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MITIGATION OF POWER QUALITY ISSUES IN DISTRIBUTION SYSTEMS USING HARMONIC FILTERS AND CAPACITOR BANKS

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Abstract. *Due to increased load demand, the power system developers are encouraged to meet power quality requirements. Using harmonic filter and capacitor bank is one of the essential solutions in mitigating power quality issues. This research aims to mitigate harmonics and improve the voltage in distribution systems by using ETAP. For this purpose, a distribution system in Homs city is considered, which is a part of Syrian power system. The capacitor banks are designed using numerical analysis and Optimal Capacitor Placement (OCP). The results indicate that this approach enhances the voltage profile, which is reflected in some buses. The voltage profile is effectively improved on several buses, and power losses are significantly reduced. The Total Harmonic Distortions (THDs) and Individual Harmonic Distortions (IHDs) of the subjected buses are reduced. Moreover, the power factor is improved from 0.877 to 0.926 for the studied system.*

Key words: *Distribution System, Harmonic Distortion, Power Factor, Power Quality, Voltage Profile*

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1. INTRODUCTION

The demand for energy consumption increases due to growth in industrial projects and other vital sectors. Generation is the energy production at power plants that use the traditional fossil fuels and renewable technologies to generate electricity. Currently, the use of renewable energy increases mainly due to the lack of fossil fuels and environmental concerns [1]–[3]. The generator connects to the grid via a transformer that steps up the voltage to transmission level voltages. The distribution delivers power to final loads through intermediate transformers. Power Quality (PQ) describes the efficiency of the network, affected by many factors such as voltage drop, low power factor, power losses, and harmonic distortion [4]. PQ becomes a significant concern due to the increase in non-linear loads and power electronics [5], [6]. Thus, mitigation of power quality issues plays a vital role in improving the performance of the power system.

In distribution systems, capacitor banks and harmonic filters are used to meet the standards of power quality. Although Flexible AC Transmission Systems (FACTS) devices such as Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM) are used to improve power quality issues, capacitor banks are a more common option and a practical technique to improve voltage profile and reduce power losses [4], [7], [8]. The costs to construct and maintain capacitor banks are low compared with other devices [9], [10]. Employing harmonic filters is a common technique in mitigating harmonic distortions, thus avoiding the injection of harmonics into the network [5], [6], [11]. This device will decrease the harmonic current injection into the network and transfer the current from the load into the filter. The filters which are commonly used in electrical networks are the by-pass filter, high-pass filter, and the single tuned filter. However, single tuned filter is of a simple design and costs less [5]; and also being a series inductance - capacitance circuit. It provides a low impedance path for a specific harmonic element [12].

According to IEEE Std 519 [13], the allowable levels of Total Harmonic Distortion (THD) is 5% with no more than 3% Individual Harmonic Distortion (IHD) for voltage levels from 1 kV to 69 kV. The harmonic load flow of the studied distribution system is analysed to verify the impact of harmonic distortion on the power system. It becomes apparent after running the harmonic analysis on the distribution system. Bus40 and Bus41 have the largest IHD magnitude which exceed the distortion limits mentioned in the IEEE Std 519, as depicted in Fig. 1.

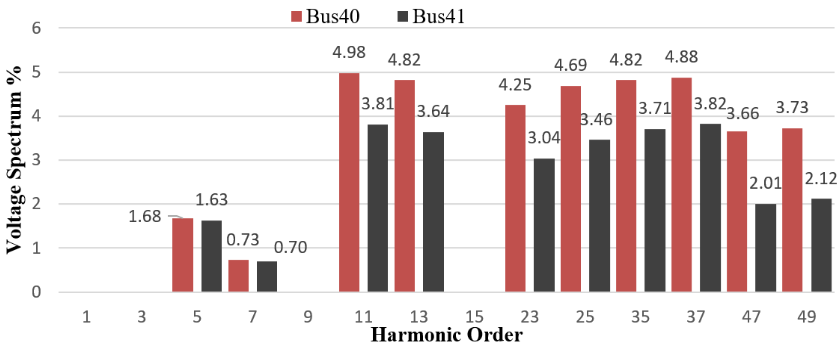


Fig. 1 IHDs for two buses exceed the harmonic limits

According to Fig. 1, the harmonics of Bus40 and Bus41 have the most distortions due to harmonic sources connected to these buses. Additionally, harmonic orders such as 11th, 13th, 23rd, 25th, 35th, and 37th have the highest harmonic magnitudes, which go beyond 3% for the IHD.

As per the Ministry of Electricity [14], the voltage variations under normal operations are within ± 6% for a 20 kV distribution system, and the minimum Power Factor (PF) value is 0.9. The load flow analysis is required, to check whether the system parameters remain within the designated limits during different load conditions [4], [15]. After analyzing the load flow of the studied system, the simulation results show that the total PF of the system is 0.877, which is below 0.90. Both active and reactive losses are 3,297 kW and 12,383 kvar, respectively. The maximum value of the voltage is 100%, representing an infinity bus, while the minimum voltage of the bus is 89.07%. Fig. 2 demonstrates the initial voltage of all buses observed in the studied system, and the low voltage issues which are, less than 94%, are highlighted. As observed in the analysis, the studied system is subject to power quality issues resulting in harmonics, voltage drop and low power factor. Fig. A in Appendix A presents the simplified diagram of the studied system. The initial data of the system is provided by the Ministry of Electricity-Syria.

