A closed-form solution to Estimate Parameters of Three-terminal Hybrid Transmission Lines

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***Abstract*—Accurate transmission line parameter values are essential to set the line protection relay applications. The existing parameter estimation methods for three-terminal hybrid lines require multiple measurement sets and employ iterative techniques to solve non-linear equations. Implementation of such methods requires high computation burden, and it is difficult to implement in protection relays. To mitigate these challenges, we proposed a closed-form solution for parameter estimation in three-terminal hybrid transmission lines using two sets of terminal voltage and current measurements recorded at 1 percent power difference. Nonlinear equations are formed by equating junction voltages calculated from two terminals. The hyperbolic terms present in nonlinear equations are replaced with corresponding Taylor's expansion to arrive at a closed-loop form. Line parameters are directly calculated using the closed-loop equation. The proposed method is verified with lines at three different voltage levels connecting conventional systems and inverter based renewable resources simulated in PSCAD/EMTDC and found to be accurate.**

***Index Terms*—parameter estimation, noniterative, three-terminal line, closed-loop solution**

I. Introduction

Parameter estimation deals with estimating the right-now parameters usually resistance, inductance, and capacitance of transmission lines (and cables) using voltage and current measurements at the terminals. The results of the many power system applications including protection application are depends on the accuracy of the line parameters. It is possible to calculate the parameters from the geometric configuration of the line, however, the physical configuration (spacing between conductors) tends to vary with age and ambient factors, and this leads to erroneous parameter calculation. Most protection and fault location applications require proper parameter settings. As per the NERC report [1], most of the relay failures contribute the incorrect settings due to erroneous parameters. Therefore, there is a need for accurate and simple parameter estimation to improve the reliability of protection applications. Parameter estimation for two terminal lines is presented in [2]–[6]. In [2], the Telegrapher's equations are approximated by Fourier and Bernstein polynomials to obtain an objective function. This objective function is then optimized using the DIRECT algorithm. The estimation error by this method is within acceptable limits and quite robust to measurement noise, load change and small levels of measurement un-synchronization. Reference [3] proposed a looped state estimation and parameter tracking method using weighted least squares and Kalman filter. Verification results from simulation and practical data indicated that this approach is capable of accurately tracking dynamically varying parameters. Reference [4] employed the equivalent Pi model to obtain a set of simultaneous non-linear equations which are then solved using the least squares solver to obtain the parameters. The initial guess to the numerical method solver is calculated by using the nominal Pi model. The method is verified on a diverse range of simulated and practical systems and proved to be very accurate. A very innovative method is proposed in [5] which used the distributed model equations of line and obtained a closed-form equation. With at least two snapshots of measurement phasors, a set of linear equations are formed which are solved by ordinary least squares method to obtain the parameters. Another method is proposed in [6]. Equations from the long line equivalent model are solved strategically to obtain a closed-form equation to estimate the parameters of two-terminal lines using only one snapshot of measurement. The method is tested on both simulated data and practical data and proved to be accurate.

