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Research paper

Sensitivity analysis index to determine the optimal location of multi-objective UPFC for improvement of power quality parameters

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ABSTRACT

Today, advanced technologies are used for the reliable operation of power systems. In order to access a reliable and practical function in the systems, it is necessary to use precise control systems with higher efficiency in the systems to minimize the problems of the distribution system. Devices that are made on the basis of power electronics have wide applications in power systems today. These devices, which are called FACTS devices, provide the possibility of improving energy transmission with the least investment cost, as well as quick control of power system problems. FACTS devices are placed in series, parallel or series-parallel transmission lines and control the operation of distribution systems in permanent states as well as the dynamic behavior of the system in transient states. FACTS devices are an effective method to solve the problems and limitations of lines. Transmission and replacement networks are used to create new lines in the network. From the point of view of power distribution control, FACTS controllers can be placed anywhere in the transmission line, but the elements are most effectively used when they are placed at the most critical point. Unified Power Flow Controller (UPFC) is one of the most important FACTS devices that can improve parameters. The quality of power used in the power system depends on the effect of this controller in improving the loss reduction, reducing the total harmonic distortion (THD), and removing the clogged lines to their proper location in the power system. This device is capable of all different effective parameters at a time. These parameters usually include voltage, impedance, and phase. This paper uses a new sensitivity analysis index to determine the optimal size and location of the UPFC to improve the power quality parameters of the distribution system. The proposed method is evaluated on the IEEE 14-bus network in the Simulink environment of MATLAB software. Finally, according to the simulation results and the results obtained from the base network, it is determined that using the proposed sensitivity analysis index in UPFC location, losses Network, total harmonic distortions (THD) and eclipses Network lines are much improved. The results indicate that the proposed method has provided a good answer to determine the optimal size and location of UPFC to improve power quality parameters. Using the results of the sensitivity analysis method, the best place to install UPFC in the power grid, mode number 6 between buses 2 and 11 is obtained. and The amount of network power losses after sensitivity analysis, compared to the base network Active losses of about 55% and reactive losses of about 11% deceased, Due to the circular structure of the network, the current passing through the lines is different depending on the amount of load in the bases near that line, and with the presence of UPFC, the network is optimized and the current passing through the lines is also reduced. 4) Percentage of total harmonic distortion (THD) mains voltage before the presence of UPFC is about 27.12%, which after installation in the 6th place with a maximum size has been reduced to about 11.11%.

1. Introduction

In recent years, Extensive efforts have been made to increase the damping and dynamic stability of power systems, the results of which have led to the emergence and design of various types of power system stabilizers (Rathore et al., 2021; Ghiasi et al.,

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2021; Ahmadi-Nezamabad et al., 2019; Mosaad et al., 2021; Appala Naidu et al., 2021). UPFC is a controller consisting of power electronics that can control the active and reactive power on the transmission line. UPFC consists of two series and parallel voltage source converters that can be modeled by variable voltage sources. The series converter is installed in series on a line by a transformer and the parallel branch of UPFC also includes a voltage source converter which, in addition to supplying the voltage of the bus connected to it, is also responsible for the active power exchange between the bus and the series converter. Two series and parallel converters are connected by a DC capacitor. The condition for the voltage to be constant on this DC capacitor is the power balance between the converters (Liaquat et al., 2021; Sanjeevikumar et al., 2022; Fakhar et al., 2021; Siddique et al., 2020). To maximize the efficiency of the UPFC in the power system, it is necessary to determine the UPFC installation goals and use them to determine the optimal installation location of this element and its capacity. An appropriate optimization algorithm can be used for optimal UPFC location. The proper location of the UPFC increases the level of network security by eliminating or minimizing overload lines and limiting voltage changes in the shafts during severe disturbances. In addition to the above, reducing system losses leads to increased network efficiency. Also, the cost of investment and installation of UPFC should be minimized. In the article Nasab et al. (2022) to find the optimal location of UPFC hybrid algorithms (HIA) such as safety-genetic algorithm (IGA) and PSO algorithm have been used to achieve optimal power flow (OPF). In this paper Veerasamy et al. (2021) the performance of GSA with other meta-heuristic search techniques such as biogeography optimization (BBO), Golmykh genetic algorithm (Stud GA), genetic algorithm (GA), ant colony optimization (ACO), in the system Different standard test systems and real power systems are compared. The results show GSA has a great ability in planning the power system and providing a quality and fast solution to operational problems. In Wei et al. (2021), Elbatawy and Morsi (2021), Alkhateeb et al. (2020), Pokhrel et al. (2021), Shayeghi et al. (2009) and He et al. (2021), a multi-objective fuzzy method based on particle swarm optimization (PSO) for the optimal location and adjustment of the UPFC parameter in a power system for a long period is presented. Article Mahadevan et al. (2021), Zhang et al. (2022), Tao et al. (2022), Huang et al. (2022), Cheng et al. (2022), Singh and Dubey (2022), Muttaqi et al. (2022) and Clairand et al. (2022) uses the newly modified bee mating optimization method, the fuzzy multi-objective method based on the multi-objective bee mating optimization (MOMO) to determine the optimal location and optimal adjustment of the UPFC parameter in a power system for a long period. Is. Article Alkhateeb et al. (2020) Using dynamic voltage stability analysis, presents a new method for locating UPFC based on fuzzy logic in the power grid. In the study (Azimi Nasab et al., 2021a; Castillo-Calzadilla et al., 2022; Davoodi et al., 2022; Li et al., 2022; Saini and Gidwani, 2022; Seresht et al., 2023; Zambrano-Asanza et al., 2021), a particle swarm optimization algorithm for density management Using the optimal size and location of a UPFC device in a market-based power system is provided. The purpose of this paper Masrur et al. (2022) was to identify the optimal location of UPFC in the power system under N-1 probability. The size and cost of FACTS devices have been defined to determine the optimal location and size, and efforts have been made to improve the UPFC installation cost as well as to improve the voltage profile parameters and maximum load. In this paper, the cat swarm optimization algorithm is used to locate multiple UPFCs and load uncertainty is considered.

