Calculation of Transmission Line Parameters: A real Case Study

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***Abstract*— The accurate transmission line parameters are important in various power system analyses, while potential uncertainty in their values affects the accuracy of control center applications and compromises the selectivity of the protection systems. The transmission line parameters are usually calculated based on manufacturers data, ignoring environmental factors (e.g. ambient temperature) which affect the accuracy of the calculated parameters. Thus, the systematic refinement of the line parameters can be very beneficial for the situational awareness of the power system operators. In this paper, the calculation of the positive sequence parameters of a transmission line of the Cyprus power system through real synchronized phasor measurements is presented. The seasonal variation of the transmission line parameters is analyzed by calculating the parameters during different periods of the year, while the impact of the instrument transformers static error is demonstrated in this real case study.**

Keywords—Instrument transformers, measurement uncertainty, synchronized phasor measurements, transmission line parameters.

I. INTRODUCTION

Transmission line parameters, including resistance, reactance, and susceptance, are used in several critical control center applications [1]. These parameters are usually calculated based on the ideal structure of the transmission line, ignoring several factors (i.e., weather, soil resistivity, coupling between parallel lines, and joints at the ends of the lines) that certainly affect the line parameter values. Consequently, any mismatches between the actual and calculated transmission line parameters directly affect the accuracy of the control center applications, such as the state estimator, power flow analysis and voltage stability analysis. At the same time, the uncertainty compromises the effectiveness of the protection schemes; for instance, impedance relays require exact knowledge of the line parameters for making a correct protection zone identification and tripping decision [1], [2].

It is therefore of great importance to update the transmission line parameters according to the environmental conditions, rather than having constant parameters in the power system models. This is also valid if one considers that the series resistance is dependent on the temperature of the conductor and typically rises as the conductor temperature increases above a standard temperature (usually at 20ºC) [3]. Moreover, series reactance of the Aluminum Conductor Steel Reinforced (ACSR) according to [4] shows an increase of around 20% for a temperature rise from 25ºC to 75ºC.

Several methods have been recently developed for the calculation of the transmission line parameters, which can be classified into offline and online methods. In [5] and [6], methods for calculating offline the line parameters are described. These methods use the geometry of the tower, the geometry and type of the conductor, and constant ambient conditions. In addition, according to [7], the offline methods based on lumped parameter model are not accurate for long-distance transmission lines. Since the environmental conditions vary throughout the year, the line parameters that are calculated through the offline methods might cause serious discrepancies between the actual and the estimated value of the line parameters.

Based on the aforementioned facts, the development of estimation methods, that can obtain line parameters in real-time, is an imperative need. In this attempt, the deployment of synchronized measurement devices, such as Phasor Measurement Units (PMUs), contributes to the correction of any erroneous parameters since PMUs can provide synchronized phasor measurements from both ends of the line [8]. Several methods have been proposed in the literature for taking advantage of online voltage and current measurements [9]-[14]. The authors in [9] developed a method which uses only RMS voltage and power measurements for the estimation of the parameters of a distribution line. Reference [10] proposed a high accuracy estimation method which calculates the positive sequence line parameters during normal operation by utilizing online voltage and current phasors. This method detects and removes faulty measurements, minimizes the impacts of measurement errors and improves the accuracy of the estimation. A method for estimating the parameters of a long line is proposed in [11]. The method estimates the parameters by obtaining the ABCD parameters by using voltage and current phasors from the two ends of the line. Reference [12] presents the estimation of the line parameters using a total least square algorithm. A moving window technique is proposed for using voltage, current, active and reactive power measurements in order to calculate the line parameters of an equivalent pi-model. The line parameters are estimated in [13] based on Laplace transform technique by utilizing three sets of synchronized voltage and current phasors. The authors of [14] proposed a method for estimating the line parameters using phasor measurements provided by only one PMU. The methodology performs well either for a single or for multiple lines. However, the magnitude of the measurement noise might affect the performance of the methodology.

"This work has been supported by the European Union's Horizon 2020 research and innovation programme under grant agreement No 739551 (KIOS CoE) and from the Government of the Republic of Cyprus through the Directorate General for European Programmes, Coordination and Development." "This work was also co-funded by the European Regional Development Fund and the Republic of Cyprus through the Research and Innovation Foundation (Project: INTEGRATED/0916/0035)".

