Fault Location for Series Compensated Lines Eliminating Parameters as a Setting

Penta Rithisha
Student Intern
Hitachi Energy
Bangalore, India
juhi-sri-sai-lakshmi.rithisha-penta@hitachienergy.com

O. D. Naidu
Senior Principal Scientist
Hitachi Energy
Bangalore, India
od.naidu@hitachienergy.com

Nandiraju Venkata Srikanth
Professor
NIT Warangal
Warangal, India
nvs@nitw.ac.in

2024 IEEE PES Innovative Smart Grid Technologies - Asia (ISGT Asia) | 979-8-3503-7392-9/24/$31.00 ©2024 IEEE | DOI: 10.1109/ISGTAsia61245.2024.10876364

***Abstract*— Unlike protection applications, precise fault locator requires accurate line parameters which are not constant over the time as a result of aging and environmental impact on conductors. Traditional fault location approaches for series compensated lines are dependent on the prior knowledge of line electrical parameters, percentage and type of compensation. However, non-linear characteristics of Metal Oxide Varistor (MOV) during fault makes the task of fault location more complex. In order to address these, a setting free fault location methodology for series compensated lines using synchronized data is proposed which is independent of MOV characteristics. The fault location algorithm is phasor-based and parameters are estimated using Dommel's time domain equations. Estimation of parameters requires computation of propagation constant which is obtained using first two travelling wave peak arrival times of arial mode component of both end fault currents. Wavelet transform technique is used to extract the travelling waves. The proposed method is independent of the percentage, type, location of the compensation and MOV characteristics. The proposed method is verified using data simulated in PSCAD/EMTDC tools. The proposed method is tested for different fault scenarios and performance is found to be accurate.**

Keywords—Series compensation, fault location, time domain, perameter estimation

I. INTRODUCTION

Traditional approaches like helicopter or drone patrolling and manual line search are tedious methods to locate the transmission line faults. Therefore, accurate estimation of fault location is essential to quickly restore the faulty line which minimizes the time of power interruption and financial loss for utilities [1].

To accommodate the increased demand for power, large-scale generating stations must be developed. Bulk power must also be transferred over long distances to the load centers from the generation resources, which is a capital-intensive process. Therefore, series compensation plays a major role to utilize the existing transmission assets to maximum extent without increasing the cost of the power delivered [2]. Series compensation is a well-established technology for improving the system voltage by placing a series capacitor in series with the transmission line. This is majorly installed in high voltage lines due to its advantages like, increase in power transfer capability, system stability improvement, optimize power sharing between parallel lines and improves voltage profile. Many series compensated lines are installed in various utilities [2]. Since the series compensated lines are spread across few hundreds of kilometers, precise fault location estimation is essential for sending the maintenance team to the locate permanent fault and facilitating a prompt restoration of the power supply. Due to non-linear characteristics of MOV, fault location for series compensated lines is challenging [3] and the source of errors are the appearance of such characteristics in fault loop and uncertainty in MOV parameters [4].

Existing literature for estimation of fault location is diverged in different categories namely instantaneous time based [5]-[6], travelling wave-based [7]-[12], impedance-based techniques [4],[13]-[20]. Time domain-based algorithms utilizes instantaneous voltage and current samples to compute unknown fault location. The algorithm [5] computes two fault locations, one for the faults before the series compensator and other for the faults after the series compensator. A special procedure is used to determine the correct solution for fault location. Although, the method is not dependent on fault resistance and source impedance, it demands for prior knowledge of series compensation parameters. An improved time domain method is proposed in [6] which is independent of location and parameters of the compensator device. It is well known that travelling wave approaches yield accurate results irrespective of the type of network. Taking this advantage into consideration, prominent work has been carried out using travelling wave methodologies for fault location estimation on series compensated lines. Due to the significance gained by wavelet transform in recent times, single ended travelling wave-based fault location techniques are proposed in [7]-[9]. However, in reference [8] placement of the fault locator is considered near the series compensator to improve accuracy which may not be practically economical. Although single ended travelling wave methods are simple, they pose difficulty in distinguishing the arrival times, if emerged from fault point or other end bus.