The paper presents a graphical user interface (GUI) based on a genetic algorithm (GA) that can find the optimal locations and parameters of multiple FACTS devices in large power systems.

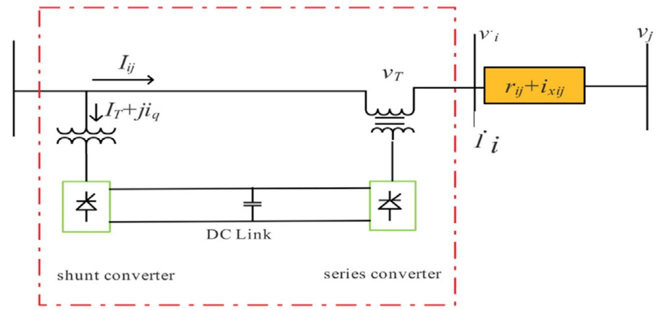

Fig. 1. The general structure of UPFC.

In the paper Adetunji et al. (2022), Ahmadi et al. (2023), Chen et al. (2021), Gamil et al. (2022), Haider et al. (2022), Samavat et al. (2023), Khan et al. (2022), Zand et al. (2020a) and Zand et al. (2020b) a combined method based on determining the optimal location and size of UPFC is presented to improve the dynamic stability. In this paper, the maximum bus power losses are defined to identify the most optimal UPFC installation location. In the paper Azimi Nasab et al. (2021b), a new method for solving the problem of locating and setting the optimal UPFC parameter based on security based on the combined search engine optimization method is provided. In Răboacă et al. (2021), the particle swarm optimization (PSO) technique and genetic algorithm (GA) are used to minimize active losses to determine the optimal location of UPFC in the power system (Sadr et al., 2020). In this paper, the location of FACTS devices in the power grid is performed in the presence of one of the combined devices, called Unified Power Flow Controller (UPFC). This research aims to reduce losses and reduce total harmonic distortion (THD) by using UPFC.

2. Principles of UPFC operation

The UPFC arises from the connection of two compensators: a static compensator (STATCOM) which injects approximately sine current with a variable amplitude at the connection point) and a static synchronous series compensator (SSSC) (which injects approximately a sine voltage with a variable amplitude at the connection point. Providing the active power demand required by the series converter is used in the DC connection terminal of the AC network. Also, the parallel converter can generate or absorb reactive power in the AC terminal which is independent of the active power transmitted from the DC terminal. General UPFC is visible as given in Fig. 1.

3. A static model of FACTS devices

3.1. Static transmission line modeling

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$$P_{ij} = V_i^2 G_{ij} - V_i V_j \left[G_{ij} Cos\delta_{ij} + B_{ij} Sin\delta_{ij}\right] \tag{1}$$

$$Q_{ij} = V_i^2 (B_{ij} - B_{sh}) - V_i V_j [G_{ij} sin\delta_{ij} - B_{ij} cos\delta_{ij}] \tag{2}$$

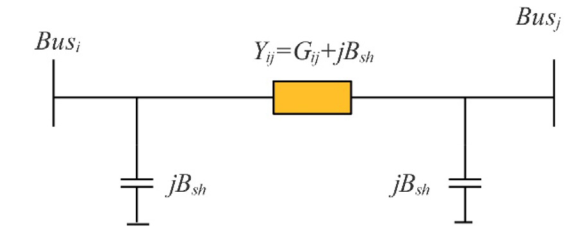


Fig. 2. Equivalent circuit π transmission line.

