Calculations of Loss Factor Based on Real-Time Data: Determining Technical Power Loss for the Electrical Distribution Network in Karbala City

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Abstract. Several empirical approaches have been used to calculate the power loss factor in electrical systems, including machine learning methods, top-down/bottom-up approaches, fuzzy-C-number algorithms, equivalent hours loss factors, and statistical analysis. Most methods for calculating power loss depend mainly on two substantial factors, the loss and load factors. These factors perform dynamic functions in terms of producing a good settlement. This research thus took into consideration a combination of actual data calculation and computation loss factor for actual distribution networks. The results observed in simulation suggest that, although that the method is simple and not complex, a suitable relationship between load and loss factors can be obtained by utilising exponential curve fitting. The proposed approach was tested on two distribution substations, with all experimental data collected from the electrical distribution network in Karbala city. The effectiveness of the proposed approach was shown through mathematical analysis and numerical simulations to determine the technical power loss, indicating an average yearly loss factor of 0.6114 using ETAP software. A further simple comparison among the loss factors generated by different methods related to the proposed approach was also completed to prove the robustness of the proposed approach.

List of Abbreviations:

| Abbreviation | Description |
|--------------|-------------|
| LDF          | Load factor |
| LSF          | Loss factor |
| FCN          | Fuzzy- clustering-number |
| PLD          | Power load |
| T            | Time period taken into consideration |

1- Introduction

Alongside economic process and reliability goals, one of the most important factors for those developing and maintaining electrical networks is the energy loss in the power system buses; in Iraq, this amounts to about 20% of the provided power [1]. Thus, it is necessary to estimate the energy losses to manage operation costs, as the costs of these losses should be deliberated against investments in addition to the base operation costs. Identifying the quantity of energy loss accurately is also important to achieving a simple comparison of distribution networks. In an electrical system, non-technical losses are sometimes called commercial
loss, whereas technical losses are based on metering errors that cannot be calculated in advance. The loss factor is usually used to compute energy losses in an electrical system where power flow is proportional to system load during the daily load cycle in the distribution and transmission networks. All losses in the main source can then be calculated, from sending to receiving, and the whole network considered [2-3]. Most power losses in distribution substations occur due to unlawful feeding resulting in unexpected results such as network overloads, transformer damage, additional cyclic maintenance, huge conductors, and bad power factors [14].

In the past, many approaches have been developed to determine the relationship between load and loss factors. Some such techniques depend on experimental relationships using both average loss and loading factors, such as that by Buller et al [4]. Other approaches depend on analytical and empirical relationships drawn from the load duration curve, as proposed in [5-6]. Loss reduction and loadability enhancement on distribution generators also offers a dual-index analytical approach [7].

Numerical approaches have been proposed more recently, with FCN techniques suggested to calculate loss factors [8-9]. A mixed approach was presented for evaluating energy losses in electrical networks [10], and another new approach was suggested to calculate and analyse loss based on extreme machine learning techniques [11]. Closed form formulae have also been used to compute losses based on a three-phase load flow model [12]. Simulation based on distribution feeders' loads’ data on typical customer load styles was also used in [13]. Difficulty in obtaining accurate data has a great influence on the accuracy of such results, however.

Mathematics offers several suitable methods for evaluating an accurate relationship between two groups of data based on curve fitting. This research paper thus offers a novel approach to computing power losses based on a nonlinear system; it is thus important to define some of fundamentals from both the Woodrow and Buller equations. All numerical results are also computed based on real-time data and compared with those produced by previous approaches.

The current study is presented as follows, section two discusses the computation of loss and load factors to guarantee the robustness of the proposed method. Section three offers the research methodology and several numerical results and their validation are discussed in sections four and five. Finally, the conclusion and a list of references are attached as sections six and seven, respectively.

