Real-Time Monitoring of Series Compensated Transmission Line Parameters using Practical Synchrophasor Measurements

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ABSTRACT

Reliable operation of power systems requires detailed models of the network during system studies. Transmission line parameters are essential for accurate simulation results as many of power system studies depend upon the precision of transmission line parameters. In this paper, a noise adaptable synchrophasor based real-time parameters monitoring algorithm for a series compensated transmission line is proposed. The algorithm requires positive sequence voltage and current phasors of the sending and the receiving ends as inputs at the phasor measurement unit (PMU) reporting rate. The proposed algorithm can be implemented in real-time monitoring due to its non-requirement of different operating points or input excitation. The accuracy and performances of the algorithm was tested with practical synchrophasor measurements in real-time digital simulator (RTDS™) as well as a hardware experimental setup.

Keywords – Nonlinear least squares, phasor measurement unit (PMU), real-time digital simulator (RTDS), real-time monitoring, series compensated transmission line

1. INTRODUCTION

Accurate transmission line parameters are important for setting protection relays, fault location, state estimation and modeling transmission systems. Most utilities estimate transmission line parameters through the traditional theoretical calculations and offline measurements, however, they do not allow tracking of parameters when they are changing [1]. Since power utilities increase the installation of phasor measurement units (PMUs) at most substations, opportunities arise such as real-time monitoring of transmission line parameters. The phasor values of the voltages and currents measured at two ends of a transmission line with proper time synchronization provide excellent information for identification of its model parameters [2]. Although transmission line parameter estimation using PMU measurements is discussed in several papers, only a few them address the calculation of parameters of a series compensated transmission lines [3]-[6]. All these published approaches require some form of input excitation, that is at least two set of measurements under different operation conditions, to successfully estimate the parameters. Moreover, the algorithms presented in literature have only been validated with simulations.

This paper proposes a new algorithm for monitoring the parameters of a series compensated transmission line in real-time, and validates the performances of the algorithm using practical synchrophasor measurements obtained in the hybrid (software-hardware) PMU model in real-time digital simulator (RTDS™) as well as a laboratory test setup. The proposed algorithm requires positive sequence voltage and current phasors of the sending and the receiving ends as inputs and the solution is based on nonlinear least squares (LS) estimation. The iterative solution procedure involves inversion of a 2×2 non-singular, complex valued matrix in each iteration irrespective of the number of measurements. The initial values of the unknown parameters can be obtained using the theoretical calculations or typical values for the given transmission line configuration. Unlike the previous methods, the solution converges to correct values without input excitation.

The remainder of this paper is organized as follows. In Section 2, the proposed algorithm for estimating parameters of a series compensated transmission line based on synchrophasor measurements is described. Section 3 is devoted to results; it validates the proposed algorithm under different test conditions to confirm its effectiveness with practical synchrophasor measurements. Finally, in Section 4, the key contributions of the paper are highlighted.

2. PROPOSED ALGORITHM

A series compensated transmission line can be represented using cascaded equivalent π-models as shown in Fig. 1.

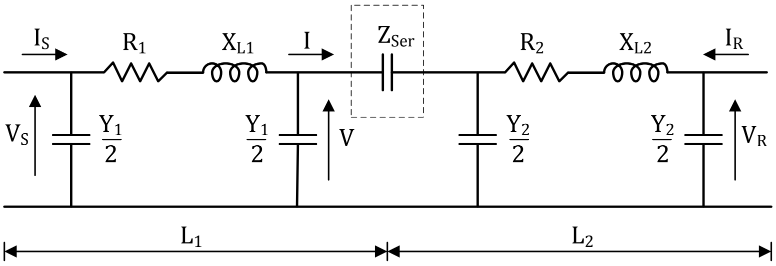

Fig. 1 : The equivalent model of a series compensated transmission line

The series compensator is located at a distance L_1 away from the sending end. The transmission line parameters can be expressed as,

$$Z_1 = R_1 + jX_{L1} = Z_C\sinh(\gamma L_1) \tag{1}$$

$$Z_2 = R_2 + jX_{L2} = Z_C\sinh(\gamma L_2) \tag{2}$$

$$Y_1 = jy_{c1} = \frac{2}{Z_C}\tanh\left(\gamma\frac{L_1}{2}\right) \tag{3}$$

$$Y_2 = jy_{c2} = \frac{2}{Z_C}\tanh\left(\gamma\frac{L_2}{2}\right) \tag{4}$$

Considering the measurement polarities indicated on Fig. 1, expressions can be derived for the transmission line segment left to the compensation device as:

$$V_S = V\cosh(\gamma L_1) + IZ_C\sinh(\gamma L_1) \tag{5}$$

$$I_S = I\cosh(\gamma L_1) + \frac{V}{Z_C}\sinh(\gamma L_1) \tag{6}$$

Similar expressions can be derived for the transmission line segment right to the compensation device as,

$$V - IZ_{Ser} = V_R\cosh(\gamma L_2) - I_R Z_C\sinh(\gamma L_2) \tag{7}$$

$$I = -I_R\cosh(\gamma L_2) + \frac{V_R}{Z_C}\sinh(\gamma L_2) \tag{8}$$

where $Z_{Ser} = -jX_{Ser}$ and X_{Ser} depends upon the degree of compensation $k = X_{Ser}/X_L$. The series compensator can be switched either fully or partially on, or it can be completely bypassed.

By eliminating V and I from (5)-(8), two equations can be obtained as:

$$f_1 = V_S - \left(V_R - \frac{I_R Z_{Ser}}{2}\right)\cosh(\gamma L) - \left(\frac{V_R Z_{Ser}}{2Z_C} - I_R Z_C\right)\sinh(\gamma L)$$

$$+\frac{I_R Z_{Ser}}{2}\cosh(\gamma L') + \frac{V_R Z_{Ser}}{2Z_C}\sinh(\gamma L') = 0 \tag{9}$$

$$f_2 = I_S - \left(\frac{V_R Z_{Ser}}{2{Z_C}^2} - I_R\right)\cosh(\gamma L) - \left(\frac{V_R}{Z_C} - \frac{I_R Z_{Ser}}{2Z_C}\right)\sinh(\gamma L)$$

$$+\frac{V_R Z_{Ser}}{2{Z_C}^2}\cosh(\gamma L') + \frac{I_R Z_{Ser}}{2Z_C}\sinh(\gamma L') = 0 \tag{10}$$

where $L = L_1 + L_2$ and $L' = L_1 - L_2$. Two nonlinear, complex equations (9) and (10) are functions of the measurements (V_S, V_R, I_S and I_R) and the unknown transmission line parameters (Z_C and γ). Considering N measurements sets collected from PMUs, a set of equations can be written in matrix form as:

$$[F] = \begin{bmatrix} {f_1}^{(1)}(V_s,\ V_R,\ I_s,\ I_R,\ Z_C,\gamma) \\ {f_2}^{(1)}(V_s,\ V_R,\ I_s,\ I_R,\ Z_C,\gamma) \\ : \\ : \\ {f_1}^{(N)}(V_s,\ V_R,\ I_s,\ I_R,\ Z_C,\gamma) \\ {f_2}^{(N)}(V_s,\ V_R,\ I_s,\ I_R,\ Z_C,\gamma) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ : \\ : \\ 0 \\ 0 \end{bmatrix} \tag{11}$$

The set of nonlinear equations in (11) can be solved with the aid of nonlinear LS method. The solution is obtained through an iterative process based on the Newton method as following. First, the matrix $[H]$ is defined as:

$$[H] = \begin{bmatrix} \frac{\partial {f_1}^{(1)}}{\partial Z_C} & \frac{\partial {f_2}^{(1)}}{\partial Z_C} & \cdot\cdot & \cdot\cdot & \frac{\partial {f_1}^{(N)}}{\partial Z_C} & \frac{\partial {f_2}^{(N)}}{\partial Z_C} \\ \frac{\partial {f_1}^{(1)}}{\partial \gamma} & \frac{\partial {f_2}^{(1)}}{\partial \gamma} & \cdot\cdot & \cdot\cdot & \frac{\partial {f_1}^{(N)}}{\partial \gamma} & \frac{\partial {f_2}^{(N)}}{\partial \gamma} \end{bmatrix}^T \tag{12}$$

The derivatives for the matrix $[H]$ in (12) are given as:

$$\frac{\partial f_1}{\partial Z_C} = \left(\frac{V_R Z_{Ser}}{2{Z_C}^2} + I_R\right)\sinh(\gamma L) - \frac{V_R Z_{Ser}}{2{Z_C}^2}\sinh(\gamma L') \tag{13}$$

$$\frac{\partial f_1}{\partial \gamma} = L\left(\frac{I_R Z_{Ser}}{2} - V_R\right)\sinh(\gamma L) - L\left(\frac{V_R Z_{Ser}}{2Z_C} - I_R Z_C\right)\cosh(\gamma L)$$

$$+L'\frac{I_R Z_{Ser}}{2}\sinh(\gamma L') + L'\frac{V_R Z_{Ser}}{2Z_C}\cosh(\gamma L') \tag{14}$$