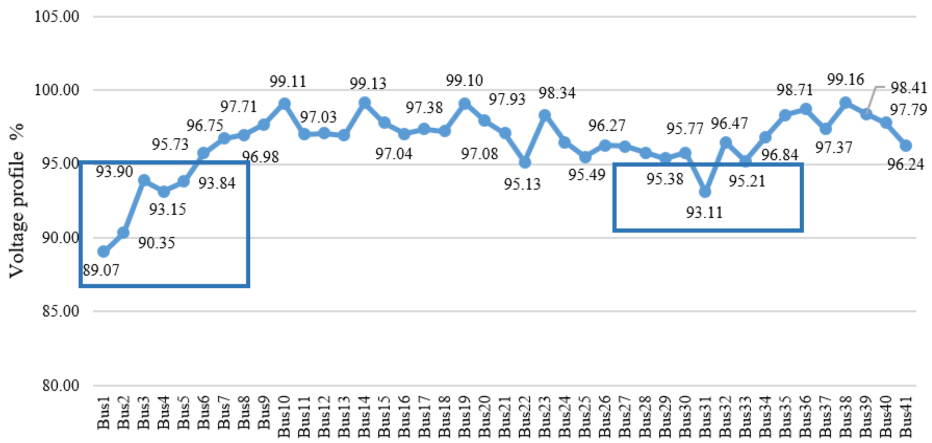


Fig. 2 The initial voltage of the studied system

This article aims to evaluate the power quality issues of an actual system, particularly voltage profile, low PF, power losses, and harmonic distortion. Besides, an appropriate and cost-effective method is proposed to mitigate power quality issues with the integration of single-tuned filters and capacitor banks. The performance of the numerical method together with the optimisation method is compared to verify the results that has been achieved. The organization of the article is as follows; Section 2 reviews some research work related to our topic. Sections 3 explains the methodologies used in this research. Next, the results and discussion are presented in Section 4. Finally, the conclusion is discussed in the last section.

2. RELATED WORK

A global harmony search was used to locate the optimal solution for capacitor banks in the radial distribution systems [7]. The objectives were to reduce power losses, operating cost and improve voltage profile. A simplified method to choose the optimal location and size of shunt capacitors in unbalanced radial distribution systems was investigated [16]. The objective was to maximize the net savings in the distribution system, considering the 25-bus and 37-bus radial distribution systems as examples.

Machine learning was applied for a fast and accurate energy loss assessment in the distribution systems [17]. The principle of the proposed method was to estimate the losses using all data. The method was tested on the 33-bus system and the results indicated that the proposed approach ensured the accuracy with 99.9965% reduction in computational time.

The Particle Swarm Optimization (PSO) was applied to determine the location and size of the shunt active power conditioner and shunt capacitor in the distribution system to minimize the cost [8]. PSO was also applied to solve the non-smooth cost function in the power system [18]. The DGs were integrated into a radial distribution system to enhance reliability and reduce power losses [19]. The PSO and gravitational search algorithm were applied to optimise the location and size of DGs. The 33-bus system was used to validate the effectiveness of the proposed method.

Mahmoud, Yorino and Ahmed [20] proposed an efficient analytical method for the multiple distributed generation (DG) optimisation in order to minimise power loss in the distribution system. The integration of efficient analytical and optimal power flow was developed to address such constraints. The authors showed the effective performance of the proposed method compared with the existing methods to speed up the solution. The sizes and locations of DGs and capacitors were optimised, based on generic analytical expressions, to minimise reactive power losses [21]. The authors evaluated the proposed method, using the 69-bus distribution system, and the results has proven the effectiveness of the proposed method for solving the problem with the integration of DGs and capacitors. The combination of multiple Distributed Generation (DG) techniques were proposed to minimise the losses in the distribution system [22]. The proposed method has the ability to solve the problem with different combination of DGs. The authors showed that the optimal solution is very fast without requiring iterative processes. Research carried on the IEEE 33-bus system, and the results showed the effectiveness of the investigated method to reach the optimal solution and minimise the power losses.

The Optimal Capacitor Placement (OCP) based on the Genetic Algorithm (GA) is an effective method to optimise capacitor banks, enhance voltage profile, and improve PF. The OCP was investigated in the Tehran metro distribution system to reduce annual losses and maximize profits [23]. GA is a random approach based on Darwin's Theory of Natural Selection [24]. It begins with populating random double strings and generate broad-ranging populations to reach the iteration boundaries or converge the population. GA is suitable method used to solve the problem of capacitor placement because of its ability to locate global solution and also its computing speed [25].

It has been observed from the previous literature that different optimisation methods and several techniques were used to improve the voltage profile and reduce the power losses of the radial distribution systems. In this research, the numerical analysis method and optimal capacitor placement are introduced in the distribution system. Moreover, the integration of harmonic filters and capacitor banks are integrated into the distribution system to reduce harmonic distortions, improve voltage profiles and PF, and reduce power losses.

3. MATERIALS AND METHODS

To mitigate harmonic distortions and improve voltage profile in the distribution system, this study designs harmonic filters that are connected to non-linear loads and capacitor banks are added to the loads at suitable locations, depending on the analysis carried out by both numerical analysis and OCP. Finally, the results of the two methods are evaluated to determine a suitable technique to improve power quality. This section provides details on the factors and numerical analysis that have been taken into consideration when the power quality is analyzed. This is then, followed by the methods which are used to mitigate harmonics, correct the PF, and enhance the voltage profile. Fig. 3 presents the flow chart to mitigate harmonics and improve the voltage profile and PF.

