Estimation of Transmission Line Parameters Using Voltage-Current Measurements and Whale Optimization Algorithm

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Abstract: Real-time estimation of transmission line (TL) parameters is essential for proper management of transmission and distribution networks. These parameters can be used to detect incipient faults within the line and hence avoid any potential consequences. While some attempts can be found in the literature to estimate TL parameters, the presented techniques are either complex or impractical. Moreover, none of the presented techniques published in the literature so far can be implemented in real time. This paper presents a cost-effective technique to estimate TL parameters in real time. The proposed technique employs easily accessible voltage and current data measured at both ends of the line. For simplicity, only one quarter of the measured data is sampled and utilized in a developed objective function that is solved using the whale optimization algorithm (WOA) to estimate the TL parameters. The proposed objective function comprises the sum of square errors of the measured data and the corresponding estimated values. The robustness of the proposed technique is tested on a simple two-bus and the IEEE 14-bus systems. The impact of uncertainties in the measured data including magnitude, phase, and communication delay on the performance of the proposed estimation technique is also investigated. Results reveal the effectiveness of the proposed method that can be implemented in real time to detect any incipient variations in the TL parameters due to abnormal or fault events.

Keywords: transmission lines; voltage-current measurements; parameters estimation; whale optimization algorithm; fault location

1. Introduction

Identification of transmission line (TL) parameters is essential for performing load flow calculation, designing a proper protection system, and locating various faults within the line [1–3]. While these parameters may be available from the manufacturer’s data sheet, especially for new installations, they are either unknown or have exhibited changes due to aging and environmental and operating conditions for most of the existing lines. This calls for a reliable technique to estimate TL parameters. Conventional methods to estimate TL parameters rely on the line’s physical properties including size and material along with line sag, tower height, and soil properties [4–6]. These methods result in a significant error in the estimated parameters due to the adoption of several assumptions to simplify the analysis.

To reduce the estimation error, several TL parameters estimation techniques based on frequency or time domain analysis were presented in the literature [7,8]. In the time-domain based methods, the TL is represented by cascaded π-networks comprising series
resistance and inductance ($R$, $L$), mutual inductance ($M$), and shunt capacitance ($C$), which is similar to the transformer modelling [9]. Estimating the values of $R$, $L$, and $C$ at the fundamental frequency is presented in [2] for setting the relays coordination and designing a protection scheme. However, the complex data processing involved in this method makes it impractical for field applications. Another estimation technique based on synchronized voltage and current measurements at both terminals of the line during fault conditions using a fault recorder is presented in [10]. However, this technique requires fast processing sensors and the estimated parameters are affected by the type of fault.

Calculating TL parameters based on short-circuit current and open-circuit voltage measurements is presented in [11]; however, this technique is not suitable for practical applications. In the few attempts published in the literature to estimate TL parameters, no technique with easy real-time implementation features has been presented. This may be attributed to the fact that most of the presented techniques focused on employing the estimated parameters to design a protection scheme for either new or existing transmission networks, which does not call for the necessity of real-time implementation. With the global trend to establish smart electricity grids, electric utilities are aiming to adopt reliable, automated, and non-invasive techniques for self-healing purposes. This calls for the essential need to establish online condition monitoring techniques to detect incipient faults and avoid catastrophic consequences, which is the main motivation of this paper. Power lines are operating under harsh environmental conditions that make them more prone to faults, which usually occur suddenly after some abnormal events such as lines swinging. While some techniques such as travelling-waves and apparent impedance methods have been developed to identify fault locations within power lines after their occurrence, no technique has so far been developed to detect the abnormal events and isolate the power line before the development of the fault [12].

