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Estimation of Transmission Line Parameters in Modern Power Systems from Phasor Measurements

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Abstract— **Transmission line parameters are susceptible to variations through time due to changes in environmental conditions and the ageing of components. Classical calculations of transmission line parameters based on geometrical data provided by manufacturers do not consider these factors introducing errors in line parameters, which affect the accuracy of real-time system operation and long-term operation applications. This paper exploits two estimation procedures of the transmission line parameters. The first one uses the equivalent π model of transmission lines' characteristic equations and phasor measurements to estimate line parameters. The second one derives the admittance matrix from sequential voltage and current phasors measurements for a fully observable power system. A case study based on the IEEE 14-bus test system is used to test the methods, and the preliminary results are presented.**

Keywords— transmission line parameter identification; phasor measurement unit; power flow; state estimation

I. INTRODUCTION

The proliferation of distributed energy resources (DERs) prefigures substantial transformations within the power system industry. The integration of DERs introduces complexities necessitating the deployment of advanced measurement, communication, and control infrastructure. Traditional power grids, designed for centralized electricity generation, must now accommodate bidirectional power flows inherent to DERs. Consequently, there is a pressing need to enhance the grid's operational intelligence to monitor and manage the network topology in real time.

Transmission line parameters are susceptible to variations with time due to changes in atmospheric conditions such as temperature, soil resistivity and ageing of line conductors and cables [1], [2], [3]. For instance, underground cables suffer an increase in line inductance with time because of the corrosion of tape shields and an increase in line capacitance due to degradation of the dielectric constant of cable insulation caused by moisture and heating from overloading [1].

In addition, inaccurate manufacturing data, construction variations, and miscalculations of line lengths, along with other human-related factors, can result in significant errors in line parameters. Some studies suggest that errors in line parameters stored in databases can reach up to 30% of the actual value [2], [3].

Errors in line parameters cause a negative impact on state estimation, operation control, reactive power optimization, line loss management, relay protection and configuration, event detection and more [2], [3], [4], [5]. Thus, it is possible to say that accurate transmission line parameters are prerequisites for all operation, control and planning studies of modern power systems and that their accuracy directly affects the stable and safe operation of the power grid [6], [7], [8].

The main techniques for transmission line parameter identification (TLPI) rely on state estimation results, but the measurements used must meet observability requirements which may not be possible in all power systems [4].

Supervisory control and data acquisition (SCADA) technology and phasor measurement units (PMUs) are being employed in modern power systems because of the need for more efficient real-time monitoring and control of the grid [3]. Their synchronized voltage and current phasor measurements (magnitudes and phase angles) improve state estimation, and many TLPI methods are based on those measurements [6], [7], [9]. However, installing a PMU on every bus of a power system may not be economically viable, and some buses actually lack measurement devices, mainly in distribution networks [3], [4].

With that in mind, some TLPI techniques involve estimating line parameters when the power system is not fully observable [10] and without voltage angles [11]. Yuan et al. [10] propose a particularly interesting approach based on the graph theory technique since it offers tools for optimal PMUs placement, state estimation and more [12], [13], [14].

This paper exploits the estimation of the transmission line parameters, represented in the equivalent π model with lumped series resistance and reactance and shunt susceptance, based on real-time synchronized phasor measurements provided by the two-line ends. In addition, an algorithm that derives the admittance matrix from sequential voltage and current phasors measurements, based on the approach described in [10], for a fully observable power system is also implemented and tested in a case study constructed from the IEEE 14-bus test system.

The paper is organized as follows: section II presents an overview of transmission line parameters estimation and presents the methodologies that are exploited hereinafter; the case study is introduced in section III and section IV presents the main results of the estimation of the parameters. Finally, section V rounds out the paper with the conclusion.

II. TRANSMISSION LINE PARAMETERS ESTIMATION

In the classical approaches, transmission line parameters are calculated from the geometry of the line conductors and the length of the lines or directly measured using specific instruments during the construction or maintenance of the transmission lines [6], [8], [9]. However, these methods are inaccurate due to simplified ideal models or inconvenient because they can only be utilized when the line is out of service [8].

Using modern techniques, line parameters can be estimated by Kirchhoff's and Ohm's laws by solving the nonlinear equations derived from the equivalent π model of the transmission line based on PMU measurements of voltage and current phasors, by weighted least squares (WLS), based on state estimation, residual sensitivity analysis and WLS-based augmented state estimation [1], [2].