Three-terminal lines pose economic and environmental benefits which has driven the increase in the number of such lines across the globe. Especially three-terminal hybrid lines are used to connect large industrial consumers, large solar farms located geographically close to a transmission line and offshore wind farms. CIGRE Report [7] presents statistics of three-terminal lines being commissioned. All the above-discussed methods proposed for two-terminal line parameter estimation cannot be used to estimate the parameters of a three-terminal hybrid line. This is because additional parameter values need to be determined and infeed/outfeed is present at the junction. Hence a separate class of methods is needed for parameter estimation in three-terminal hybrid lines. Many papers in the literature focus on fault section identification and fault location in three-terminal lines. Few notable papers [8]–[12] present estimating the parameters of the line before or along with fault section identification and fault location. In [8] KCL and KVL are applied on the Equivalent Pi model circuit to obtain nonlinear equations and solved employing numerical methods. Parameters are obtained upon solving these equations. Nonlinear equations from pre-fault, positive and negative sequence circuits were obtained and solved using Newton-Raphson method in [9]. Along with parameters, fault section and fault location are estimated. The method is tested to be robust to measurement noise and small levels of un-synchronization. A similar method considering equations from pre-fault circuit of the line is found in [10]. In [11], parameter are estimatied in a scenario where PMUs are present on 2 end of the main line and RTU is present on the tapped line. Nonlinear equations were formulated and solved by Nonlinear Weighted Least Squares for parameters. The method is tested on data from software and hardware simulation. The estimation errors are close to zero assuring good performance. Very recently in [12] an algorithm where a set of simultaneous non-linear equations from the pre-fault circuit of the three-terminal hybrid line are solved using least squares estimation proposed. The impedance parameters of the line are calculated and supplied as an initial guess to the estimation algorithm. The method is proved accurate after being tested on a diverse range of simulated data and practical data. From the literature, it can be concluded that, the existing parameter estimation methods for three-terminal hybrid lines requires initial guess and iterative techniques to solve non-linear equations. Implementation of such methods in protection relays requires high computational hardware. Therefore, there is a requirement of closed-form parameter estimation which can be implemented in existing relay platforms.

This paper proposes a novel algorithm to estimate the parameters of three terminal hybrid lines requiring two sets of pre-fault measurement data from all terminals of the line only. From the distributed model equations of the main line, a bi-quadratic equation is derived and solved to obtain four sets of parameters of the main line. Certain plausibility conditions are employed to choose the correct parameter set. Using the estimated parameters of the main line, the junction voltage and currents are calculated. Current flowing from the junction into the tapped line is calculated by applying KCL at the junction. Tapped line parameters are calculated using estimated junction voltage and currents and measured voltage and current at the tapped line as proposed in [6]. This process does not require any iterative or initial guess to estimate the parameters of three-terminal hybrid line. Section II presents the numerical methodology of the proposed algorithm. Section III presents a workflow illustration of the algorithm, algorithm verification on different systems and the effect of measurement noise. Section IV concludes this paper.

II. Numerical Methodology

This section presents a closed-form algorithm to estimate the parameters of a three-terminal hybrid line. Consider a three-terminal hybrid line depicted in Fig. 1 consisting of a main line of length l_{MN} from terminal M and terminal N and a tapped line of length l_{PJ} having different parameters. The length of section MJ is l_{MJ} and that of section NJ is l_{NJ}. The propagation constant (γ_{MN}) and characteristic impedance (Z_{cMN}) of line MN are estimated first and then the propagation constant (γ_{PJ}) and characteristic impedance (Z_{cPJ}) of tapped line PJ are estimated later. In Fig. 1, the

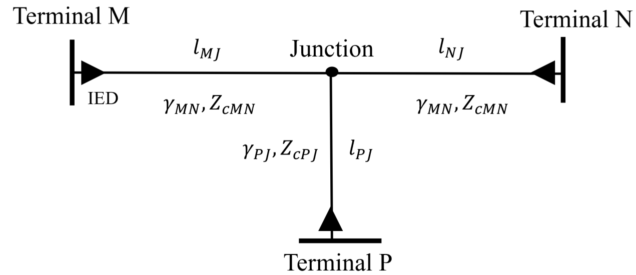

Fig. 1. Depiction of Three terminal hybrid line

junction voltage (V_{JM}) and current flowing from junction J to terminal M (I_{JM}) estimated from terminal M using the distributed transmission line model are defined in (1) and (2) respectively.

$$V_{JM} = V_M cosh(\gamma_{MN} l_{MJ}) - I_M Z_{cMN} sinh(\gamma_{MN} l_{MJ}) \tag{1}$$

$$I_{JM} = \frac{V_M}{Z_{cMN}} sinh(\gamma_{MN} l_{MJ}) - I_M cosh(\gamma_{MN} l_{MJ}) \tag{2}$$