Some classical optimization techniques are used to estimate the TL parameters [13]. The convergence of these classical techniques is not guaranteed and division by zero may take place during the optimization process. In addition, classical optimization techniques need an accurate definition for the objective function that should be minimized/maximized along with the symbolic differentiation of this function, which increases the process time and complicates the optimization process. These drawbacks call for using simple concepts and easily implemented optimization techniques with no need for gradient definitions. Genetic algorithm and particle swarm optimization (PSO) techniques are considered benchmark methods and they find many applications in power systems; however, other modern and efficient techniques are presented in the literature [13,14]. Some new optimization techniques provided higher efficiency than genetic algorithm and PSO in many applications. Some of these new methods include whale optimization algorithm (WOA) [15], elephant herding [16], and harmony search [17].

With the rapid advancement in optimization techniques, few attempts to estimate equivalent circuit parameters of some systems based on these techniques can be found in the literature [18]. Using a proper objective function and by employing easily accessible data, various optimization methods can be utilized to effectively estimate electric system parameters. While various optimization techniques were utilized to estimate the parameters of different power system components such as the power transformer, induction motor, and photovoltaic system [17–19], a transmission line parameter estimation method based on PSO is presented in [13]. In this method, PSO is used to minimize the error between the actual voltage/current measurements and the corresponding estimated values. However, the accuracy of the method is not properly investigated and its real-time implementation is not discussed. Furthermore, uncertainty in the measured data is not investigated.

The main contribution of this paper is the presentation of a new technique based on the WOA to estimate the TL electric parameters ($R$, $L$, $C$, and $M$). The proposed technique can be performed every one quarter of the power cycle which facilitates its application in real time. Estimation of these parameters in real time will be of great help to identify the location of any incipient or abnormal event that results in a change to these parameters.
Correlation of fault type and location with the change in the TL parameters is out of the scope of this paper.

The remaining sections of the paper are organized as provided below:

The proposed technique along with the WOA is presented in Section 2. Simulation results including case studies are presented in Section 3 and the main conclusion is drawn in Section 4.

2. Proposed Technique and Whale Optimization Algorithm

The proposed technique is based on performing synchronized measurements for the voltages and currents at both ends of the line using phasor measurement units (PMUs). One quarter of the measured instantaneous data is sampled and employed by the WOA to estimate the TL parameters. The four voltage and current signals at buses 1 and 2 \((V_1, I_1, V_2, I_2)\) are measured and sampled at a sampling rate of 0.2 \(\mu s\). These four signals are considered as the actual (target) values. An objective function comprising the sum of squares error of the actual and estimated values of the four signals is proposed as given by (1). The WOA is used to minimize the objective function and estimate the optimum values of the four TL parameters in real time as is elaborated below. The objective function is solved subject to maintaining the voltage and current limits, and hence the power is maintained at both ends of the line within their permissible ranges.

\[
J = \sum_{i=1}^{k} \left( \alpha \left( \frac{(V_i)_{\text{actual}} - (V_i)_{\text{est}}}{\max(V_i)_{\text{actual}}} \right)^2 + \beta \left( \frac{(V_i)_{\text{actual}} - (V_i)_{\text{est}}}{\max(I_i)_{\text{actual}}} \right)^2 + \gamma \left( \frac{(I_i)_{\text{actual}} - (I_i)_{\text{est}}}{\max(I_i)_{\text{actual}}} \right)^2 + \delta \left( \frac{(I_i)_{\text{actual}} - (I_i)_{\text{est}}}{\max(I_i)_{\text{actual}}} \right)^2 \right)
\]

(1)

where \(\alpha, \beta, \gamma, \) and \(\delta\) are weighting factors with a sum of one and \(k\) represents the number of sampled points for any quarter of a complete power cycle. The subscript “actual” is referred to the measured data while the subscript “est” refers to the estimated data obtained from the WOA. \(V_1, I_1\) and \(V_2, I_2\) are the voltages and currents at buses 1 and 2, respectively.