$$\frac{\partial f_2}{\partial Z_C} = \frac{V_R Z_{Ser}}{{Z_C}^3}\cosh(\gamma L) + \left(\frac{V_R}{{Z_C}^2} - \frac{I_R Z_{Ser}}{2{Z_C}^2}\right)\sinh(\gamma L) - \frac{V_R Z_{Ser}}{{Z_C}^3}\cosh(\gamma L') - \frac{I_R Z_{Ser}}{{Z_C}^2}\sinh(\gamma L') \tag{15}$$

$$\frac{\partial f_2}{\partial \gamma} = L\left(I_R - \frac{V_R Z_{Ser}}{2{Z_C}^2}\right)\sinh(\gamma L) - L\left(\frac{V_R}{Z_C} - \frac{I_R Z_{Ser}}{2Z_C}\right)\cosh(\gamma L)$$

$$+L'\frac{V_R Z_{Ser}}{2{Z_C}^2}\sinh(\gamma L') + L'\frac{I_R Z_{Ser}}{2Z_C}\cosh(\gamma L') \tag{16}$$

The vector $[\Psi]$ is defined as:

$$[\Psi] = [Z_C \quad \gamma]^T \tag{17}$$

Starting from an initial guess, $[\Psi]$ can be updated iteratively. The N^{th} update is obtained as,

$$[\Psi]^{(p+1)} = [\Psi]^{(p)} + [\Delta\Psi]^{(p)} \tag{18}$$

where $[\Delta\Psi] = -([H]^T[H])^{-1}[H]^T[F]$. The matrix $[H]^T[H]$ is a 2×2, non-singular, complex-valued, symmetrical matrix irrespective of the number of measurements and therefore, its inverse can easily be calculated regardless of the number of measurements sets. The iteration process is terminated when the variable update reaches within a specified tolerance. Once Z_C and γ are known, final transmission line parameters of the equivalent π-model of the transmission line can be obtained:

$$R = \mathrm{Real}\big(Z_C \sinh(\gamma L)\big) \tag{19}$$

$$X_L = \mathrm{Imag}\big(Z_C \sinh(\gamma L)\big) \tag{20}$$

$$y_c = 2 \times \mathrm{Imag}\left(\frac{\tanh(\gamma L/2)}{Z_C}\right) \tag{21}$$

Algorithm can be easily modified to estimate the parameters when the series compensator is completely bypassed or the parameters of an uncompensated transmission line by substituting $Z_{Ser} = 0$ in (9) and (10).

As real-time synchrophasor measurements are used to estimate the line parameters, the data window is advanced with each PMU reporting. It is assumed that both the sending and the receiving end PMUs ensure the same reporting rate. The proposed algorithm treats parameters constant during the data window. The estimated transmission line parameters are updated each time a new PMU measurement set is reported.

3. RESULTS AND DISCUSSION

The performance of the proposed algorithm was validated using a power system simulated in a RTDS real-time simulator as well as using a hardware experimental setup.

3.1. RTDS Simulations

A simplified power system with a series compensated transmission line is shown in Fig. 2. It was assumed that PMUs are installed at two ends of the transmission line as indicated in Fig. 2. The transmission line is operated at 230 kV and has a length of 220 km, and transfers 600 MW under base case conditions. The series compensator was located at 154 km from the sending end with 50% compensation. The power system was simulated in a RTDS real-time simulator and the distributed parameter transmission line model (Bergeron) available in the RTDS simulator was used to represent the transmission line under study. The RTDS transmission line module calculates the theoretical values of line parameters from the conductor data and the line geometry [7]. This detailed model considers the distributed nature of parameters, mutual coupling between phases and travel times. The synchrophasor measurements required as inputs were obtained through the M-class PMU model available in the RTDS simulator [8], at a reporting rate of 60 frames/s. The positive sequence voltage and current phasors of the sending and the receiving ends were fed to the proposed algorithm, which was implemented in the RTDS. The output of the algorithm is the estimates of transmission line series resistance, series inductive reactance and shunt capacitive susceptance. A data window of 15 synchrophasor measurements was used for estimation. Estimations obtained under different conditions are compared with the theoretical values given by the RTDS transmission line model in Table I.

