Secure Third Zone Operation of Distance Relay using Impedance Prediction Approach

Prashant Gawande and Sanjay Dambhare
Department of Electrical Engineering, College of Engineering, Pune-411005, India

***Abstract*—The large reach setting of distance relays third zone along with its inability to distinguish system stresses from symmetrical faults is often the reason for its insecure operation. The distance relays mal-operation during such system stressed conditions has led to numerous major blackouts in the recent times. This paper proposes a new technique based on the impedance prediction approach to detect three phase faults during system stresses, namely power swing and load encroachment. The *k* step ahead predictor is used to predict the apparent impedance seen by the distance relay; which is compared with the actual impedance seen by the distance relay. The difference in the actual and predicted impedances is minimal during system stresses; whereas there is significant deviation observed when a symmetrical fault occurs. The proposed methodology is tested on the WSCC three generator, nine bus system modeled in ATP-EMTP environment and encouraging results are obtained.**

***Index Terms*—Distance relay, Zone 3, power swing, load encroachment, *k* step ahead predictor.**

I. Introduction

The characteristic ability of the distance relay to estimate the fault location, provide remote backup protection to the adjacent transmission line segments along with its speed of operation have dominated its use in the transmission line protection [1]. Due to the increased power demand, inadequate power transfer corridors, integration of renewable energy sources and market deregulation; the present day power system is operated very close to security margins due to which the system may experience stresses. Despite the advantages delivered by the distance relay, its inability to extricate between symmetrical faults and system stresses have led to severe blackouts [2]–[4] in the past. Due to the large reach setting of zone 3, the apparent impedance seen by the distance relay happens to enter the relay characteristic during the stressed condition [5]. Due to the symmetrical nature of system stresses, the distance relay misinterprets this condition for the symmetrical fault and insecurely issues the trip decision. Owing to the severity of the issue, many researchers have been drawn towards developing algorithm to enhance the security of distance relay operation.

978-1-4799-5141-3/14/$31.00 ©️ 2016 IEEE

Oscillation in the active and reactive power flows in the transmission line following a sudden large disturbance on the power system such as line switching, generator outage, faults, heavy loads switching is termed as power swing. This power swing condition may cause the impedance trajectory to enter distance relay trip zone and cause its mal-operation. In [6] the circular locus of the admittance trajectory and its center behavior are investigated to detect power swing. Time frequency domain approaches can be seen used in [7]–[9] for detecting symmetrical faults during power swings. In [10] the authors predict the current and voltage signals using an auto-regression technique which are used in the calculation of differential power. The use of rate of change of current magnitude is seen in [11], [12] to securely unblock distance relay during three phase faults. Using the sign and time criteria of the moving window average, the symmetrical faults are distinguished from power swing in [13].

The necessity to fulfill the load demand using the limited power transfer corridors leads to overloading of certain transmission lines. This increase in the power flows through the line also reduces the voltage at the bus. This causes the apparent impedance seen by the relay to enter its operating zone and issue undesired trip signal. A new adaptive load encroachment prevention scheme based on steady-state security analysis and adaptive anti-encroachment zone is proposed in [14]. In order to distinguish between line overloads and faults, the line outage distribution factor and generation shift factor based power flow estimation method, and a secure peer-to-peer communication structure are adopted in [15]. An approach of comparison of bus voltage values calculated through dissimilar paths is made in [16] to identify load encroachment. In [17] a combination of the steady-state components and the transient components using a state diagram is made to distinguish load encroachment from fault conditions. An adaptive distance protection scheme based on demodulation of current and voltage signals is shown in [18] for secured third zone operation.

In this paper an impedance prediction technique is proposed for the secure operation of distance relay during power swing and load encroachment. The apparent impedance seen by the distance relay is used by the k step ahead prediction algorithm to predict the apparent impedance 'k' samples ahead. This predicted apparent impedance value is very close to the actual apparent impedance seen by the relay during that k^{th} instant when the system is under stress. However, when a sudden three phase fault strikes the system, the predicted impedance and the actual impedance deviate by a significant amount. This detection criteria can be reliably used for detecting symmetrical faults during system stresses.

II. Proposed Philosophy

The idea behind the proposed philosophy lies in the fact that a given series of information tends to replicate its own behavior along the time. Therefore, for the series under observation it is possible to predict its behavior in the future as it will bear a symmetry with the past observations.

