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Fault Detection, Classification and Location of Series Compensated Transmission Line Using Power Swing Protection

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Abstract: *There is a significant difference in fault detection technique of series compensated transmission line during normal operating condition and power swing condition due to several reasons like frequency modulation, sub-harmonic oscillations, transients etc. Especially during power swing condition the frequency of power change is modulated and it is twice of frequency of voltage change and current change. So, cycle to cycle or sample to sample comparison is not reliable here. Other techniques like Voltage Change, Current Change or Impedance change methods are also not applicable during power swing condition. Further inclusion of capacitor in transmission line evokes transients and sub-synchronous resonance activity in series compensated line. So, fault detection during power swing . condition in case of series compensated line is extreme difficult. In this project a method is developed to detect fault of series compensated transmission line during power swing condition. Further the study carried out to identify the proper location and Classification and estimated zone of the fault. In proposed work negative sequence current was analysed as it keeps the other parameters in the system in healthy state. The proposed approach is a cumulative sum (CUSUM) of change in the magnitude of the negative-sequence current-based approach. The task of series compensation is to reduce the transmission lines inductivity. Means, the line length is virtually shortened. The simulation of proposed work is done using MATLAB toolbox, comparative analysis of proposed and existing techniques is performed using MAE, RMSE, and accuracy performance measuring parameter and found that accuracy of proposed work is about 100%.*

Keywords: *CUSUM, Transmission line, Fault, Series compensated, MATLAB, MSE, Power swing.*

1. Introduction

Fault detection during power swing condition is a challenge for stable operation of power system due to several reasons like protection problems, Voltage/current inversion, sub-harmonic oscillations and transients especially if it is series compensated modulation of voltage and current waveforms with swing frequency etc. Here it proposes a negative-sequence current–based technique for detecting presence of fault, classification of fault occurred, estimated zone and location of the fault occurred and the fault inception time with respect to system reference clock during the power swing condition in a series compensated line [1-2]. In proposed work negative sequence current was analysed as it keeps the other parameters in the system in healthy state. The technique is tested for different series-compensated power systems including a SMIB system and a WSCC-9bus-3machine power system with their different configurations and contingency combinations. Power swing caused by various faults are simulated with PSCAD / EMTDC and MATLAB/SIMULINK and compared with available techniques to prove the effectiveness of the proposed technique algorithm.

Fast and accurate determination of a fault in electrical power system is a vital part in power restoration. Power Swing is caused by large disturbances in power system, which if not blocked caused mal-operation of distance relays and undesired tripping of breakers, change in load impedance, unwanted relay operations at different locations of the network, major power-outages or even power blackout. If a fault occurs during the power swing, the relay must detect the fault and operate quickly. The detection of faults in a series-compensated line during power swings is more challenging due to different frequency components in the fault signals which depend on the fault location, type, level of compensation etc cause the apparent impedance seen by the relay to oscillate and imposes difficulty to distinguish faults from the power swing.[10] It proposes a technique for detecting faults in a series-compensated line during the power swing. During unbalanced faults, the negative-sequence components become significant and due to transients in current signals in the initial period, a negative sequence component is present even in three-phase faults. To detect the faults during swing in a series-compensated line, a cumulative sum (CUSUM) of change in the magnitude of the negative-sequence current-based approach is proposed in this paper. The performance is tested for numerous cases for an SMIB system and a 9-bus system simulated with SIMULINK/PSCAD.

2. Power Swing

Power swing is nothing but large disturbance of power or lost of equilibrium in the flow of power due to sudden change in system voltage and or current. During power swing if voltage and current chances with a frequency f, then the power will change with a frequency 2f.So, cycle to cycle or sample to sample comparison is not valid here.[11-13]

The current flowing through the transmission line depends upon the phase difference between the voltages generated at the two ends of the line. The phase difference is equal to the rotor angle. The phase angle between the generated voltages changes during disturbances, which may arise because of the removal of a fault or a sudden change in the load.