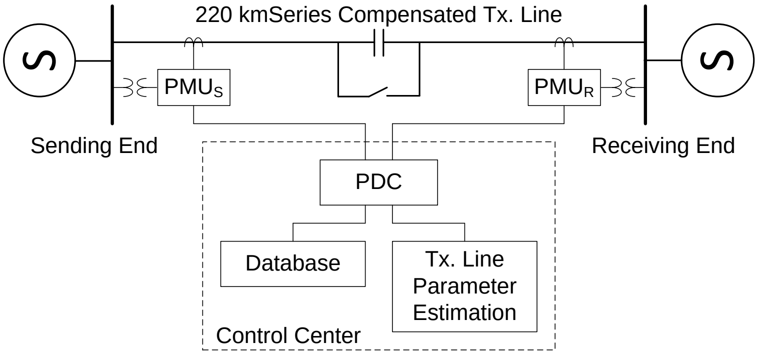

Fig. 2 : Simplified power system with a series compensated transmission line

3.1.1. *Transmission line parameters under ideal conditions*

The transmission line parameters were estimated under ideal conditions, where the transmission line was ideally transposed and the PMU measurements are noise free. The estimated parameters are shown in Table I. According to the results, the proposed algorithm performs very well under ideal conditions. The estimated errors are less than 1.5% for all parameters compared to the theoretical values. The algorithm always converges within 8 iterations under noise free conditions.

Table I: Comparison of parameters of the series compensated transmission line

	R		$\mathrm{X_L}$		$\mathrm{y_c}$	
	Value (Ω)	Error (%)	Value (Ω)	Error (%)	Value (S)	Error (%)
Theoretical	11.64	--	116.40	--	6.898×10^{-4}	--
Ideal condition	11.54	0.86	114.87	1.32	6.946×10^{-4}	0.69
Transposed unbalanced	11.53	0.89	114.87	1.32	6.945×10^{-4}	0.69
Non-transposed unbalanced	11.86	1.87	114.58	1.56	6.963×10^{-4}	0.95

3.1.2. *Effect of the degree of compensation*

The proposed algorithm was tested under different degrees of compensation. According to the variations of the estimation errors are shown in Fig. 3, performance is not affected by the degree of compensation.

3.1.3. *Effect of the location of series compensator*

In this experiment, the location of the series compensator was varied from sending end to receiving end. The percentage estimation errors for R, $\mathrm{X_L}$, and $\mathrm{y_c}$ are shown in Fig. 4. The errors of resistance estimation seemed to slightly increase when the series compensator is close to an end of the line, but the errors remained below 1.5% for all cases. Generally, the algorithm is not affected by the location of series compensator.