A. k Step Ahead Predictor

The k step ahead predictor is a model validation algorithm which is used to predict the response of the model k steps ahead. These predictions are made using the current and past values of the measured input and output variables. The factor k, called the prediction horizon corresponds to the predicting output at time kTs, where Ts is the sampling time.

For predicting the behavior of any series k steps ahead from a given time t, the inputs up to time $t+k$ along with the outputs up till time t are required. For, a given series with input $u(t)$ and corresponding output $y(t)$, the output at time $t+k$ is given as,

$$\begin{aligned} y_p(t+k) = f(u(t+k), u(t+k-1), ..u(t), \\ u(t-1), ..., u(0) \\ y(t), y(t-1), .., y(0)) \end{aligned} \quad (1)$$

where $u(0)$ and $y(0)$ are the initial states. The predictor, $f()$ is a dynamic autoregressive moving average model with exogenous terms whose form depends on the structure of the model whose output is to be predicted. If the output to be predicted is a time series, the input $u(t)$ is not required for k step ahead prediction.

B. Implementation of the Proposed Algorithm

The current signals from the CT's and voltage signals from the CCVT's are processed using full cycle recursive Discrete Fourier Transform [19] algorithm to obtain the corresponding current and voltage phasors. These phasors are then used for computing the apparent impedance seen by the distance relay. An algorithm trigger boundary (ATB) is set at 120% of the zone 3 reach of the distance relay. The purpose of this ATB is to reduce the computational burden on the processor. The proposed algorithm remains at "hibernate" and is initiated only when the apparent impedance seen by the relay is less than the set ATB. The time at which the algorithm is initiated is the time 't' in (1).

Once the impedance trajectory enters the ATB zone, the k step ahead predictor starts predicting the apparent impedance k samples ahead of the actual seen impedance. A larger value of k will cause significant deviation in the actual and predicted impedances even during smaller disturbance; whereas a smaller value of k will show minimal deviation even after a major transient event. For the implementation of this algorithm, the value of k is wisely chosen as one-fourth of N, the number of samples in one fundamental cycle. Here, N = 20; hence k = 5.

The difference in the predicted and the actual apparent impedance is noted at every sampling instant thereafter. Depending on the type of disturbance, model estimated and predictor used; the calculated difference in the apparent impedance may be non-zero during stressed conditions and may be very close to zero during high impedance three phase faults in zone 3. To overcome this issue, cumulative sum (CUSUM) [20] technique is used. Once, the difference in apparent impedance crosses a set threshold, the output of CUSUM is the sum of present sample and the previous sample. After rigorous simulations, the threshold of 6.5 is used in this proposed algorithm. During system stressed conditions like power swing and load encroachment, the CUSUM output remains zero; however after the inception of symmetrical faults the output becomes non-zero.

After the CUSUM output goes high, the trip signal to the circuit breaker is set after an intentional time delay of 60 fundamental cycles [21] for zone 3 protection. The flowchart for the proposed algorithm is shown in Fig. 1.

To evaluate the performance of the k step ahead predictor, a test scenario is generated where a symmetrical fault strikes at 0.8 sec on a steady state operating system. The current and voltage signals are shown in Fig. 2. The computed impedance using FCDFT and the predicted impedance using k step ahead predictor is shown in Fig. 3. As seen from the result, during steady state operation the computed and predicted impedances are same; whereas there is significant deviation after the fault inception. This validates the accuracy of the predictor.

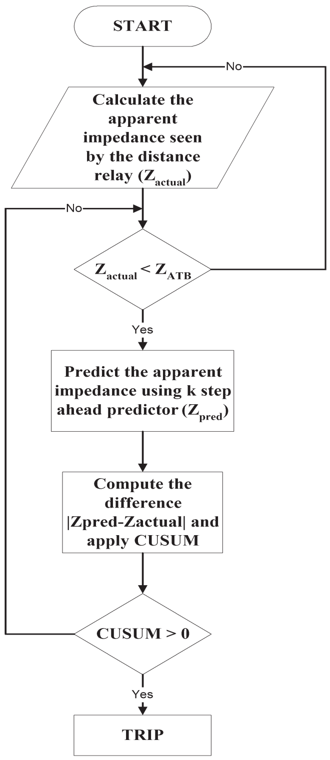

Fig. 1. Flowchart for the proposed methodology.