Similarly, the junction voltage (V_{JN}) and current flowing from junction J to terminal N (I_{JN}), estimated from terminal N are given by (3) and (4) respectively.

$$V_{JN} = V_N cosh(\gamma_{MN} l_{NJ}) - I_N Z_{cMN} sinh(\gamma_{MN} l_{NJ}) \tag{3}$$

$$I_{JN} = \frac{V_N}{Z_{cMN}} sinh(\gamma_{MN} l_{NJ}) - I_N cosh(\gamma_{MN} l_{NJ}) \tag{4}$$

The junction voltage (V_{JP}) and current flowing from junction J to terminal P (I_{JP}), estimated from terminal P are given by (5) and (6) respectively.

$$V_{JP} = V_P cosh(\gamma_{PJ} l_{PJ}) - I_P Z_{cPJ} sinh(\gamma_{PJ} l_{PJ}) \tag{5}$$

$$I_{JP} = \frac{V_P}{Z_{cPJ}} sinh(\gamma_{PJ} l_{PJ}) - I_P cosh(\gamma_{PJ} l_{PJ}) \tag{6}$$

By equating the junction voltage estimated from terminal M and terminal N we get (7).

$$Z_{cMN} = \frac{V_M^I cosh(\gamma_{MN} l_{MN}) - V_N^I cosh(\gamma_{MN} l_{MN})}{I_M^I sinh(\gamma_{MN} l_{MN}) - I_N^I sinh(\gamma_{MN} l_{MN})} \tag{7}$$

Equation (7) has two unknown variables to solve for. To obtain a unique solution, another equation is required. From a 2$^{\text{nd}}$ set of measurements an equation similar to (7) could be obtained as in (8). Superscript - I denote measurement set 1 and Superscript - II denotes measurement set 2.

$$Z_{cMN} = \frac{V_M^{II} cosh(\gamma_{MN} l_{MN}) - V_N^{II} cosh(\gamma_{MN} l_{MN})}{I_M^{II} sinh(\gamma_{MN} l_{MN}) - I_N^{II} sinh(\gamma_{MN} l_{MN})} \tag{8}$$

Taking a closer look at the hyperbolic trigonometric terms – $cosh()$ and $sinh()$ in both the equations, they are infinitely differentiable in both $\mathbb{R}$ (real) domain and $\mathbb{C}$ (complex) domain and satisfy the necessary and sufficient conditions for generating Taylor Series Expansion [13]. The general form of their respective Taylor Series is defined in (9).

$$cosh(x) = 1 + \frac{x^2}{2!} + \frac{x^4}{4!} + ... \\ sinh(x) = x + \frac{x^3}{3!} + \frac{x^5}{5!} + ... \quad (9)$$

In this particular application, the argument of the $cosh(.)$ and $sinh(.)$ is small. Thus with good accuracy, the higher-order terms of the series can be ignored. On substituting (9) after truncation and with further simplification, we get (10)

$$\gamma_{MN} Z_{cMN} = \frac{\gamma_{MN}^2 (\frac{V_M l_{MJ}^2}{2} - \frac{V_N l_{NJ}^2}{2}) + (V_M - V_N)}{\gamma_{MN}^2 (\frac{I_M l_{MJ}^2}{6} - \frac{I_N l_{NJ}^2}{6}) + (I_M l_{MJ} - I_N l_{MJ})} \quad (10)$$

The term on the left side of (10) and (8) is the series impedance of the line which can be assumed to be constant for all loading conditions. Now, the left-hand sides of the equations are equal which allows us to equate the right-hand sides of the same. This results in (11).

$$\frac{\gamma_{MN} a_1^2 + b_1}{\gamma_{MN} c_1^2 + d_1} = \frac{\gamma_{MN} a_2^2 + b_2}{\gamma_{MN} c_2^2 + d_2} \quad (11)$$