Due to the availability of both local and remote end measurements, double ended travelling wave methods using synchronized [10]-[11] and unsynchronized measurements [12] are proposed. Since the impedance-based algorithms are economically efficient approaches due to low hardware cost [2], they are widely used traditionally. Impedance-based algorithms demands estimation of phasors that attenuates the noise and

979-8-3503-7392-9/24/$31.00 ©2024 IEEE

harmonics present in measurements which allows the fault location estimates immune to effect of noise and harmonics [13]. Series compensated lines poses challenge for impedance-based fault location algorithms due to involvement of MOV during fault scenarios and in turn introduces non-linear impedance of series compensation. Reference [4], [14] deals with the estimation of fault location considering SC and MOV equivalented as current dependent resistance and reactance. However, these methods do not consider the shunt capacitance of the line, aging and temperature effect on MOV. To avoid limitations with MOV model, [15] uses natural fault loops to obtain the fault location results. Unlike the preexisting algorithms, in [16] a technique is proposed that does not depend on MOV status whether conducting, idle or bypassed. Optimization based algorithms that consider data synchronization effect are proposed in [17]-[18]. In [17], a cuckoo search-based optimization algorithm is proposed, but it requires prior knowledge of SCL parameters. Dynamic Differential Optimizer based optimization algorithm using π-equivalent model of transmission line is proposed in [18] which is independent of MOV characteristics. Although robust, accuracy of the optimization methods is dependent on the initial guess. However, all the discussed techniques [4]-[18] are not parameter free and their accuracy is subjected to line parameters. PMU based fault location algorithm which is completely adaptive is proposed in [19] where SCL parameters and system Thevenin's equivalent are determined online. However, the method requires three independent sets of pre-fault measurements. Reference [20] presents fault location algorithm for SCL that does not rely on the line parameters, but it is only designed for line to ground fault type and demands prior knowledge of series capacitor value. Reference [21] discusses a method for parameter estimation for series compensated lines using time-domain data of both ends of the line and utilises first two travelling wave arrival times generated during disturbance from fault point i.e., difference between arrival times of first incident wave and first reflection from the fault point is utilized to estimate propagation constant of the line. However, the method is iterative and the two arrival times at a bus must emerge or reflect from the fault point but not from the other end bus. In some scenarios like close faults, the initial reflection from fault point can be greater than third arrival time which is not always practically possible to capture. Therefore, there is a need for a reliable setting-free fault location methodology for series compensated lines.

In this paper, a setting free phasor-based fault location methodology is proposed where parameters are estimated in time domain approach. The proposed method requires computation of propagation constant which is obtained using first two travelling wave peak arrival times of arial mode component of both end fault currents. Travelling wave is extracted using wavelet transform technique. Inductance and capacitance are then computed using time domain Dommel's lossless equation followed by computation of resistance using time domain Dommel's lossy equation. The fault location is computed using the estimated line parameters along with voltage and current phasors. The proposed method is independent of the percentage as well as type of compensation, value of series capacitor and MOV characteristics. The proposed method is validated using laboratory experimental data and is found to be accurate.

II. PROPOSED METHOD

In this section, mathematical derivation for the important steps and the implementation methodology are discussed.

A. Computation of Propagation Constant

Depending on the type of fault, travelling wave is extracted from arial mode component of both end currents using wavelet transform signal processing technique. Daubechies 2 (db2) is one of the types of wavelets known for extracting closely spaced features for power system applications, hence considered as the mother wavelet. Firstly, fault section is determined using [22] to identify if the fault is before the series capacitor or after the series capacitor. Then, the propagation velocity is computed as given below depending on the fault section.

1) Fault before the series capacitor: If the fault is before the series capacitor as shown in the lattice diagram Fig.1 where 'd' is the fault location from Bus R and l_{RS} is total length of the line, propagation velocity 'v' can be computed as follows,

$$t_{R1} = t_0 + \frac{d}{v};\ t_{R2} = t_0 + \frac{3d}{\vartheta} \tag{1}$$

$$t_{S1} = t_0 + \frac{l_{RS} - d}{v};t_{S2} = t_0 + \frac{l_{RS} + d}{\vartheta} \tag{2}$$

Using (1) and (2) propagation velocity can be computed as,

$$v = \frac{l_{RS}}{t_{S2} - t_{R1}} \tag{3}$$

Where, t_{R1} and t_{R2} are the arrival times of first two traveling waves measured at Bus R; t_{S1} and t_{S2} are the arrival times of first two traveling waves measured at Bus S and t_0 is the fault inception time.

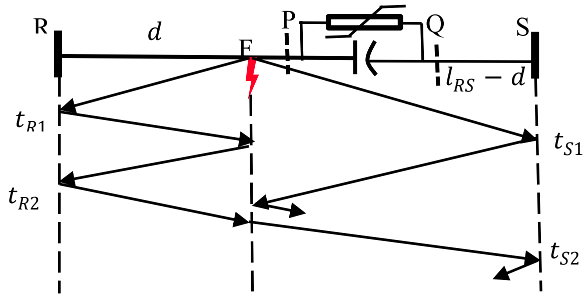

Fig. 1. Lattice diagram for fault before series compensator.