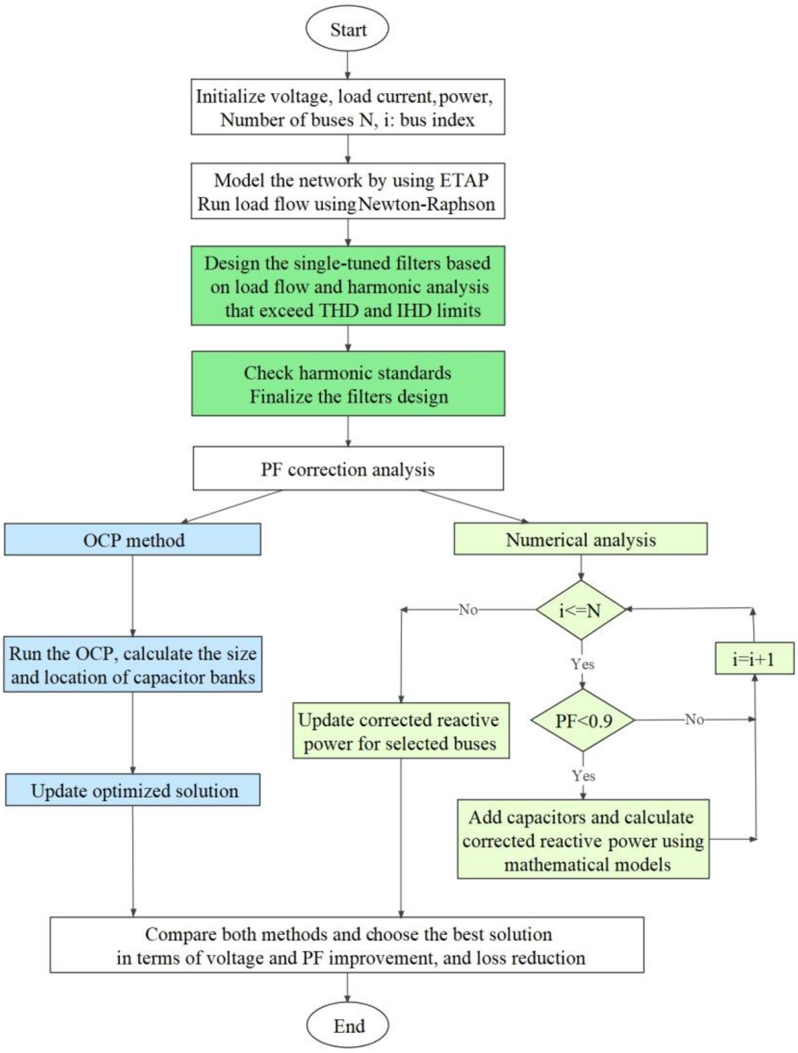


Fig. 3 Flow chart displaying the procedures to mitigate harmonics, and improve voltage and PF

3.1. System Modelling

The studied system is made up of five power grids, 75 buses (41 buses on 20 kV and 34 buses on 66 kV), 66 kV transmission lines, and 66/20 kV substations to step-down the voltage to 20kV. The diagram of the simplified system is presented in Fig. A in Appendix A. The frequency of the system is 50 Hz. The system contains many vital loads like industrial, commercial and residential facilities. Two non-linear loads are proposed to represent the harmonics' sources in Bus40 and Bus41. The harmonics source is modeled based on the harmonic load characteristics; the 12 pulse Typical-IEEE harmonics are selected from the harmonic library in ETAP, as shown in Fig. 4. The data of the network, including the transmission lines and loads are provided by the Ministry of Electricity in Syria; the peak loads were recorded on the 13th November 2019 in Homs city. Table 1 shows the load current of the studied system on 20 kV buses. The studied system is a modified system, and PFs of loads and non-linear loads have been proposed in this research.

Table 1 Load current of the system on 20 kV buses

Bus No.	Load Current [A]	Bus No.	Load Current [A]	Bus No.	Load Current [A]
Bus1	530	Bus15	400	Bus29	380
Bus2	330	Bus16	530	Bus30	330
Bus3	440	Bus17	240	Bus31	520
Bus4	460	Bus18	265	Bus32	130
Bus5	360	Bus19	35	Bus33	255
Bus6	280	Bus20	450	Bus34	50
Bus7	415	Bus21	330	Bus35	100
Bus8	375	Bus22	500	Bus36	45
Bus9	298	Bus23	35	Bus37	200
Bus10	98	Bus24	380	Bus38	50
Bus11	533	Bus25	510	Bus39	190
Bus12	522	Bus26	165	Bus40	230.9
Bus13	360	Bus27	210	Bus41	144.3
Bus14	55	Bus28	330		

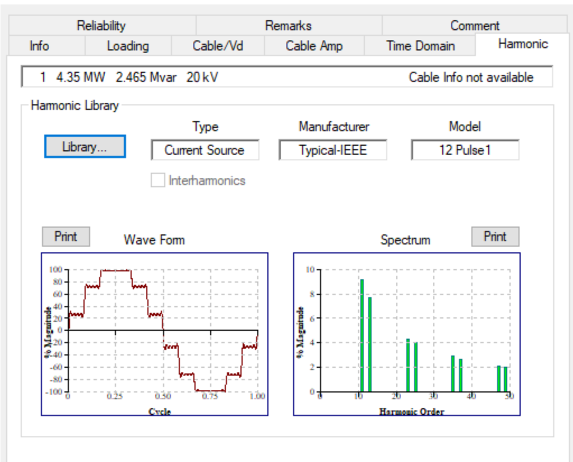


Fig. 4 Harmonic load characteristics

3.2. Power Flow Analysis

In this research, Newton-Raphson has been utilised for load flow analysis. The parameters of transmission lines were used to build the Y_{bus}. Eq. (1) which then would calculate the current I_i injected into a network at bus i [26].

