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Optimized echo state networks using a big bang–big crunch algorithm for distance protection of series-compensated transmission lines

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A B S T R A C T

Distance protection of transmission lines compensated by Thyristor-Controlled Series Capacitor (TCSC) suffers malfunction due to series variable voltages injected by TCSC. To mitigate the problem, echo state networks (ESNs) are used in this paper through the voltage compensation technique by subtracting estimated TCSC voltages from measured phase voltages where fault loop observed by the relay contains TCSC. The design parameters of ESNs are optimized using a big bang–big crunch (BB–BC) algorithm with an especial random generation scheme in big bang phase. Main features of our study are: (a) only locally measured phase currents at the relaying point is used, assuming firing angles and other variables of TCSC are not accessible there; and (b) high accuracy of estimations is achieved using optimized ESNs for a large number of test cases. The method is tested on a 400 km, 500 kV line for all fault types using Matlab/Simulink. Tests for 7680 cases with varying fault resistance, fault inception-angle, fault location, load angle and compensation degree show much improved accuracy of estimations by ESN in comparison to time-delay neural network (TDNN), radial basis function neural network (RBFNN), nonlinear autoregressive network with exogenous inputs (NARX) and Elman network particularly at instants immediately after fault incidence. The effectiveness of the ESN-based method is examined using two distance relay algorithms.

1. Introduction

Thyristor-Controlled Series Capacitor (TCSC) may be applied to transmission lines to boost power transfer capability, damp power oscillations, mitigate subsynchronous resonance, enhance transient stability and voltage profiles [1]. However, the presence of TCSC affects the performance of line distance protection due to injecting variable voltages in series with the line thereby causing the measured impedance to change as studied in [2,3]. The consequent overreach/underreach protection eventually leads to loss of security/dependability. TCSC is often equipped with parallel protection devices such as metal oxide varistor (MOV) and bypass circuit breaker that complicate the behavior of the injected voltages under different conditions. When fault loops observed by the relay contain no TCSC, the fault current consists of decaying DC component in addition to steady state fundamental component and high frequency components [4]. When fault loops contain TCSC, non-fundamental decaying components and odd harmonics (due to MOV conduction) are also observed in the fault current [4]. Such voltages and currents cause the mitigation of the TCSC impact on distance protection of series-compensated transmission lines to be difficult. There are some approaches proposed in the literature to mitigate such an impact of series compensators. A protection scheme based on traveling waves was used in [5]. Also, a method for swiveling relay characteristic was proposed in [6]. However, no multiphase fault was considered in both works. An adaptive Kalman filter-based protection scheme was developed in [7]. But the fault resistance was not modeled, and the impedance between relay and fault point was evaluated only for bypass mode of TCSC. A fault location method that uses instantaneous signals directly instead of their estimated phasors was proposed in [8]. But the MOV conduction was not modeled. In [9], wavelet transform (WT) was used for protection of series compensated lines. But, the sampling frequency in this approach is rather high (200 kHz) for practical implementations. A combination of WT and support vector regression was proposed in [10] for fault location. The sampling frequency of 12.8 kHz used in this approach is more practical, but the scheme has been applied only for lines compensated by series capacitors. A *voltage compensation technique* was proposed in [11] for distance protection of transmission lines compensated by *series fixed capacitors*. Instantaneous voltages across the combination of capacitors and their parallel MOVs are estimated on-line and then subtracted from phase voltages measured at the relaying point when fault loops contain the capacitors. The simplicity is the main advantage of this technique. However a linear model is used while

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MOV is conducting during fault. Feed forward artificial neural networks (ANNs) were used in [12] for on-line estimation of voltages across series capacitors. They have also been used for distance protection of lines with and without compensation [13–17]. The extreme learning machine was used in [18] to train feed forward ANNs while combined with WT for fault location as well as fault section identification and classification in transmission lines compensated by series capacitors. As feed forward ANNs have no feedback, they are more suitable to learn static input–output relationships. For learning complex dynamic behaviors, for example time series, they most often use time-lagged inputs and are called time-delay neural networks (TDNNs). They often need a relatively large training set as well as a sufficient number of lagged inputs to reach acceptable results. Sometimes the selection of inputs among a number of lagged inputs is important so that correlation analyses are used for this purpose. In [19], such correlation analyses were used to find the lagged inputs with high correlations to outputs and low correlations to other selected lagged inputs. These analyses are however time-consuming and impose much burden. Radial basis function neural networks (RBFNNs) were used in [20] for distance protection of series compensated lines in a straightforward manner. Also, they were employed through the voltage compensation technique in [21] for distance protection of series-compensated transmission lines. Recurrent neural networks (RNNs) that resemble biological neural networks very closely are more appropriate to estimate dynamic behaviors. They benefit feedbacks from hidden and output layers to input and hidden layers, and can thus theoretically model any complex dynamic system. But their training is often complex. RNNs were used in [22] for distance protection of transmission lines without compensation. The concept of *reservoir computing* has been used to make RNN training very simple and fast thereby producing other RNN paradigms like echo state networks (ESNs) [23]. The ESN includes a fixed reservoir of randomly connected neurons in hidden layer generated before training stage and requires only a simple training for readouts. It is capable to learn complex nonlinear dynamic behaviors in a brief time with high accuracy using a small number of input neurons. As the ESN has recently attracted much attention and has been successfully applied to some fields [24–30], its application to distance protection of series-compensated lines using minimum inputs is needed to be investigated.