III. Test Cases

The performance of the proposed algorithm is tested on the WSCC three generator, nine bus system. The details of the simulated model can be obtained from [22]. The model is simulated in the ATP-EMTP environment and the load flow results are verified before simulating the test cases. The relay is located on line 7-8 near bus 7 as shown in Fig. 4. All lines are 100 km long. The purpose of the proposed algorithm is secure zone 3 operation; so symmetrical faults are simulated in the zone 3 of the relay i.e. on line 6-9.

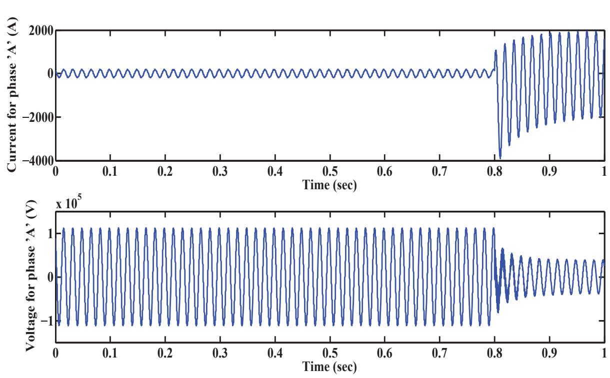

Fig. 2. Current and voltage signals for testing the proposed algorithm.

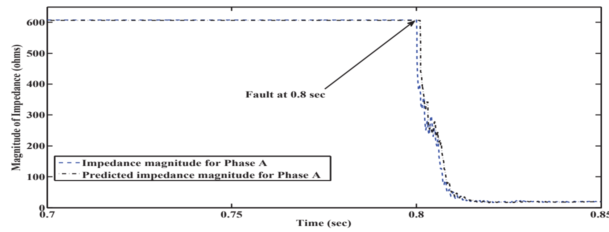

Fig. 3. Computed and predicted apparent impedances for the test signals.

A. Performance during Power Swing

The power system under study experiences power swing when a three phase fault on line 7-5 is cleared by opening breakers at bus 7 and bus 5. The impedance trajectory enters the zone 3 of the distance relay at 1.21 sec and leaves at 2.45 sec which is larger than the intentional trip time for the third zone. Thus, the conventional distance relays may mal-operate during such circumstances. A three phase fault strikes the system under power swing at 2.4 sec at the midpoint of line 6-9. The voltage and current waveforms for the simulated condition are shown in Fig. 5.

The apparent impedance crosses the ATB at 0.5165 sec, activating the *k* step ahead predictor which starts predicting the impedance thereafter. As seen from the zoomed section in Fig. 6, during power swing the computed apparent impedance and the predicted apparent impedance are equal; whereas when the symmetrical fault strikes the deviation in the computed and predicted impedance is noticeable.

In Fig. 7, the output of the CUSUM algorithm is shown along with the trip signal sent to the circuit breaker.

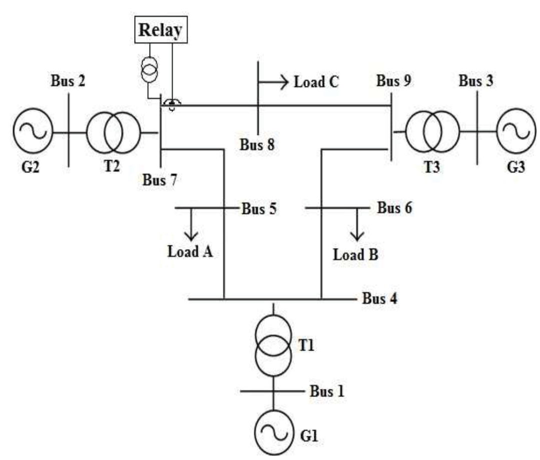

Fig. 4. One line diagram of the simulated WSCC three generator, nine bus system.

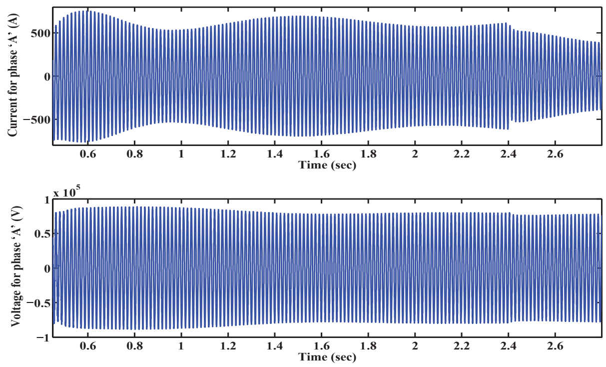

Fig. 5. Current and voltage waveforms of phase A for a bolted three phase fault during power swing at the midpoint of line 6-9 at 2.4 sec.

