Impact of replacing overhead lines with aerial bundled cable, and installation of new transformers to reduce losses and improve distribution network voltage profiles, technical and economic analysis

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Abstract

Today, reducing distribution system losses is a top priority in the design and operation of electricity grids. In an electricity grid, a significant percentage of the power and energy generated in power stations is wasted on the way to the transmission system. Losses can occur at all levels of the system’s power, namely, production, transmission, and distribution system. The low voltage level, high current level, and radial distribution system structure leads to an increase in the percentage of losses in the distribution sector. For example, in 2018, about 80% of power system losses occurred in distribution systems in Iran. Several methods have been proposed to reduce the losses such as placing capacitors at medium and low voltage levels, reconfiguring the grids, increasing the cross-section in conductors, and so on in recent years. In this article, two practical and effective solutions to reduce losses in the distribution system are studied and analyzed. The first solution is to install transformers in overload points of the network to reduce technical losses and increase the reliability and stability of the grid and improve voltage profiles, and the second solution is the plan to replace the overhead lines with the aerial bundled cable to reduce nontechnical losses. Sheet 13 of Qom distribution system is considered as a study network in order to investigate and analyze the impact of implementing these two proposed solutions in reducing losses and it also uses the data of data logger device installed in the distribution system as well as the simulation data obtained in the CYMDIST software. In order to more accurately and comprehensively analyze the impact of the proposed solutions on loss reduction, based on the annual load growth in the Qom distribution system, studies are presented for 5 years. Finally, based on two suggested solutions, three scenarios are presented and the effective scenario is identified and
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the economic justification and duration of return on the effective scenario are presented.

KEYWORDS
distribution grid, economic analysis, overhead lines with aerial bundled cable, technical and nontechnical losses, transformer installation

1 | INTRODUCTION

According to the available statistics on total losses in the power system, including the generation, transmission, and distribution systems, the distribution system has the highest losses. The loss rate on transmission and production systems is almost unavoidable. Ideally, losses in an electrical system should be 3% to 6%. In developed countries, the losses rate is no more than 10%. However, in developing countries, the percentage of power losses is about 20%; for this reason, users in the electricity industry are now enthusiastic to reduce losses in order to compete more, in the Qom Province Electricity Distribution grid in Iran in 2018, technical and nontechnical losses accounted for 18% of total energy input. The main reason for the high losses rate is the outdated distribution grids, the poor technical condition of the grids, and impermissible divisions.

Global experience shows that in high loss grids, 1$ investment in loss reduction saves 10.15$ per grid. Therefore, with the reduction of distribution system losses, the return on capital can be achieved in the future years. In recent years, several methods have been proposed, such as capacitors at medium and low voltage levels, reconfiguring grids and increasing the conductor cross-section, using distributed generations (DGs), and so on. Capacitors are widely used in distribution systems to compensate for reactive power to achieve reduced power and energy losses, release system capacity, and achieve acceptable voltage profiles. Generally, attention is paid to reducing costs by optimizing the conductor characteristics in Reference 4. In Reference 5, a method is proposed to determine the minimum energy loss configuration for a given period. Strategies and solutions for reconfiguring the feeder are suggested in References 6-11.

DG, These days have become an attractive option for integration in power distribution systems due to several advantages such as improving voltage characteristics, reduction of power losses with high reliability, and high-security capability. DGs can support system voltage, reduce system losses, improve the reliability and security of the system, and relieve the distribution and upgrade of the system. The impact of distributed DG generation on voltage regulation and power loss in distribution systems is discussed in Reference 15. In Reference 16 a technique is presented to evaluate the effect of DG size and layout on losses, reliability, and voltage profiles of distribution grids. In Reference 17, a model is presented to optimize to minimize losses in a DG distribution grid. Reference 18 use a combination of genetic algorithm (GA) and particle swarm optimization using to optimize DG in distribution networks. The review article presented by Jordi shows that proper allocation of DGs can enhance reliability and reduce investment and operational costs. The proposed review work at Reference 19 identifies the research gaps and offers some helpful suggestions for future research on the allocation of DG. Karami et al. employs a GA for optimal location and optimal size of DGs and shunt capacitors due to the capability of the loading. In Reference 21, a methodology is presented for the sustainable operation of the distribution network with optimal placement and sizing of dispatchable DGs and shunt capacitors. In addition, photovoltaic generations can improve power quality and distribution network voltage regulation. In Reference 24, an approach is presented for voltage sag. In References 25,26, battery energy storage systems are presented for loss reduction in distribution networks.