It should be noted that instantaneous voltage and current waveforms at both ends are sampled and used in the calculations to facilitate solving the sending and receiving end equations of the TL and identify the electric parameters under various operating conditions. The optimization technique is used to guarantee minimum calculation error in the estimated parameters. While iterative techniques can be used to solve the set of equations relating to input and output parameters, the WOA is used to ensure a global or near global optimum solution is obtained in a rapid time frame which facilitates the application of this method in real time.

The WOA is employed to identify the TL parameters through minimizing the objective function given by (1). As stated above, the proposed objective function is the weighted sum of the normalized square errors of the actual and estimated voltages and currents at both ends of the line sampled over one quarter of the cycle. This optimization technique is based on imitating the social behavior of humpback whales.

The technique is inspired by the amazing and mediating features of whales that include:

- Whales never sleep completely as they need to inhale air from above the water;
- Whales can control emotion and behave in a human manner in many situations due to some brain similarities;
- The humpback whale (HW) preys on schooling fish in a bubble-net feeding method. HW’s chase large groups of small fish at or close to the water surface by generating individual bubbles along a circle. This technique inspired a new and effective optimization method.

The HW starts by searching for the location of the prey group and encircles them. Other search mediators try to update their positions as follows:

\[
\vec{D} = |\vec{M} \times \vec{X}^*(t) - \vec{X}(t)|
\]

(2)

\[
\vec{X}(t + 1) = \vec{X}^*(t) - \vec{K} \times \vec{D}
\]

(3)
where $\vec{X}(t)$ is the vector of the best solution at iteration step $t$ while $\vec{K}$ and $\vec{M}$ are the coefficients vectors.

In the investigated application, the vector $\vec{X}(t)$ represents a set of the required electric parameters of the TL i.e., $(R, L, C, \text{and } M)$. The WOA starts by proposing random positive values for these four parameters as initial values for the vector $X$. These random initial values are used to determine the initial value of the objective function given in (1). The vector values are then updated using the coefficient vectors $\vec{K}$ and $\vec{M}$ that are calculated from:

$$\vec{K} = 2\vec{a} \times \vec{r} - \vec{a} \quad (4)$$

$$\vec{M} = 2\vec{r} \quad (5)$$

where $\vec{r}$ is a random vector whose value is in the range 0 to 1, and $\vec{a}$ is a parameter that is linearly decreasing through the iteration steps from 2 to 0 [20–22].

The updated value of the objective function is compared to the preceding value and the best one is stored while the other is eliminated. Other updates are made for the vectors $\vec{K}$ and $\vec{M}$ and consequently the vector $\vec{X}(t)$ and the objective function are updated. This process is repeated until the maximum number of iterations is reached. Each time, the minimum objective function and the corresponding four TL parameters $(R, L, C, \text{and } M)$ represented by the vector $\vec{X}(t)$ are stored and compared with the values obtained from the previous step to finally determine the minimum objective function with the optimal TL parameters.

The technique can be simply explained on an objective function with two variables to be optimized $(X, Y)$ of which the best current position of the mediator is $(X^*, Y^*)$. There are many positions around the nest one may achieve based on the update of the vectors $\vec{K}$ and $\vec{M}$. All these possible positions for a two-variable problem are shown in Figure 1.

![Figure 1](image1.png)

**Figure 1.** All possible positions for two-dimensional optimization problem.

The WOA is used in this paper to minimize the objective function defined in (1) and consequently estimate the optimum values for the four parameters of the TL $(R, L, C, \text{and } M)$. In this case, the size of the problem is four variables instead of the two variables illustrated in Figure 1. The flow chart of the proposed WOA to estimate the TL parameters is shown in Figure 2. The technique starts by initiating four random values of the TL parameters $(R, L, M, \text{and } C)$ that are used to calculate the voltages and currents at both ends of the line using load flow analysis, performed on a simulation model of the practical network. The voltage and current signals calculated from the network model and the corresponding on-line measured signals using PMU are sampled over a one-quarter cycle. The difference between the voltages and currents at both sides for the measured and calculated values are determined based on the objective function given by (1). The initial value of the objective function resulted from this iteration step is stored for comparison
with the following step. Updating of the position (value) of each TL parameter based on (2) through (5) is performed in a similar way to the position distribution of Figure 1, but in 4 dimensions. This distribution comprises all possible updates of each parameter. Based on the updated parameters, a new load flow analysis is performed on the network model to calculate a new estimated set of the voltages and currents at both ends of the line. These estimated values are used with the corresponding measured values to recalculate $J$, which is then compared with the previously stored value and the minimum value is retained along with the corresponding four TL parameters. This process is repeated until the least value of the objective function or the maximum iteration numbers is attained at which point optimum TL parameters can be identified.