During disturbances, the rotor of the generator swings around the final steady state value. When the rotor swings, the rotor angle changes and the current flowing through the line also changes. Such currents are heavy and they are known as power surges. So, long as the phase angle between the generated voltages goes on changing, the current seen by the relay is also changing. Therefore, the impedance measured by the relay also varies during power swings. The current flowing through the transmission line depends upon the phase difference between the voltages generated at the two ends of the line. The phase difference is equal to the rotor angle. The phase angle between the generated voltages sudden change during disturbances which may arise because of the removal of a fault or a sudden change in the load. When the rotor swings, the rotor angle changes and current flowing through the line also changes. Such currents are heavy and known as power surges. So, long as the phase angle between the generated voltages goes on changing, the current seen by the relay is also changing. Therefore the impedance measured by the relay also varies during power swings. The Characteristics of some important distance relays and power surge characteristics are shown in R-X diagram. It is evident from the figure that the relay characteristics occupying greater area on the R-X diagram remains under the influence of power surge. The MHO relay having least area on R- X diagram is least affected. The impedance relay is moderately affected. The reactance relay occupying the largest area is most affected.

3. Related Work

line protection (HSTLP) using the Stockwell transform (ST), Wigner distribution function (WDF), and alienation coefficient (ACF) is designed. Current signals are analyzed using the ST, WDF, and ACF to compute the Stockwell fault index (SFI), Wigner fault index (WFI), and alienation coefficient fault index (ACFI), respectively. &ese fault indexes are used to derive a hybrid signal processing fault index (HSPFI), which is implemented for the detection of transmission line fault events. &e peak magnitude of HSPFI is compared with a preset threshold magnitude (TH) to identify the fault. & statistical formulation is proposed for fault location on the power transmission line. Fault classification is achieved using the number of faulty phases. A hybrid ground fault index (HGFI) is used to recognize the involvement of the ground during the fault
event. &is HGFI is determined by processing zero sequence current using ST and WDF. The performance of algorithm is tested by various case studies for fault impedance variation, variable sampling frequency, fault incidence angle variation, reverse power flow on transmission line, highly loaded line, different fault locations online, and noisy conditions. &e algorithm is also validated to detect a fault on a practical transmission line of large area utility grid of Rajasthan Rajya Vidyut Prasaran Nigam Limited (RVPN) in India. &e algorithm performs better than the Hilbert–Huang transform (HHT)-based protection scheme and wavelet transform (WT)-based protection scheme available in the literature in terms of mean error of fault location, fault location accuracy, and noise level. [3] The proposed protection scheme efficiently detected, classified, and located the faulty events such as single-phase-to-ground fault (SPGF), two-phase fault (TPF), two-phase-to-ground fault (TPGF), three-line fault (TLF), and three line- to-ground fault (TLGF). Transmission line fault location accuracy of 99.031% is achieved. &e algorithm performs well even with a high noise level of 10 dB SNR.[4]

Rohan Kumar Gupta(2014) new technique to detect fault during power swing. In the proposed technique process starts by simulating the double transmission line with one line series compensated. When we connect a fixed capacitor in one transmission line, fault detection become more difficult. The detection of symmetrical fault during swing is more difficult. So the proposed technique can easily detect any fault during swing with series compensated line. Sampled data of current and voltage passes through wavelet transform. It decomposes it into different levels. Then we calculate total energy of some selective levels of current and voltage. A double circuit line model is simulated in EMTDC/PSCAD.[5]

Khalfan Al Kharusi et al. (2022) presents a comprehensive machine-learning-based approach for detecting and classifying faults in transmission lines connected to inverter-based generators. A two-layer classification approach was considered:

fault detection and fault type classification. The faults were comprised of different types at several line locations and variable fault impedance. The features from instantaneous three-phase current and voltages and calculated swing-center voltage (SCV) were extracted in time, frequency, and time–frequency domains. A photovoltaic (PV) and a Doubly-Fed Induction Generator (DFIG) wind farm plant were the considered renewable resources. The unbalanced data problem was investigated and mitigated using the synthetic minority class oversampling technique (SMOTE). The hyperparameters of the evaluated classifiers, namely decision trees (DT), Support Vector Machines (SVM), k-Nearest Neighbors (k-NN), and Ensemble trees, were optimized using the Bayesian optimization algorithm. The extracted features were reduced using several methods. The classification performance was evaluated in terms of the accuracy, specificity, sensitivity, and precision metrics. The results show that the data balancing improved the specificity of DT, SVM, and k-NN classifiers (DT: from 99.86% for unbalanced data to 100% for balanced data; SVM: from 99.28% for unbalanced data to 99.93% for balanced data; k-NN: from 99.64% for unbalanced data to 99.74% for balanced data). The forward feature selection combined with the Bag ensemble classifier achieved 100% accuracy, sensitivity, specificity, and precision for fault detection (binary classification), while the Adaboost ensemble classifier had the highest accuracy (99.4%), compared to the other classifiers when using the complete set of features. The classification models with the highest performance were further tested using a new dataset test case. They showed high detection and classification capabilities.[6]