It can be seen that the output of the CUSUM remains low during the power swing condition; whereas it is non zero after the symmetrical fault inception. After the CUSUM output goes high, the trip signal to the circuit breaker is sent after the intentional time delay of zone 3.

B. Performance during Load Encroachment

The increase of power flows through a transmission line due to change in network topology or generation shift leads to the load encroachment problem. Load encroachment phenomenon is the major player amongst the system stresses to have caused cascaded tripping in the past.

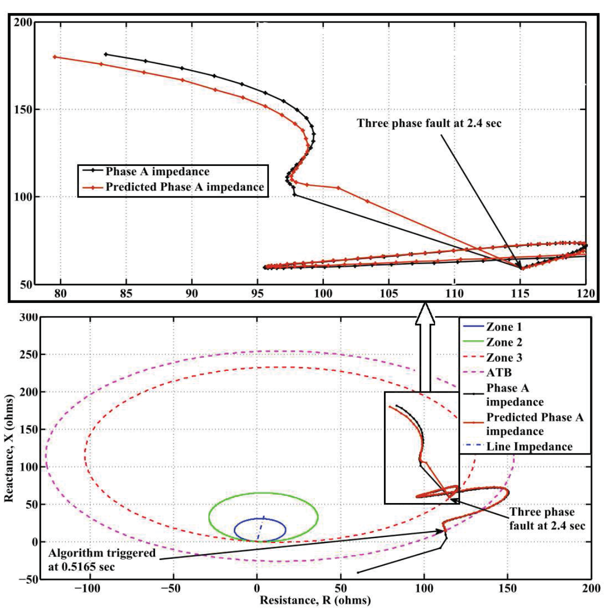

Fig. 6. FCDFT computed and predicted impedance trajectory of phase A for a bolted three phase fault during power swing at the midpoint of line 6-9 at 2.4 sec.

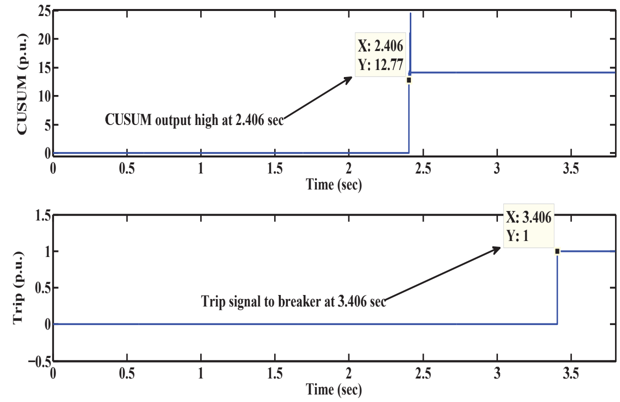

Fig. 7. CUSUM output and trip signal to breaker for a bolted three phase fault during power swing at the midpoint of line 6-9 at 2.4 sec.

To simulate the load encroachment condition, the load on bus 8 is increased gradually from 0.1 sec to 4.4 sec. This causes the apparent impedance seen by the distance relay to enter its zone 3. A three phase fault strikes the line 6-9 at a distance of 30 km from bus 9 at 5.3 sec. The current and voltage waveform for this simulated case is shown in Fig. 8.

The apparent impedance seen by the relay triggers the algorithm in hibernate at 2.828 sec. The impedance prediction algorithm starts predicting the impedance k steps ahead. The computed impedance trajectory and the predicted impedance trajectory are shown in Fig. 9. It is observed that during load encroachment, the predicted and computed impedances are equal; whereas on the symmetrical fault inception the computed and predicted impedances tend to mismatch.

The output of the CUSUM technique and the trip signal to the breaker are shown in Fig. 10. The symmetrical fault is reliably detected during the load encroachment condition and the distance relay is operated securely.