$$I_i = \sum_{j=1}^{N_i} Y_{ij} * V_j \tag{1}$$

where N_i is the number of buses connected to bus i, Y_{ij} is bus admittance, and V_j is the voltage of bus j. Eq. (2) shows the apparent power obtained from current and voltage, or S_i may be calculated from active power and reactive power [26].

$$S_i = P_i + jQ_i = V_i * I_i^* \tag{2}$$

where S_i is the apparent power. P_i and Q_i are the active power and reactive power, respectively.

3.3. Harmonic Distortion

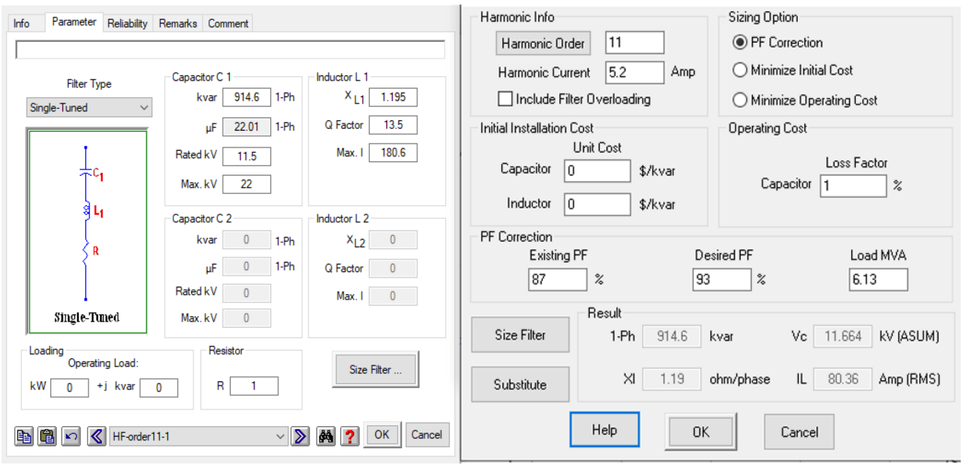
Total Harmonic Distortion (THD) measures voltage and the current levels of harmonic distortion, showing the ratio of the root mean square of all harmonics to the fundamental element. THD is defined by Eq. (3) based on the amplitude of the fundamental element and other harmonic orders [27].

$$THD = \frac{\sqrt{\sum_{2}^{\infty} F_n^{\,2}}}{F_1} \tag{3}$$

where F_1 represents the fundamental harmonic order, and F_n is the harmonic orders without the fundamental element. A single-tuned filter was selected and designed in ETAP to mitigate the harmonic distortion. Fig. 5 shows the harmonic filter editor and harmonic filter sizing for the 11th harmonic order in Bus40. The initial PF was 0.87, the apparent power was 6.13 MVA, and the desired PF was 0.93, to meet future load increase. The quality factor of the filter Q_{Factor} is calculated from Eq. (4) [11].

$$Q_{Factor} = \frac{n * X_{Lf}}{R_f} \tag{4}$$

where n is the harmonic order, and X_{Lf} is the reactance. In this research, the resistance R_f is equal to 1 Ohm [12]. The other harmonic filters were designed using the same technique.



(a) (b)

Fig. 5 Design of single-tuned filter in Bus40, a) Harmonic filter editor, b) Harmonic filter sizing

3.4. Power Factor Correction

The use of capacitor banks is proposed to enhance the PF. The reactive power of capacitors Q_C is calculated according to the difference between the reactive power before correction and the reactive power after correction. The formula of Q_C is given by Eq. (5) [5].

$$Q_c = P_{Load} * (\tan\phi_1 - \tan\phi_2) \tag{5}$$

where P_{Load} is the active power of load. *tan* $\o_1$ and *tan* $\o_2$ are the tangent of PF angles before and after correction. After selecting the reactive power of the capacitors from Eq. (5), it is essential to correct the value of the reactive power, taking into consideration the maximum working voltage. For safety reasons, the designed capacitor should be around 10% over the nominal voltage.

The conventional method to correct PF was based on numerical analysis using Eq. (5) after taking the maximum working voltage. The active power, the existing PF, and the desired PF are utilised to calculate the size of the capacitor banks. The reactive power required for each load, having a PF of less than 0.9, is considered an improvement. After calculating the required reactive power using the numerical method, the capacitor banks are added to the selected buses to address the PF requirement. However, this method does not achieve the optimal solution for large systems, and computation time is relatively long. Furthermore, the conventional method does not consider the cost of capacitor banks and power losses. Therefore, minimizing the cost is not addressed via this method.

OCP is an effective technique in determining the size and placement of the capacitor banks for voltage support, PF correction, and the reduction of the costs. The installation and operating costs of capacitor banks are found in the following literature [23]. The objective is to minimise the cost and this is represented by Eq. (6) [23], [28].

$$\text{Objective Function}=\sum_{i=1}^{N}(X_i * C_{Ini} + Q_{Ci} * C_{Ci} + B_i * C_{Opi} * Y) + C_{Loss}\sum_{l=1}^{N_{Load}} h_l * P^l{}_{TotLoss} \tag{6}$$

where the index X_i is equal to 1 in case of bus i is equipped with the capacitor bank; otherwise, X_i is equal to 0, and C_{Ini} is the installation cost for the capacitor bank. Q_{Ci} is the size of each capacitor bank, C_{Ci} is the cost of capacitor bank. B_i is number of capacitor banks for bus i, Y represents the planning period and C_{Opi} is the operating cost. C_{Loss} is the cost of power loss, h_l represents duration, and $P^l{}_{TotLoss}$ is total loss at load level l.