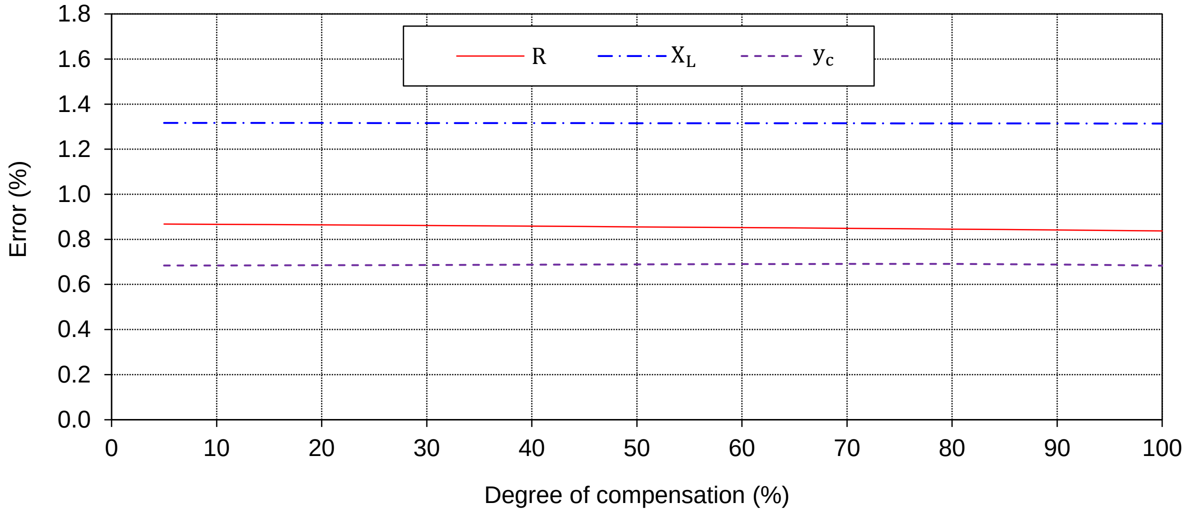

Fig. 3 Variations of errors with the degree of compensation

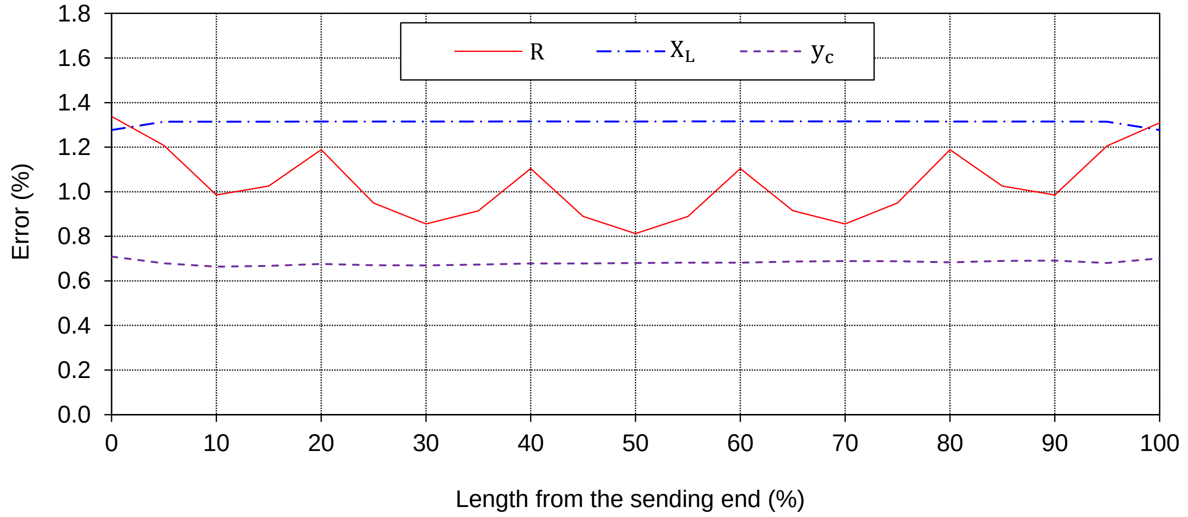

Fig. 4. Variations of the errors with the location of the series compensator

3.1.4. Effect of unbalance

The parameter estimation algorithm was developed based on the per-phase equivalent model of a transmission line, where balanced three-phase voltages and currents are implicitly assumed. However, in practice power systems are not ideally balanced. In order to test the performance of the algorithm under an unbalanced condition, unbalanced loads were introduced to the simulated power system. The estimated transmission line parameters are compared with the theoretical values in Table I. The estimated errors are less than 1.5% even under the unbalanced conditions. Voltage and current unbalance had minimal effect because the positive sequence phasor measurements were used in the calculations.

Long transmission lines are usually transposed but there are cases where transmission lines are not transposed. The impact of unbalanced currents is higher when a transmission line is not transposed.

Thus, the previous simulation experiment was repeated with a non-transposed line model, and the estimated transmission line parameters are also compared with the theoretical values in Table I. Even for this case, the estimated parameters have an error less than 2%.

3.1.5. Parameter estimation under noisy conditions

Phasor estimation itself is a filtering process and the anti-aliasing filters as well as additional backend performance class filters [9] in PMUs provide good immunity against the high frequency noise in measured signals. However, it is impossible to completely eliminate the effect of noise in practice. The performance of the proposed algorithms under noisy conditions was evaluated by adding a zero mean Gaussian noise to the input voltage and current waveforms before they are fed into the PMU models. The accuracy of synchrophasor measurements is expressed in terms of total vector error (TVE) [9]. Tests showed that with this type of noise, signal-to-noise ratios (SNRs) lower than 30 dB can result in TVEs exceeding 1%, which is the acceptable limit under most steady-state and dynamic conditions [9].

Random fluctuations in the estimated values become higher with increasing noise levels (decreasing SNR). The maximum estimation errors observed under different noise levels during a period of 10 seconds are shown in Fig. 5. Careful examination of the results show that (i) estimations of X_L is least affected by the noise, (ii) estimation errors of R and y_c start to quickly increase when SNRs drop below 40 dB. It was also observed that the proposed algorithm did not converge for some data points when SNRs drop below 20 dB. The algorithm was programmed to stop after 12 iterations and report the output, thus the maximum errors are high for such cases. Occasional non-convergence and larger error under extremely high noise (SNR < 20 dB) is a drawback of the proposed algorithm.