This article presents two effective solutions to reduce the technical and nontechnical losses of the distribution system. The main features of this work are:

- Implementation of two effective methods and three scenarios to reduce the technical and nontechnical losses of the distribution system.
- Minimizing the power loss, improving the voltage profile.
- Minimizing the annual energy losses and thus maximizing the energy savings.
The economic aspects of the proposed sustainable performance of the distribution network are investigated with the help of cost analysis.

2 | POWER LOSS COMPONENTS IN DISTRIBUTION SYSTEM

Losses in the distribution system have different components. Therefore, identifying the different components requires careful assessment and analysis of the losses in each grid. The analysis of losses in power grids shows that several factors cause losses, but in general, they can be divided into three main categories: technical losses, nontechnical losses, and technical management losses.

Technical losses: This part of the losses depends on the technical specifications of the equipment in the power distribution system. In a system with proper operating conditions, most system losses are due to technical losses. The most important components of these losses include ohmic losses in the power distribution system, leakage current losses, distribution transformer losses, poor connection losses, loss of metering equipment, losses due to improper design, losses due to harmonics in the power distribution grid.

Nontechnical losses: Improper performance, noninspection, and care, lack of repairs, nonreplacement of equipment, and delays in the development of electricity grids an important role in the nontechnical grid losses. These losses are not dependent on the technical specifications of the equipment. Hence, they are called nontechnical casualties. The most important factors that lead to nontechnical losses include unauthorized use of electricity, errors in calculations, metering device errors, use of inadequate transformers, street and park lighting, lack of attention to grid improvement.

Technical management losses: Although a significant portion of the energy losses in power grids are of the technical cause, there are losses in the grid due to improper performance (management and planning) and can be termed technical management losses. Some of the factors that lead to technical management losses include abnormal active power flow in the power distribution system, abnormal reactive power flow in the power distribution system, and low power factor in the power distribution system, high capacity capacitors, and lack of scheduled service for lines or equipment, lack of planned development for grids, load imbalances in the grid. Further details on each of these components are described in Reference 27.

3 | DISTRIBUTION LOSS REDUCTION STRATEGY

Several strategies to reduce losses in the distribution grid have been introduced and tested so far. Strategies such as reducing phase and natural conductor resistance (cross-sectional area correction), placing capacitors in medium and low voltage grids, reducing the length of low voltage grids, reducing harmonics using active or inactive filters, middle voltage ringing, placing capacitors on electric motors, reducing tree leaf loss in the street, reducing insulation losses, reducing iron and copper losses in transformers, reducing losses due to increasing or decreasing customer voltage, reducing ohmic losses on power grid equipment, reducing the errors of the measuring device, and the use of low power and high-efficiency lights are the most important strategies to reduce distribution grid losses. These strategies reduce one or more sources of casualties. With the advent of new technology and scientific innovations and the discovery of new phenomena or properties of materials, and so on, these solutions are expanding. Since some losses are caused by a combination of two or more factors, using two or more strategies can be effective in reducing losses. In this article, two practical and effective strategies for replacing overhead lines with aerial bundled cable, installing transformers in overload areas in the grid, and DG to reduce losses at Qom province distribution company are studied and analyzed.