In this paper, the calculation of the positive sequence parameters of the line that connects two important substations (Vasilikos power station and Costas Petrou substation) of the Cyprus power system will be presented. The calculations were carried out for different seasons of the year in order to investigate the seasonality variation of the transmission line parameter values. The calculation of the line parameters is done offline considering the equivalent pi-model, and synchronized voltage and current phasor measurements obtained by PMUs from both ends of the line. The contributions of this paper are: 1) the utilization of multiple real phasor measurements from the PMUs at Vasilikos power station and Costas Petrou substation in order to calculate the line parameters; 2) the demonstration of the impact of the static error of the instrument transformers (ITs) and the necessity to consider it in the process for the calculation of the line parameters, and 3) the investigation of the relationship of the transmission line parameters with environmental and loading conditions.

The rest of the paper is organized as follows. Section II describes the estimation method that is followed in this work, while the calculation of the transmission line parameters is presented in Section III along with the effect of instrument transformers static error on the calculation of the line parameters. Section IV demonstrates two case studies regarding the line parameter calculation and their variation due to environmental and loading conditions. The paper concludes in Section V.

II. ESTIMATION OF TRANSMISSION LINE PARAMETERS

The transmission lines are usually represented in a pi model with lumped series resistance/reactance and shunt susceptance as shown in Fig. 1. In this work, the transmission line that connects Vasilikos and Costas Petrou substations is represented with the equivalent pi-model of a medium length line (Fig. 1). The aim of this work is to calculate the parameters of the pi model based on real time synchronized phasor measurements provided by the two line ends.

Nowadays, PMUs are installed in selected substations (usually in the transmission level) of the power systems. The PMU measurements are transferred to the control center of the power system where they are concentrated by a Phasor Data Concentrator. Since PMUs are GPS synchronized equipment, measurements with the same time stamp can be used for either real time monitoring and control applications or for power system model refinement such as line parameter calculation. Regarding the latter, the measurements with the same time stamp provided by the two PMUs at the two ends of the line can be used to estimate the transmission line parameters. In case some measurements from one of the two ends are missing (there is not a pair of measurements with the same time stamp), the time instances that correspond to the missing measurements are ignored.

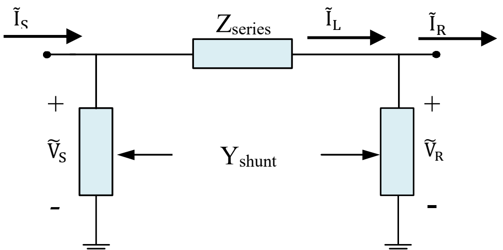

Fig. 1: Equivalent pi-model of a medium length line

According to Fig. 1, the sending and receiving voltage and current phasors can be expressed using the line parameters as,

$$\tilde{I}_L = \tilde{I}_R + \left(\frac{Y}{2}\,\tilde{V}_R\right) \tag{1}$$

$$\tilde{I}_R = \tilde{I}_L - \left(\frac{Y}{2}\,\tilde{V}_R\right) \tag{2}$$

$$\tilde{V}_S = \tilde{V}_R\left(1 + \frac{ZY}{2}\right) - Z\tilde{I}_R \tag{3}$$

$$\tilde{I}_S = \tilde{V}_R\left[Y\left(1 + \frac{ZY}{4}\right)\right] + \tilde{I}_R\left(1 + \frac{ZY}{2}\right) \tag{4}$$

where, $\tilde{V}_S$, $\tilde{V}_R$ are the sending and receiving end voltage phasors and $\tilde{I}_S$, $\tilde{I}_R$ are the sending and receiving end current phasors, respectively. Z and Y are the series impedance and shunt admittances of the equivalent pi-model of the medium line.

The series resistance and reactance, and shunt susceptance, can be obtained through the voltage and current phasors of the sending and receiving end when captured in balanced three-phase conditions. Thus, using (3) and (4), one can obtain the series and shunt susceptance as,

$$Y_{series} = \frac{\tilde{I}_S\tilde{V}_R + \tilde{V}_S\tilde{I}_R}{\tilde{V}_S^2 - \tilde{V}_R^2} = \frac{1}{Z_{series}} = \frac{1}{R+jX} \tag{5}$$

$$Y_{shunt} = \frac{\tilde{I}_S - \tilde{I}_R}{\tilde{V}_S + \tilde{V}_R} \tag{6}$$

In the case that there is a PMU at both ends of the line as shown in Fig. 2, the sending and receiving end voltage and current $\tilde{V}_S, \tilde{V}_R, \tilde{I}_S, \tilde{I}_R$, are available. Therefore, voltage and current phasor measurements can be used in (5) and (6) for the line parameter calculation.