2) Fault after the series capacitor: If the fault is located after the series capacitor as shown in the lattice diagram Fig. 2 where the fault location from Bus S is $(l_{RS} - d)$, propagation velocity can be computed as follows,

$$t_{R1} = t_0 + \frac{d}{v};\ t_{R2} = t_0 + \frac{2l_{RS} - d}{v} \tag{4}$$

$$t_{S1} = t_0 + \frac{l_{RS} - d}{v}\ ;t_{S2} = t_0 + \frac{3(l_{RS} - d)}{v} \tag{5}$$

Using (4) and (5) propagation velocity can be computed as,

$$v = \frac{l_{RS}}{t_{R2} - t_{S1}} \tag{6}$$

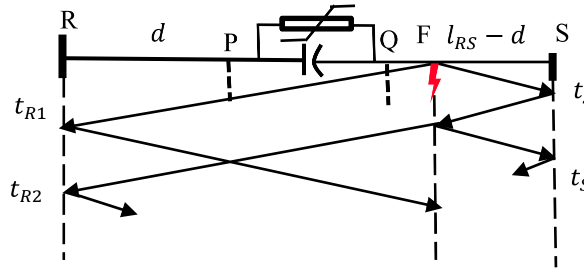

Fig. 2. Lattice diagram for fault after series compensator.

Final propagation velocity (v_f) can be given as follows,

$$v_f = \frac{v}{k} \tag{7}$$

where k is the dispersion constant which is included in the formulation of the method due to dispersion effect phenomenon in travelling waves [23]. In this method, wavelet technique is employed, and k is found out to be 1.02 from experimental analysis.

Propagation constant (τ_{RS}) is computed as,

$$\tau_{RS} = \frac{l_{RS}}{v_f} \tag{8}$$

l_{RP} represents the total transmission line length before series compensator and l_{SQ} represents the line length after the series compensator. The propagation constant for the sections RP (τ_{RP}) and SQ (τ_{SQ}) are given as follows,

$$\tau_{RP} = \tau_{RS} * \frac{l_{RP}}{l_{RS}};\ \tau_{SQ} = \tau_{RS} * \frac{l_{SQ}}{l_{RS}} \tag{9}$$

Mathematical methodology for the estimation of line parameters is discussed in the next section.

B. Parameter Estimation

A closed loop solution for the estimation of line parameters using Dommel's time domain equations is discussed in this section. Depending on the type of fault, arial mode components of currents and voltages are considered for the analysis. Current at point P, at time instant 't' as shown in Fig. 3, $i_{P,t}$ is obtained using Dommel's lossless equation having Bus R voltage and current. Similarly, current at point Q at time instant 't' is obtained using Bus S voltage and current. During no fault, sum of the currents at point P and Q is zero [21].

$$i_{P,t} + i_{Q,t} = 0 \tag{10}$$

$$i_{P,t} = \frac{\left(V_{R,t+\tau_{RP}} - Z_c\, i_{R,t+\tau_{RP}}\right) - \left(V_{R,t-\tau_{RP}} + Z_c\, i_{R,t-\tau_{RP}}\right)}{2Z_c} \tag{11}$$

$$i_{Q,t} = \frac{\left(V_{S,t+\tau_{SQ}} - Z_c\, i_{S,t+\tau_{SQ}}\right) - \left(V_{S,t-\tau_{SQ}} + Z_c\, i_{S,t-\tau_{SQ}}\right)}{2Z_c} \tag{12}$$

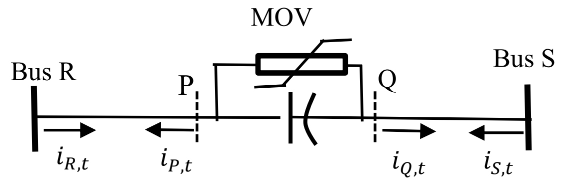

Fig. 3. Representation of series compensated line.

where,

$V_{R,t+\tau_{RP}}, V_{R,t-\tau_{RP}}$ – Bus R arial mode component of voltage at time instant $t + \tau_{RP}$ and $t - \tau_{RP}$ respectively

$i_{R,t+\tau_{RP}}, i_{R,t-\tau_{RP}}$ – Bus R arial mode component of current at time instant $t + \tau_{RP}$ and $t - \tau_{RP}$ respectively

$V_{S,t+\tau_{SQ}}, V_{S,t-\tau_{SQ}}$ – Bus S arial mode component of voltage at time instant $t + \tau_{SQ}$ and $t - \tau_{SQ}$ respectively