To analyze and evaluate the impact of two proposed strategies and solution on loss reduction, the section 13 of Qom power distribution grid due to outdated structure and the consequently large amount of unauthorized divisions and nontechnical losses as well as numerous subscriber complaints regarding severe grid voltage drop, the selection criteria for the study network were in the Qom distribution network. The software used for the calculation is CYMDIST, which is recognized as powerful software for analyzing power distribution grids. In the first step based on the information extracted from the geographic information system of Qom distribution company (Figure 1), section 13 of the Qom distribution network as a study network is fully modeled in CYMDIST software (Figure 2).

The sum of the technical and nontechnical losses of the study network is calculated based on the difference in power delivered to the network and the power sold in the network using the information extracted from the
instabilities installed in the study network. Technical losses are then calculated based on the calculations made in CYMDIST software. Finally, nontechnical casualties of the network, calculated from the difference of total casualties from technical casualties, are calculated with an acceptable approximation. The status and power losses of the study network in Table 1 and the results of the technical analysis of the study network in CYMDIST software are presented in Table 2.

As can be seen in Table 1, based on the difference of losses delivered and sold by Qom distribution company in the study network, the total power loss at peak time is equivalent to 2814.03 kW, based on the calculations made in CYMDIST software and the results presented in Table 2, the total technical loss of the study network is 844.28 kW. From the difference
TABLE 1 Existing power and loss of study network without load growth

| Type                                | Maximum power (kw) | Average power (kw) | Annual energy (kWh) | Percentage of Power loss (%) | Percentage of Energy losses (%) |
|-------------------------------------|--------------------|--------------------|---------------------|------------------------------|---------------------------------|
| Total of production (delivery)      | 12 068.660         | 2413.00            | 24 838 902.923      | 23.32                        | 21.28                           |
| Total consumption (sold)            | 9 254.360          | 1984.68            | 17 385 829.659      |                              |                                 |
| Total of technical losses + nontechnical | 2814.03          | 603.49             | 5 286 614.98        | 23.32                        | 21.28                           |
| Technical losses calculated by Cymedist | 844.00              | 175.50             | 1 537 380.00        | 6.99                         | 6.19                            |
| Nontechnical losses                 | 1970.03            | 422.49             | 3 701 022.92        | 16.32                        | 14.90                           |

TABLE 2 Study network technical analysis results in CYMDIST software

| Total summary | Total generation | Total loads | Line losses | Cable losses | Transformer load losses | Transformer no-load losses |
|---------------|------------------|-------------|-------------|--------------|-------------------------|---------------------------|
| kW            | 12 068.66        | 11 224.39   | 568.16      | 129.05       | 105.59                  | 41.48                     |

in total losses from technical losses, the nontechnical losses of the study network are estimated to be 1970.03 kWh. These nontechnical losses are mainly due to the worn-out texture and traditional structure of the grid and due to the existence of numerous unauthorized divisions in the study network.

The amount of energy losses can be calculated based on Equation (1).

\[ E_{L_{av}} = T \times P_{L_{max}} \times L_{SF} \]  \hspace{1cm} (1)

\( E_{L_{av}}, T, P_{L_{max}}, \) and \( L_{SF} \) are energy losses, study period, peak power losses, and loss coefficients, respectively.

The \( L_{sf} \) loss coefficient can be calculated from Equation (2).

\[ L_{SF} = 0.15 \times L_{F} + 0.85 \times L_{F}^2 \]  \hspace{1cm} (2)

where \( L_{F} \) is the load factor. This factor is obtained by dividing the average power by the maximum power. The average power is also obtained from the average measurements made at feeders and at different times, which coefficient of load at Qom electricity distribution company is 0.422. According to Equation (2) and based on loading data and a load factor of 0.422, the losses coefficient is calculated to be 0.2145. So, energy lost:

\[ E_{L_{av}} = (365 \times 24) \times P_{L_{max}} \times 0.2145 . \]  \hspace{1cm} (3)

Based on the Equation (3) and according to the data in Table 1 and taking into peak power time losses equal to 2814.03 kW, the amount of available energy losses is calculated to be 5 286 614.98 kWh. By analyzing the data presented in Table 1, it can be concluded that in the study network, nontechnical losses are about two times the technical losses and the major part of losses, therefore, the main strategy to reduce distribution losses in this article is to replace overhead lines with the aerial bundled cable to reduce nontechnical losses. In addition, to reduce the technical losses and increase the reliability and stability of the grid and improve the voltage profile of the grid, a solution has been proposed to install transformers in overload points of the network and disperse generation by installing photovoltaic systems.