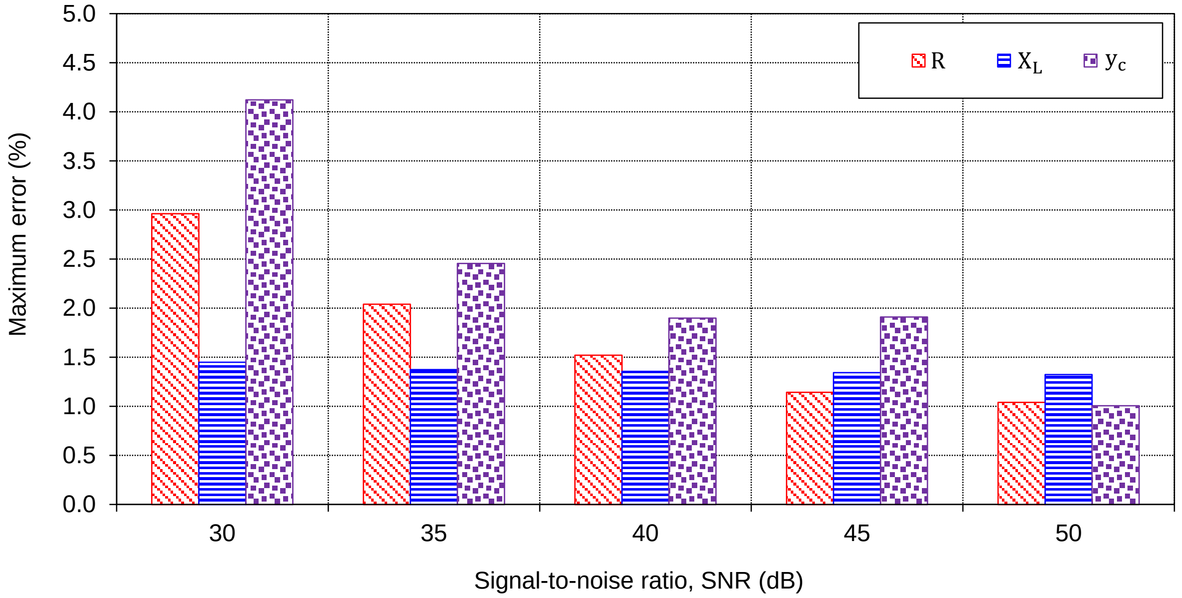

Fig. 5 Maximum errors under different noise levels

3.1.6. Data window length

If PMU measurements are totally noise free then a single set of measurements is enough to estimate transmission line parameters. However, practical measurements are contaminated with noise from various sources and therefore, use of several measurements can help to increase the accuracy of parameters estimations. For example, the variation of line resistance R estimated with a single measurement is compared with that estimated using 15 measurements (data window size, w = 15) when the SNR = 35 dB in Fig. 6.