Where,

$$\begin{aligned} a_1 &= (\frac{V_M^I l_{MJ}^2}{2} - \frac{V_N^I l_{NJ}^2}{2}) & a_2 &= (\frac{V_M^I I l_{MJ}^2}{2} - \frac{V_N^I I l_{NJ}^2}{2}) \\ b_1 &= (V_M^I - V_N^I) & b_2 &= (V_M^I I - V_N^I I) \\ c_1 &= (\frac{I_M^I l_{MJ}^2}{6} - \frac{I_N^I l_{NJ}^2}{6}) & c_2 &= (\frac{I_M^I I l_{MJ}^2}{6} - \frac{I_N^I I l_{NJ}^2}{6}) \\ d_1 &= (I_M^I l_{MJ} - I_N^I l_{NJ}) & d_2 &= (I_M^I I l_{MJ} - I_N^I I l_{NJ}) \end{aligned} \quad (12)$$

Rearranging (11), a bi-quadratic equation in γ_{MN} is obtained.

$$(a_1 c_2 - a_2 c_1)\gamma_{MN}^4 + (a_1 d_2 + b_1 c_2 - a_2 d_1 - b_2 c_1)\gamma_{MN}^2 \\ +(b_1 d_2 - b_2 d_1) = 0 \quad (13)$$

Solving (13) we get four solutions for γ_{MN}. Substituting the four values of γ_{MN} in (7), we get four values of Z_{cMN}. To choose the correct set of γ_{MN} and Z_{cMN}, the absolute difference between the junction voltage estimated from terminals M and N defined in (14) are calculated for each of the options.

$$error = |V_M cosh(\gamma_{MN} l_{MJ}) - I_M Z_{cMN} sinh(\gamma_{MN} l_{MJ}) \\ -V_N cosh(\gamma_{MN} l_{NJ}) + I_N Z_{cMN} sinh(\gamma_{MN} l_{NJ})| \quad (14)$$

Along with (14), the technically trivial conditions (15) and (16) from [9] are considered while choosing the apt set of γ_{MN} and Z_{cMN}.

$$real(\gamma_{MN}^2) < 0 \quad \& \quad imag(\gamma_{MN}^2) > 0 \quad (15)$$

$$real(Z_{cMN}^2) > 0 \quad \& \quad imag(Z_{cMN}^2) < 0 \quad (16)$$

With estimated parameters of line MN, the junction voltage (V_{JP}) and current flowing from junction to terminal P (I_{JP}) can be estimated using (5) and (6) respectively. From this information and terminal P measurements, the parameters of tapped line PJ can be estimated using the closed loop solution proposed in [6].

III. Results and Discussion

The proposed closed-loop algorithm for parameter estimation is applied on three-terminal hybrid line systems at different voltage levels and also on systems where Inverter Based Resource (IBR) - wind and solar are connected to the existing grid via three-terminal hybrid lines to project the generality of the proposed method (PM). Such systems are simulated in PSCAD/EMTDC environment employing frequency-dependent models for modelling transmission lines and cables to be more realistic. Terminal voltage and current signals are sampled at 1kHz and recorded in COMTRADE99 format. Phasors which are given as input to the parameter estimation algorithm are estimated using full cycle Discrete Fourier Transform.

A. Illustrative Case - Extra high voltage 400kV system

Consider a 400kV, 50Hz extra high voltage system of 3 conventional generators directly feeding power to busses M, N and P connected by a main overhead line of length 250km and an underground cable of length 15km. The main line is tapped at a distance of 100km from Bus M at J by the underground cable. This makes the length of section MJ to be 100km, and that of section NJ to be 150km. The system looks similar to the depiction in Fig. 1. The underground tapped line is 15km long (section PJ). Usually, the disturbance recorded by a protection IED is triggered by a fault event. The proposed algorithm in this paper requires only the pre-fault phasors estimated using samples before the fault event. The estimated phasors are input to the algorithm and a closed-form bi-quadratic equation similar to (13) is obtained and solved. The solutions γ_{MNi} to $(i = 1, 2, 3, 4)$ are tabulated in Table I along with corresponding Z_{cMNi} and error-index value calculated from (14).