2- Computation of loss and load factors

The methods proposed by Woodrow and Buller are used in the empirical equation given in (3), which includes relationship between loss factor and load factor. Both assumed idealised conditions of the load curve, which was divided into two sections: 1) time (t) denotes a peak load; and 2) time (T – t) denotes the off-peak load, as shown in Figure 1. As the power loss changes in proportion with the square of the line current (I²) in the electrical network, the loss also changes alongside the square of the loading rate. For this reason, the curve of losses is similar to the load curve, which represents load diversity as a function of time for a limited group of users. This resemblance reflects the fact that the loss curve is a schema of loss diversity as a function of time. The load factor can thus be written for a specific interval (T) as illustrated in (1) [4]:

\[ LDF = \frac{t}{T} \left[ \frac{P_{LD2}}{P_{ID1}} \right] \left[ 1 - \frac{t}{T} \right] \]  \hspace{1cm} (1)

The loss factor is then the average load loss to load loss at peak load in the period (T), as given in (2):

\[ LSF = \frac{t}{T} \left[ \frac{P_{LD2}}{P_{ID1}} \right]^2 \left[ 1 - \frac{t}{T} \right] \]  \hspace{1cm} (2)
Figure 1. Loss and load curves with time variation.

It is obvious that the method proposed by Woodrow and Buller considers the boundary conditions for the relationship between loss and load factors with full peak at $t = T$ and full off-peak at $t = 0$. To obtain the relationship between load and loss factors, these two sections can be drawn, and curve fitting used on the zone inside the two curves, as shown in Figure 2. This step helps to develop of (3) with a constant coefficient of 0.3. The constant coefficient was also derived through load curves, though these were based on finite computing capability and the obtainable data at that time [5].

$$LSF = (LDF)^2(1 - x) + (LDF)x$$

(3)

where $x$ indicates a constant coefficient, $LDF$ denotes a load factor, and $LSF$ is a loss factor.

Figure 2. Curve of load factor versus loss factor

The approach proposed by Woodrow and Buller has been very useful for small scale networks. The considered load curve was an excellent idea, based as it is on peak and off-peak points as seen in Figure 1. The average in Woodrow and Buller’s work is thus is proportional to peak and off-peak values only, leading to the following equation for loss factor in terms of load factor at same integer parameter, $k$ [6]

$$p_{LS}^k = C_k p_{LD}^k$$

(4)
Based on the hypothesis \( C_1 \neq C_2 \), this is not a condition that can be varied between both the off-peak and the peak point, however.

Hoebel utilised the main equation given in (3) and developed the equation used in (5) based on load and loss factors via an exponential coefficient. Generally, the value for the exponent as utilised empirically is 1.6 [6].

\[
\text{Loss factor} = (\text{Lad factor})^{1.6}
\]

Gustafson developed a quadratic equation for determining losses in both sub-distribution systems and transmission systems, as well as demonstrating that values of 30% for the coefficients and 1.6 for the exponential function are not suitable. Gustafson thus proposed 8% as suitable for the constant coefficient and 1.912 as suitable for the exponential function. The same approach was used for determining losses in the transmission system, but with some further special considerations [8].

3- The Research Methodology

3.1- The Proposed Approach

Many operations have nonlinear dynamic performance, including exponential dependencies, in many practical applications. Recently, exponential equations have been found to offer correct values for such numerical coefficients, as exponential equations can approximate any time response within a finite section of the given database. Most mathematical functions can be approximated with exponential curve fitting as follows. Take

\[
Y = a e^{bx} = a \left(1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \cdots \right)
\]

where the definition of mathematical exponential function, \( e^x \), using the Maclaurin series with a state variable \( x \in R^+ \) for the \( n^{th} \) order is

\[
e^x = \sum_{n=0}^{\infty} \frac{x^n}{n!} = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \cdots.
\]

A feature of this equation is that the parameter \( a \), determines the solution of the function defined in (6) while parameter \( b \) grants the function its curvature. Taking the natural logarithmic function \( \ln(.) : R^{+} \rightarrow R^{+} \) for both sides of (6) and using properties of \( \ln(.) \) thus gives

\[
\ln (Y) = \ln (a) + b(x)
\]

The parameters used in (8) are defined in the following equations [8]

\[
a = \frac{\sum_i^n x_i y_i \sum_i^n x_i^2 - \sum_i^n x_i \sum_i^n y_i}{n \sum_i^n x_i^2 - \left[\sum_i^n x_i\right]^2}
\]

\[
b = \frac{n \sum_i^n x_i y_i - \sum_i^n x_i \sum_i^n y_i}{n \sum_i^n x_i^2 - \left[\sum_i^n x_i\right]^2}
\]

where \( x \) and \( y \) are defined as the variables of data base group, and \( i = 1, 2, \ldots, N \), with \( N \) being a positive integer with an upper allowable limit of 8,760 (hours per year). Using (6) to appropriate the curve, which consist of two factors, the relation between them is

\[
\text{LSF} = A e^{B \cdot LDF}
\]