Elhadi Aker et al. (2020) presents the methodology to detect and identify the type of fault that occurs in the shunt compensated static synchronous compensator (STATCOM) transmission line using a combination of Discrete Wavelet Transform (DWT) and Naive Bayes (NB) classifiers. To study this, the network model is designed using Matlab/Simulink. Different types of faults, such as Line to Ground (LG), Line to Line (LL), Double Line to Ground (LLG) and the three-phase (LLLG) fault, are applied at disparate zones of the system, with and without STATCOM, considering the effect of varying fault resistance. The three-phase fault current waveforms obtained are decomposed into several levels using Daubechies (db) mother wavelet of db4 to extract the features, such as the standard deviation (SD) and energy values. Then, the extracted features are used to train the classifiers, such as Multi-Layer Perceptron Neural Network (MLP), Bayes and the Naive Bayes (NB) classifier to classify the type of fault that occurs in the system. The results obtained reveal that the proposed NB classifier outperforms in terms of accuracy rate, misclassification rate, kappa statistics, mean absolute error (MAE), root mean square error (RMSE), percentage relative absolute error (% RAE) and percentage root relative square error (% RRSE) than both MLP and the Bayes classifier.[7]

Mohammed Hussien Hassan Musa et al. (2021) proposes a new scheme for recognizing the faulted-phase in TCSC-compensated transmission lines during the power swing. Primarily, the fault feature is extracted by using a modified Interclass correlation coefficient. The scheme utilizes the system-current samples during the fault period and system-current samples during the health state as two variables for obtaining the modified interclass correlation coefficient. Then a cumulative approach is used to enlarge the fault feature. The proposed scheme has been subjected to a wide variety of tests through different faults circumstances under different compensation levels. The experimental results have shown good performance against the high impedance/resistance fault different TCSC-compensation levels during the power swing. Also, the results showed a distinction in terms of time response due to its simple computation process.[8]

N. Perera (2014) Use of series capacitors on transmission lines has become popular due to a variety of factors such as rapid increase in electricity demand, delays in implementing new transmission facilities and interconnection of new generation facilities such as large scale wind-farms. Most of these transmission lines are protected using conventional phasor based distance relays that operate based on voltage and current signals, measured locally. The presence of series capacitors can create abnormal system conditions (voltage inversions, current inversions, sub-harmonics and DC offsets) that potentially lead to unintended operation of conventional distance relays. This paper describes how such factors can affect the performance of the conventional distance relays and outlines solutions to overcome these challenges.[9]

Md. Sihab Uddin et al. (2022) the design and development of an intelligent machine learning framework is presented to identify and classify faults in a power TL. The design of the proposed framework is done with the goal of reducing computational load and ensuring resilience against source noise, source impedance, fault strength, and sampling frequency variation. The design is carried out based on the selection of the optimal model parameters using a search optimization algorithm called Grid Search CV. The effectiveness of the proposed model is verified by testing the model on the IEC standard microgrid model in a MATLAB environment. The results show that the proposed model has more than ninety-nine per cent overall accuracy in the identification and classification of the TL faults. The results are also compared with some state-of-the-art approaches such as LSTM, RNN, DBN, DRL, and CNF to further examine the performance of the proposed framework. The comparison demonstrates that the proposed model outperforms other existing techniques in terms of accuracy, computational cost, and response speed.[10]