$i_{S,t+\tau_{SQ}}, i_{S,t-\tau_{SQ}}$ – Bus S arial mode component of current at time instant $t + \tau_{SQ}$ and $t - \tau_{SQ}$ respectively

Substituting (11) and (12) in (10) and rearranging, characteristic impedance (Z_c) is given as,

$$Z_c = \frac{\left(V_{R,t+\tau_{RP}} - V_{R,t-\tau_{RP}}\right) + \left(V_{S,t+\tau_{SQ}} - V_{S,t-\tau_{SQ}}\right)}{\left(i_{R,t+\tau_{RP}} + i_{R,t-\tau_{RP}}\right) + \left(i_{S,t+\tau_{SQ}} + i_{S,t-\tau_{SQ}}\right)} \tag{13}$$

The characteristic impedance and propagation constant of the transmission line are,

$$Z_c = \sqrt{\frac{L}{C}} \tag{14}$$

$$\tau_{RS} = l_{RS}\sqrt{LC} \tag{15}$$

By combining and rearranging (14) and (15),

$$\mathrm{L} = \frac{Z_c * \tau_{RS}}{l_{RS}} \tag{16}$$

$$\mathrm{C} = \frac{\tau_{RS}}{Z_c l_{RS}} \tag{17}$$

where, L is inductance per unit length and C is capacitance per unit length. Resistance per unit length (r) is estimated using Dommel's time domain lossy equation.

$$i_{P,t} = \frac{1}{2Z_c^2}\left\{\left(Z_c + \frac{R_1}{4}\right)\left[V_{R,t+\tau_{RP}} - \left(Z_c + \frac{R_1}{4}\right) i_{R,t+\tau_{RP}}\right] - \left(Z_c - \frac{R_1}{4}\right)\left[V_{R,t-\tau_{RP}} + \left(Z_c - \frac{R_1}{4}\right) i_{R,t-\tau_{RP}}\right] - \frac{R_1}{4}\left[2V_{R,t} - \frac{R_1}{2} i_{R,t}\right]\right\} \tag{18}$$

Similarly, as (18) $i_{Q,t}$ is written in terms of R_2 Bus S voltage and current. Substituting in (10), a quadratic equation with unknown r is formulated where R_1=rl_{RP} and R_2=rl_{SQ}. On solving the quadratic equation, two roots for resistance r (r_1, r_2) are obtained.

The correct solution of resistance is found out by estimating Bus S current as shown in (19) and compared with measured Bus S current ($i_{S,t,meas}$). Bus S current is estimated as below where R is the total resistance of the line.

$$i_{S,t} = \frac{1}{2Z_c^2}\left\{\left(Z_c+\frac{R}{4}\right)\left[V_{R,t+\tau_{RS}} - \left(Z_c+\frac{R}{4}\right) i_{R,t+\tau_{RS}}\right] - \left(Z_c - \frac{R}{4}\right)\left[V_{R,t-\tau_{RS}} + \left(Z_c-\frac{R}{4}\right) i_{R,t-\tau_{RS}}\right] - \frac{R}{4}\left[2V_{R,t} - \frac{R}{2} i_{R,t}\right]\right\} \quad (19)$$

$$F = abs(i_{S,t} - i_{S,t,meas}) \quad (20)$$

The resistance with minimal value of F is considered as the valid solution.

C. *Estimation of Fault Location*

Using obtained line parameters, fault location is estimated using a phasor-based approach discussed in [14]. In this analysis, zero sequence impedance is computed as 2.5-3.5 times the positive sequence impedance, however this may not be valid for all the systems.

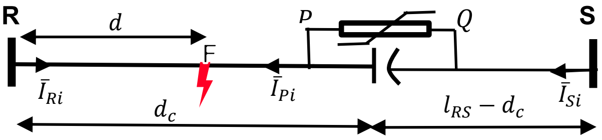

Fig. 4. Series compensated line with fault before the series capacitor.

When the fault is before the series capacitor as shown in Fig. 4 fault location is computed as,

$$d = \frac{real(\bar{V}_{R,fl})imag(\bar{I}_{R,fl}) - imag(\bar{V}_{R,fl})real(\bar{I}_{R,fl})}{real(Z_{1RP}\bar{V}_{R,fl})imag(\bar{I}_{R,fl}) - imag(\bar{V}_{R,fl})real(\bar{I}_{R,fl})} \quad (21)$$

