



# A non-unit protection scheme for double circuit series capacitor compensated transmission lines



Aleena Swetapadma<sup>a</sup>, Praveen Mishra<sup>b</sup>, Anamika Yadav<sup>b</sup>, Almoataz Y. Abdelaziz<sup>c,\*</sup>

<sup>a</sup> School of Computer Engineering, KJ Somaiya Institute of Technology, Bhamburda, Mumbai 400 072, India

<sup>b</sup> Department of Electrical Engineering, National Institute of Technology, Raipur 492010, Chhattisgarh, India

<sup>c</sup> Electrical Power and Machines Department, Faculty of Engineering, Ain Shams University, Egypt

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## ABSTRACT

This paper presents a non-unit protection scheme for series capacitor compensated transmission lines (SCCTL) using discrete wavelet transform and k-nearest neighbor (k-NN) algorithm. All the protective relaying functions such as fault detection, fault classification, faulty phase identification and fault location estimation have been considered in this work. Such a comprehensive work providing all protective relaying functions for protection of double circuit SCCTL utilizing k-NN has not been reported so far. The signal processing and feature extraction are done using discrete wavelet transform due to its capability to differentiate between high and low frequency transient components. For fault detection and classification, only approximate wavelet coefficient of current signal up to level 1 has been used; while for k-NN location estimation, both voltage and current signals of the two circuits are decomposed up to level 3 have been used. Finally, the standard deviation of one cycle pre-fault and one cycle post-fault samples of the approximate wavelet coefficients are calculated to form the feature vector for the k-NN-based algorithm. The performance of the proposed technique is evaluated for large number of fault events with variation in fault type including inter-circuit faults, fault inception angle, fault location and fault resistance. The change in position of series capacitor and different degree of compensation has been discussed. The accuracy of the proposed k-NN-based fault detection and classification module is 100% for all the tested fault cases with a decision period of less than half cycle. The k-NN-based fault location scheme estimates the location of fault with  $\leq 1\%$  error for most of the tested fault cases, which is an exceptional attribute of the proposed scheme as compared with 10–15% error of conventional distance relaying scheme.

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## 1. Introduction

Series compensation involves insertion of reactive power element in series with the transmission lines to increase power transferring capacity, improve the system transient stability, voltage control, power flow control and reduce losses [1]. But protection of parallel SCCTL is more complicated than uncompensated lines due to mutual coupling, variable fault impedance loop, inter-circuit faults, remote infeed, etc. A complete protection scheme for SCCTL involves detecting the faults, identifying the fault type and phase(s) and locating the fault for speedy repair of the transmission lines. Several techniques have been reported for fault detection and classification in series compensated transmission lines till date. Wavelet transform has been used widely in power system tran-

sient analysis during past one decade [2]. Wavelet packet-based digital relaying for advanced series compensated line is proposed in Ref. [3], but this method is based on thresholding which may not be a sufficient criterion for protection of parallel SCCTL due to mutual coupling effect. The authors of Ref. [4] has proposed the fault detection, classification and faulted phase selection approach based on high-frequency voltage signals for series-compensated line. High-speed superimposed-based protection of SCCTL is discussed in Ref. [5]. Application of extreme learning machine for SCCTL protection is demonstrated in Ref. [6] with 96.53% accuracy of fault classification scheme and this method requires large number of neurons in the hidden layers. Artificial neural-network-based protection scheme for controllable series-compensated EHV transmission lines is demonstrated in Ref. [7]. But it gives better output only with two or three cycle post-fault data. A modern approach for protection of series compensated lines is proposed in Ref. [8]. Support vector machines are also applied for fault classification in SCCTL as demonstrated in Ref. [9,10]. Wavelet transform in com-

\* Corresponding author.

E-mail address: [almoatazabdelaziz@hotmail.com](mailto:almoatazabdelaziz@hotmail.com) (A.Y. Abdelaziz).

### Nomenclature

$\Phi_i$	Fault inception angle
AC	Alternating current
ANN	Artificial neural network
DWT	Discrete wavelet transform
EHV	Extra high voltage
k-NN	k-Nearest neighbor
SCCTL	Series capacitor compensated transmission lines

combination with fuzzy logic [11] and in combination with adaptive neuro-fuzzy inference system [12] is proposed for classification of fault in series compensated lines. Decision tree-based fault classification in flexible AC transmission line is demonstrated in Ref. [13]. A wide-area back-up protection and faulted line identification scheme for series-compensated power transmission network is proposed in Ref. [14]. A Chebyshev neural network-based improved artificial intelligence technique for fault classification of series compensated transmission line is proposed in Ref. [15]. However, all the above methods [2–15] only detect and classify the faults in SCCTL and do not find the location of the fault which is equally important to initiate the repair work as early as possible in order to reduce the down time.