A proper selection of the weighting factors in (1) is essential for improved and reliable estimation accuracy of the TL parameters. In this regard, the four weighting factors in (1) are firstly selected to be of equal values, i.e., $\alpha = \beta = \gamma = \delta = 0.25$. Then, all possible combinations of these factors with a 0.1 increment for each selection while maintaining their sum at unity are investigated by estimating the parameters of seven specific transmission

Figure 2. The proposed WOA flowchart for TL parameters estimation.

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lines of known parameters. From this analysis, the best values for the weighting factors are found to be \( \alpha = \beta = 0.2, \gamma = \delta = 0.3 \). Figure 3 shows the performance of the objective function for two sets of the weighting factors from which it can be observed that the above-mentioned set converges faster and results in a smaller value of \( J \). These weighting factors are used in the proposed objective function to estimate the parameters of various TLs of different ratings, topologies, and operating conditions as is elaborated below.

The key feature of the proposed technique is its ability to estimate TL parameters in real time. As can be seen in the flow chart of Figure 2, two sets of voltage and current data are required. These are synchronized online measured signals at both ends of the line using PMU and the voltage and current signals calculated offline on the transmission network model in the control center. As such, the execution time is a key factor to assess this feature in the proposed technique. The proposed method is used to estimate the parameters of seven different TLs and the execution time, number of iterations, and the least value of \( J \) are recorded as shown in Table 1. The results show that the WOA is effective in minimizing the proposed objective function for all investigated lines with a maximum value of 1.235 that is obtained for TL 2, which is still acceptable. Furthermore, the execution time for any of the seven TLs is less than 1 s which facilitates the real time implementation of this technique.

### Table 1. Performance of the WOA for parameter estimation of seven TLs.

| TL | \( J_{\text{min}} \) | Iterations | Execution Time (s) |
|----|----------------|------------|-------------------|
| 1  | 0.9192         | 96         | 0.68              |
| 2  | 1.235          | 86         | 0.51              |
| 3  | 0.8654         | 56         | 0.52              |
| 4  | 1.12           | 68         | 0.74              |
| 5  | 0.658          | 72         | 0.35              |
| 6  | 0.789          | 45         | 0.43              |
| 7  | 0.657          | 86         | 0.63              |

### 3. Simulation Results

The proposed TL parameters estimation technique can be performed using any one quarter of the complete ac cycle, i.e., 5 ms based on 50 Hz networks. The robustness of the proposed technique is assessed through the below case studies.

A. Case study-1:
The proposed technique is firstly employed to estimate the parameters of a 50 Hz, 400 MVA, 447.8 kV, 100 km TL that is shown in Figure 4. The actual parameters of this TL are listed in the first column of Table 2.