The individual terms of (21) formulation is as follows,

$$\bar{V}_{R,fl} = x_1\bar{V}_{R1} + x_2\bar{V}_{R2} + x_0\bar{V}_{R0} \quad (22)$$

$$\bar{I}_{R,fl} = x_1\bar{I}_{R1} + x_2\bar{I}_{R2} + x_0\frac{Z_{0RP}}{Z_{1RP}}\bar{I}_{R1} \quad (23)$$

where, $\bar{V}_{R,fl}$ is the fault loop voltage; $\bar{I}_{R,fl}$ is the fault loop current; Z_{1RP} is positive sequence impedance of line section RP; Z_{0RP} is zero sequence impedance of line section RP; $\bar{I}_{Ri}, \bar{I}_{Si}, \bar{I}_{Pi}$ are i^{th} sequence component of Bus R, Bus S and point P current respectively where i: 1-positive, 2-negative, 0-zero sequence component; d_c is the distance from Bus R to series compensator; x_1, x_2, x_0 are weighing coefficients and $\bar{V}_{R1}$, $\bar{V}_{R2}, \bar{V}_{R0}$ are positive, negative, zero sequence Bus R voltage respectively.

Similarly same approach can be extended for a fault after the series compensation by using Bus S voltage along with Bus R and S currents and the fault location is given as $(l_{RS} - d)$. High level overview of the work is shown in Fig. 6.

III. Experimental Results

The results presented in this section are based on a two terminal 400kV, 50 Hz test system as shown in Fig. 5. Series compensator is placed at 50% of the line with 40% compensation. A transmission line of length 292 km is modelled using frequency dependent phase model of PSCAD/EMTDC tool. Even though the experimental analysis is provided for the series compensator at middle of the line, the method is valid and can be extended for different locations of series compensator. Voltage and current measurements from both ends of the line are sampled and collected at a sampling frequency of 1MHz for parameter estimation, however the data is collected at 1 kHz sampling frequency for fault location application.

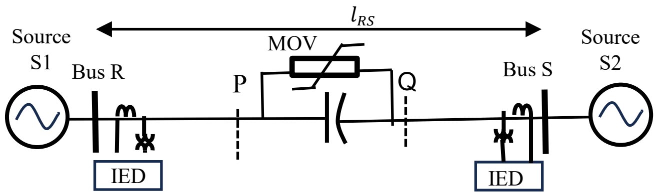

Fig. 5. Single Line Diagram of a series compensated line.

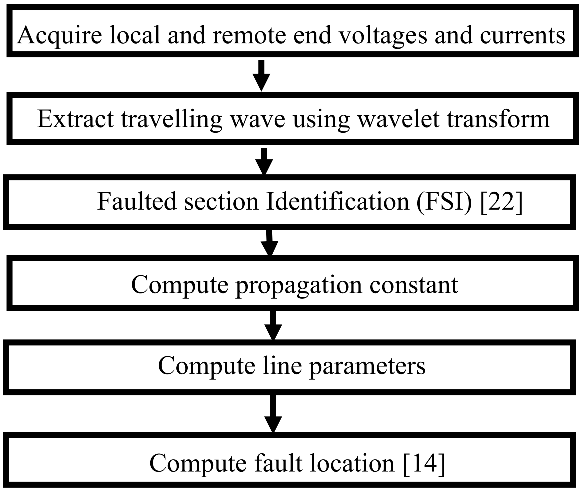

Fig. 6. Overview of the proposed method.

A. *Illustrative Examples*

1) Fault before the series capacitor: An AG fault of fault resistance 50Ω is considered at 70km from Bus R. The fault section is identified as before the series capacitor using [22]. The current travelling waves of both Bus R and Bus S are shown in Fig. 7.

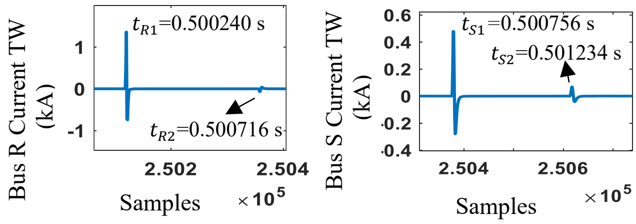

Fig. 7. Bus R and Bus S Current Travelling wave.

The estimated line parameters with the proposed method and the corresponding errors when compared with the actual line parameters are given in Table I. The estimated line parameters are close to the actual line parameters and are further used for the estimation of fault location.

TABLE I. ACTUAL AND ESTIMATED LINE PARAMETERS

Method	R (Ω/km)	L (mH/km)	C (μF/km)
Actual	0.00359	0.6306	190.5946
Proposed	0.00357	0.6313	190.9625
Error (%)	0.56	0.11	0.19

The estimated fault location using these line parameters and faulted phasors is obtained as 70.209 km. The corresponding error and error percentage is 209 m and 0.07% which is desirable.