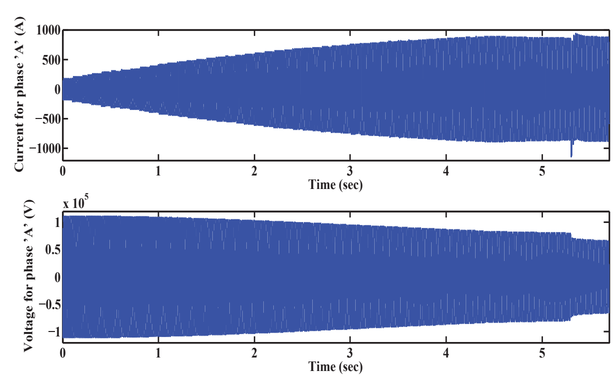

Fig. 8. Current and voltage waveforms of phase A for a bolted three phase fault during load encroachment on line 6-9 at a distance of 30 km from bus 9 at 5.3 sec.

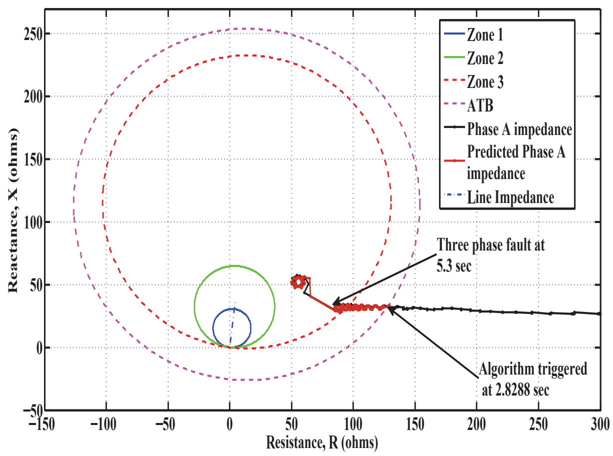

Fig. 9. FCDFT computed and predicted impedance trajectory of phase A for a bolted three phase fault during load encroachment on line 6-9 at a distance of 30 km from bus 9 at 5.3 sec.

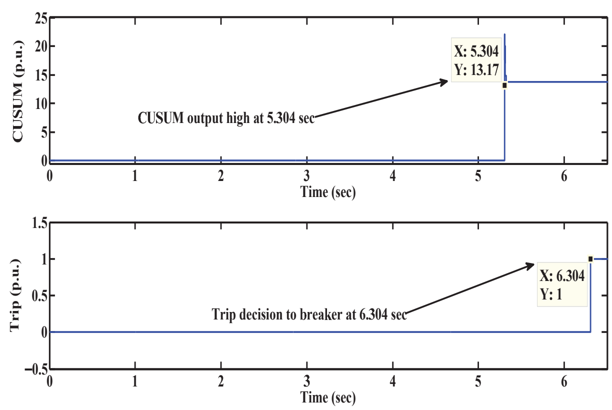

Fig. 10. CUSUM output and trip signal to breaker for a bolted three phase fault during load encroachment on line 6-9 at a distance of 30 km from bus 9 at 5.3 sec.

IV. Conclusion

The drawback of the distance relay to distinguish between symmetrical faults and system stressed conditions leading to cascaded tripping is highlighted in this paper. The security of the distance relay's zone 3 operation during power swing and load encroachment is enhanced by implementing the impedance prediction approach. The apparent impedance seen by the distance relay is compared with the impedance predicted by the k step ahead predictor. The difference in the actual and predicted impedances is found to be negligible during the power swing and load encroachment conditions. Symmetrical fault on the other hand being an unpredictable event, the actual impedance fails to follow the predicted impedance giving rise to a significant difference. The computational requirements of the proposed algorithm are minimal since the ATB function employed significantly reduces the burden on the processor. The simulation results demonstrate the reliability of the scheme.

Acknowledgement

The authors would like to thank the Center of Excellence in Smart Renewable Energy Systems (CoE-SRES) and Technical Education Quality Improvement Programme - II (TEQIP - II) at College of Engineering, Pune, India for supporting the work.

References

[1] S. Soman, *A web course on digital protection*. NPTEL Accessed Jan 2015.

[2] "August 14, 2003 Blackout: NERC Actions to Prevent and Mitigate the Impacts of Future Cascading Blackouts," 2004. [Online]. Available: http://www.nerc.com/comm/PC/System Protection and Control Subcommittee SPCS DL/NERC_Recommendations_2-10-04.pdf Accessed October 2015

[3] "Report of the enquiry committee on grid disturbance in northern region on 30th July 2012 and in northern, eastern & north-eastern region on 31st July, 2012," 2012. [Online]. Available: http://www. powermin. nic. in/pdf/GRID_ENQ_ REP_16_8_12. pdf Accessed October 2015

[4] G. Andersson, P. Donalek, R. Farmer, N. Hatziargyriou, I. Kamwa, P. Kundur, N. Martins, J. Paserba, P. Pourbeik, J. Sanchez-Gasca *et al.*, "Causes of the 2003 major grid blackouts in North America and Europe, and recommended means to improve system dynamic performance," *IEEE Transactions on Power Systems*, vol. 20, no. 4, pp. 1922–1928, 2005.