4. Methodology

Fast and accurate determination of a fault in electrical power system is a vital part in power restoration. Power Swing is caused by large disturbances in power system, which if not blocked caused mal-operation of distance relays and undesired tripping of breakers, change in load impedance, unwanted relay operations at different locations of the network, major power-outages or even power blackout. If a fault occurs during the power swing, the relay must detect the fault and operate quickly. The detection of faults in a series-compensated line during power swings is more challenging due to different frequency components in the fault signals which depend on the fault location, type, level of compensation etc. cause the apparent impedance seen by the relay to oscillate and imposes difficulty to distinguish faults from the power swing. This paper proposes a technique for detecting faults in a series-compensated line during the power swing. During unbalanced faults, the negative-sequence components become significant and due to transients in current signals in the initial period, a negative sequence component is present even in three-phase faults. To detect the faults during swing in a series-compensated line, a cumulative sum (CUSUM) of change in the magnitude of the negative-sequence current-based approach is proposed in this chapter. The performance is tested for numerous cases for an SMIB system and a 9-bus system simulated with SIMULINK/PSCAD.

Proposed Fault Detection Technique

The computational methods are provided as follows :

$$\bar{I_2} = \frac{(\bar{I_a} + \alpha^2 \bar{I_b} + \alpha \bar{I_c})}{3}$$

I_2=negative sequence current;

$$\alpha = \frac{j^2 \pi}{3}$$

and I_a, I_b,I_c are line currents

$$s_k = \Delta(I_{2k} = I_{2k} - I_{2k-1}) \qquad \text{For } S_k > €,$$

$$g_k = max(g_{k-1} + s_k - €, 0)$$

Where, g_k = fault index and

€= the drift parameter in g_k .

A fault is registered if $g_k > h$

Where h is a constant and ideally equals zero.

Epsilon provides the low-pass filtering effect and influences the performance of the detector. When S_k > epsilon, the g_k value increases by a factor of difference between S_k and €.

After each fault detection index g is reset to zero. The selection of € and h is important for determining the performance of the algorithm. Epsilon is a very small quantity which having a value greater than zero. The value of h is set such that the algorithm can maintain the balance between dependability versus security and speed versus accuracy requirements of the relaying scheme. Considering all extreme fault situations during the power swing we worked with hmax=0.48 and €max=0.05 value. The proposed method is based on the CUSUM approach and therefore, a distinctly much higher index value is obtained during the fault.

5. Simulation and Results

The algorithm for is tested for different conditions including balanced and unbalanced faults etc. Using SIMULINK/PSCAD with distributed parameter line model data was generated. The data-sampling rate was maintained at 4 kHz for the 50-Hz power system.

A . Line-to-Ground Fault in the Series-Compensated Line

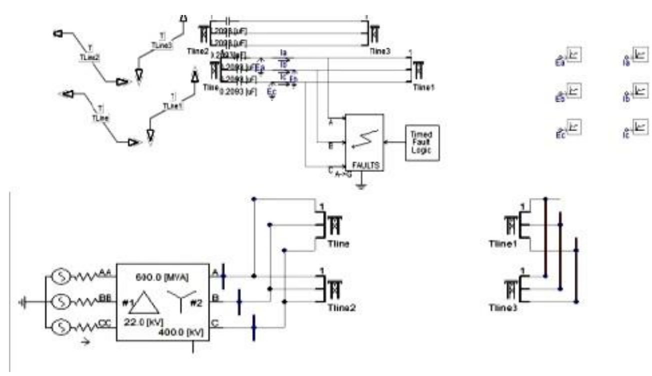
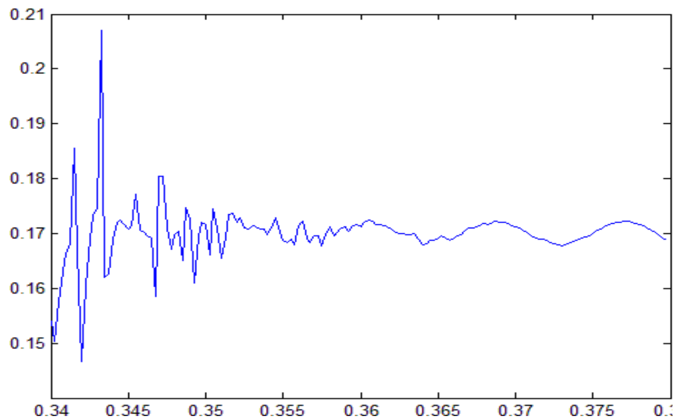
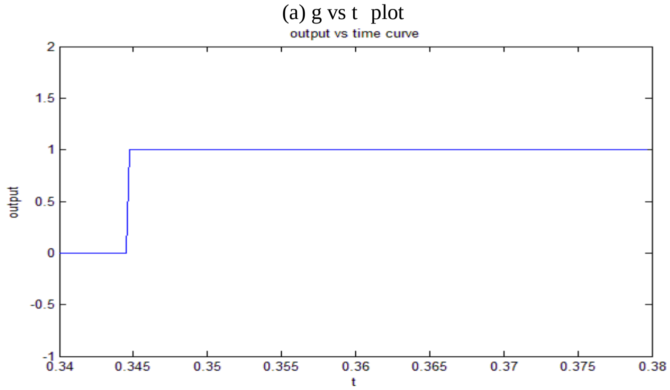