2) Fault after the series capacitor: A ABCG fault of fault resistance 0.01Ω is considered at 216 km from Bus R. The fault section is identified as after the series capacitor using [22].The waveforms corresponding to the current travelling waves of both Bus R and Bus S are shown in Fig. 8.

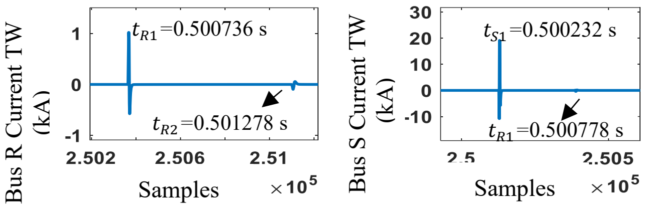

Fig. 8. Bus R and Bus S Current Travelling wave.

The estimated line parameters with the proposed method and the corresponding errors when compared with the actual line parameters are tabulated in Table II. The estimated line parameters are close to the actual line parameters and are further used for the fault location estimation.

TABLE II. ACTUAL AND ESTIMATED LINE PARAMETERS

Method	R (Ω/km)	L (mH/km)	C (μF/km)
Actual	0.00359	0.6306	190.5946
Proposed	0.00356	0.6297	190.9774
Error (%)	0.84	0.14	0.20

The fault location is estimated using the estimated line parameters and faulted phasors which is obtained as 75.652 km from Bus S which corresponds to 216.348 km from Bus R. The corresponding error and error percentage is 348 m and 0.12% which is within ±1-2 tower span and is desirable.

B. *Performance of the Proposed Method*

The method is tested for different fault scenarios and the results are presented in Table III. A total of seven test scenarios are considered with 20% and 40% compensation of the line covering all the fault types to prove the validity of the method.

TABLE III. FAULT SECTION AND FAULT LOCATION ESTIMATION

Test Cases	Actual FL (km)	FSI [22]	Estimated FL (km)	Error in m (%)	Estimated FL (km)	Error in m (%)
			20% Compensation		40% Compensation	
AG fault 50Ω	30	Before the SC	30.282	282 (0.09)	29.771	229 (0.08)
BG fault 100 Ω	50	Before the SC	49.698	302 (0.10)	50.311	311 (0.11)
BCG fault 20Ω	75	Before the SC	75.336	336 (0.12)	75.389	389 (0.13)
ABC fault 0.01Ω	120	Before the SC	119.745	255 (0.09)	120.257	257 (0.09)
AB fault 10 Ω	175	After the SC	175.231	231 (0.08)	174.687	313 (0.11)
CG fault 40 Ω	216	After the SC	215.679	321 (0.11)	215.588	412 (0.14)

ABCG fault 0.01Ω	270	After the SC	270.412	412 (0.14)	270.449	449 (0.15)

The first four test cases are related to the fault occurring before the series compensator followed by three test cases for the fault occurring after the series compensator. From the results, it is observed that the fault section is identified correctly in both the cases, whether the fault is before the series compensator (SC) or after the series compensator. The fault location is estimated with good accuracy in all the test cases irrespective of the fault section, fault type, fault location and fault resistance. The fault is located within 2 tower span which helps the utilities to identify the fault quickly with reduced time of power interruption. A comparative analysis with existing model free method [21] is discussed in following section.

C. *Comparative Analysis*

A Comparative analysis is performed for the proposed method with the literature in [21]. Two fault scenarios are considered for the analysis are simulated. For case 1, an AB fault with a fault resistance of 10 **Ω** is considered at 120 km from Bus R. Lattice diagram and current travelling wave of both Bus R and S are shown in Fig. 9. Fault location estimated is 120.523 km and 120.257 km using [21] and proposed method respectively. The error in meters is 523m and 257m that corresponds to 0.18% and 0.09% respectively which is in ±1-2 tower span which is desirable.

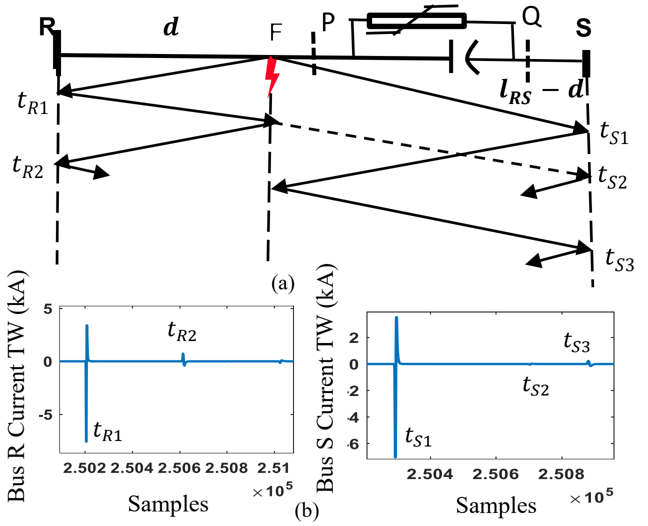

Fig. 9. (a) Lattice Diagram (b) Bus R and Bus S Current Travelling waves.