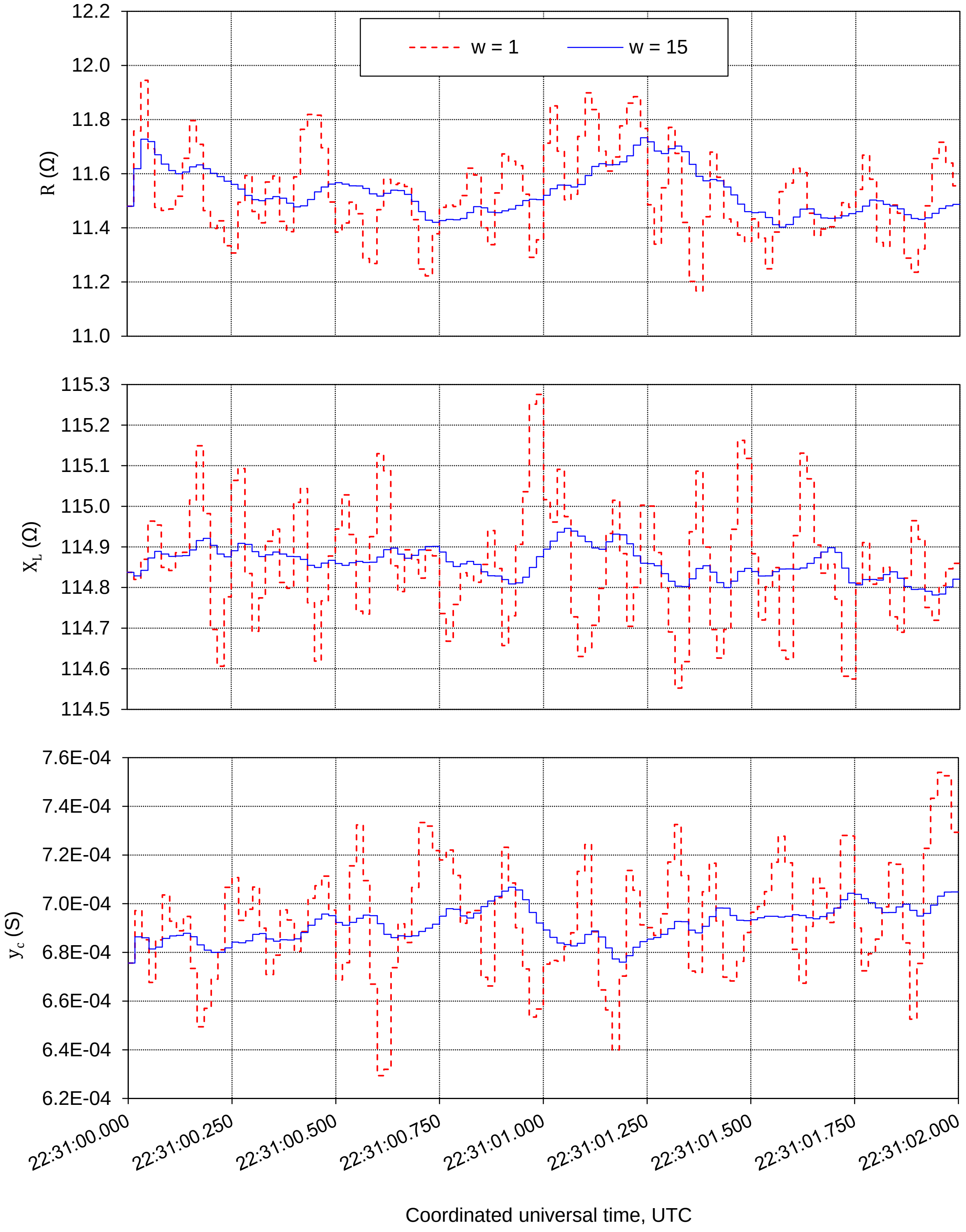

Fig. 6 Line parameters with different data window lengths (SNR = 35 dB)

The fluctuations and the maximum error in the estimated parameters are higher with the single dataset compared to the estimated parameters with 15 datasets. Increasing window lengths reduce the maximum error in estimated transmission line parameters, but these reductions become insignificant for data window lengths above 15 as seen in Fig. 7, when the SNR in input analog signals is around 35 dB.

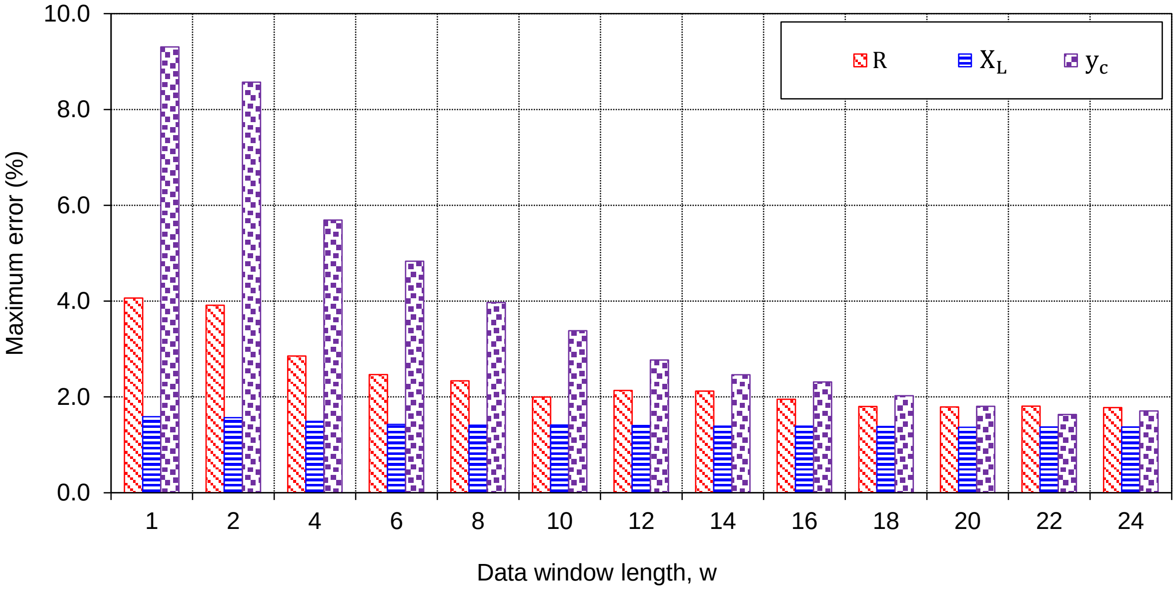

Fig. 7 Maximum error at different data window lengths (SNR = 35 dB)

3.2. Experimental Setup

This aim of this experiment is to validate the proposed algorithm under practical measurements. It should be noted that usefulness of field measurements for validations is limited, because the actual parameters of a transmission line cannot be established without specialized offline tests. The arrangement of the experimental setup is shown in Fig. 8.