(11)
Taking, \( \ln(.) \) function for both sides of (9) and after some of mathematical manipulation, it yields:

\[
\ln (LSF) = \ln A + B * LDF
\]

This gives a linear relation between the natural logarithmic function \( \ln(.) \) for the load and loss factors. Thus, the general formula that links load and loss factors is

\[
\ln(LSF) = a + b LDF
\]

The coefficients of (13) can be calculated using (9) and (10), respectively. The specified intercept value \( y \) and curvature are utilized to calculate the loss factor of an electrical network for a specified of load factor based on the basic definition of loss factor.

Thus, \( \text{average loss} \triangleq LSF \times \text{peak loss} \)

However, the loss factor was calculated according to the approach in (9), so that

\[
\text{average loss} = (A e^{B \times LDF}) \text{peak loss}
\]

This allows computation of the total power losses for the \( i^{th} \) three-phase distribution substation as

\[
p_i^{loss} = 3l_i^2 R_i
\]

with \( R_i = \frac{\rho l_i}{A_i} \) where \( l_i \) and \( A_i \) are the length and the cross-sectional area of \( i^{th} \) distribution line, respectively,

such that \( \text{average loss} \triangleq \mu e^{B \times LDF} \)

where \( \mu \triangleq A \times \text{peak loss} \).

The relationship given in (16) can be utilised to compute the average losses for the \( i^{th} \) distribution feeder in this study. The next subsection thus discusses the scenario required to determine the boundary conditions for the coefficients denoted by \( A \) and \( B \) as given in (15).

3.2-Boundary Conditions

The relationship between two factors usually relies on the form of the load curve in load zone LA; the load curve is either in the peak load region or the zero region. In this situation, the load factor is equal to the loss factor. For load zone LB, however, the load curve is constant through the entire period except for a short interval when it arrives at the peak load as shown in Figure 3. The two of load curves indicate the main boundaries for the relationship between loss and load factors, as shown in Figure 4. The line LA denotes the load factor when directly proportional to the loss factor, and the line LB denotes the loss factor that varies with the square of the load factor; the loss factor lies in the coloured zone within the limits.

To prove the robustness of the proposed method, it was applied to one of the electrical distribution substations in Karbala city; this is discussed in the next section.
4- Simulation Results

The proposed approach was applied to a 132 kV transmission line length of 13.43 km connecting the West and South Karbala distribution substations. All technical operation data for the energy losses and yearly load profiles were collected for 2018 [16]. Transmission line parameters for copper and iron losses were used as listed in Table 1. The load factor per month and corresponding loss factor were estimated by sketching a loss curve per month; the corresponding load curve as clarified in Figures 7 and 8. Based on Woodrow and Buller, the variable \( \alpha \) was computed based on the average monthly loss and load factors, and the computed value for the coefficient was thus 0.643. This was utilised to compute the loss factors based on component monthly load factors.

The coefficients in the offered approach for \( A \) and \( B \) were computed based on the monthly average loss factor and load factor. The computations for the coefficients \( A \) and \( B \) were bounded between \([-2.20693,\]

![Figure 3. Load curves displaying the boundaries between load and loss factors](image1)

![Figure 4. Boundaries of the relationship for load factor and loss factor; the possible scope is shaded.](image2)
These were used to compute the loss factors based on the monthly components for load factors. Single line diagrams for Southern and Western distribution substations in Karbala city are shown in Figures 5 and 6, respectively.

From the numerical simulation results, the proposed method, though a novel tool, is capable of evaluating the transmission and distribution systems at high precision. It is also clear that the coefficient values are very significant in evaluating power loss, but that these values cannot be propagated to other systems, as every system has a distinct load profile, which affects the values for the coefficients. Thus, it is recommended that each distribution company utilise its own prior data to compute the coefficient values for the load profiles in their respective networks.