For case 2, a BG fault with a fault resistance of 30 **Ω** at 25km from Bus R is considered. The lattice diagram along with Bus R and S current traveling waves are shown in Fig. 10. Using [21], the second travelling wave from fault point to Bus S is 10^{th} reflection which is not possible to capture due to attenuation in travelling waves. Due to this limitation, the method is not desirable for close faults, however using proposed method the estimated fault location is 24.776 km. The error in fault location is 224m which corresponds to 0.08%. The comparative analysis proves that the proposed method is superior to the existing method [21] and provides desirable results even for close fault scenarios.

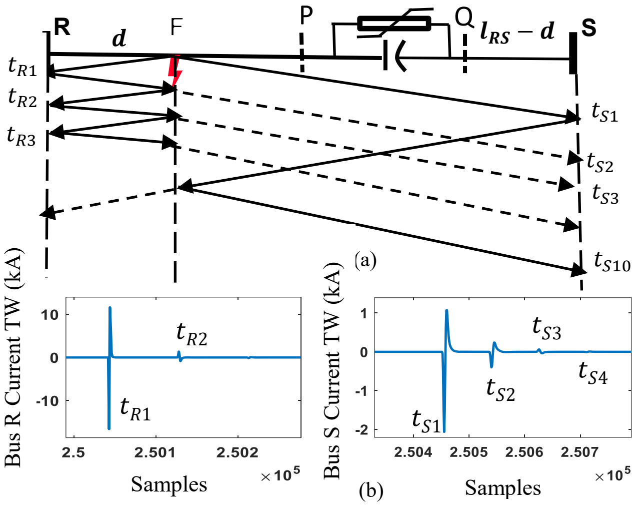

Fig. 10. (a) Lattice Diagram (b)Bus R and Bus S Current Travelling waves.

IV. CONCLUSION

A setting free methodology for estimation of fault location on series compensated lines using synchronized data is proposed. A phasor-based fault location application is discussed however a time domain approach is proposed to determine the line parameters. The method uses Dommel's time domain lossless and lossy equations to estimate the line parameters. Travelling waves are extracted using wavelet transform technique for the computation of propagation constant. The fault location is computed once the line parameters are estimated. The proposed method is not dependent on the percentage and type of compensation, value of series capacitor and MOV characteristics. The method is tested for different fault types, fault resistances, fault locations using PSCAD/EMTDC simulations and is found to be accurate. Unlike the existing model free method, the proposed setting free method can accurately estimate the fault location even for close faults. The fault location estimates are within ±1-2 tower span while the existing methods validity is dependent on the accuracy of known/stored line parameters, MOV characteristics and percentage of compensation. Further research can be conducted to eliminate the dependency of the methodology on zero sequence impedance considered as a multiple of positive sequence impedance which is not valid for all the systems.

REFERENCES

[1] "IEEE Guide for Determining Fault Location on AC Transmission and Distribution Lines," *in IEEE Std C37.114-2014* (Revision of IEEE Std C37.114-2004) , vol., no., pp.1-76, 30 Jan. 2015.

[2] CIGRE Working Group. (2010). Protection, Control and Monitoring of Series Compensated Networks, e-CIGRE. [Online]. Available: https://e-cigre.org/publication/411-protection-control-and-monitoring-of series-compensated-networks.

[3] Series Capacitor Bank Protection Tutorial, 1st ed., *IEEE Power System Relaying Committee WG K13*, Piscataway, NJ, 1997, pp. 1-35.

[4] M. M. Saha, J. Izykowski, E. Rosolowski and B. Kasztenny, "A new accurate fault locating algorithm for series compensated lines," in *IEEE Transactions on Power Delivery*, vol. 14, no. 3, pp. 789-797, July 1999.

[5] J. Sadeh, N. Hadjsaid, A. M. Ranjbar and R. Feuillet, "Accurate fault location algorithm for series compensated transmission lines," in *IEEE Transactions on Power Delivery*, vol. 15, no. 3, pp. 1027-1033, July 2000.

[6] Sadeh, Javad and Aniseh Adinehzadeh. "Accurate fault location algorithm for transmission line in the presence of series connected FACTS devices." *International Journal of Electrical Power & Energy Systems 32 (2010)*: 323-328.