It can be seen that the all obtained solutions satisfy the plausibility criteria defined in (14). However, only the highlighted solution satisfies the conditions in (15),(16) and hence is chosen as the correct parameters of line MN. The junction voltage V_J is calculated from the average of (1) and (3) and the current from junction into the tapped line is calculated from (6) using the chosen(highlighted) parameter values from Table I. Now, using the closed-form solution for estimating the parameters of a two-terminal line proposed in [6], the propagation constant (γ_{PJ}) and characteristic impedance (Z_{cPJ}) of section PJ are calculated and tabulated in Table I.The estimated R(Ω), X(Ω) and B(S) of the main line and the tapped cable are calculated

TABLE I
ILLUSTRATION - MATHEMATICALLY POSSIBLE SETS OF PARAMETERS

i	γ_{MNi}	Z_{cMNi}	Error	γ_{PJ}	Z_{cPJ}
1	$7.7809e^{-7} + 1.6643e^{-5}\ i$	$-2.9025e^{3} + 5.0471e^{2}\ i$	39.2744	$7.1614e^{-7} + 4.0193e^{-6}i$	$47.2014 - 8.0214\ i$
2	$-7.7809e^{-7} - 1.6643e^{-5}\ i$	$2.9025e^{3} - 5.0471e^{2}\ i$	39.2744		
3	$\mathbf{1.1894e^{-7} + 1.2082e^{-6} i}$	$\mathbf{2.0894e^{2} - 2.0913e^{1}\ i}$	**39.2414**		
4	$-1.1894e^{-7} - 1.2082e^{-6}\ i$	$-2.0894e^{2} + 2.0913e^{1}\ i$	39.2414		

TABLE II
ILLUSTRATION - ESTIMATED PARAMETERS USING PROPOSED METHOD

Method	Main Line			Tapped Line		
	$R(\Omega)$	$X(\Omega)$	$B(S)$	$R(\Omega)$	$X(\Omega)$	$B(S)$
Actual	5	25	$5.71e^{-4}$	0.99	2.76	$13e^{-4}$
PM	5.01	24.99	$5.78e^{-4}$	0.99	2.76	$13e^{-4}$

TABLE III
ESTIMATED PARAMETERS OF EXTRA HIGH VOLTAGE 765KV, 50HZ SYSTEM

	Main Line			Tapped Line		
Method	$R(\Omega)$	$X(\Omega)$	$B(S)$	$R(\Omega)$	$X(\Omega)$	$B(S)$
Actual	17.49	87.5	0.002	1.66	4.60	0.0022
PM	17.49	87.57	0.002	1.58	4.66	0.0022

TABLE IV
ESTIMATED PARAMETERS OF HIGH VOLTAGE 220KV, 50HZ SYSTEM

	Main Line			Tapped Line		
Method	$R(\Omega)$	$X(\Omega)$	$B(S)$	$R(\Omega)$	$X(\Omega)$	$B(S)$
Actual	1.22	19.08	$2.96e^{-4}$	0.66	1.84	$8.71e^{-4}$
PM	1.23	19.09	$2.89e^{-4}$	0.65	1.85	$8.72e^{-4}$

TABLE V
ESTIMATED PARAMETERS OF IBR CONNECTED LINE - CASE 1

	Main Line			Tapped Line		
Method	$R(\Omega)$	$X(\Omega)$	$B(S)$	$R(\Omega)$	$X(\Omega)$	$B(S)$
Actual	1.50	26.11	$4.07e^{-4}$	0.33	2.10	$16.17e^{-4}$
PM	1.51	26.10	$4.07e^{-4}$	0.31	2.10	$16.15e^{-4}$

using the generalized formula (17) and tabulated in Table II along with their corresponding actual values.

$$Z = R + iX = (\gamma Z_c)l$$
$$Y = jB = \frac{\gamma}{Z_c} \tag{17}$$

The maximum error among the estimated values of resistance(R), inductive reactance(X) and capacitive susceptance (B) is 1.22%.

