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A Review on Power Swing Protection of Series Compensated Transmission Line

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Abstract

Due to a variety of factors, including protection issues, voltage/current inversion, sub-harmonic oscillations, and transients—especially when there is series compensated modulation of voltage and current waveforms with swing frequency—fault detection during power swing conditions is a challenge for the stable operation of power systems. This study suggests a negative-sequence current-based method for identifying the presence of a fault, its classification, its estimated zone and location, and its time of occurrence relative to the system reference clock in a series compensated line. For fault detection various techniques has been developed and a lots of work has been done in this field. In this paper, we present the review of literature for the fault detection in transmission lines.

Keywords: *Transmission line, Fault, Series compensated.*

1. Introduction

The High Priority Incremental Load Study (HPILS) was initiated in 2013 to develop a long range plan that identified system reinforcements required in the Southwest Power Pool (SPP) footprint in order to accommodate the unprecedented load growth that had not been identified by previous planning studies. This rapid expansion of load was brought about by an increase in the development of oil and gas fields, the firming of previously interruptible loads and an increase in the forecast expansion of major industrial loads.[1]

As part of the HPILS process, initial screening of options by SPP staff suggested that 50% series compensation (SC) should be considered on the existing Tolk – Eddy Country 345kV line as part of a potential EHV solution set to address the reliability needs associated with large load additions in southeast New Mexico and west Texas. Due to the fact that the proposed solution would introduce the first series compensated line in the SPP footprint, significant concerns and uncertainties were expressed about the merits and implications of adding SC to existing or planned EHV lines in SPP.[2-3]

Series compensation has been in use in electrical networks worldwide since the 1950s. It is a tried and true technology that continues to grow in popularity as an effective means of resolving a number of network issues such as:

- Improving transient system performance of the system following system disturbances by reducing rotor angle difference between generators;
- Compensating for reactive power losses in transmission lines to better regulate system voltages;
- Modifying and improving the balance of power flows between adjacent transmission corridors by changing impedances, similar in effect to phase shifting transformers and HVDC;
- Damping of system oscillations when used with actively controlled Thyristor Controlled Series Capacitors (see Section 2.3); and
- Mitigating geomagnetic induced currents by blocking low frequency current flow.

By addressing the above issues with less capital intensive solutions such as series compensation, the capacity of existing transmission lines can be increased thereby allowing for the deferral of major transmission line investments and the optimization of total build out. This permits better management of risk through the preservation of right of ways and corridors for future needs using an option that requires minimal permitting and siting requirements.

Overall asset utilization increases and losses are lowered. Series compensation improves system reliability while minimizing the impact on rate payers.

The various sub synchronous interactions between the network and the series capacitor are well known phenomena and there are a variety of ways available to counter-act them.

The literature on the topic is extensive and the techniques are well documented and their relative merits are discussed at length.

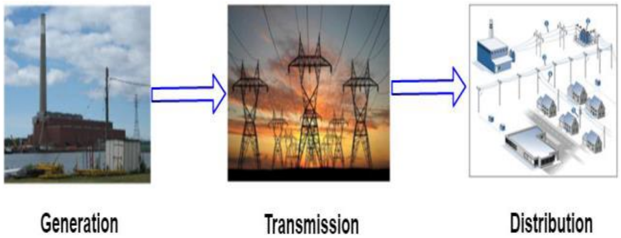

Figure 1 Traditional power system structure

The main objective of a 'protection system or scheme' is to keep the power system stable by isolating only the components that are under fault, whilst leaving as much of the network as possible still in operation. Thus, protection schemes must apply with very practical and pessimistic approach to clearing system faults. 'Protection devices' are the devices used to protect the power systems from faults. There are so many protection systems available namely 'Differential', 'Directional', 'Distance', 'Over-current' and 'Over-voltage' etc. Dependability, Security, Reliability, Selectivity, Sensitivity and Speed are performance measures for any protection system, to use in power systems.

2. Review of Literature

Anup Kumar (2022) proposed a hybrid scheme for transmission 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. 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].