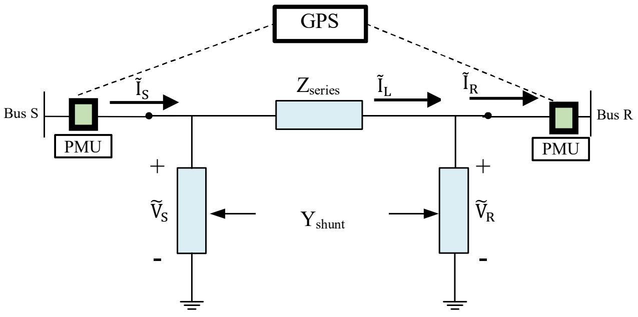

Fig. 2: Two-bus system with PMUs at both ends of the line

III. CALCULATION OF LINE PARAMETERS FOR THE VASILIKOS-COSTAS PETROU TRANSMISSION LINE

The transmission line parameters were calculated with measurements of the installed PMUs in the two substations of the Cyprus power system. The reporting rate of the PMUs is 50 phasors per second, which corresponds to 180000 measurements per hour. Considering that the value of the parameters remains constant within one hour interval the average value of the parameters calculated in one hour (using the 180000 measurements) was used for representing the parameters' value of each hour.

A. Calculation using unprocessed PMU measurements

Initially, for the calculation of the parameters, the measurements were used in equation (5) as they were recorded by the PMUs. Since it is relatively short line (approximately

25 km), only the series resistance and reactance were calculated. It is worth mentioning that the nominal values of the resistance and reactance as calculated by the geometry of the line and the manufacturers data is 1.28 Ω and 13.18 Ω respectively. As it is shown in Fig. 3, the calculated resistance shows a significant deviation compared to the nominal value of the line resistance (1.28 Ω), while the calculated values of the resistance are not correct since the calculated resistance is negative. It should be noted that the phenomenon with the negative resistance is observed to all the dates under examination and not only for the day that is depicted in Fig. 3 (22/01/2019). In the case of the reactance, as depicted in Fig. 4, the calculated values are between acceptable limits and are close to the nominal value (13.18 Ω).

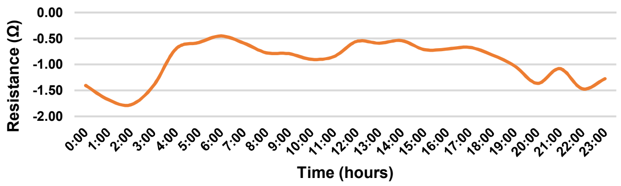

Fig. 3: Calculated resistance with recorded data as they were measured

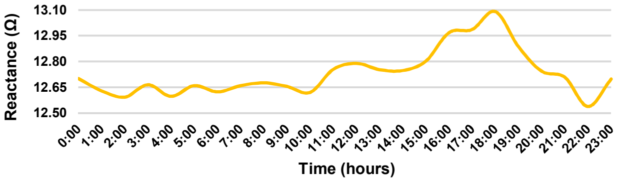

Fig. 4: Calculated reactance with recorded data as they were measured

B. *Calculation of line parameters considering PMU Measurement chain uncertainties*

Although the procedure for calculating the transmission line parameters through the PMU measurements is simple, the quality of the PMU measurements should be always considered in this procedure. As it is indicated in Fig. 5, the instrument transformers (ITs) and PMU are the two main components in a PMU measurement chain that might introduce uncertainties in the PMU measurements. Even though PMUs can be characterized as high accuracy devices, the accuracy of their measurements may be low especially when ITs belong to a low accuracy class [5]. In this sense, the low accuracy of the instrument transformer can deteriorate the quality of the PMU measurements and eventually lead to the calculation of erroneous parameters.