These techniques represent an advantage when compared to classical approaches, but their accuracy not only depends on their convergence but also on the accuracy of phasor measurements and state estimation [1]. For instance, since PMUs are synchronized via GPS equipment, measurements are transferred to the control center with a time stamp which is used to pair measurements at the two ends of a line. Some measurements may be missing, and the measurement chain may also introduce uncertainties, as the instrument transformers typically have a different, low-accuracy class. In addition, interference and distortions in the measurement signals can also contribute to inaccurate data.

This study utilizes two techniques to estimate transmission line parameters. A case study is conducted on a fully observable power system utilizing a modified IEEE 14-bus test system. The first technique employs equations derived from the equivalent π model of the transmission line to determine line parameters from current and voltage phasors. The second technique utilizes a set of current and voltage phasors to estimate the system's admittance matrix by solving an optimization problem.

A. *Calculation of the equivalent π model parameters of a transmission Line*

For a given transmission line with PMUs installed at both ends, providing voltage and current phasor measurements on a time basis, the equivalent π model of the transmission line is used to estimate the lumped values of the line series resistance and reactance and shunt susceptance.

Figure 1 depicts the equivalent π model of a medium-length transmission line. The model can be simplified further when the line is regarded as short; in such instances, only the series resistance and reactance are taken into account.

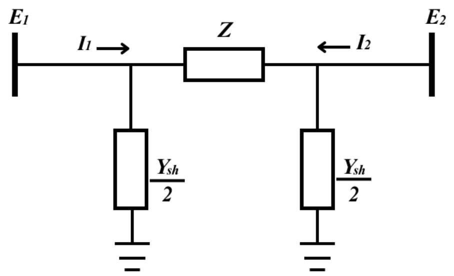

Figure 1- Equivalent π model of a medium-length transmission line.

From Figure 1 the series impedance of the line, Z, and the shunt admittance, Y_{sh}, are calculated as follows:

$$Z = \frac{(E_1 - E_2)(E_1 + E_2)}{I_1(E_1 + E_2) - E_1(I_1 + I_2)} \quad (1)$$

$$\frac{Y_{sh}}{2} = \frac{I_1 + I_2}{E_1 + E_2} \quad (2)$$

Lumped series resistance and reactance are then obtained by taking the real and imaginary parts of the calculated impedance, respectively. The shunt conductance and susceptance are obtained by taking the real and imaginary parts of the calculated shunt admittance.

This method can be used online, meaning that it may provide timed line parameter values based on real-time measurements of the system as long as the data uncertainties are concurrently managed.

B. *Estimation of the line parameters by admittance matrix identification*

This approach is based on the method developed in [10] for the inverse power flow problem, without hidden nodes. The method consists of obtaining the admittance matrix of the power system by using Kirchhoff's law for a given set of phasor measurements of bus voltages and current injections.

For a given bus *i* of a network composed of *N* buses and having *K* measurements, Kirchhoff's law, in vectorial form, is shown in (3).

$$\underbrace{\begin{bmatrix} I_i(1) \\ I_i(2) \\ \vdots \\ I_i(K) \end{bmatrix}}_{I_i(K)} = \underbrace{\begin{bmatrix} V_1(1) & V_2(1) & \cdots & V_N(1) \\ V_1(2) & V_2(2) & \cdots & V_N(2) \\ \vdots & \vdots & \ddots & \vdots \\ V_1(K) & V_2(K) & \cdots & V_N(K) \end{bmatrix}}_{V(K)} \underbrace{\begin{bmatrix} Y_{i1} \\ Y_{i2} \\ \vdots \\ Y_{iN} \end{bmatrix}}_{Y_i} \tag{3}$$

The admittance matrix is then obtained by solving the optimization problem (4).

$$\begin{gathered} \hat{Y}^{K,l_2} \triangleq \arg\min_{Y} \left\| V(K)Y - I(K) \right\|_F \\ s.t.: Y \in S^N, Y_{ii} = -\sum_{j \neq i} Y_{ij} \qquad \forall i = 1, \dots, N \end{gathered} \tag{4}$$

In (4), $I(K)$ is a $K \times N$ matrix representing the K measurements of all N buses of the network, as exemplified in (5).

$$I(K) = \left[I_1(K) \quad I_2(K) \quad \cdots \quad I_N(K) \right] \tag{5}$$

With the admittance matrix estimated through the optimization problem, it is then possible to estimate the line series resistance and reactance of the power system's transmission lines.