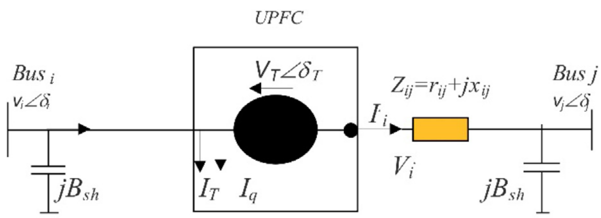


Fig. 3. Transmission line model with a UPFC between the two bus bars.

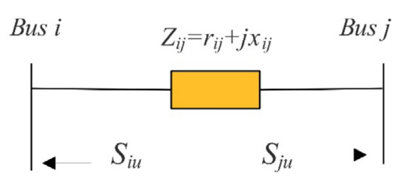


Fig. 4. UPFC injection model.

That $\delta_{ij} = \delta_i = \delta_j$. Similarly, the power transfer from bus j to bus i is as follows,

$$P_{ij} = V_i^2 G_{ij} - V_i V_j \left[G_{ij} Cos\delta_{ij} + B_{ij} Sin\delta_{ij}\right] \tag{3}$$

$$Q_{ij} = V_i^2 (B_{ij} - B_{sh}) - V_i V_j \left[G_{ij} sin\delta_{ij} - B_{ij} cos\delta_{ij}\right] \tag{4}$$

3.2. UPFC model

The transmission line model with a UPFC between the two busbars is shown in Fig. 3. The UPFC has three control parameters called the size and angle of the injection voltage (δ_T and V_T) and the size of the injection current $\left(I_q\right)$. Load distribution relationships from bus i to j and vice versa are written as follows (Ghiasi et al., 2021).

$$S_{ij}^u = P_{ij}^u + Q_{ij}^u = V_i I_{ij}^* = V_i [I_{sh} + I_j^i + (I_T + I_q)]^* \tag{5}$$

$$S_{ij}^u = P_{ij}^u + Q_{ij}^u = V_i (I_{sh} + I_j^i)^* \tag{6}$$

In the steady-state, the UPFC installed in the line is converted to the active, reactive power of the injection into a bus. Fig. 4. shows the injection model of the UPFC power. The active power of the injection in $(P_{iu})i$ and bus $\left(P_{ju}\right)j$ as well as the reactive power of injection (Q_{ju} *and* Q_{iu}) and in the presence of UPFC is as follows (Ghiasi et al., 2021).

$$P_{iu} = -V_T^2 G_{ij} - 2V_i V_T G_{ij} cos\left(\delta_T - \delta_i\right) + V_j V_T G_{ij} cos\left(\delta_T - \delta_i\right) + B_{ij} \sin\left(\delta_T - \delta_i\right) \tag{7}$$

$$P_{ju} = V_i V_T [G_{ij} cos\left(\delta_T - \delta_i\right) + B_{ij} sin\left(\delta_T - \delta_i\right)] \tag{8}$$

$$Q_{ju} = V_i V_T [G_{ij} sin\left(\delta_T - \delta_i\right) + B_{ij} cos\left(\delta_T - \delta_i\right)] \tag{9}$$

4. Problem objective functions

In this work, three objective functions are considered that can be improved by placing UPFC in the network.

4.1. Network losses

Losses in transmission systems are unavoidable, which limits the transmission capacity of the lines and always imposes additional costs on the network. Therefore, reducing it as much as possible is always the goal of transmission line designers. In this work, total network losses are used as one factor of the objective function, which is expressed as follows (Ahmadi-Nezamabad et al., 2019).

$$min\ P_1\left(x\right) = P_{Loss} = \sum_{i=1}^{n}\sum_{i=1}^{n} A_{IJ}\left(P_I P_I + Q_I Q_J\right) + B_{IJ}(Q_I P_J - P_I Q_J) \tag{10}$$

where $\left(B_{IJ}\ and\ A_{IJ}\right)$ is defined and depends on the set of branches and lines of the network that i and j are two buses of the network.

4.2. Total Harmonic Distortion (THD)

The Total harmonic distortion, or THD, is a qualitative parameter that indicates how close a waveform or signal is to a sine waveform. The amount of THD is expressed as a percentage and the lower the THD, the better the sine waveform. In this study, the aim is to reduce the total harmonic distortion in the lines using UPFC (Rathore et al., 2021).

$$min\ F_3\left(x\right) = \frac{\sqrt{\sum_{h=2}^{n}(E_h)^2}}{E_1} \times 100. \tag{11}$$

where E_h is the harmonic component of h, and E_1 is the main harmonic component.