B. Extra high voltage 765kV system

A 765kV three-terminal transmission line that has an overhead main line 500km long and an overhead tapped line with parameters different from the main line 25km long is simulated in PSCAD/EMTDC. The length of section MJ is 350km and that of section NJ is 150km. The proposed method is verified to estimate the parameters of this system whose estimation results are tabulated in Table III along with actual values. The estimations are numerically close to the actual values.

C. High Voltage 220kV system

A 220kV, 50Hz three-terminal transmission line having 120km overhead main line and 10km underground tapped cable is simulated in PSCAD/EMTEDC. The length of section MJ is 90km and that of section NJ is 30km. The parameters estimated by the proposed method are presented in Table IV along with the actual values. The estimates are close to the actual values and the errors are within 2.5%.

D. Three terminal hybrid lines connecting renewable sources

The previous subsections discussed applying the algorithm to three terminal hybrid lines at high and extra-high voltage levels that connect conventional generators. Apart from conventional generators, several renewable resources are integrated with the grid all over the globe and this is predicted as the future of power grids. The proposed algorithm is applied to 2 such systems taken for analysis and the results of such application are presented in this section.

1) Case 1 - Line connecting a wind farm to conventional grid : A main overhead line 120km long connects two conventional generators as part of a power grid. A Type-IV wind farm is connected to this grid section via an underground cable 20km long as shown in Fig. 2. This is eventually a three-terminal hybrid line. This scenario is simulated in PSCAD/EMTDC environment similar to all the other case studies presented in previous sections. The details of the wind turbine model are explained in [12]. The parameters of such a line connecting such a setup are estimated using the proposed algorithm and presented in Table V along with the actual values. The estimations are close to the actual values and the errors are less than 1%.

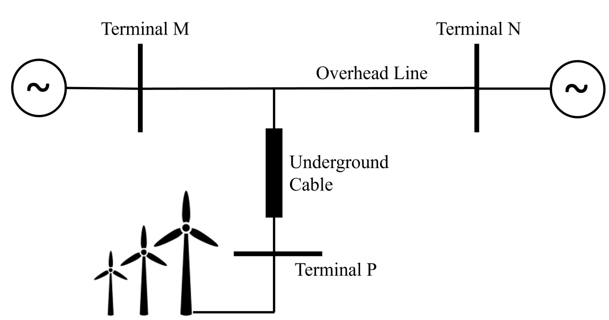

Fig. 2. Type-IV wind farm connected to conventional grid

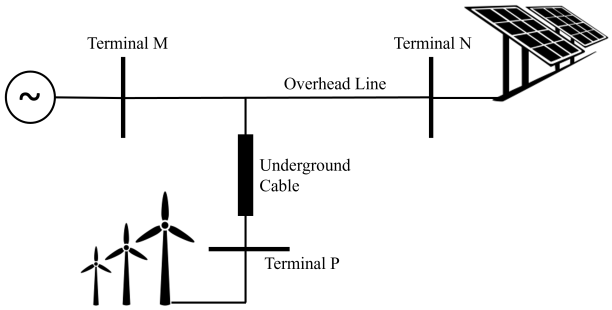

Fig. 3. Type-IV wind farm and solar farm connected to conventional generator

TABLE VI
ESTIMATED PARAMETERS OF IBR CONNECTED LINE - CASE 2

	Main Line			Tapped Line		
Method	$R(\Omega)$	$X(\Omega)$	$B(S)$	$R(\Omega)$	$X(\Omega)$	$B(S)$
Actual	1.50	26.11	$4.07e^{-4}$	0.33	2.10	$16.17e^{-4}$
PM	1.52	26.10	$4.28e^{-4}$	0.36	2.09	$15.85e^{-4}$