![Figure 4. Single line diagram for case study-1.](image)

Table 2. Actual and estimated parameters using four quarters of the measured signals.

| Parameter | Actual  | 1st Quarter | 2nd Quarter | 3rd Quarter | 4th Quarter |
|-----------|---------|-------------|-------------|-------------|-------------|
| $R$ Ω/km  | 0.137   | 0.136       | 0.1356      | 0.136       | 0.1356      |
| $L$ mH/km | 1.9979  | 1.999       | 1.993       | 1.999       | 1.993       |
| $M$ mH/km | 1.0642  | 1.053       | 1.052       | 1.053       | 1.052       |
| $C$ nF/km | 12.74   | 12.71       | 12.75       | 12.71       | 12.75       |

Power flow calculation is performed on the system shown in Figure 4 using Matlab/Simulink to calculate the voltages and currents at both buses. The instantaneous voltages and currents at the two ends of the line are sampled over one complete cycle using a sampling time of 0.2 µs. It should be noted that, in real application, these values are measured using PMU. As mentioned above, the proposed technique can employ any quarter of the complete power cycle to estimate the TL parameters. The WOA is used to estimate the TL parameters based on the procedure shown in the flow chart of Figure 3. For this case study, the WOA converges at iteration step 48 with a minimum objective function of 0.563. The estimated TL parameters along with the percentage estimation error when employing each quarter of the complete cycle of the voltage/current signals are given in Table 2. It was observed that the proposed technique can estimate the TL parameters with high accuracy. The maximum percentage error is observed for estimating the mutual inductance which is only 1.05%. Results in Table 2 also reveal the ability of the proposed technique to estimate the parameters of the TL using any quarter of the power frequency cycle. This feature facilitates the ability of the proposed technique to detect incipient faults and abnormal events on the TL in real time by comparing the estimated parameters for a certain period and by using any quarter of the measured signals. Any significant changes in the estimated parameters can be considered as an early alarm for incipient faults. The voltage and current waveforms at buses 1 and 2, calculated based on the estimated TL parameters along with the waveforms obtained from the power flow calculation using actual TL parameters, are shown in Figure 5. It can be seen that the actual and estimated waveforms are of a good agreement which attests to the robustness of the proposed WOA in estimating TL parameters.
B. Case study-2:

The above case study assumes that data measured at both ends of the transmission line are perfectly synchronized with no uncertainty in the used data. This case study assumes errors in the measured data. The performance of the proposed technique to estimate the parameters of the TL of Figure 4 is assessed when the voltage/current measured data exhibits errors in magnitude along with synchronization delay time. It is assumed that the voltage and current at bus 2 exhibit a measurement error of ±10% of their nominal values. Furthermore, a delay time of 4 µs, corresponding to 20% synchronization error of the measured data at bus 2, is assumed. The proposed optimization technique is employed to estimate the TL parameters under these measurement errors. Estimated parameters are listed in Table 3. While the estimated parameters in Table 3 exhibit a larger error than the ideal measurement data shown in Table 2, the estimated parameters are still in good agreement with the actual TL data. The actual and estimated voltages and currents at buses 1 and 2 with +10% magnitude error in the measured signals at bus 2 and 20% synchronization error are shown in Fig. 6. The figure shows good agreement between the obtained results based on the estimated line parameters and the actual data.

**Figure 5.** Voltages and currents waveforms at both ends of the TL from case study-1.
synchronization error are shown in Figure 6. The figure shows that a small deviation takes place due to such errors, but this deviation is still within a small margin.

Table 3. Actual and estimated parameters with ±10% magnitude error in $V_2$ and $I_2$ and 20% synchronization error.

| Parameter | Actual | +10% Error | −10% Error | 20% Delay Error |
|-----------|--------|------------|------------|-----------------|
| $R \ \Omega/km$ | 0.1373 | 0.13 | 5 | 1.24 | 0.1388 | 1 |
| $L \ \text{mH/km}$ | 1.9979 | 1.69 | 15.4 | 1.76 | 11.6 | 2.32 | 16 |
| $M \ \text{mH/km}$ | 1.0642 | 0.98 | 7.9 | 1.21 | 13.7 | 1.23 | 15 |
| $C \ \text{nF/km}$ | 12.74 | 11.2 | 12.1 | 11.1 | 12.8 | 14.8 | 16 |

Figure 6. Voltages and currents waveforms at both ends of the TL with 10% error in $V_2$ and $I_2$ measurements along with a 20% synchronization error from case study-2.