3. Problem Statement

Series compensation is a common practice to reduces the electrical distance of transmission lines, and this is beneficial in improving the stability of a power grid. With the gradual promotion of UHV long-distance transmission in China, the application of series compensation is more and more extensive. Therefore, it is necessary to study the influence of series compensation on out-of-step oscillation characteristics and the reliability of out of step oscillation separation devices. At present, to solve the problems caused by the application of series compensation to the secondary equipment, power engineers around the world have undertaken a lot of theoretical and practical research. Most of it has focused on the Field of relay protection [11–13], while there have been only few studies on the reliability of out-of-step oscillation separation devices,

4. Series Compensation

Fixed Series Compensation (FSC)

A fixed series compensation installation consists of a parallel combination of capacitors, over-voltage protection, and a bypass breaker, which are all installed on an elevated platform insulated to the line voltage. The FSC main circuit components are shown in Figure 2. The capacitor bank is usually rated to line currents associated with normal peak power flow and power swing conditions[14-20]. Rating the capacitor banks to current and voltage levels associated with fault conditions is generally not considered economical and over voltage protection is provided to limit the voltage across the capacitor during fault conditions. The over voltage protection typically consists of two parts:

- A zinc oxide varistor (MOV) with highly non-linear characteristics that conducts negligible current during normal operation and conducts freely once the voltage across it reaches the protection level thereby bypassing the capacitor bank. The MOV is built up of individual MOV blocks placed in series to obtain the desired voltage protection level and in parallel to be to absorb the desired energy during faults. If the fault is cleared without the ratings of the MOV being exceeded, the MOV will stop conducting once the voltage across it drops below the protection level and the capacitor will return to normal operating conditions.
- A fast protective device (FPD) that can be triggered for certain fault conditions such as faults on compensated line segments or for extreme faults when the energy absorbed by the MOV exceeds rated values. Fast protective devices have typically consisted of triggered air gaps although new technologies are being introduced that use arc-plasma injectors in parallel with a fast contact to avoid the difficulty of correctly distancing and maintaining the electrodes in the air gap. The bypass breaker is normally in the open position and can be used to switch the series capacitor in or out during planned operations. It also serves to bypass the series capacitor, MOV and FPD if the fault is not cleared within a pre-determined time. It must be able to carry the rated MOV voltage as well as the maximum capacitor discharge current. Bypass breakers are specially designed and rated to withstand the higher transient frequency and interrupting currents when bypassing a series capacitor. Bypass breakers are normally SF6 puffer type with controls at ground level.

A damping circuit - usually an air core reactor - is placed in series with the FPD and the by-pass breaker to limit and dampen capacitor discharge currents when the FPD triggers or the bypass breaker is closed.

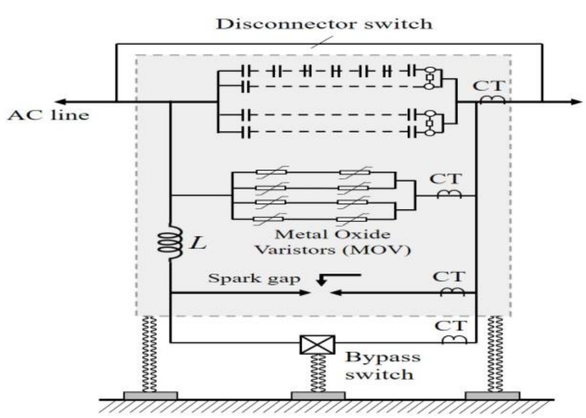

Fig. 2-Fixed Series Compensation System

Thyristor Controlled Series Compensation (TCSC)

A thyristor controlled series compensation installation typically consists of two modules connected in series:

- A fixed series compensation module (as described above), and
- A module consisting of a series capacitor in parallel with a thyristor controlled, air core reactor.

As with the FSC, the TCSC is platform mounted and insulated at line voltage. A TCSC installation can be green field or thyristors can be added to control part or all of an existing FSC installation [2].