4.3. Clogged lines

One problem in the electricity industry is the problem of line congestion. With the restructuring of the electricity industry and increasing demand, using the maximum capacity of transmission lines becomes more important, but using the maximum capacity of lines and transferring high power from lines may increase loads and problems due to the thermal limits of the line. This is called transmission line density. Density occurs in situations such as transmission line interruption or load increase (Appala Naidu et al., 2021).

$$min\ F_4\left(x\right) = \sum_{j=1}^{k}(1 - \frac{I_k}{I_{max}}) \tag{12}$$

In the above relation, I_k is the line current, and I_{Max} is the maximum line current that must be reduced. or heads, are organizational devices that guide the reader through your paper. There are two types: component heads and text heads.

5. Sensitivity analysis index

In this paper, sensitivity analysis based on the sensitivity of various network parameters to load changes (load power) has been implemented in the network. The implementation steps are as follows:

- Step 1: Initially, network study modes are generated in a scenario in which the UPFC installation location is different, and, in each case, it is installed in a different location.
- Step 2: The modes obtained in the first step, in this step with the rated load of the network and considering the rated power of UPFC to perform the amount of THD, losses, and line clogging in this step for all modes.

- Step 3: In this stage, the nominal load of the network is increased to a certain extent and all the modes of the first stage are performed with a new load in this stage to get the amount of THD, losses, and clogged lines in this stage for all modes.
- Step 4: In this step, the sensitivity of changes in each indicator is measured and the case with the most changes will be considered as the UPFC installation location.

In the following relations, only three targets of THD, line clogging, and network losses are considered THD_{step}. The amount of harmonic distortion of the network is $L_{lines_{step}}$, the amount of line clogging and $P_{LOSS_{Total_{step}}}$ is the number of total network losses in each stage (Liaquat et al., 2021).

$$\frac{\partial THD}{\partial P_L}, \frac{\partial I_{Lines}}{\partial P_L}, \frac{\partial P_{LOSS_{Total}}}{\partial P_L}$$

$$F_1(x) = \frac{(THD_{step\ 2} - THD_{stop\ 3})}{max(THD_{step\ 2} - THD_{stop\ 3})} \tag{13}$$

$$F_2(x) = \frac{(L_{Linesstep\ 2} - I_{Linesstop\ 3})}{max(L_{Linesstep\ 2} - I_{Linesstop\ 3})} \tag{14}$$

$$F_3(x) = \frac{(P_{LossLinesstep\ 2} - P_{LossLinesstep\ 3})}{max(P_{LossLinesstep\ 2} - P_{LossLinesstep\ 3})} \tag{15}$$

The amount of change of each quantity with increasing the network load between the second and third stages is calculated. Then the maximum amount of changes is calculated by the following equation and the case with the most changes will be considered as the optimal place for installation:

$$case\ Num. = \max(F_1 + F_2 + F_3) \tag{16}$$

To obtain the optimal location:

- UPFC is on the k line and between the j and i buses, which is the most sensitive to changes in losses, line trucks, and THD.
- UPFC should not be placed in lines that are close to the production bases, even if the sensitivity of those modes is higher.

6. Numerical simulation results

6.1. Sensitivity analysis indicators

To prove the practicality of the proposed method, we simulate a 14-bus test network (Fig. 5) in the Simulink environment of MATLAB software. This network consists of 5 generators and 21 transmission lines. Shin 1 is the slack bus. The amount of rate power is equal to *111 MVA* Other information about this network is given in Sanjeevikumar et al. (2022).

6.2. Scenario 1: Results of 14-bus network without nonlinear load and UPFC

By performing a 14-bus network simulation without the presence of compensating sources and nonlinear loads, the active and reactive power loss reduction curve of the network and the line current profile curve are obtained. Fig. 6 shows the loss reduction curve and Fig. 7 shows the 14-bus network flow profile. Network line losses are an almost high value for a 14-bus network. Active line losses are related to lines that have an ohmic section, and reactive line losses, which are negative, mean that they have capacitive properties. Due to the circular structure of the network, the current passing through the lines is different depending on the amount of load in the nearby buses. Therefore, it is necessary to install the compensating device to optimize the power

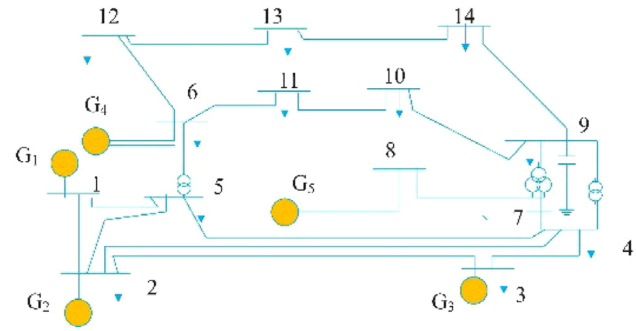


Fig. 5. IEEE 14-bus network.