The constraints for compensation are to meet the load flow limits. The following requirements are taken into consideration when designing the capacitor banks:

- *Voltage limits:*

Voltage of the bus at 20 kV should stay within the set limits V_{min} = 0.94 pu, V_{max} = 1.06 pu as described in Eq. (7).

$$V_{\min} \le V_i \le V_{\max} \tag{7}$$

- *Minimum value of the power factor*

The minimum value of power factor is 90% (as recommended by the Ministry of Electricity).

3.5. Power Losses

The total power losses for N buses are given by Equations (8) and (9) [29]:

$$P_{T\,Loss} = \sum_{\substack{1\le j\le N \\ i\ne j}}^{1\le i\le N} P_{ij(Loss)} \tag{8}$$

$$Q_{T\,Loss} = \sum_{\substack{1\le j\le N \\ i\ne j}}^{1\le i\le N} Q_{ij(Loss)} \tag{9}$$

where $P_{T\,Loss}$ and $Q_{T\,Loss}$ are the total active and reactive power losses. $P_{ij(Loss)}$ and $Q_{ij(Loss)}$ are active and reactive power losses from bus i to bus j. The percentage of active and reactive power loss reduction is evaluated by Equations (10) and (11):

$$\Delta P_{Loss}\,\% = \frac{P_{T\,Loss} - P_{T\,Loss\,New}}{P_{T\,Loss}} \times 100 \tag{10}$$

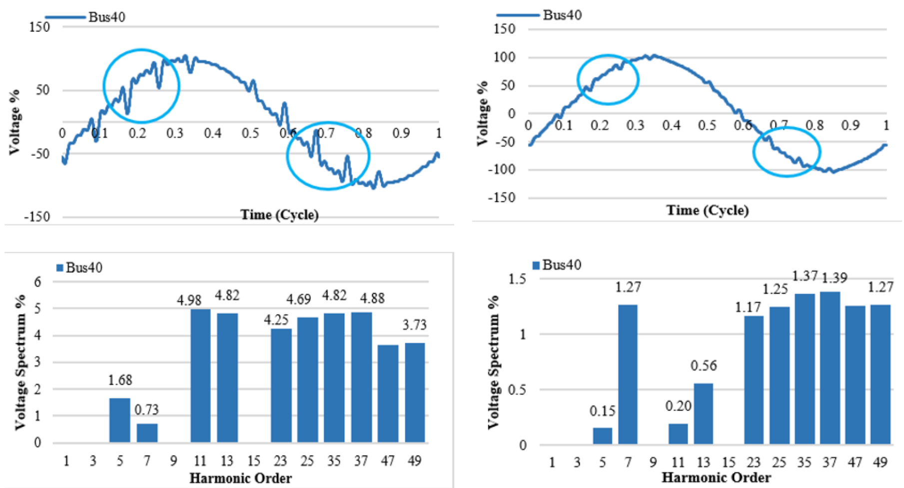
$$\Delta Q_{Loss}\,\% = \frac{Q_{T\,Loss} - Q_{T\,Loss\,New}}{Q_{T\,Loss}} \times 100 \tag{11}$$

where $\Delta P_{Loss}\%$ and $\Delta Q_{Loss}\%$ represent active and reactive power losses that have been reduced in percentage. $P_{T\,Loss}$ and $P_{T\,Loss\,New}$ are active power losses before and after compensation, respectively.

4. RESULTS AND DISCUSSION

As illustrated in the harmonic load flow analysis in Fig. 1, the 11th harmonic order has a large harmonic magnitude contributing to the harmonic distortions in Bus40 and Bus41. When these harmonic orders are mitigated, most of the harmonics would be limited. Firstly, single-tuned filters for the 11th order were added to Bus40 and Bus41. The initial results indicated that the 5th harmonic order does contribute to the harmonic distortion in some buses such as Bus23, Bus40, and Bus41. In order to mitigate the harmonic orders, single-tuned filters for the 5th order were added to the three affected buses. Fig. 6 presents the percentage of IHD and voltage waveforms in Bus40 for the existing system and presents a comparison of the results after adding harmonic filters and capacitor banks using ETAP.

As observed in Fig. 6, the highlighted segments show that the voltage waveforms became smooth after addition of the harmonic filters. Additionally, there was a decrease in the voltage wave distortion in Bus40. The harmonic orders 11th, 25th, and 35th decreased from 4.98%, 4.69%, and 4.82% to 0.20%, 1.25%, and 1.37%, respectively. It is worth mentioning that the IHDs in all buses are less than 3% and meet the limits set by the IEEE standards.



(a) (b)

Fig. 6 Comparison of the voltage waveform and IHD after using filters and capacitor banks with the existing system, a) existing system, b) system after compensation

This is based on the load flow analysis after using the numerical analysis and the OCP method. The size of the capacitor bank is designed to correct the PF from the initial value of each load below 0.9 to a value of 0.93 and to meet the predicted future load increase. Table 2 summarises the results, including the load flow analysis, total power factor, power losses and the reactive power correction by capacitor banks using the two methods mentioned in the methodology.