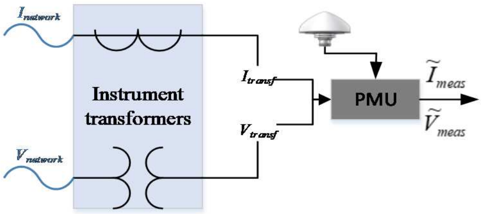

Fig. 5: Generic PMU measurement chain [5]

In this direction, after the calculation of erroneous line resistance, this work was focused on the errors of the voltage and current transformers that are connected to the two PMUs. The manufacturers of the installed voltage and current transformers at the two ends of the line provided data sheets which include routine tests that indicate the static error (magnitude and angle) of each instrument transformer. The current transformers are class PX and are characterized by high accuracy with negligible error, while the static errors of the voltage transformers are shown in Table I.

TABLE I. STATIC ERROR OF THE VOLTAGE TRANSFORMERS AT VASILIKOS POWER STATION AND COSTAS PETROU SUBSTATION

Vasilikos Power Station				**Costas Petrou Substation**		
Phase	***Magnitude (%)***	***Angle (min)***		***Phase***	***Magnitude (%)***	***Angle (min)***
A	+0.19	0.9		A	-0.36	1.8
B	+0.19	1.3		B	-0.36	0.6
C	+0.16	1.1		C	-0.30	1.7

Therefore, in the view of the impact of low accuracy instrument transformer on the resistance calculation, it was decided to add static error in the synchronized voltage phasor measurements of Vasilikos power station and Costas Petrou substation. It should be noted that the static error of the voltage angle is negligible (as shown in Table I) and was omitted. More specifically, the synchronized voltage phasor measurements of each phase from the Vasilikos and Costas Petrou substation were modified as,

$$\tilde{V}_S^m = V_S^{PMU}(1 + e_S^V) \angle (\delta_S^{PMU}) \tag{12}$$

$$\tilde{V}_R^m = V_R^{PMU}(1 + e_R^V) \angle (\delta_R^{PMU}) \tag{13}$$

where $\tilde{V}^m$ is the modified voltage phasor, V^{PMU} and δ^{PMU} are the measured (from PMU) magnitude and angle of the voltage respectively, and e^V is the static error of the voltage magnitude. The S and R subscripts refer to sending and receiving end, respectively.

In Figs. 6 and 7, the calculated resistance and reactance including the above static errors are shown, respectively. Based on these two figures, the calculated resistance is very close to the reference value and the deviation from its nominal value is minimized considerably. Regarding the reactance of the line, it can be concluded that is not affected by the static errors of the voltage transformers as it can be concluded by the comparison of Figs. 4 and 7 (calculated reactance before and after the consideration of the voltage transformers static errors). In this sense, this case study demonstrates through a real-life example that the voltage transformer static error is dominant to the calculation of the line resistance and it should be always considered to the calculation of the line parameters.

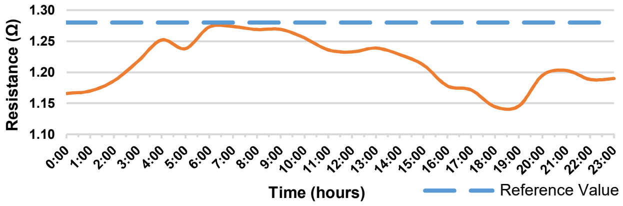

Fig. 6: Calculated resistance including the voltage static error

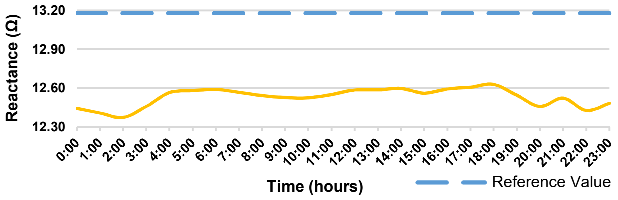

Fig. 7: Calculated reactance including the voltage static error

IV. LINE PARAMETER VARIATION DUE TO ENVIROMENTAL AND OPERATIONAL FACTORS

Based on the modified voltage phasor measurements considering the voltage transformer static error, the variation of the line parameters in different weather (Summer/Winter) and loading conditions (Weekday/Weekend) is investigated in this case study. Specifically, the line parameters were calculated in the following days: 21st of January 2018 (Sunday), 8th of July 2018 (Sunday), 22nd of January 2019 (Tuesday), and 22nd of August 2019 (Thursday) in order to derive any conclusions regarding the variation of the line parameters in different environmental and operational conditions.