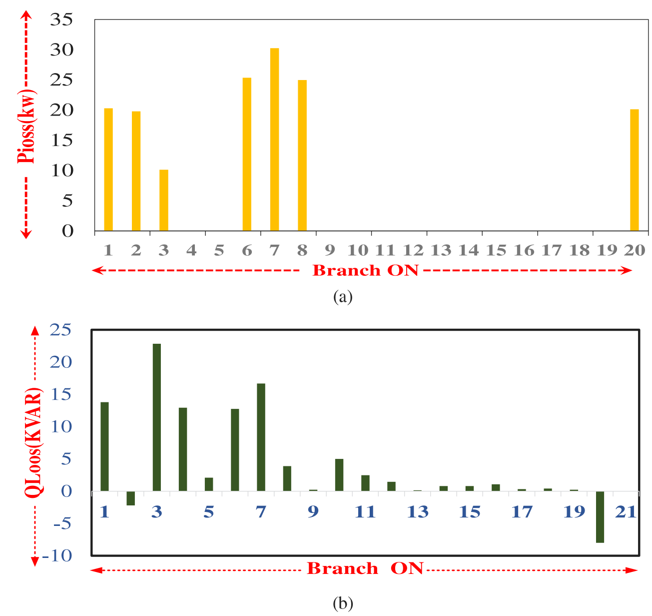


Fig. 6. Loss curve in each 14-bus network line (without UPFC and nonlinear load), (a) Active power losses, (b) Reactive power losses.

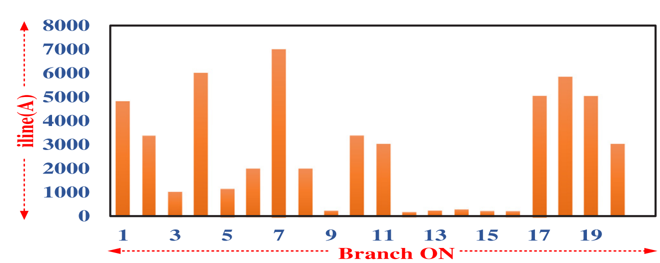


Fig. 7. Flow profile of each 14-bus network line (without UPFC presence and nonlinear load).

quality parameters and proven it from collapsing. The basic 14-bus network has no nonlinear load and its THD is close to zero. To create a harmonic and increase the network THD, 6 nonlinear loads, including DC RL load, which is fed by a diode rectifier, are placed in the network and the network is changed. These bars are placed on bases 1, 2, 3, 5, 6, and 12.

6.3. Scenario 2: Results of 14-bus network in the presence of nonlinear load without UPFC

The UPFC and network parameters are presented in Table 1. Fig. 8 is the loss reduction curve and Fig. 9 shows the flow profile

Table 1
UPFC and network parameters in the simulation.

Symbol	Quantity	Amount
Network information		
v_{p-p}	Line voltage (phase to phase, RMS)	232 kV
f_s	Network frequency	62 Hz
S_{base}	Base power	122 MVA
R_n	Nonlinear load resistance	2 kΩ
L_n	Nonlinear load inductance	1 mH
UPFC Information		
	Number installed on the network	1 unit
S_{UPFC}	Nominal power UPFC	2–122 MVA
P_{ref}	Active reference power	+12 p.u.
Q_{ref}	Reactive power reference	+2.7 p.u.
Shunt converter		
V_{ref}	Voltage adjustment point	1 p.u.
Droop	Droop	2.1 p.u./100 MVA
Q_{ref}	Reactive power setting point	2 p.u.
I_{qref}	Reactive current setting point	2 p.u.
Series converter		
P_{ref}	Active reference power	8.7 p.u. 7100 MVA
Q_{ref}	Reactive power reference	−2.6 p.u. 7100 MVA