Table 2 Load flow analysis and reactive power corrected of the existing system and system after compensation

Bus No. at Voltage 20kV	Existing system	Reactive power corrected [Mvar] Numerical Analysis	Reactive power corrected [Mvar] OCP
Bus1	-	3.2	7.2
Bus2	-	2	4
Bus3	-	2.4	3.2
Bus4	-	2.8	2.4
Bus5	-	2	2.4
Bus6	-	1.6	2
Bus22	-	2.8	3.2
Bus25	-	2.8	3.2
Bus28	-	2	2.4
Bus29	-	2.4	3.2
Bus30	-	2	2
Bus31	-	2.8	3.6
Bus33	-	1.6	1.6
Total PF	0.877	0.917	0.926
$P_{T\,Loss}$ kW	3,297	2,951	2,850
$Q_{T\,Loss}$ kvar	12,383	10,400	9,868
$\Delta P_{Loss}\%$	-	10.49%	13.56%
$\Delta Q_{Loss}\%$	-	16.01%	20.31%

It is evident in Table 2 that the PF is improved from 0.877 to 0.926, this improvement is significant when the OCP method is used. Moreover, the total active and reactive power losses decreased from 3,297 to 2,850 kW and 12,383 to 9,868 kvar, respectively. By utilizing Equations (10) and (11), the active and reactive power loss reductions were calculated as 13.56 % and 20.31 %, respectively.

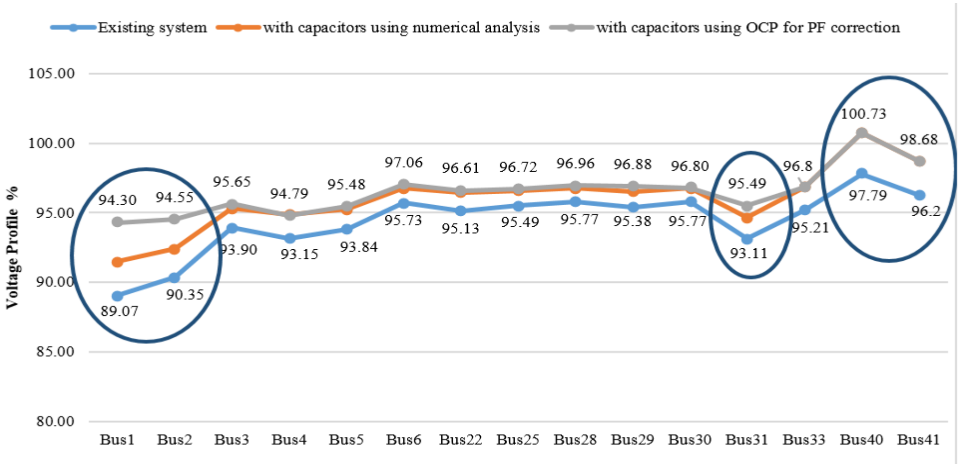


Fig. 7 Comparison of voltage profile after compensation with the existing system

As seen in Fig. 7, using the OCP method leads to better results compared to using the numerical analysis in terms of voltage improvement. After considering the OCP method, the maximum value of the voltage was 100.73%, while the minimum value was at 94.3%. It is worth mentioning that the system voltage requirements were achieved. Fig. 8 shows that there were reductions in power losses. These reductions led to a decrease in produced electricity and reduction in the capacity of transformers and the size of transmission lines.

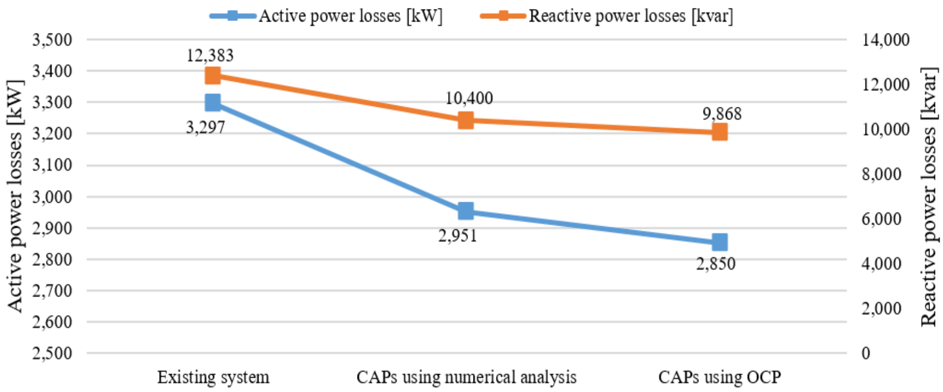


Fig. 8 Comparison of active and reactive power losses after compensation by using the two different methods

5. Conclusion

This research focuses on improving the power quality of the Homs distribution system using ETAP. The problems were identified by performing harmonic and load flow analysis. The solution proposed for harmonic distortions was the use of single-tuned filters to mitigate harmonics. Voltage profile and PF were effectively improved by installing capacitor banks. Active and reactive power loss reductions were up to 13.56% and 20.31%, respectively. Total PF was corrected from 0.877 to 0.926. Based on the results, the utilization of the OCP method is an effective way to optimise the best location, capacitor banks sizing and costs minimisation. This method is applicable for any electric power system, as it will help the engineers, industry, and operators of distribution system to define the optimal size and location of capacitor banks in order to improve the quality of the power systems.