A. *Variation of series resistance*

The variation of the series resistance (Ω) in different weather conditions for weekdays and weekends is shown in Figs 8 and 9, while Figs. 10 and 11 depict the variation of the resistance (Ω) in different loading conditions in winter and summer respectively.

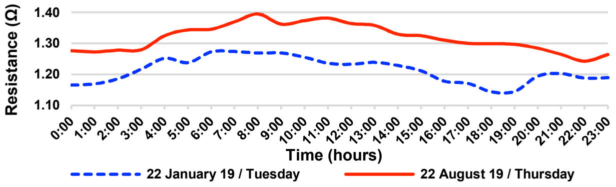

Fig. 8: Comparison of series resistance between different weather conditions for weekdays

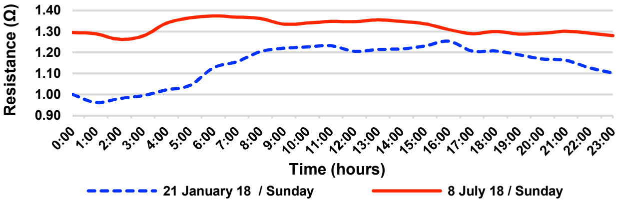

Fig. 9: Comparison of series resistance between different weather conditions for weekends

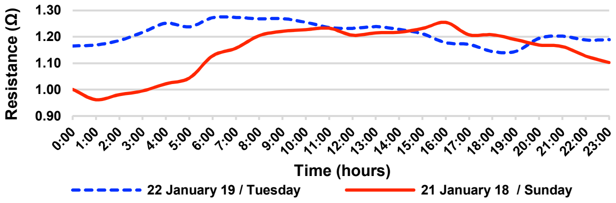

Fig. 10: Comparison of series resistance between different loading conditions in winter

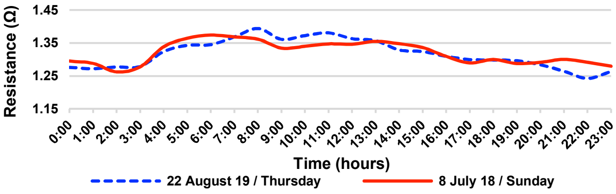

Fig. 11: Comparison of series resistance between different loading conditions in summer

The deviation of the calculated series resistances from the nominal during the day for these cases ranges from 9% to 25%. In addition, as shown in Figs. 8 and 9, during the summer, the value of the series resistance is higher in comparison to the winter periods. This is also verified by (14) in which the resistance varies linearly with respect to the operating temperature. Therefore, as temperature rises, the resistance increases linearly.

$$R = R_f[1 + a(t + \theta)] \tag{14}$$

where, R_f is the resistance at reference temperature, a is the temperature coefficient of resistance per °C, t is the ambient temperature and θ is the difference between the reference and the final temperature.

Moreover, in summer the value of the resistance is very similar either for a weekday (high loading condition) or a day in the weekend (low loading conditions). However, in winter the resistance during the early morning hours for the weekdays is greater than in weekends, and then the value is similar for both cases. This is due to the relatively higher loading conditions in weekday in the morning hours than in the weekend.

B. *Variation of series reactance*

Regarding the series reactance, Figs. 12 and 13 show the variation of the series reactance (Ω) for different weather conditions for weekdays and weekends, respectively. Further, Figs. 14 and 15 show the variation of the series reactance (Ω) for different loading condition in winter and summer, respectively.

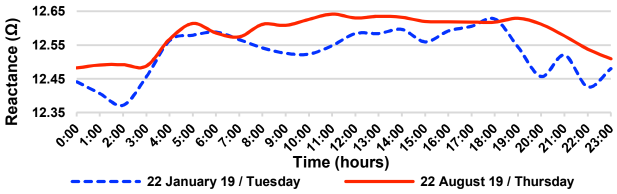

Fig. 12: Comparison of series reactance between different weather conditions for weekdays

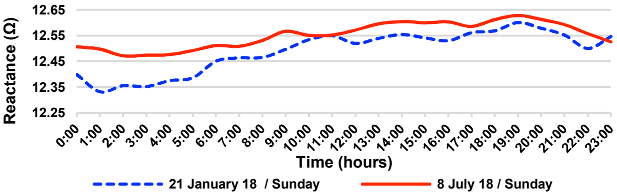

Fig. 13: Comparison of series reactance between different weather conditions for weekends