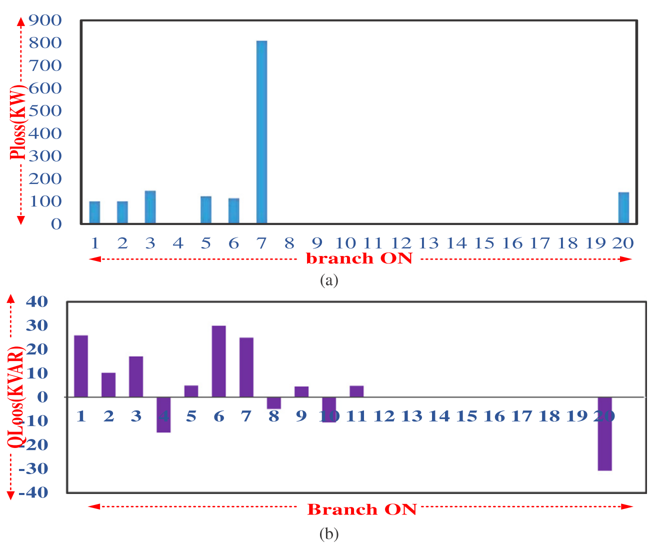


Fig. 8. Loss curve in each 14-bus network line in the presence of nonlinear load (without UPFC) (a) Active power losses, (b) Reactive power losses.

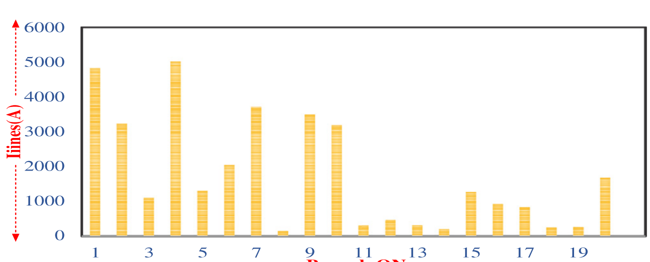


Fig. 9. 14-bus network line flow profile curve in the presence of nonlinear load (without UPFC).

of each 14-bus network line in the presence of nonlinear load and without UPFC. With 1.2 MW and 1.263 MVAr, compared to the network without the presence of nonlinear load, active losses have increased about 1-fold while reactive losses have

Table 2
Locations intended for UPFsC installation.

Case	18	17	16	15	14	13	12	11	12	9	8	7	6	5	4	3	2	1
The bus first (i)	1	1	1	1	1	1	3	3	3	3	3	3	2	2	2	2	2	2
Bus end (j)	11	6	9	13	1	5	11	6	7	1	1	5	11	6	3	1	1	5

decreased by about 2.5-fold. From Fig. 10, the nonlinear load has a good effect on the network bus voltage and has harmonized the network voltage, because according to Fig. 10(a), the network voltage is non-sinusoidal and includes harmonic. The THD of the main voltage before the presence of UPFC is about 12.27%, which is reduced by installing UPFC. The reason for the reduction of reactive losses can be considered the use of rectifiers and low reactive power consumption and the creation of network harmonics.

6.4. Scenario 3: Sensitivity analysis results to find UPFC

In this scenario, a suitable place to install UPFC is obtained using sensitivity analysis. The right place to install this compensator is very important due to its high cost. For this purpose, 18 states have been selected for UPFC installation by default in the 14-bus test network. The analysis process selects the installation location from among these 18 states according to the indicators. 18 states of locations intended for UPFC installation are given in Table 2. At this stage, the UPFC size is considered to be equal to 111 MVA. Also, to determine network load changes. In the third stage of sensitivity analysis, the network load increases by 21%. Fig. 11 shows how the indicators change in different modes in a sensitivity analysis. Fig. 11 shows that according to Equation 17, which calculates the maximum indices and considers the desired state as the situation with the most changes, mode 6 is considered a suitable place to install UPFC. The results of the network parameters are presented in the following figures. By performing a 14-bus network simulation in the sensitivity analysis scenario, the curve of reducing the active and reactive power losses of the network are obtained. Fig. 12 shows the loss reduction curve and Fig. 13 shows the flow profile of each 14-bus network line. The number of losses in this scenario in this network is equal to 3.85 MW and 1.19 MVAr. Due to the absence of UPFC, active losses have decreased by about 2% and reactive losses by about 16%. Due to nonlinear loads in the 14-bus network and compensation by UPFC, its THD rate has decreased to the amount of 11.11%. Fig. 14 shows the Voltage curve and harmonic analysis of bus voltage in sensitivity analysis in the presence of nonlinear load.