2) Three terminal hybrid lines connecting two renewable sources with a conventional generator: A three-terminal hybrid line which connects two renewable sources with a conventional generator is a futuristic system that is worth testing the proposed algorithm. An overhead head main line 120km long connects a solar farm with a conventional generator. An underground tapped line 20km long connects a wind farm to the main line as shown in Fig. 3. The parameter values estimated by the algorithm are tabulated in Table VI. The estimates are numerically close to the actual values and the maximum error obtained is 5% on capacitance of the main line.

The above analyses project the generality of the proposed algorithm in estimating line parameters irrespective of the power source connected by the line.

E. Effect of measurement noise

The effect of noise in measurements on the performance of the proposed method is presented in this section and tested on all the 3 conventional systems discussed in the previous subsection. Both Voltage and current measurements are corrupted with 5% and 10% noise. Table VII, Table VIII and Table IX present the estimated parameter values with noisy measurements given as input to the algorithm. It can be seen that the proposed algorithm is robust to measurement error when both voltage and current are corrupted by the same amount. This is attributed to (11) where the error in voltage and the error in current are nullified during estimating γ_{MN}.

IV. CONCLUSION

A closed-loop solution for estimating the parameters of a three-terminal hybrid line using two sets of terminal voltage and current measurements recorded at different power levels is presented in this paper. The proposed method is tested on three

TABLE VII
EFFECT OF NOISE ON PARAMETER ESTIMATION - VALIDATION SYSTEM 1 - 400KV, 50HZ

	Main Line			Tapped Line		
Noise Level	$R(\Omega)$	$X(\Omega)$	$B(S)$	$R(\Omega)$	$X(\Omega)$	$B(S)$
Actual	5	25	$5.71e^{-4}$	0.99	2.76	$13e^{-4}$
PM - 5%	5.01	24.99	$5.78e^{-4}$	0.99	2.76	$13e^{-4}$
PM - 10%	5.01	24.99	$5.78e^{-4}$	0.99	2.76	$13e^{-4}$

TABLE VIII
EFFECT OF NOISE ON PARAMETER ESTIMATION - VALIDATION SYSTEM 2 - 765KV, 50HZ

	Main Line			Tapped Line		
Noise Level	$R(\Omega)$	$X(\Omega)$	$B(S)$	$R(\Omega)$	$X(\Omega)$	$B(S)$
Actual	17.49	87.5	0.002	1.66	4.60	0.0022
PM - 5%	17.49	87.57	0.002	1.58	4.66	0.0022
PM - 10%	17.49	87.57	0.002	1.58	4.66	0.0022

TABLE IX
EFFECT OF NOISE ON PARAMETER ESTIMATION - VALIDATION SYSTEM 3 - 220KV, 50HZ

	Main Line			Tapped Line		
Noise Level	$R(\Omega)$	$X(\Omega)$	$B(S)$	$R(\Omega)$	$X(\Omega)$	$B(S)$
Actual	1.22	19.08	$2.96e^{-4}$	0.66	1.84	$8.71e^{-4}$
PM - 5%	1.23	19.09	$2.89e^{-4}$	0.65	1.85	$8.72e^{-4}$
PM - 10%	1.23	19.09	$2.89e^{-4}$	0.65	1.85	$8.72e^{-4}$

systems at different voltage levels with different line lengths connected with conventional and inverter based renewable sources. The estimated parameters are compared with the actual parameters, and it is found that the error is less than 2% and this accuracy is enough for relay application settings. The method is also tested with IBR connected systems and the performance of the method is not affected. The effect of measurement noise is also analysed, and the performance is satisfactory. The proposed method is simple in calculation and it can be implemented in existing relay platforms.

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