparing the ANN output with the optimal target for the 5th real harmonic content

The agreement between the ANN-based settings and the GA-based optimal target reflects the high accuracy of the training process, ensuring the high capability of the ANN to extract the features of the optimal performance.

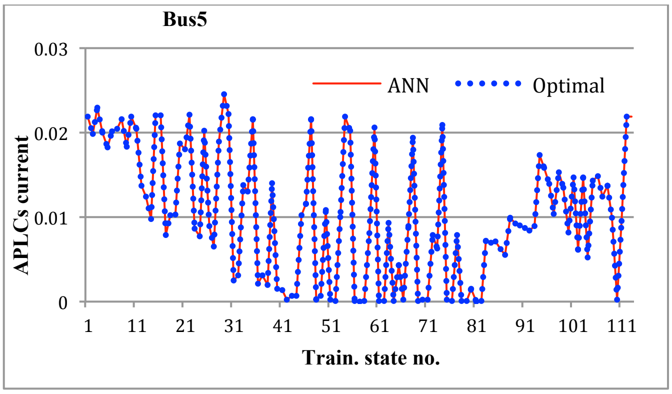

Figure 5. Comparing the ANN output with the optimal target for the 7th imaginary harmonic content

7.3 Testing the trained neural network

In the testing phase, the trained ANN is activated by new testing data to verify the generalization capability of the network. Eight different loading conditions, which are not used in the training process, are used to test the trained network for 16 real and imaginary harmonic contents for the eighth selected buses. This includes 112 different cases with a total number of 896 patterns. Figures 6 and 7, as test examples, illustrate comparisons between the optimal target and the ANN-based settings for the total APLC current for each bus as obtained from the test results for all selective buses.

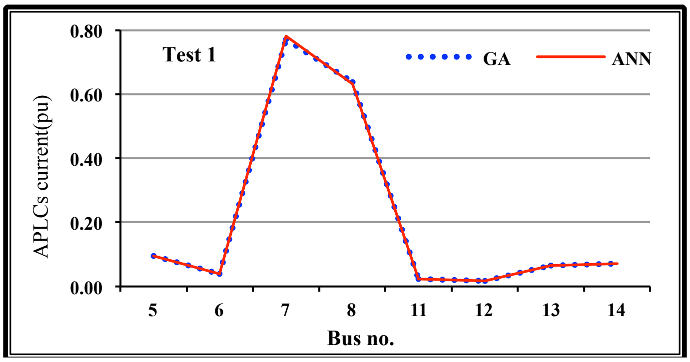

Figure 6. Comparing the ANN output with the optimal target for the total APLC current (test case 1)

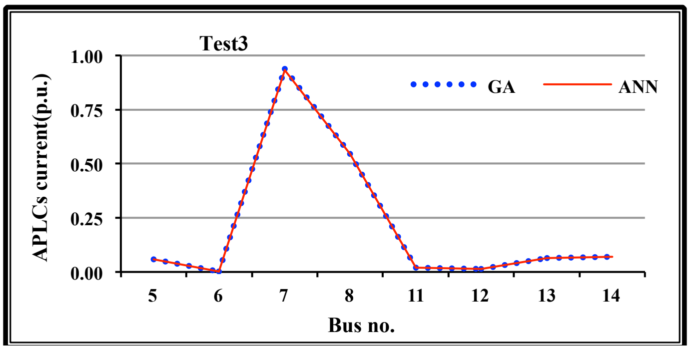

Figure 7. Comparing the ANN output with the optimal target for the total APLC current (test case 3)

From the abovementioned figures, it can be noticed that the ANN outputs show good agreements with the target, which demonstrates the capability of the ANN and the effectiveness of the presented approach. It is expected that defining the settings depending on ANN decisions will not lead to a significant increase in the operating cost compared to the optimal cases.

To emphasise the effectiveness of the centralized controller, a comparison between the optimal real and imaginary APLCs currents and the output from the ANN at the selective buses and the corresponding percentage error in each case is demonstrated in table 3.

Table 3. A comparison between the APLCs current at each bus and their corresponding percentage Error

	APLCs current in (pu)					
	Real IF			Imaginary IF		
	GA	ANN	% Error	GA	ANN	% Error
Bus 5	0.0053	0.0053	0	0.00944	0.00946	-0.2119
Bus 6	0.0019	0.0019	-1.0526	0.0389	0.0387	0.4370
Bus 7	0.0617	0.0615	0.3079	0.7695	0.7777	-1.0656
Bus 8	0.0544	0.0537	1.25	0.6347	0.6302	0.709
Bus 11	0.0012	0.0012	-0.0819	0.0236	0.0234	0.7203
Bus 12	0.0026	0.0027	-3.9109	0.0171	0.0172	-0.5263
Bus 13	0.0056	0.0056	0.4464	0.0655	0.0658	-0.5191
Bus 14	0.0062	0.0062	0.0968	0.0718	0.0716	0.2786

From the previous table, it can be noticed that the highest value of APLCs current is that for bus 7 and 8, where these buses have the biggest ratings of the nonlinear loads as shown in Appendix A. Also, it is noticeable that, the percentage error for both the real and imaginary part does not exceed 5%. This means that, ANN can accomplish the online implementation of the centralized controller successfully.