III. Case Study

The case study used to implement and test the methodologies previously introduced is based on the IEEE 14-bus test case system, presented in Figure 2. The test case has 14 buses, 5 generators and 11 loads.

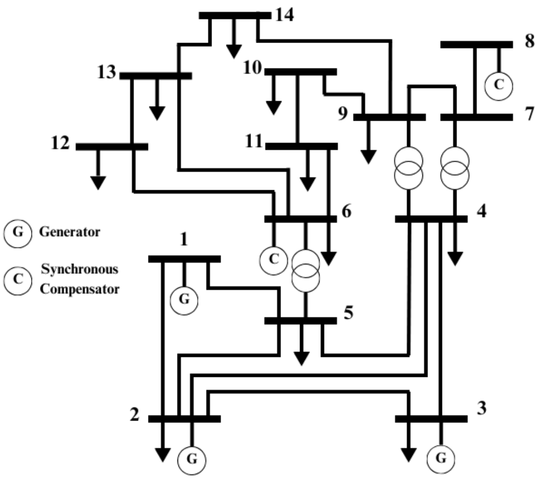

Figure 2. IEEE 14-bus test system.

Bus 1 is the slack bus, buses 2, 3, 6 and 8 are PV buses and the remaining are PQ buses.

Generators 1, 2, and 3 are modelled as voltage sources, and generators 6 and 8 act like synchronous compensators. PMUs are positioned at every system bus.

A time series with a one-hour resolution, totalling 24 hours, is constructed for the loads and generators, aiming to simulate the system's behaviour in a day.

The loads considered in the time series are based on a mixed dataset of hourly load profiles [15], scaled accordingly to better fit the original system data given in [16].

Figure 3 depicts the total active load and generated power of the power system.

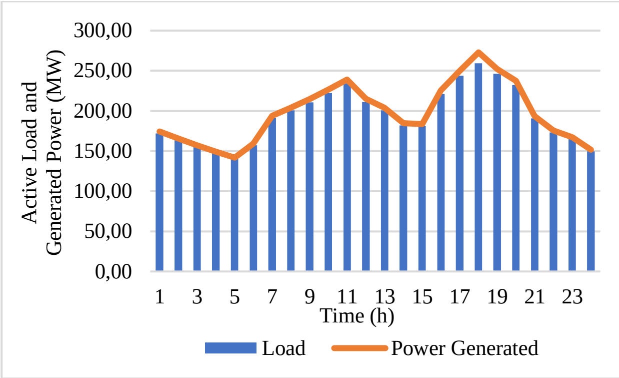

Figure 3. Load curve during the test day.

To simulate the phasors measurements a series of power flows were conducted using Matpower, a package of open-source Matlab-language M-files designed for solving steady-state power system simulations [17]. The Newton method was employed for each case to determine the bus voltages and line current values required for estimating the line parameters. Minor variations in the magnitudes and phases of voltages and currents were intentionally incorporated into the power flow results to emulate errors within the measurement chain.

IV. Results and Discussion

A. *Equivalent π model parameters of a transmission Line*

The lumped parameters for the transmission lines are obtained from the 24-hour time series voltages and line currents derived from the case study by using the equations (1) and (2), previously introduced.

For the sake of simplicity, results are presented for a subset of the transmission lines, 5 out of 20 lines. Tables 1, 2, and 3 present the mean value, relative error, and standard deviation of the series resistance, series reactance, and shunt susceptance, respectively, when compared with the original line parameters of the IEEE 14-bus test system [16].

The variation of the lumped series resistance over time for the line between nodes 1 and 2 is presented in Figure 4, from which is possible to monitor the deviation of the resistance compared with the nominal value.

TABLE 1- LUMPED SERIES RESISTANCES OF SELECTED LINES.

Line	*R* nominal (pu)	*R* estimated (mean value) (pu)	Relative error	Standard Deviation
1-2	0,01938	0,01936	-0,13%	0,0001882
1-5	0,05403	0,05396	-0,12%	0,0005246
2-3	0,04699	0,04693	-0,13%	0,0004562
2-4	0,05869	0,05804	-1,11%	0,0005642
2-5	0,05695	0,05688	-0,13%	0,0005529

TABLE 2- LUMPED SERIES REACTANCES OF SELECTED LINES.