[7] Zijun Huang, Yunping Chen and Qingwu Gong, "A protection and fault location scheme for EHV line with series capacitor based on travelling waves and wavelet analysis," *Proceedings. International Conference on Power System Technology,* Kunming, China, 2002, pp. 290-294 vol.1.

[8] M. Abedini, A. Hasani, A. H. Hajbabaie and V. Khaligh, "A new traveling wave fault location algorithm in series compensated transmission line," *2013 21st Iranian Conference on Electrical Engineering (ICEE)*, Mashhad, Iran, 2013, pp. 1-6.

[9] N. E. Eng and K. Ramar, "Single-ended traveling wave based fault location on two terminal transmission lines," *TENCON 2009 - 2009 IEEE Region 10 Conference*, Singapore, 2009, pp. 1-4.

[10] Y. Liu, S. Meliopoulos, N. Tai, L. Sun and B. Xie, "Protection and fault locating method of series compensated lines by wavelet based energy traveling wave," *2017 IEEE Power & Energy Society General Meeting*, Chicago, IL, USA, 2017, pp. 1-5.

[11] B. Sahoo and S. R. Samantaray, "An enhanced travelling wave-based fault detection and location estimation technique for series compensated transmission network," *2017 7th International Conference on Power Systems (ICPS)*, Pune, India, 2017, pp. 61-68.

[12] O. D. Naidu and A. K. Pradhan, "A Traveling Wave-Based Fault Location Method Using Unsynchronized Current Measurements," *in IEEE Transactions on Power Delivery*, vol. 34, no. 2, pp. 505-513, April 2019.

[13] T. P. S. Bains and M. R. D. Zadeh, "Supplementary Impedance-Based Fault-Location Algorithm for Series-Compensated Lines," *in IEEE Transactions on Power Delivery*, vol. 31, no. 1, pp. 334-342, Feb. 2016.

[14] M. M. Saha, J. Izykowski and E. Rosolowski, "Fault location on series-compensated transmission line using measurements of current differential protective relays," *2010 Modern Electric Power Systems*, Wroclaw, Poland, 2010, pp. 1-6.

[15] Chi-Shan Yu, Chih-Wen Liu, Sun-Li Yu and Joe-Air Jiang, "A new PMU-based fault location algorithm for series compensated lines," *in IEEE Transactions on Power Delivery*, vol. 17, no. 1, pp. 33-46, Jan. 2002.

[16] T. P. S. Bains, T. S. Sidhu, Z. Xu, I. Voloh and M. R. D. Zadeh, "Impedance-Based Fault Location Algorithm for Ground Faults in Series-Capacitor-Compensated Transmission Lines," *in IEEE Transactions on Power Delivery,* vol. 33, no. 1, pp. 189-199, Feb. 2018.

[17] D. C. Huynh, T. H. Truong and M. W. Dunnigan, "Fault Location on Series-Compensated Transmission Lines of a Power System," *2021 IEEE 2nd International Conference on Smart Technologies for Power, Energy and Control (STPEC)*, Bilaspur, Chhattisgarh, India, 2021, pp. 1-6.

[18] S. G. Di Santo, A. D. R. Albertini and R. R. Tiferes, "Optimization-Based Fault Location Algorithm for Series-Compensated Power Transmission Lines," in *IEEE Access*, vol. 10, pp. 46864-46877, 2022.

[19] A. H. Al-Mohammed and M. A. Abido, "A Fully Adaptive PMU-Based Fault Location Algorithm for Series-Compensated Lines," *in IEEE Transactions on Power Systems*, vol. 29, no. 5, pp. 2129-2137, Sept. 2014.

[20] S. Padmanabhan and V. Terzija, "Line parameter-free fault location algorithm for series compensated transmission lines," *2013 IEEE Power & Energy Society General Meeting*, Vancouver, BC, Canada, 2013, pp. 1-5.

[21] S. Gajare, A. K. Pradhan and V. Terzija, "A Method for Accurate Parameter Estimation of Series Compensated Transmission Lines Using Synchronized Data," *in IEEE Transactions on Power Systems*, vol. 32, no. 6, pp. 4843-4850, Nov. 2017.

[22] O. D. Naidu and A. K. Pradhan, "Model Free Traveling Wave Based Fault Location Method for Series Compensated Transmission Line," in *IEEE Access*, vol. 8, pp. 193128-193137, Oct.2020.

[23] Huibin Jia, "An Improved Traveling-Wave-Based Fault Location Method with Compensating the Dispersion Effect of Traveling Wave in Wavelet Domain", *Mathematical Problems in Engineering,* vol. 2017, Article ID 1019591, 11 pages, 2017.