C. Case study-3

To investigate the effectiveness of the proposed technique to estimate the parameters of various TLs of a large interconnected network, the IEEE 14-bus system [23] shown in Figure 7 is simulated using MATLAB/Simulink. This system comprises fourteen buses, two generators, three static compensators, and twenty transmission lines. It is to be noted that the provided data for the IEEE 14-bus system [23] do not comprise mutual inductance and hence are omitted from the estimation process. Power flow calculation is performed to identify the bus voltages and currents. Similar to the above case study, the voltage/current waveforms at both ends of each TL are sampled and the first quarter of each waveform is
employed by the proposed WOA to estimate the TL parameters. The WOA used in this estimation process is set to a maximum of 100 iteration steps and the recorded execution time is found to be 1.5 s. The actual and estimated data for the 20 TLs in Figure 7 are listed in Table 4. Error results in Table 4 indicate that the average error in estimating line resistance is 4.36%, self-inductance is 3.4%, and capacitance is 4.69%. These results confirm the high accuracy of the proposed technique to estimate the parameters of TLs of different ratings in a complex interconnected power system. The small error in the estimated parameters did not have an observable effect on the load flow calculation as can be seen from the voltage magnitude and phase angle at each bus and the lines active and reactive powers calculated using actual and estimated TL parameters as shown in Figures 8 and 9, respectively. A summary of the load flow calculation for the IEEE 14-bus system based on actual and estimated TL parameters is given in Table 5 which reveals a good agreement between the obtained results based on the estimated line parameters and the actual data.

![Diagram of the IEEE 14-bus system used in case study-3.](image-url)

Figure 7. IEEE 14-bus system used in case study-3.
Table 4. Actual and estimated parameters of the 20 TLs of the IEEE 14-bus system from case study-3.

| Line | Actual | Estimated | % Error |
|------|--------|-----------|---------|
|      | R (Ω)  | L (mH)    | C (F)   | R (Ω)  | L (H)    | C (F)   | R      | L      | C      |
| 1    | 0.019  | 0.059     | 0.052   | 0.019  | 0.053    | 0.053   | 0      | 10.17  | 1.92   |
| 2    | 0.0540 | 0.2230    | 0.0492  | 0.0519 | 0.2135   | 0.0483  | 3.9    | 4.26   | 1.83   |
| 3    | 0.0470 | 0.1980    | 0.0438  | 0.049  | 0.1947   | 0.0427  | 4.25   | 1.67   | 2.51   |
| 4    | 0.0581 | 0.1763    | 0.0374  | 0.0557 | 0.1696   | 0.0360  | 4.13   | 3.80   | 3.74   |
| 5    | 0.0570 | 0.1739    | 0.0340  | 0.058  | 0.1695   | 0.0362  | 1.75   | 2.53   | 6.47   |
| 6    | 0.0670 | 0.1710    | 0.0346  | 0.0609 | 0.1627   | 0.0296  | 9.1    | 4.85   | 14.45  |
| 7    | 0.0134 | 0.0421    | 0.0128  | 0.0134 | 0.0433   | 0.0109  | 0      | 2.85   | 1.92   |
| 8    | 0      | 0.2091    | -       | 0      | 0.2134   | -       | -      | 2.06   | -      |
| 9    | 0      | 0.5562    | -       | 0      | 0.5476   | -       | -      | 1.55   | -      |
| 10   | 0      | 0.252     | -       | 0      | 0.2421   | -       | -      | 3.93   | -      |
| 11   | 0.0950 | 0.1989    | -       | 0.0965 | 0.1938   | -       | 1.58   | 2.56   | -      |
| 12   | 0.1229 | 0.2558    | -       | 0.1163 | 0.2646   | -       | 5.37   | 3.44   | -      |
| 13   | 0.0662 | 0.1303    | -       | 0.0620 | 0.1244   | -       | 6.34   | 4.53   | -      |
| 14   | 0      | 0.1762    | -       | 0      | 0.1747   | -       | -      | 0.85   | -      |
| 15   | 0      | 0.1100    | -       | 0      | 0.1080   | -       | -      | 1.82   | -      |
| 16   | 0.0318 | 0.0845    | -       | 0.0292 | 0.0804   | -       | 8.17   | 4.85   | -      |
| 17   | 0.1271 | 0.2704    | -       | 0.1210 | 0.2629   | -       | 4.8    | 2.77   | -      |
| 18   | 0.0820 | 0.1921    | -       | 0.0762 | 0.1838   | -       | 7.1    | 4.32   | -      |
| 19   | 0.2209 | 0.1999    | -       | 0.2155 | 0.1920   | -       | 2.44   | 3.95   | -      |
| 20   | 0.1709 | 0.3480    | -       | 0.1822 | 0.3523   | -       | 6.61   | 1.24   | -      |