Fig. 1: Implementation of SMIB Test System Using PSCAD

Algorithm is tested for a line to ground fault of ag –type with a fault resistance of 0.1 ohm initiated at 0.34 sec for 0.04 sec duration at a distance 240KM from bus1.



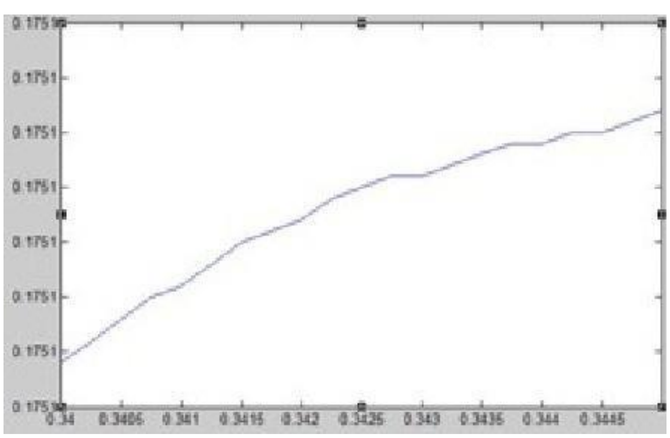
(a) g vs t plot



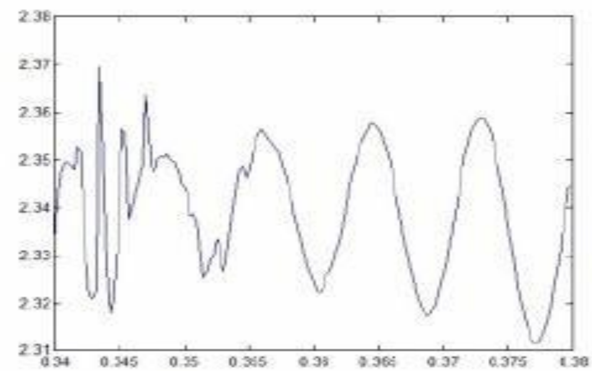
(b) Output vs. time plot

Fig.2 (a,b)-LG Fault Analysis

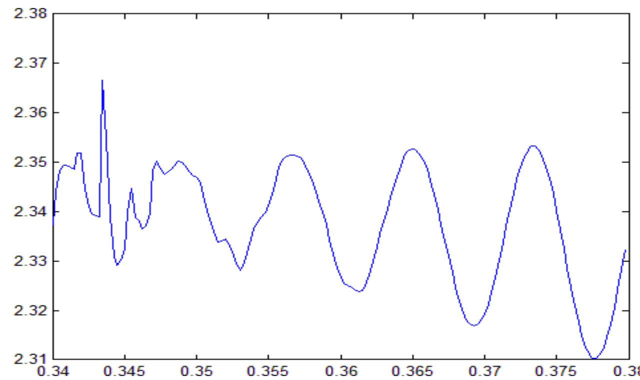
The fault is detected after 4.75 ms of fault initiation. At the time of fault inception the fault index g glows enormously high. Output shows 1 after inception of the fault and 0 before inception.