This paper presents the application of the ESN through the voltage compensation technique for distance protection of transmission lines compensated by TCSC. ESNs estimate instantaneous phase voltages across the combination of TCSC and its associated protections using only locally measured phase currents at the relaying point without any access to variables of TCSC. The estimated voltages are subtracted from phase voltages measured at the relaying point when fault loop contains TCSC. The method is tested on a 400 km, 500 kV series-compensated line with TCSC at the midpoint for all ten types of fault with varying fault resistance, fault inception-angle, fault location, load angle and compensation degree. The results of estimated TCSC voltages using ESN are first compared with those of TDNN. Next, the comparison is made between ESN and other three ANNs, namely RBFNN, NARX network and Elman network for estimation of TCSC voltages. Two digital distance relay algorithms are implemented using the ESN-based voltage compensation method, and obtained impedances are investigated with emphasis on the first zone protection.

2. Structure and operation of the TCSC

TCSC consists of a fixed capacitor in parallel with a thyristor-controlled reactor (TCR). The current through the reactor is controlled by firing angle α of thyristors measured from the zero-crossing of the fundamental line current at each half-cycle. The steady-state variable impedance of TCSC is depicted in Fig. 1(a) while α changes from zero (fully closed thyristor valve) to 90° (open thyristor valve) [1]. TCSC is normally operated in the capacitive region avoiding an inhibited region around parallel resonance. Firing thyristors at angles less than 90° causes a current flow through the TCR that is opposite to the capacitor current. This loop current causes the voltage across the capacitor to increase by reversing its polarity about zero-crossings thereby increasing the overall series compensation degree. In the capacitive region, gradual decrease in the firing angle causes the loop current and the compensation degree to increase further. This operation mode of TCSC is called capacitive-boost mode. TCSC is equipped with parallel protective devices like MOV and bypass circuit breaker as shown in Fig. 1(b). The MOV output characteristic is often approximated by $i_{MOV} = I_{REF}(u_{MOV}/U_{REF})^q$ [31] where i_{MOV} and u_{MOV} are MOV current and voltage, respectively. I_{REF} and U_{REF} are MOV reference values, and q is the exponent. The MOV prevents high capacitor overvoltages at high levels of fault currents. The bypass circuit breaker operates in abnormal system conditions, equipment malfunction and to prevent the MOV from overheating. The current limiting inductor L_d in series with the bypass circuit breaker restricts the current when the circuit breaker operates. As described in [2], there are different operation modes of TCSC during fault conditions as:

2.1. Mode1 – Capacitive-boost mode without MOV conduction

For low levels of fault currents while the capacitor voltage is within the safe range, TCSC remains constantly in its capacitor-boost mode without any conduction of protection devices.

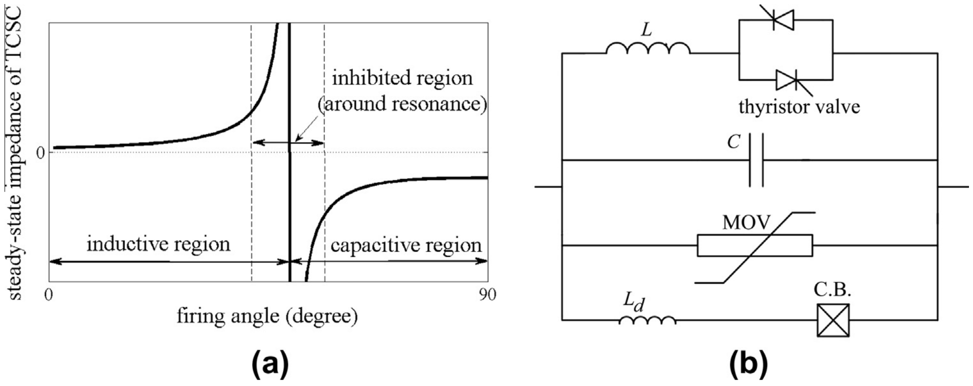

Fig. 1. (a) Plot of steady-state TCSC impedance versus thyristor firing angle and (b) TCSC and its associated protections.