8. CONCLUSION

In this paper, a general methodology is developed to optimally compensate line-current distortion. The proposed technique is based on active power line conditioners (APLCs) supervised by a centralized controller. This can help to build an automated decision for online implementation. A genetic algorithm (GA) optimization technique is applied to solve allocation and sizing (AAS) problem. To show the validity of this technique, it is applied to a water desalination plant in Algeria as a real system under full load conditions. In the optimization algorithm, the total harmonic distortion is limited to meet the IEEE standard limits and APLC current is restricted by the total nonlinear load current as two constraints. Since all buses are considered as candidates, the APLC allocation and size are defined depending on the distortion level of all buses at the same time. The obtained results concerning this model show that, a centralized controller can be effectively used in defining APLCs current at all buses simultaneously according to their distortion levels. An artificial neural network is used to facilitate the online implementation of the centralized controller. The training and test results show the success of ANN within the implemented centralized controller.

9. APPENDIX

Ratings of some linear and non-linear loads in the water treatment plant are given in Table A-1: In addition, the single line diagram of the water desalination plant under study is given in Fig. A-1.

Table A-1 Ratings of some linear and non-linear loads in the water treatment plant

Electrical load	Fed from	Rating (kW)	Cable size and type	Circuit length (m)
Ratings of Cmtr1				
Sea water intake pump	Bus7	430	3×120 XLPE	305
WE feed pump	Bus7	870	3×150 XLPE	120
HPRO boost pump	Bus7	2250	3×185 XLPE	70, 90, 110, 130 and 150
Ratings of Cmtr2				
Sea water intake pump	**Bus7**	**430**	**3×120 XLPE**	**305**
HPRO boost pump	**Bus7**	**1700**	**3×150 XLPE**	**120**
Ratings of the individual induction motor				
Product pump	**Bus7**	**3000**	**3×300 XLPE**	**385**
Ratings of Cmtr4				
Product pump	Bus8	3000	3×300 XLPE	385
Ratings of Cmtr5				
Sea water intake pump	Bus8	430	3×120 XLPE	305
HPRO boost pump	Bus8	1700	3×150 XLPE	120
Sea water intake pump	Bus8	430	3×120 XLPE	305
WE feed pump	Bus8	870	3×150 XLPE	120
HPRO boost pump	Bus8	2250	3×185XLPE	80, 100, 120 and 140

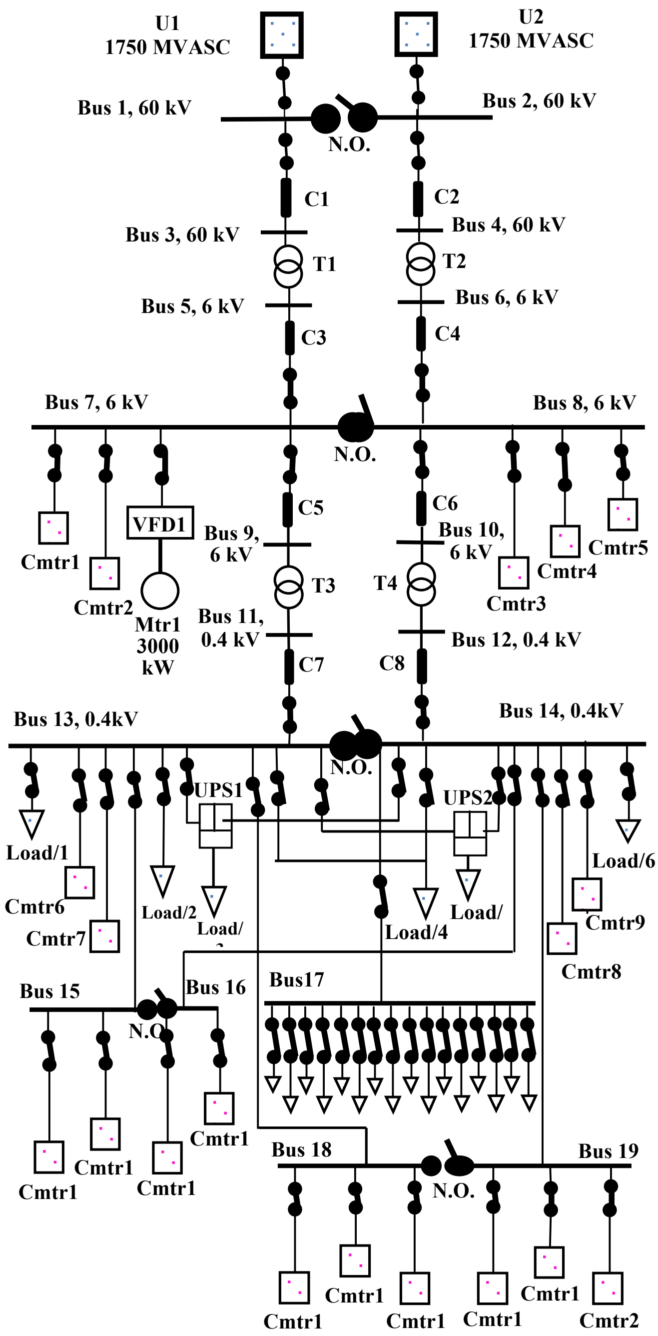

Figure A-1 Water Desalination Plant single line diagram

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