(a) A Healthy Signal g vs. t plot



(b) LG Fault I2 VS t with Low Resistance (0.1Ohm)



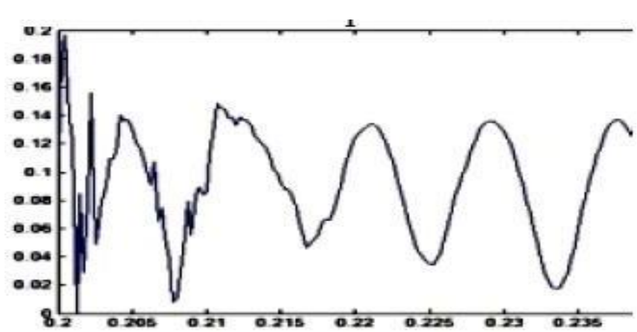
(c) LG Fault I2 vs. t with High Resistance (100 Ohm)

Fig. 3 (a, b, c) Performance Analysis of a Healthy System with a system contains LG Fault

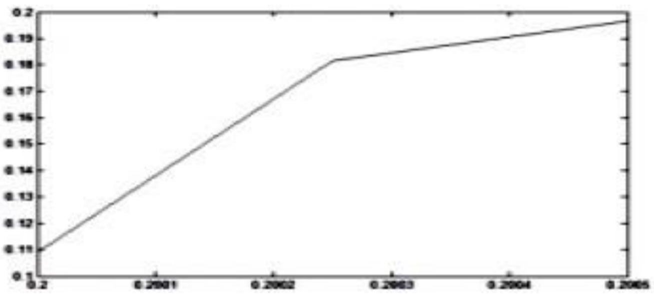
of a faulty system there must be a sharp rise in the plot.

B. Fault Detection during Single-Pole Tripping

Initially phase-a of Line-1 is out of service following an ag- fault occurring during normal operation. It introduced swing into the system. A line-to-ground fault of bg-type with a fault resistance 100 Ohm is created at 0.2s at a distance of 160 km from the relay location toward bus N during swing. For this case, and the fault detection is possible after 0.6-ms fault inception.



(a) g vs. t during single pole tripping



(b) I2 vs. t during single pole tripping

Fig. 4 (a, b) Performance Analysis during Single Pole Tripping

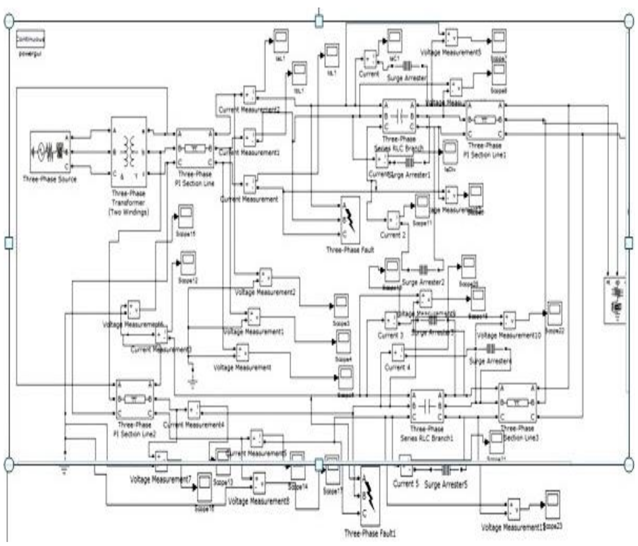


Fig. 5 Simulink Implementation of SMIB Test System

Result Analysis

Here the analysis of proposed methodology is perform by existing technique using various measuring parameters such as MSE, RMSE and accuracy.

Mean Absolute Error (MAE)

It is the difference between the measured value and "true" value.

The formula for the absolute error (Δx) is:

$$(\Delta x) = x_i - x,$$

Where:

- x_i is the measurement,
- x is the true value.