Three scenarios are defined to implement and analyze these two strategies: scenario 1: transformer installation, scenario 2: overhead lines with aerial bundled cable replacement, scenario 3: transformer installation, and replacement of conductors.
3.1 | Scenario 1: Plans to install new transformers in overload points of the network to reduce technical losses and increase electrical grid stability

In Reference 28, a method is proposed for optimal location, size, and the number of distribution. In this plan, overload points of the network have been identified and nine new transformers have been installed in overload points of the network to increase network reliability and stability. Figure 3 shows the layout of the new transformer installation in the CYMDIST software.

3.2 | Scenario 2: Plan to replace overhead lines with aerial bundled cable

One of the most important advantages of self-supporting cable is the impossibility of unauthorized branching. Mostly nontechnical losses in Iran include unauthorized splits, with the replacement of air conductors with self-supporting cables in scenario 2, the possibility of unauthorized splitting is eliminated and nontechnical losses are reduced to almost zero. The purpose of this plan is to reduce the nontechnical losses due to unauthorized splits, but in the implementation of this scenario as an aerial bundled cable with higher cross-section are replaced by overhead lines, this scenario, in addition to reducing nontechnical losses, also leads to reduced technical losses. This scenario also greatly reduces the losses due to poor and inadequate connections in the distribution company, and in addition to reducing losses, it also results in increased reliability and reduced power outage in the distribution grid. Table 3 overhead lines replacement information is shown.

![Figure 3](image)

**FIGURE 3** Implementation of scenario 1 in CYMDIST software

| Replacement aerial bundled cable                     | Overhead lines                      |
|------------------------------------------------------|-------------------------------------|
| Self-supporting aluminum cable with cross-section 120 mm² | Copper wire with cross-section 50 mm² |
| Self-supporting aluminum cable with cross-section 70 mm² | Copper wire with cross-section 35 mm² |
| Self-supporting aluminum cable with cross-section 70 mm² | Copper wire with cross-section 16 mm² |
3.3 | Scenario 3: Simultaneous transformer installation design and replacement of overhead lines with aerial bundled cable

In scenario 1, it was observed that the installation of transformers in overload points of the network, in addition to reducing technical losses, would increase grid stability, implementation of scenario 2 also results in reduced technical losses and complete elimination of nontechnical losses due to unauthorized divisions.

4 | RESULTS AND DISCUSSION

In order to achieve the effective design in terms of both technical and nontechnical losses reduction as well as to increase the reliability and reliability of the grid, in scenario 3 of the transformer installation plan at the overload points of the network and replacing the overhead lines with aerial bundled cable simultaneously, it is evaluated and checked.

Table 4 reports the output of the CYMDIST software and the impact of scenarios. As can be seen in Table 4, after the implementation of scenario 1, the technical losses of the study network decreased from 844.28 to 745.26 kW. As a result by implementing scenario 1, the total technical losses of the study network were reduced to 99 kW using Equation (3), a reduction of energy losses of 186 022.98 kWh in 1 year. According to the rate approved by the Ministry of Energy of Iran, the cost of energy in Iran is 1000 Rials per kilowatt-hour. Therefore, the savings resulting from a reduction of energy losses by 1 year is 186 022 980 Rials. It should be noted that the cost of implementation of scenario 1, is 10 270 000 000 Rials.