[5] S. Horowitz and A. Phadke, "Third zone revisited," *IEEE Transactions on Power Delivery*, vol. 21, no. 1, pp. 23–29, 2006.

[6] R. Jafari, N. Moaddabi, M. Eskandari-Nasab, G. Gharehpetian, and M. Naderi, "A novel power swing detection scheme independent of the rate of change of power system parameters," *IEEE Transactions on Power Delivery*, vol. 29, no. 3, pp. 1192–1202, 2014.

[7] C. Pang and M. Kezunovic, "Fast distance relay scheme for detecting symmetrical fault during power swing," *IEEE Transactions on Power Delivery*, vol. 25, no. 4, pp. 2205–2212, 2010.

[8] R. Dubey and S. R. Samantaray, "Wavelet singular entropy-based symmetrical fault-detection and out-of-step protection during power swing," *IET Generation, Transmission & Distribution*, vol. 7, no. 10, pp. 1123–1134, 2013.

[9] P. Gawande and S. Dambhare, "Protection and fault identification in presence of power swing blocking/unblocking function," in *Power and Energy Society General Meeting (PES), 2013 IEEE*. IEEE, 2013, pp. 1–6.

[10] J. G. Rao and A. K. Pradhan, "Differential power-based symmetrical fault detection during power swing," *IEEE Transactions on Power Delivery*, vol. 27, no. 3, pp. 1557–1564, 2012.

[11] P. Gawande and S. Dambhare, "A novel algorithm to detect symmetrical faults during power swing for a double circuit multi-terminal transmission line," in *2016 IEEE/PES Transmission and Distribution Conference and Exposition (T&D)*. IEEE, 2016, pp. 1–7.

[12] P. N. Gawande and S. S. Dambhare, "A novel unblocking function for distance relay to detect symmetrical faults during power swing," in *2016 IEEE Power & Energy Society General Meeting*. IEEE, 2016, pp. 1–6.

[13] J. G. Rao and A. Kumar Pradhan, "Power-swing detection using moving window averaging of current signals," *IEEE Transactions on Power Delivery*, vol. 30, no. 1, pp. 368–376, 2015.

[14] M. Jin and T. S. Sidhu, "Adaptive load encroachment prevention scheme for distance protection," *Electric Power Systems Research*, vol. 78, no. 10, pp. 1693–1700, 2008.

[15] S.-I. Lim, C.-C. Liu, S.-J. Lee, M.-S. Choi, and S.-J. Rim, "Blocking of zone 3 relays to prevent cascaded events," *IEEE Transactions on Power Systems*, vol. 23, no. 2, pp. 747–754, 2008.

[16] J. Zare, F. Aminifar, and M. Sanaye-Pasand, "Synchrophasor-based wide-area backup protection scheme with data requirement analysis," *IEEE Transactions on Power Delivery*, vol. 30, no. 3, pp. 1410–1419, 2015.

[17] C.-H. Kim, J.-Y. Heo, and R. K. Aggarwal, "An enhanced zone 3 algorithm of a distance relay using transient components and state diagram," *IEEE Transactions on Power Delivery*, vol. 20, no. 1, pp. 39–46, 2005.

[18] P. Gawande, P. Bedekar, M. Bagewadi, and S. Dambhare, "An adaptive distance relay protection scheme for enhanced protection security," in *2016 IEEE International Conference on Power Systems*. IEEE, 2016, pp. 1–6.

[19] A. G. Phadke and J. S. Thorp, *Synchronized phasor measurements and their applications*. Springer, 2008.

[20] P. K. Nayak, A. K. Pradhan, and P. Bajpai, "A fault detection technique for the series-compensated line during power swing," *IEEE Transactions on Power Delivery*, vol. 28, no. 2, pp. 714–722, 2013.

[21] G. Ziegler, *Numerical distance protection: Principles and Applications*. John Wiley & Sons, 2011.

[22] P. M. Anderson and A. A. Fouad, *Power system control and stability*. John Wiley & Sons, 2008.