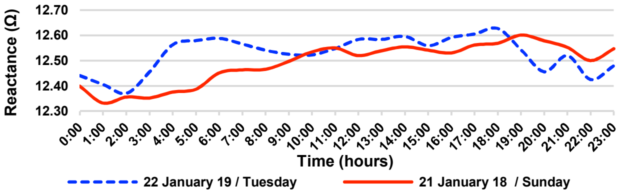

Fig. 14: Comparison of series reactance between different loading conditions in winter

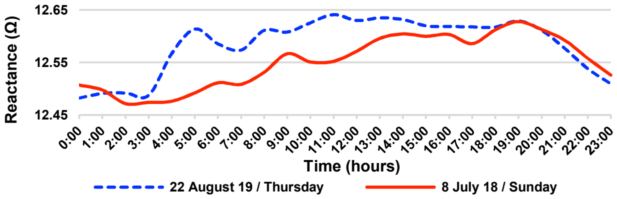

Fig. 15: Comparison of series reactance between different loading conditions in summer

The deviation of the calculated series reactance from the nominal value during the day, for these cases, ranges between 4% to 6.5%. Based on Figs. 12 and 13, the value of the series reactance is a bit larger in summer than in winter. Also, as indicated in Figs. 14 and 15, in weekdays around at 2:00-3:00 am, the value of the reactance has a sharp increase for the whole year, while this is not the case in the weekends.

However, the value of the reactance is not higher in summer due to the temperature increase but it is dependent on the loading condition of the line, and hence on the current of the transmission line (that flows through the line) which is larger in summer than in winter. Moreover, the current flow in weekdays increases sharply in the early morning hours, which affects the reactance's value and as a result shows an increase in the corresponding time.

This is verified in Figs. 16 and 17, in which the daily variation of the reactance is compared to the daily variation of the current measured by the PMUs. In particular, Fig. 16 shows the reactance and the current on July 8, 2018 (Sunday), and there is no sharp increase during the early morning hours. Further to that, the similarity in the variation of the current and reactance is obvious. In Fig. 17, the reactance and the current on January 22, 2019 is shown. In this day, a sharp increase in the value of both reactance and current at around 2:00-3:00 am can be observed, while their shape is quite similar. Moreover, by comparing the current in winter and summer it is obvious that the current has higher values in summer ranging between 225 and 335 Amperes, while in winter the current ranges between 140 and 240 amperes.

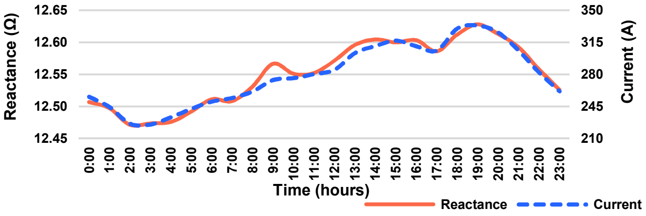

Fig. 16: Form of calculated reactance and measured current for weekend in summer

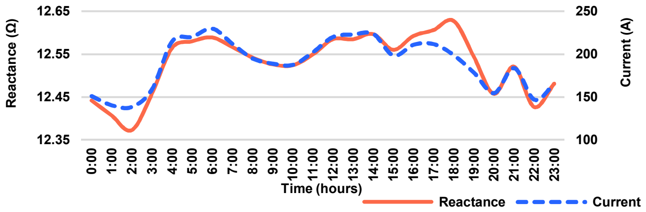

Fig. 17: Form of calculated reactance and measured current for a weekday in winter

V. CONCLUSIONS

In this paper the variation of the parameters in different seasons and operating conditions of the transmission line that connects Vasilikos and Costas Petrou substations is investigated. The value of the resistance depends mainly on the temperature. Actually, as the temperature increases beyond the reference temperature (20°C), the resistance increases accordingly. However, the value of the reactance depends mainly on the loading conditions and more specific to the current flow of the transmission line.

Moreover, it is crucial to include the static error of the instrument transformers in the PMU measurements (especially when the line resistance is calculated). It is indicated in this paper that the calculation of the parameters by using the measurements as they are recorded by the PMUs is compromised. However, the compensation of the static error of the instrument transformers in the PMU measurements results in accurate line parameter calculation.

It should be noted that as a part of the future work, the PMU measurements will be used for the calculation of zero sequence parameters of the line. This can be done by using PMU measurements from time instants that an asymmetric disturbance has occurred in the system.

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