The prevalent wind conditions in Homs city allows for the implementation of distributed generation via wind turbines. Considering the immense penetration of wind energy in the future, this can be further enhancement by the present work to mitigate power quality issues.

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REFERENCES

[1] C. V. Aravind, M. Al-Atabi, J. Ravishankar, A. Malik, Arkar and E. Ambikairajah, "Eco-Tourism Sustainability through PV Technology: A Comprehensive Review", *J. Eng. Sci. Technol.*, vol. 8, no. 6, pp. 654–669, Dec. 2013.

[2] A. A. Alsakati, C. A. Vaithilingam, J. Alnasseir and A. Jagadeeshwaran, "Simplex Search Method Driven Design for Transient Stability Enhancement in Wind Energy Integrated Power System Using Multi-Band PSS4C", *IEEE Access*, vol. 9, pp. 83913–83928, June 2021.

[3] S. A. Khan, R. K. Rajkumar, C. Aravind and Y. W. Wong, "Feasibility Study of a Novel 6V Supercapacitor based Energy Harvesting Circuit Integrated with Vertical Axis Wind Turbine for Low Wind Areas", *Int. J. Renew. Energy Res.*, vol. 6, no. 3, pp. 1167–1177, Sept. 2016.

[4] R. A. Gamboa, C. V. Aravind and C. A. Chin, "Power System Network Contingency Studies", in Proceedings of the IEEE Student Conference on Research and Development (SCOReD), Selangor, Malaysia, Nov. 2018, pp. 1–6.

[5] M. Awadalla, M. Omer and A. Mohamed, "Single-Tuned Filter Design for Harmonic Mitigation and Optimization with Capacitor Banks", In Proceedings of the International Conference on Computing, Control, Networking, Electronics and Embedded Systems Engineering (ICCNEEE), Khartoum, Sudan, Sep. 2015, pp. 242–247.

[6] N. Attik, A. E. Badoud, F. Merahi, A. Laib and Y. Ayat, "Design of an Effective Control for Grid-Connected PV System Based on FS-MPC", *Facta Univ. Ser.: Electron. Energ.*, vol. 34, no. 1, pp. 21–35, Mar. 2021.

[7] R. Sirjani and M. G. Bade, "A Global Harmony Search Algorithm for Finding Optimal Capacitor Location and Size in Distribution Networks", *J. Cent. South Univ.*, vol. 22, no. 5, pp. 1748–1761, May 2015.

[8] M. Mohammadi, "Particle Swarm Optimization Algorithm for Simultaneous Optimal Placement and Sizing of Shunt Active Power Conditioner (APC) and Shunt Capacitor in Harmonic Distorted Distribution System", *J. Cent. South Univ.*, vol. 24, no. 9, pp. 2035–2048, Sep. 2017.

[9] A. Sode-Yome and N. Mithulananthan, "Comparison of Shunt Capacitor, SVC and STATCOM in Static Voltage Stability Margin Enhancement", *Int. J. Electr. Eng. Educ.*, vol. 41, no. 2, pp. 158–171, April 2004.

[10] R. Sirjani, A. Mohamed and H. Shareef, "Comparative Study of Effectiveness of Different Var Compensation Devices in Large-Scale Power Networks", *J. Cent. South Univ.*, vol. 20, no. 3, pp. 715–723, March 2013.

[11] A. A. Abou El-Ela, S. Allam and H. El-Arwash, "An Optimal Design of Single Tuned Filter in Distribution Systems", *Electr. Power Syst. Res.*, vol. 78, no. 6, pp. 967–974, June 2008.

[12] N. A. Bhuiyan, "Power System Harmonic Analysis using ETAP", Master thesis, Brunel University, 2011.

[13] IEEE Std 519^{TM}, "IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems", *(Revision of IEEE Std 519-1992)*, pp. 1–29, Jun. 2014.

[14] Public Establishment for Distribution of Electricity, Ministry of Electricity, Syria, *Electricity Distribution Code*. 2016.

[15] M. Hafiz, C. V. Aravind and C. R. Sarimuthu, "Intelligent Distribution Network Using Load Information Management", *J. Eng. Sci. Technol., 8th EURECA 2017 Special Issue*, pp. 17–27, Aug. 2018.

[16] J. B. V. Subrahmanyam and C. Radhakrishna, "A Simple Method for Optimal Capacitor Placement in Unbalanced Radial Distribution System", *Electr. Power Compon. Syst.*, vol. 38, no. 11, pp. 1269–1284, Aug. 2010.

[17] K. Mahmoud and M. Abdel-Nasser, "Fast yet Accurate Energy-Loss-Assessment Approach for Analyzing/Sizing PV in Distribution Systems Using Machine Learning", *IEEE Trans. Sustainable Energy*, vol. 10, no. 3, pp. 1025–1033, July 2018.

[18] S. Prakash, N. P. Gopinath and O. K. S. Prakash, "A New Approach for Real Power Optimization of Generation with Nonsmooth Cost Function Using Particle Swarm Optimization", In Proceedings of the IEEE National Conference on Emerging Trends In New & Renewable Energy Sources And Energy Management (NCET NRES EM), Chennai, India, Dec. 2014, pp. 59–62.

[19] S. S. Parihar and N. Malik, "Optimal Allocation of Multiple DGs in RDS Using PSO and its Impact on System Reliability", *Facta Univ. Ser.: Electron. Energ.*, vol. 34, no. 2, pp. 219–237, Jun. 2021.