Table 1 : Comparison of proposed and existing method using Mean Absolute Error

	MAE	
Case	**Proposed Method**	**Existing Method (MLP)**
1	0.025	0.159
2	0	0.201
3	0.033	0.172
4	0	0.155

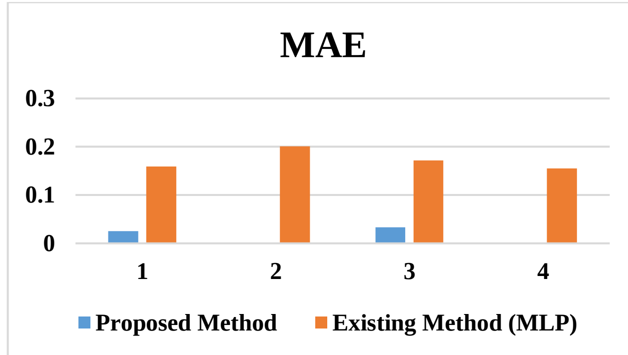


Fig. 6 Comparison of proposed and existing method using Mean Absolute Error

Root Mean Square Error (RMSE)

It is a measure of total error defined as the square root of the sum of the variance and the square of the bias that is a frequently used measure of the differences between values predicted by a model.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(Predicted_i - Actual_i)^2}{N}}$$

Table 2 : Comparison of proposed and existing method using root mean square error

	RMSE	
Case	**Proposed Method**	**Existing Method (MLP)**
1	0.088	0.236
2	0	0.292
3	0.097	0.248
4	0	0.227

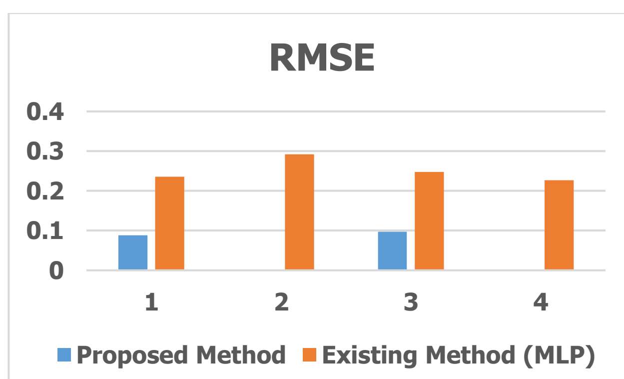


Fig. 7 : Comparison of proposed and existing method using root mean square error

Accuracy
The ability of an instrument to measure the accurate value is known as accuracy. In other words, it is the closeness of the measured value to a standard or true value.
Accuracy= 100%- error rate
Error rate= [(Observed value- Actual value)/Actual value] *100

Table 3 : Comparison of proposed and existing method using accuracy

	Accuracy	
Case	**Proposed Method**	**Existing Method (MLP)**
1	100	80
2	100	60
3	100	60
4	100	80

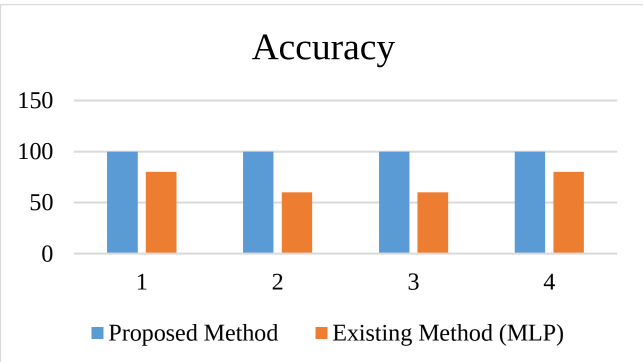


Fig. 8 : Comparison of proposed and existing method using accuracy

6. Conclusion

The study made on Power Swing Protection of Series Compensated Transmission Line with Fault Detection Classification and Location leads to the following conclusions.

- Fault Detection, Identification, Location and Classification Including detection of the phase of the fault can be possible by the study of the properties of voltage and current waveforms generated by it in both normal and power swing conditions. The Test Systems used here SMIB and Multi-Machine-9- Bus System. By sampling of Voltage and Current Waveform and by doing certain mathematical Analysis all the above parameters including fault inception time can be predicted.
- The Estimated fault Zone can be predicted and analysis of all types of fault can be done using LG, LLG, LLLG, LL and LLL fault.

With the information and the knowledge available, by the study made on Fault Detection, Location, Classification of series compensated transmission line during power swing condition, the following points can be added for the extended work that can be carried out on the thesis.

- The Study of Close-in fault and Auto-fault Protection Scheme.
- Study of the same problem with higher test systems than 9-bus can be done.

The same work can be done with more precise methodology and accuracy.

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