Fault location estimation in SCCTL becomes more complicated due to appearance of non-linear current-dependent circuit between substation and fault point. Algorithms for locating faults on series compensated lines using neural network and deterministic methods is proposed in Ref. [16]. Wavelet and ANN is used for fault location of thyristor controlled series compensated lines in Ref. [17]. In [18] wavelet packet decomposition and support vector machines have been utilized for fault location estimation in fixed series compensated lines. An accurate fault location algorithm using synchronized voltage and current phasors of both the ends is proposed in Ref. [19]. Fault location method using measurements of differential relays for parallel transmission lines with series capacitor compensation at both ends is discussed in Ref. [20]. In past decades, phasor measurement units (PMU) are being used by researchers for obtaining the signals [21,22]. In SCCTL measured current and voltage signals include considerable sub-synchronous frequency components which are not sufficiently damped within a typical fault clearing time, which may lead to inaccurate phasor estimation. An accurate algorithm which filters unwanted frequency components and noise to estimate accurate phasors for fault location in series-compensated lines is proposed in Ref. [23]. Fault location of uncompensated/series compensated lines using two-ends synchronized measurements are proposed in Ref. [24]. It is worth to mention here that only a single paper has been reported till date employing k-NN for fault location estimation in transmission line [25]. Here k-NN algorithm has been applied for only single line to ground fault location estimation in un-compensated single circuit transmission line. However, this technique does not take into account other types of shunt faults and it is not applicable for series compensated line. Furthermore, cases of inter-circuit faults and mutual coupling effect of double circuit line were not considered. A fault location method for multi-circuit series compensated line using phasor data from intelligent electronic devices available at both ends is proposed in Ref. [26]. An impedance-based supplementary fault-location algorithm for series capacitor-compensated transmission lines has been reported in Ref. [27]. A fault location estimation scheme using artificial neural network is proposed in Ref. [28] for multi-location faults, transforming faults and shunt faults in SCCTL. As per recent survey on different protection schemes reported for series compensated transmission line [29], it has been evident that protection of mutu-

ally coupled series compensated lines is more complicated due to the effect of mutual coupling between parallel lines. As will be discussed later in this paper, all the aforementioned limitations will be overcome in this work.

In this paper, combined discrete wavelet transforms and k-NN algorithm-based fault detection, classification and location schemes have been proposed for mutually coupled SCCTL. Such a comprehensive work, providing all protective relaying functions for protection of double circuit SCCTL utilizing kNN, has not been reported so far. In order to develop the kNN algorithm and to evaluate the proposed scheme, a double circuit series compensated transmission line network is modeled and simulated in MATLAB Simulink's Simpowersystem toolbox [30]. Signal processing and feature extraction are done with discrete wavelet transform. kNN algorithm is used as pattern recognizer for fault detection, classification and location estimation. The rest of this paper is organized as follows. Section 2 briefly describes the k-NN algorithm; in Section 3, the implementation of DWT and k-NN-based fault detection, classification and fault location estimation schemes are presented. The simulation results and discussion are given in Section 4, and Section 5 concludes the paper.

## 2. k-Nearest neighbor (k-NN) algorithm

k-NN has been used in different fields of engineering such as medical signal processing, intrusion detection system, power system protection, etc. In this work, k-NN is used because it is very simple and easy to implement. k-NN algorithm works by obtaining the nearest neighbor of unknown sample based on certain distance. k-NN algorithm is a simple supervised learning algorithm which calculates the outputs by comparing the unknown sample with its nearest neighbors. The notation “k” represents the number of nearest neighbor. k-NN algorithm consists of two stages: training and testing. The training data set comprises different attributes or features that contribute to define the problem. Each data represents a point in an  $n$ -dimensional space where  $n$  is the number of attributes. The training data are stored in an  $n$ -dimensional pattern space. The number of nearest neighbors “k” is chosen and k-NN classifier then searches the pattern space for the  $k$  training samples that are closest to the new test data [31] based on distance matrices. In nearest-neighbor classification, both distance metric (“nearest”) and number of neighbors can be altered. After checking the performance of algorithms with different distance matrices e.g. Euclidean distance, city block metric, Minkowski distance and Chebychev distance; finally Euclidean distance matrix has been used in this work. The Euclidean distance between two samples,  $X1 = (x_{11}, x_{12}, \dots, x_{1n})$  and  $X2 = (x_{21}, x_{22}, \dots, x_{2n})$ , can be given as follows:

$$\text{dist}(X1, X2) = \sqrt{\sum_{i=1}^n (x_{1i} - x_{2i})^2} \quad (1)$$

In k-nearest-neighbor classification algorithm, the unknown sample is assigned to the most common class among its  $k$  nearest neighbors. Fault detection and classification in this work are carried out using k-NN classification algorithm. k-NN algorithm can also be used for prediction/approximation tasks that means it can be used to return a real-valued prediction for a given unknown sample. For value prediction/approximation problems, the classifier returns the average value of the real-valued labels associated with the  $k$  nearest neighbors of the unknown sample. This is also called as k-NN regression algorithm and it is used in this work for fault location

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