[20] K. Mahmoud, N. Yorino and A. Ahmed, "Optimal Distributed Generation Allocation in Distribution Systems for Loss Minimization", *IEEE Trans. Power Syst.*, vol. 31, no. 2, pp. 960–969, April 2015.

[21] K. Mahmoud and M. Lehtonen, "Simultaneous Allocation of Multi-Type Distributed Generations and Capacitors Using Generic Analytical Expressions", *IEEE Access*, vol. 7, pp. 182701–182710, Dec. 2019.

[22] K. Mahmoud and N. Yorino, "Optimal Combination of DG Technologies in Distribution Systems", In Proceedings of the IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), Brisbane, QLD, Australia, 2015, pp. 1–5.
[23] M. Ghiasi and J. Olamaei, "Optimal Capacitor Placement to Minimizing Cost and Power Loss in Tehran Metro Power Distribution System Using ETAP (A Case Study)", *Complexity*, vol. 21, no. S2, pp. 483–493, Nov. 2016.
[24] S. Sundhararajan and A. Pahwa, "Optimal Selection of Capacitors for Radial Distribution Systems Using a Genetic Algorithm", *IEEE Trans. Power Syst.*, vol. 9, no. 3, pp. 1499–1507, Aug. 1994.
[25] G. Boone and H.-D. Chiang, "Optimal Capacitor Placement in Distribution Systems by Genetic Algorithm", *Int. J. Electr. Power Energy Syst.*, vol. 15, no. 3, pp. 155–161, 1993.
[26] P. S. R. Murthy, *Power system analysis*. Hyderabad, India: BS Publications, 2007.
[27] R. R. Nasyrov, R. I. Aljendy and T. Kherbek, "Study and Analysis of Power Quality Situation in Electrical Power Network. Case Study: Lattakia-Syria", in Proceedings of the IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (EIConRus), Moscow, Jan. 2018, pp. 712–718.
[28] M. J. Tahir, B. A. Bakar, M. Alam and M. S. Mazlihum, "Optimal Capacitor Placement in a Distribution System using ETAP Software", *Indones. J. Electr. Eng. Comput. Sci.*, vol. 15, no. 2, pp. 650–660, Aug. 2019.
[29] Y. M. Shuaib, M. S. Kalavathi and C. C. A. Rajan, "Optimal Capacitor Placement in Radial Distribution System Using Gravitational Search Algorithm", *Int. J. Electr. Power Energy Syst.*, vol. 64, pp. 384–397, Jan. 2015.

APPENDIX A

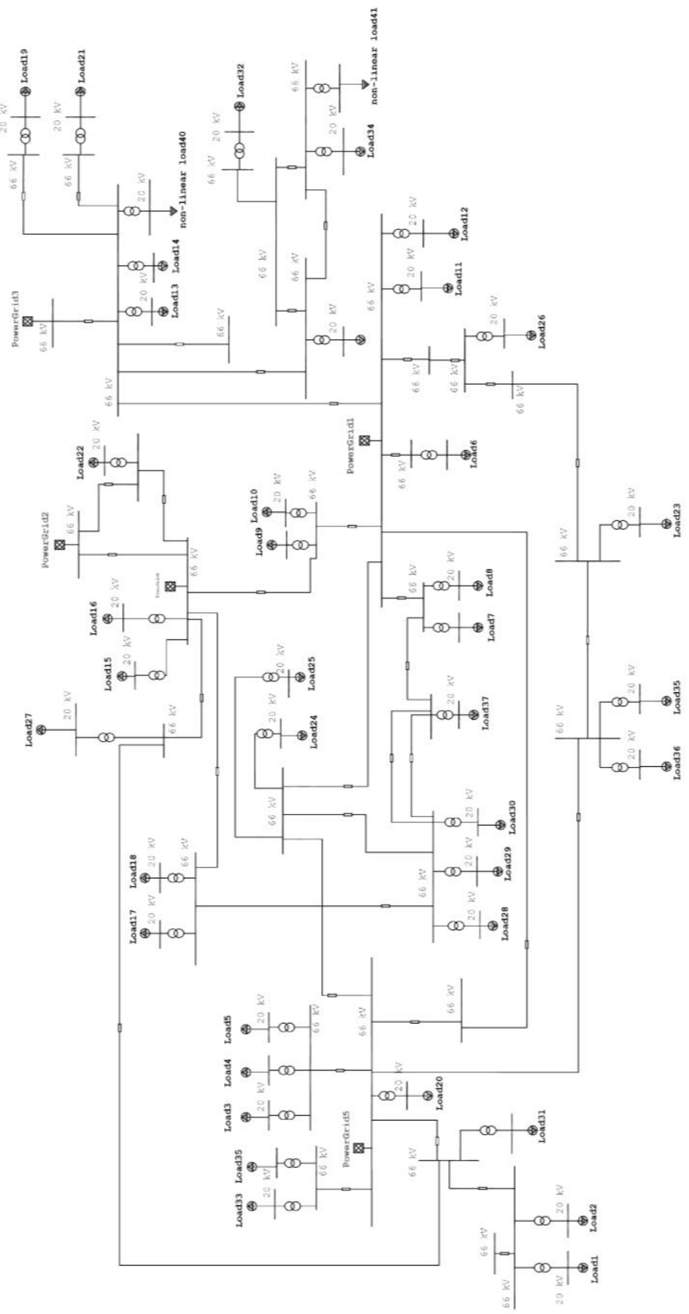

Fig. A Diagram of the simplified 66/20 kV system investigated in this research (The initial data of the distribution system comes from the Ministry of Electricity-Syria)