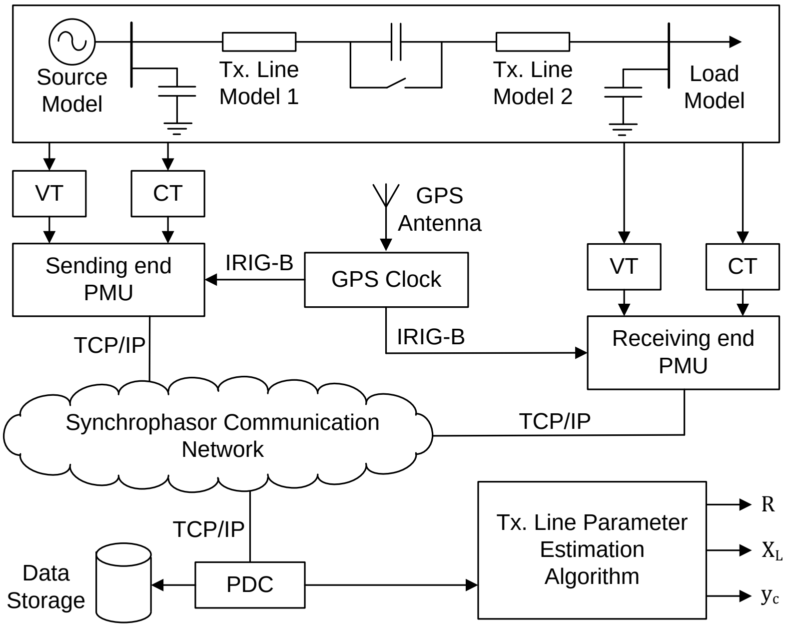

Fig. 8 Experimental setup

Two transmission line modules of a LabVolt^{TM} power system test bench [10] augmented with shunt capacitances and a series capacitance were used to create a three-phase series compensated transmission line model similar to one shown in Fig. 1. The three-phase source and load modules of the same test bench were connected to sending and receiving ends of π-networks respectively. The voltage and current signals at two ends of the transmission line are fed to two ERLPhase™ TESLA 4000 recorders with PMU capability through instrument voltage and current transformers [11]. A SEL-2407 GPS clock [12] provided inter-range instrumentation group time code format B (IRIG-B) signal to PMUs. The PMUs in TESLA 4000 were configured to report synchrophasors at 60 frames/s to openPDC™ v2.0 [13] phasor data concentrator (PDC) through a TCP/IP network. The PDC, which aligns the data according to the time tags, provided data to the transmission line parameter estimation algorithms. Similar to the simulations based study, a data window of 15 reportings was used.

The estimations obtained under different conditions are compared with the direct measurements obtained for the LabVolt transmission line modules given in Table II. The degree of compensation is 33%. The transmission line parameters are estimated under balanced and unbalanced conditions (obtained using unbalanced loads) are also provided in Table II.

Table II: Comparison of parameters for the experimental transmission line setup

	R		$\mathrm{X_L}$		$\mathrm{y_c}$	
	Value (Ω)	Error (%)	Value (Ω)	Error (%)	Value (S)	Error (%)
Direct measurements	9.2	--	120.0	--	10.25×10^{-4}	--
Balanced condition	9.5	2.93	118.6	1.16	10.90×10^{-4}	6.32
Unbalanced condition	9.6	4.67	118.6	1.16	10.87×10^{-4}	6.03

The estimation errors for R and $\mathrm{X_L}$ are below 3%; however, $\mathrm{y_c}$ is slightly high about 6%. Furthermore, it is observed that the error of R increases under unbalanced conditions whereas errors of $\mathrm{X_L}$ and $\mathrm{y_c}$ remain in the same order. It should be noted that the LabVolt transmission line model uses iron-core reactors, and the slight waveform distortions due to core saturation, although minimized, contribute to increase the estimation errors.

4. CONCLUSION

Synchrophasor measurements based real-time line parameters monitoring algorithm for a series compensated transmission line were proposed. The iterative, nonlinear LS-based algorithm requires inversion of a 2×2 complex-valued matrix in each iteration irrespective of the number of measurements. It requires voltage and current phasors of the sending and the receiving ends of the transmission line and the estimated line parameters are updated with each PMU reporting. It has ability of estimating line parameters of a series compensated transmission line without input excitation. The accuracy of the proposed algorithm is evaluated through a series of simulation and laboratory experiments. The test results demonstrated the effectiveness of the algorithm under different degrees of compensation, varying the location of the series compensator, and various noise conditions.

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