When the thyristor gate is blocked, full current flows through the capacitance and the line is fully compensated. When the thyristor gate is fully conducting, the capacitor is effectively bypassed. If the valves are gated for partial conductance, it is possible to smoothly vary the impedance of the TCSC. Over-voltage protection is assured by the connection of an MOV across the capacitor [21-24]. A bypass breaker or disconnect is generally included to allow for maintenance and better over-voltage protection. Depending on the network requirements TCSC installations may be 100% variable although most typically have a fixed level of compensation combined with a variable level of compensation as shown in Figure 3. This allows the cost to be optimized by only controlling the series capacitance that provides reliability or other benefits. The controlled part can be scaled as required.

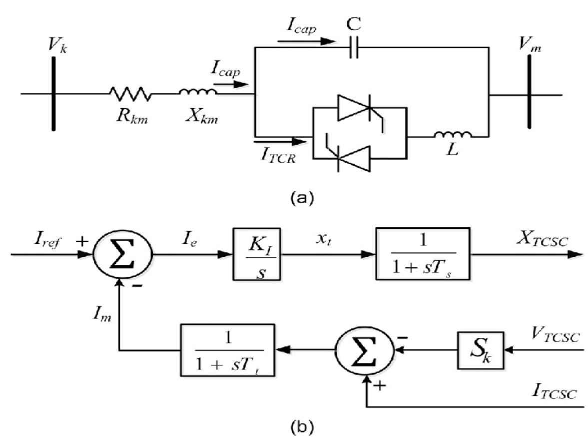

Fig. 3 Thyristor Controlled Series Compensation (TCSC).

5. Matrix Laboratory (MATLAB)

MATLAB is a programming language developed by MathWorks. It started out as a matrix programming language where linear algebra programming was simple. It can be run both under interactive sessions and as a batch job. This tutorial gives you aggressively a gentle introduction of MATLAB programming language. It is designed to give students fluency in MATLAB programming language. Problem-based MATLAB examples have been given in simple and easy way to make your learning fast and effective.[15]

It allows matrix manipulations; plotting of functions and data; implementation of algorithms; creation of user interfaces; interfacing with programs written in other languages, including C, C++, Java, and FORTRAN; analyze data; develop algorithms; and create models and applications.
It has numerous built-in commands and math functions that help you in mathematical calculations, generating plots, and performing numerical methods. MATLAB allows writing two kinds of program files −

- Scripts − script files are program files with .m extension. In these files, you write series of commands, which you want to execute together. Scripts do not accept inputs and do not return any outputs. They operate on data in the workspace.
- Functions − functions files are also program files with .m extension. Functions can accept inputs and return outputs. Internal variables are local to the function.

Features of MATLAB

Following are the basic features of MATLAB −

- It is a high-level language for numerical computation, visualization and application development.
- It also provides an interactive environment for iterative exploration, design and problem solving.
- It provides vast library of mathematical functions for linear algebra, statistics, Fourier analysis, filtering, optimization, numerical integration and solving ordinary differential equations.
- It provides built-in graphics for visualizing data and tools for creating custom plots.
- MATLAB's programming interface gives development tools for improving code quality maintainability and maximizing performance.
- It provides tools for building applications with custom graphical interfaces.
- It provides functions for integrating MATLAB based algorithms with external applications and languages such as C, Java, .NET and Microsoft Excel.

Uses of MATLAB

MATLAB is widely used as a computational tool in science and engineering encompassing the fields of physics, chemistry, math and all engineering streams. It is used in a range of applications including −

- Signal Processing and Communications
- Image and Video Processing
- Control Systems
- Test and Measurement
- Computational Finance
- Computational Biology

5. Conclusion

Fault detection during power swing condition is a challenge for stable operation of power system due to several reasons. In this paper, we present the review of literature in the field of power swing transmission line fault detection and presented the types of compensations. We also discusses about the MATLAB which is a powerful tool to simulate the electrical system which is used for various applications of Electrical. In future work, we will develop such technique which can detect the fault effectively in power swing condition and will be implemented in MATLAB toolbox.

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