Figure 8. Bus voltages (magnitude and phase angle) of the IEEE 14-bus system from case study-3.
Figure 8. Bus voltages (magnitude and phase angle) of the IEEE 14-bus system from case study-3.

Figure 9. Active and reactive power flow of the IEEE 14-bus system from case study-3.

Table 5. Power flow summary based on actual and estimated TLs parameters from case study-3.

| Parameter        | Actual       | Estimated    |
|------------------|--------------|--------------|
| Total generation |              |              |
| Real power (p.u.)| 2.729473     | 2.719726     |
| Reactive power (p.u.)| 1.712068 | 1.700404 |
| Total load       |              |              |
| Real power (p.u.)| 2.59         | 2.59         |
| Reactive power (p.u.)| 0.814   | 0.814        |
| Total losses     |              |              |
| Real power (p.u.)| 0.139473     | 0.129726     |
| Reactive power (p.u.)| 0.898068 | 0.886404 |

In the above case studies, required voltage and current data at both ends of the line are obtained through power flow analysis. For the practical implementation of the proposed method, synchronized measurements of the instantaneous three-phase voltages and currents at both ends of the line through PMU and a global positioning system, is required. If PMU is not available, in particular for distribution grids, an electronic measurement device [24–31] along with the new substation automation system based on IEC 61850 [32] can be employed. Alternatively, a simple voltage and current data accusation hardware setup for current and voltage measurements and harmonic and noise elimination such as the one presented in [33] can be used for the online implementation of the proposed technique.
4. Conclusions

This paper presents a cost-effective technique for estimating TL parameters in real-time using one quarter of the cycle of the instantaneous values of the voltages and currents at both ends of the line. The WOA is used to minimize an objective function comprising the square error of the actual and estimated voltages and currents. Simulation analyses conducted on a simple two-bus and the IEEE-14 bus systems reveal that:

- The proposed technique can estimate the TL electric parameters with an acceptable accuracy level;
- The technique can employ any quarter of the measured data to estimate the TL parameters with a high degree of consistency. This feature facilitates the real-time detection of any incipient variation in the TL parameters and hence helps detect emerging faults and abnormal events;
- Errors in the measured data or any synchronization delay will have an impact on the performance of the proposed technique, but the error in the estimated parameters is still not very significant;
- The proposed technique is easy to implement for existing and new installations. Furthermore, the technique can be used for various TLs of different ratings, topologies, and operating conditions.

Future research studies should be conducted to:

- Further investigate the feasibility of the proposed technique to detect abnormal events in real-time, in particular, the overall execution time with a significant communication delay;
- Correlate the change in each of the TL parameters with the location and type of fault or abnormal event;
- Investigate the suitability of the proposed technique for distribution networks in which measuring devices may not be available at both terminals of each line.

While the proof of concept of the proposed approach is verified through simulation analysis in this paper, the method should be validated through laboratory and practical field measurements.

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