With the implementation of scenario 2, the technical losses of the study network decreased from 844.28 to 665.30 kW and the equivalent of 178.98 kW, as well as the nontechnical losses and unauthorized divergences of the sample 1970.03 kW, is almost eliminated. Consequently, with the implementation of scenario 2, the total of technical and nontechnical losses was reduced to 2149 kW, using Relation 3, the reduction of energy losses in 1 year equals 4 038 013.98 kWh and the amount of savings resulting from the reduction of energy losses. The equivalent is 4 038 013 980 Rials. It should be noted that the cost of implementing scenario 2 is 17 024 063 568 Rials. In addition, with the implementation of scenario 3, the technical losses of the study network decreased from 844.28 to 586.42 kW and 275.86 kW, respectively, as well as the nontechnical losses and unauthorized divergences of the 1970.03 kW, is almost eliminated. Consequently, with the implementation of scenario 3, of the total technical and nontechnical losses, 2227.89 kW have been reduced, using relation 3, a reduction of energy losses over a year equivalent to 4 186 249.87 kWh and the saved amount due to energy loss reduction is 4 186 249 870 Rials. It should be noted that the cost of implementing scenario 3 is 27 294 063 568 Rials.

In order to study the economic analysis and to estimate the effective plan capital return rate, estimate the loss situation in the study network over the next 5 years, taking into account the annual load growth in the CYMDIST software, and the outputs of the software are presented in Table 5. It should be noted that according to studies of the Qom distribution network, annual load growth is assumed to be 8.8%. Based on the data in Table 5 and using Equation (3), the cost of energy losses over the next 5 years is presented in Table 6. According to the data presented in Table 8 the cost of energy loss in the 5 years in the study, the network is 8 997 423 483 Rials.

### Table 4 Results from the implementation of scenarios

| Scenario | Total generation (kW) | Total loads (kW) | Technical total losses (kW) |
|----------|-----------------------|------------------|-----------------------------|
|          |                       |                  | Line losses | Cable losses | Transformer load losses | Transformer no-load losses |
| 1        | 11 966.36             | 11 221.11        | 495.00      | 111.96       | 90.13                   | 48.16                     |
|          |                       |                  |             |              |                         | 745.26                     |
| 2        | 11 910.38             | 11 245.09        | 394.10      | 126.47       | 103.25                  | 41.48                      |
|          |                       |                  |             |              |                         | 665.30                     |
| 3        | 11 831.75             | 11 245.33        | 339.56      | 110.17       | 88.52                   | 48.16                      |
|          |                       |                  |             |              |                         | 586.42                     |
TABLE 5  It should be noted that according to studies of the Qom distribution network, annual

| Year | Zero | First | Second | Third | Forth | Fifth |
|------|------|-------|--------|-------|-------|-------|
| Total of production power (delivery) | 12 068.66 | 13 231.11 | 14 363.78 | 15 602.1 | 16 810.38 | 18 170.2 |
| Total consumption power (sold) | 11 224.39 | 12 215.66 | 13 188.62 | 14 232.02 | 15 254.63 | 16 384.36 |
| Technical losses calculated (W) | 844 | 1015.45 | 1175.16 | 1370.09 | 1555.05 | 1785.84 |
| Nontechnical losses (W) | 1970 | 2143 | 2332 | 2537 | 2761 | 3003 |

TABLE 6  Costs of losses in the study network, taking into account an 8.8% annual load growth over the next 5 years

| Year | Zero | First | Second | Third | Forth | Fifth |
|------|------|-------|--------|-------|-------|-------|
| Total of production energy (delivery) | 22 672 951.87 | 24 856 804.34 | 26 984 710.21 | 29 311 096.88 | 31 581 048.49 | 34 135 692.79 |
| Total consumption energy (sold) | 17 385 829.66 | 18 922 402.48 | 20 395 916.25 | 21 970 580.21 | 23 472 259.8 | 25 138 269.31 |
| Technical energy losses (kWh) | 1 585 592.053 | 1 907 688.922 | 2 207 730.28 | 2 573 938.17 | 2 921 415.784 | 3 354 992.549 |
| Nontechnical energy losses (kWh) | 3 701 022.923 | 4 026 712.94 | 4 381 063.679 | 4 766 597.283 | 5 186 057.844 | 5 642 430.934 |
| Cost of energy losses (Rial) | 5 286 614 976 | 5 934 401 862 | 6 588 793 959 | 7 340 535 453 | 8 107 473 627 | 8 997 423 483 |