Table 1: Transmission Line Technical Features [15]

| Features         | Value     | Units  |
|------------------|-----------|--------|
| $R_1$            | 0.0485    | Ω/km   |
| $X_1$            | 0.2725    | Ω/km   |
| $R_0$            | 0.0485    | Ω/km   |
| $X_0$            | 1.154     | Ω/km   |
| Nominal Power    | 76        | MW     |
| Nominal Losses   | 465.637   | Watt   |
| Power Factor     | 0.85      | -      |
| Rated Voltage    | 132       | kV     |
| Line Length      | 13.24, short type | km |
| Rated Frequency  | 50        | Hz, cycle /sec. |
Figure (5): Single line diagram for the southern distribution substation in Karbala city.

Figure (6): Single line diagram for the Western distribution substation in Karbala city.
Figure 7. Monthly average load curve for the distribution between South and West Karbala substations.

Figure 8. Monthly average loss curve for the distribution between South and West of Karbala distribution substations.
5 - Validation

Buller was generally correct, but his method included too many assumptions to converge to the actual value. Due to the approximation used in the Buller calculation, its error ratio thus is largest for loss factors. Hoebel was able to obtain a curvature that lay close to the actual values, but this neglected constant losses. However, each link between the two groups of data can be extracted based on the infinite powers of the $x$ coefficient. Gustafson utilised polynomial equations, but only to the extent of second order equations only. This is an error source, and most of the results with respect to improved errors are still in the range of 10%, as listed in Table 2. As the current proposed approach takes all the conditions in the polynomial equations including the expansion of $e^x$ into account, the proposed method in this study comes much closer to the actual results as seen in Figure 9. Figure 10 clarifies the monthly average wiring losses calculated using the proposed approach from the current study.

| Month | Actual data [16] | Comparison with expected loss factors | Average Power Loss |
|-------|------------------|---------------------------------------|-------------------|
|       | Load Factor      | Loss Factor              | Buller | Hoebel | Gustafson | Proposed Approach |                   |
| Jan.  | 0.75149          | 0.6027                  | 0.685  | 0.633  | 0.658     | 0.577             | 268.673           |
| Feb.  | 0.6599           | 0.4741                  | 0.580  | 0.514  | 0.529     | 0.478             | 222.570           |
| Mar.  | 0.7379           | 0.5794                  | 0.669  | 0.616  | 0.638     | 0.572             | 266.34            |
| Apr.  | 0.7546           | 0.5899                  | 0.689  | 0.637  | 0.662     | 0.592             | 275.657           |
| May   | 0.8481           | 0.7304                  | 0.802  | 0.768  | 0.798     | 0.729             | 339.449           |
| Jun.  | 0.8517           | 0.7301                  | 0.807  | 0.773  | 0.802     | 0.734             | 341.776           |
| Jul.  | 0.7974           | 0.6481                  | 0.740  | 0.697  | 0.723     | 0.651             | 303.13            |
| Aug.  | 0.7361           | 0.5717                  | 0.667  | 0.623  | 0.636     | 0.567             | 264.016           |
| Sep.  | 0.7764           | 0.6388                  | 0.715  | 0.668  | 0.693     | 0.622             | 289.626           |
| Oct.  | 0.7880           | 0.6484                  | 0.729  | 0.683  | 0.710     | 0.637             | 296.61            |
| Nov.  | 0.7997           | 0.6581                  | 0.743  | 0.699  | 0.727     | 0.656             | 305.458           |
| Dec.  | 0.7064           | 0.5360                  | 0.633  | 0.573  | 0.594     | 0.522             | 243.063           |
| Yearly Average |                   |                        | 0.705  | 0.657  | 0.681     | 0.6114            | 284.697           |
6- Conclusion

Quantifying energy loss is a serious goal for a simple study of electrical network, yet it gives a good overall idea of the current state and required expansion of the electric networks with a view to unexpected future load growth. Energy loss computations are considered the largest challenge for developing the electrical networks of many countries, yet in this study, a mathematical approach to calculating the relationships between various loss and load factors has been successfully applied to one of the electrical distribution networks in Karbala city. The proposed approach takes all the conditions in the polynomial equations,
including the expansion of $e^x$, into account, and this explains why the proposed method comes much closer to the actual results compared with other methods used to compute the loss factor as listed in Table 2.

The approach used in this study takes into consideration the effect of total constant losses caused by the major electrical parts of the power systems; it must also be emphasised that this approach for checking power loss is a sufficiently good to be utilised in all electrical networks. The next step of this research will focus on the advanced capabilities of minimizing the power losses in electrical networks.

7- References

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