Line	X nominal (pu)	X estimated (mean value) (pu)	Relative error	Standard Deviation
1-2	0,05917	0,05910	-0,13%	0,0005745
1-5	0,22304	0,22276	-0,12%	0,002165566
2-3	0,19797	0,19797	0,00%	5,55112E-17
2-4	0,17632	0,17610	-0,13%	0,001711947
2-5	0,17388	0,17366	-0,13%	0,001688256

TABLE 3- LUMPED SERIES SUSCEPTANCES OF SELECTED LINES.

Line	*B* nominal (pu)	*B* estimated (mean value) (pu)	Relative error	Standard Deviation
1-2	0,0528	0,05287	0,13%	0,0005127
1-5	0,0438	0,04386	0,13%	0,0004253
2-3	0,0374	0,03745	0,13%	0,0003632
2-4	0,0492	0,04927	0,13%	0,0004778
2-5	0,034	0,03405	0,13%	0,0003302

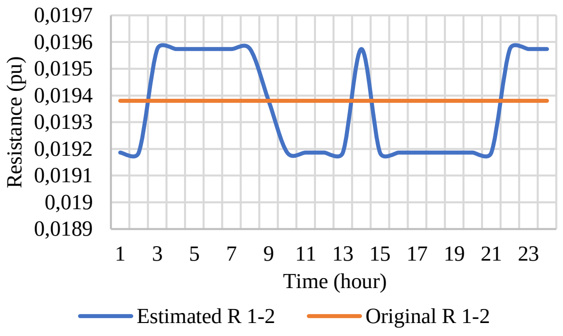

Figure 4. Lumped series resistance of line 1-2 over time.

B. Estimation of the line parameters by admittance matrix identification

From the methodology that infers the nodal admittance matrix based on a set of measurements, it was possible to estimate the values of the series resistance and series reactance of the branches.

Tables 4 and 5 present the estimated series resistances and reactances of some selected lines of the test system.

From the obtained results, it was possible to estimate the series parameters of the lines with an error of minus 1% of the original value, representing a high accuracy. However, in some cases, the accuracy of the method varied, and the most inaccurate data represented a relative error of minus 11% of the nominal value.

TABLE 4. ESTIMATED SERIES RESISTANCES.

Line	Nominal *R* (pu)	Estimated *R* (pu)	Relative error
1-2	0,01938	0,01920	-1%
1-5	0,05403	0,04816	-11%
2-3	0,04699	0,04309	-8%
2-4	0,05869	0,06188	5%
2-5	0,05695	0,05566	-2%

TABLE 5. ESTIMATED SERIES REACTANCES.

Line	Nominal *X* (pu)	Estimated *X* (pu)	Relative error
1-2	0,05917	0,05835	-1%
1-5	0,22304	0,22158	-1%
2-3	0,19797	0,19669	-1%
2-4	0,17632	0,16696	-5%
2-5	0,17388	0,16391	-6%

It should be noted that the shunt parameters estimated by this methodology are not consistent with the expected results. Nevertheless, if the system lines may be considered short, only the resistances and reactances are of interest.

V. CONCLUSION

Precise transmission line parameter values are essential for ensuring the stability and secure operation of the power grid. However, the electrical characteristics of transmission lines that are determined using theoretical formulas derived from the physical dimensions and material properties of the lines do not track the changes of these parameters over time caused, for instance, by environmental conditions and the ageing of the components of the line, which affect the accuracy of real-time system operation and long-term operation applications. From this point of view, it is critical to exploit estimation procedures of the transmission line parameters.

This work outlined two techniques for identifying the parameters of the equivalent π model of transmission lines. The obtained results using a modified IEEE-14 bus test system demonstrate a high degree of accuracy, contingent upon each node in the system being equipped with measurement devices capable of providing phasor measurements of bus voltages and line currents. It is worth noting that the method based on the identification of the admittance matrix fails to estimate the shunt parameters accurately. Further investigation should be performed to enhance the methodology in this regard.

Additionally, it is important to note that not all buses in practical power systems are monitored, and installing PMUs can incur significant costs. Therefore, future research endeavours should focus on exploring techniques capable of estimating line parameters for networks where phasor measurements are not available at every bus.

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