TABLE 7  Power and losses in the study network after implementation of scenario 3, taking into account 8.8% annual load growth over the next 5 years

| Year | Zero | First | Second | Third | Forth | Fifth |
|------|------|-------|--------|-------|-------|-------|
| Total of production power (delivery) | 11 875 | 12 985.25 | 14 196.88 | 15 492.21 | 16 869.7 | 18 440.53 |
| Total consumption power (sold) | 11 245 | 12 235 | 13 303.8 | 14 445 | 15 639.8 | 16 974.3 |
| Technical losses (W) | 586 | 696 | 830 | 976 | 1151 | 1363 |
| Nontechnical losses (W) | 0 | 0 | 0 | 0 | 0 | 0 |

TABLE 8  Costs of losses in the study network after implementation of scenario 3, taking into account 8.8% annual load growth over the next 5 years

| Year | Zero | First | Second | Third | Forth | Fifth |
|------|------|-------|--------|-------|-------|-------|
| Total of production energy (delivery) | 22 309 129.89 | 24 394 916.11 | 26 671 161.26 | 29 104 650.54 | 31 692 490.82 | 34 643 551.91 |
| Total consumption energy (sold) | 21 125 571.84 | 22 985 448.77 | 24 993 364.39 | 27 137 295.26 | 29 381 922.49 | 31 888 999.03 |
| Technical energy losses total energy savings (kWh) | 1 100 896.852 | 1 307 549.844 | 1 559 290.763 | 1 833 575.644 | 2 162 341.768 | 2 560 618.445 |
| Nontechnical energy losses total energy savings (kWh) | 0 | 0 | 0 | 0 | 0 | 0 |
| Cost of energy losses (Rial) | 1 100 896.852 | 1 307 549.844 | 1 559 290.763 | 1 833 575.644 | 2 162 341.768 | 2 560 618.445 |
| Total energy savings (kWh) | 4 185 718.124 | 4 626 852.017 | 5 029 503.197 | 5 506 959.809 | 5 945 131.859 | 6 436 805.038 |
| Total cost of energy savings (Rial) | 4 185 718.124 | 4 626 852.017 | 5 029 503.197 | 5 506 959.809 | 5 945 131.859 | 6 436 805.038 |

Existing losses resulting from the implementation of the effective scenario 3 in the study network over the next 5 years are estimated using the annual load growth in the CYMDIST software, and the software output results are presented in Table 7. As can be seen in Table 7, the energy saved in the current year amounts to 4 185 718.124 kWh and in the fifth year to 6 436 805 kWh.

The cost of implementing Optimal Scenario 3 is 27 294 063 568 Rials. In addition, according to Table 8, the total cost of energy savings resulting from the reduction of losses in 4 years plus 95% of the fifth year is 27 294 063 568 Rials and it
is equal to the cost of implementing Scenario 3. As a result, the rate of return on capital is 4.95 years (4 years 11 months 14 days).

5 | CONCLUSION

In this article, two applications and effective strategies to reduce losses in sheet 13 of distribution companies of Qom province as a sample network are studied and analyzed. The first solution is to install new transformers in overload points of the network to reduce technical losses and increase reliability and stability of the network, and the second solution is to replace the overhead lines with the aerial bundled cable to reduce nontechnical losses. Based on two proposed strategies, three scenarios have been proposed and studied with regard to annual load growth in CYMDIST software. Based on the simulation results, the effective scenario of transformer installation and replacement of the overhead lines with aerial bundled cable are specified simultaneously and the economic justification and duration of return on the effective design are presented. Considering the cost of reducing energy losses and revenue generated by the implementation of the effective scenario and the cost of implementing the project, the return on investment is estimated to be 4.95 years, confirming the high technical and economic capability of the effective plan.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

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