7. Conclusions

The Unified Power Flow Controller (UPFC) is one of the most important FACTS devices that can be used to improve power quality and reduce power system losses, the effectiveness of this controller depends on its proper location in the power system. Installing UPFC in the wrong place and with the wrong parameters not only does not improve the performance of the power system but may also have negative effects. In this paper, the positioning of the Unified Power Flow Controller (UPFC) in the power grid was investigated by a proposed sensitivity analysis index. This UPFC positioning paper was performed by the sensitivity analysis method. The network under study in this study is the IEEE 14-bus network, which is evaluated and evaluated raw. After simulating the proposed method, the following results are obtained from the system: (1) Using the results of the sensitivity analysis method, the best place to install UPFC in the power grid, mode number 6

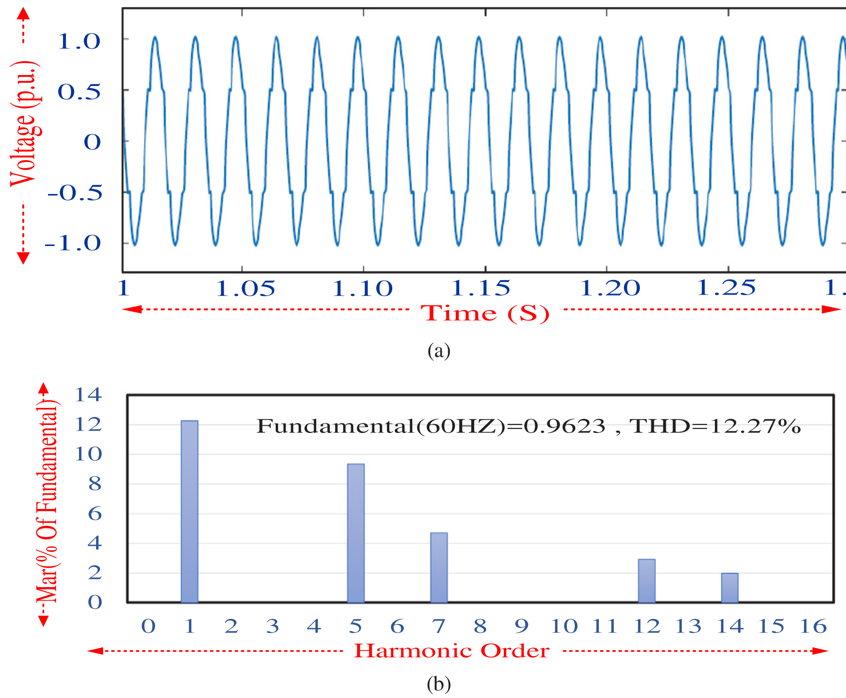


Fig. 10. Presence of nonlinear load (a) 1 mains bus voltage curve, (b) Harmonic analysis.

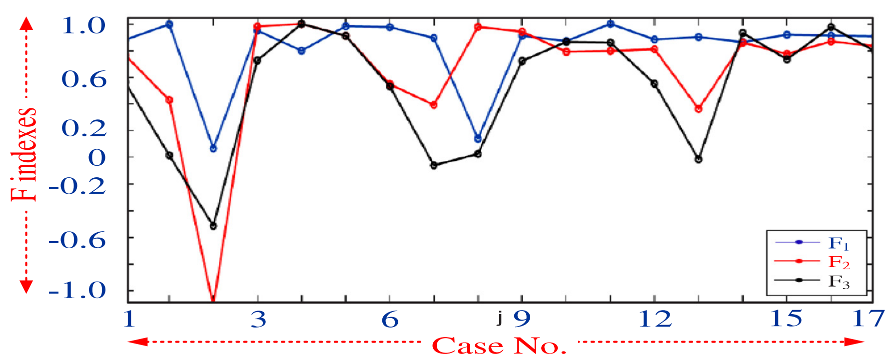


Fig. 11. How do the indicators change in the states in the sensitivity analysis.

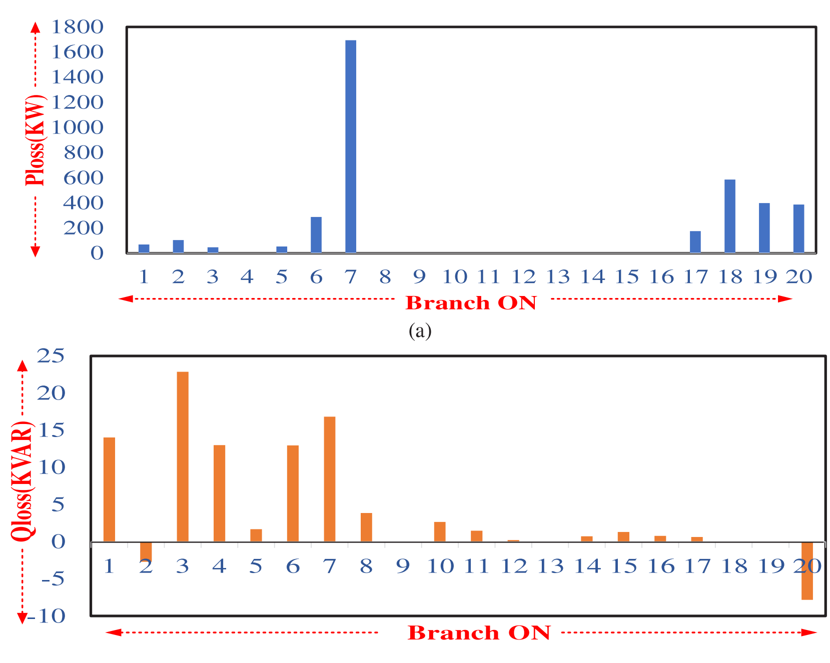


Fig. 12. Loss curve in each 14-bus network line in sensitivity analysis, (a) Active power losses, (b) Reactive power losses.

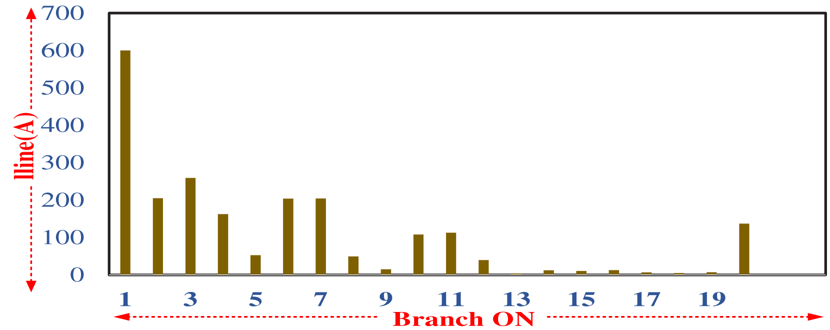
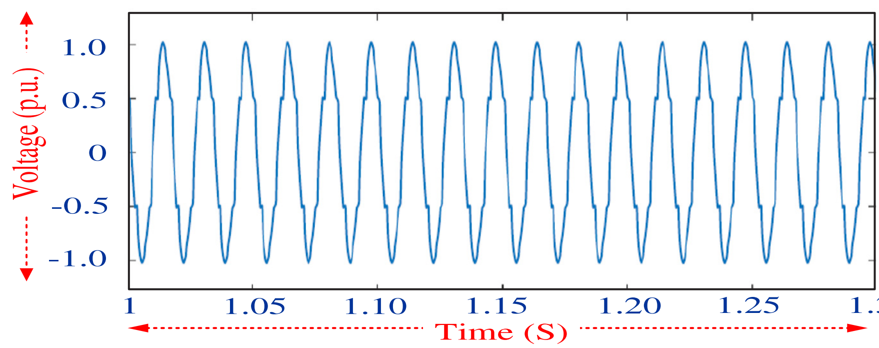
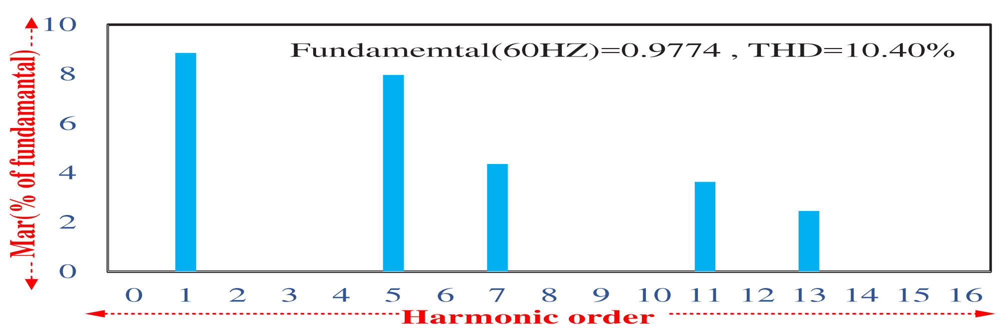


Fig. 13. Flow profile of each 14-bus network line in sensitivity analysis.



(a)



(b)

Fig. 14. Voltage curve and harmonic analysis of bus voltage 1 bus in sensitivity analysis (a) voltage curve (b) Harmonic analysis.

between buses 2 and 11 is obtained. (2) The amount of network power losses after sensitivity analysis, compared to the base network Active losses of about 55% and reactive losses of about 11% deceased, (3) Due to the circular structure of the network, the current passing through the lines is different depending on the amount of load in the bases near that line, and with the presence of UPFC, the network is optimized and the current passing through the lines is also reduced. (4) Percentage of total harmonic distortion (THD) mains voltage before the presence of UPFC is about 27.12%, which after installation in the 6th place with a maximum size has been reduced to about 11.11%.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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