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Differential Protection of ISPST Using Chebyshev Neural Network

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Abstract- *An Indirect Symmetrical Phase Shift Transformer (ISPST) represents both electrically connected and magnetically coupled circuits, which makes it unique compared to a power transformer. Effective differentiation between transformer inrush current and internal fault current is necessary to avoid incorrect differential relay tripping. This research proposes a system that uses a Chebyshev Neural Network (ChNN) as a core classifier to distinguish such internal faults. For simulations, we used PSCAD/EMTDC software. Internal faults and inrush have been simulated in various ways using various ISPST parameters. A large, simulated dataset is used, and performance is recorded against different sized ISPSTs. We observed an overall accuracy greater than 99%. The ChNN classifier generated exceptionally favorable results even in case of noisy signal, CT saturation, and different ISPST parameters.*

Keyword: Energization; Internal Fault; Chebyshev Neural Network (ChNN); ISPST; PSCAD/EMTDC.

1. INTRODUCTION

Phase Shifting Transformers (PSTs) are commonly employed to regulate active power flow through the complex transmission network. Compared to flexible alternating current transmission system devices for controlling power flow in an interconnected network, PST offers a cost-effective and dependable option. PSTs are available in both direct and indirect designs, and they may also be divided into two categories: symmetrical and asymmetrical [1][2]. A symmetrical PST modifies the PAS without altering the voltage amplitude about the input voltage. Still, an asymmetrical PST changes the voltage amplitude while altering the PAS, which might result in an alteration of the reactive power flow [3]. The benefit of prior PSTs over later PSTs is that the PAS is the only parameter that impacts the flow of power in the system (Eq. (1)).

$$P = \frac{|V_S||V_L|}{X_T}\sin(\delta \pm \Delta\theta) \quad (1)$$

Where, V_S and V_L are two ends voltages of ISPST, δ is PAS between V_S and V_L, $\Delta\theta$ is PAS due to ISPST. As seen in Fig. 1, ISPST is extensively utilized because of its characteristics and ease of fabrication.

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Research paper

To safeguard both power transformers and PSTs, the Differential Protection (DP) technique has been widely deployed. Numerous current-based strategies for various types of PSTs have been reviewed in the literature section [4- 7]. DP of an ISPST and Delta-hexagonal PSTs has been discussed in [5, 8]. [8] has done the hardware implementation of the previously proposed technique which is based on the Kirchhoff's current law and magnetic coupling. However, the method fails to operate in case of turn-to-turn fault because it follows Kirchhoff's current law even in case of inter turn fault. DP may be affected by un-faulted conditions such as magnetizing inrush current and non-standard phase shift of an ISPST that can result in false tripping of the differential relay. To avoid this condition, Harmonic Restraint (HR) methods, based on the second harmonic component, are used widely [5] [9]. [10] presents a technique for the protection of PST based on the conventional method. Time taken for the protection is less than two-cycles. The disadvantage of the discussed approach is that the second harmonics component is used to restraint from inrush condition. Nowadays, due to modern core material, second harmonic contents become low during the magnetizing inrush condition, affecting HR schemes' operation, [3]. Additionally, the PST protection, which relies on the voltage-current relationship and tap-changer tracking, requires the usage of a current transformer (CT) [3] [11]. [12] presents a method for the protection of transmission line considering the PST in the transmission line. In this paper, the author has modified the distance protection by considering the PST parameters. Still, the paper has not evaluated the effect of fault in the PST, which may mal-operate the relay. In recent, literature reveals that many researchers have focused on the minor faults in the transformer, which is important for security but has not discussed the impact of external fault and inrush conditions on the proposed technique [13, 14].

Furthermore, the literature reveals that Artificial Intelligence (AI) based classifier also plays a vital role in protection application due to their excellent performance in an approximation of nonlinear function [15-17]. Due to high generalization capability, Artificial Neural Networks (ANNs) have been frequently used in the power system field. In recent years, pattern categorization and protection applications have become more widespread. However, selecting the most effective neural network design for a given classification application remains a significant challenge for all forms of ANNs [18] [19]. A Chebyshev polynomial based unified model neural network for static function approximation is reported in [20]. Being a single-layer network, Chebyshev Neural Network (ChNN) possesses an advantage in design and learning complexities. Furthermore, the classifier outperforms conventional classifiers such as SVM and fuzzy logic-based systems since no performance-controlling parameter governs its performance [21]. In this research, we described a new DP method for discriminating the internal fault state from magnetizing inrush situations that takes advantage of the benefits of the ChNN. The case of magnetizing inrush following an internal fault and the effect of CT saturation during internal fault is also considered. The present technique is taken into consideration, which addresses the issue of non-standard PAS between the source and loads side by tracking the tap position of an ISPST for the DP [6]. A sampling frequency of 1 kHz is used in the suggested method, which operates with discrete samples of one cycle duration of the differential current during an internal fault situation. Test cases totaling 8489 were used to determine the algorithm’s efficacy under consideration. The suggested approach is also evaluated in the presence of 15dB Gaussian noise in differential current samples, which is a significant amount of noise. The suggested method demonstrates its superiority by achieving overall classification accuracy greater than 99 percent in the experiments.

The article is formulated with the introduction and literature review being discussed in Section 1 followed by detailed discussion on Chebyshev Neural Network (ChNN) in Section 2. The methodology of the paper and implementation of the proposed algorithm is formulated in Section 3 and Section 4 respectively. Results along with discussion is presented in Section 5 and the article is concluded in Section 6.

2. CHEBYSHEV NEURAL NETWORK

ChNN is a sort of functional link ANN (FLANN) that is based on Chebyshev polynomials (ChPs) and is used in neural networks. A flat structure with a single layer in which the hidden layers of MLP are removed by translating the input patterns to a higher dimensional space is known as a single-layer flat structure. It has the power to generalize on a global scale. Each sample of the input vector is expanded using the ChPs expansion to get the necessary number of samples in the ChNN implementation. In differential equations, ChPs are described as sets of orthogonal polynomials that are specified as solutions of the Chebyshev differential equation [22]. The ChPs converge more quickly than any other set of orthogonal polynomials compared to any different set of orthogonal polynomials. As a result, ChPs is regarded as a fundamental function of neural networks [20].

For an input *x*, the m^{th} order ChPs can be generated by the following recursive formula [23].

$$T_0(x) = 1$$
$$T_1(x) = x$$
$$T_2(x) = 2x^2 - 1$$
$$\vdots$$
$$T_{m+1}(x) = 2xT_m(x) - T_{m-1}(x) \quad (2)$$

If an input $x = [x_1\ x_2]^T$, than higher-order pattern obtained by using ChPs is given by:

$$T = [T_1(x_1)\ T_2(x_1)....T_m(x_1)T_1(x_2)\ T_2(x_2)....T_m(x_2)]^T \quad (3)$$

The basic structure of the ChNN is shown in Fig. 2. As shown in the figure, *l* dimensional input pattern $[x_1\ x_2.....\ x_l]^T$ is enhanced into a *(lm+1)* dimensional expanded pattern $[1\ T_1(x_1)......T_m(x_l)]^T$ using m^{th} order ChPs.

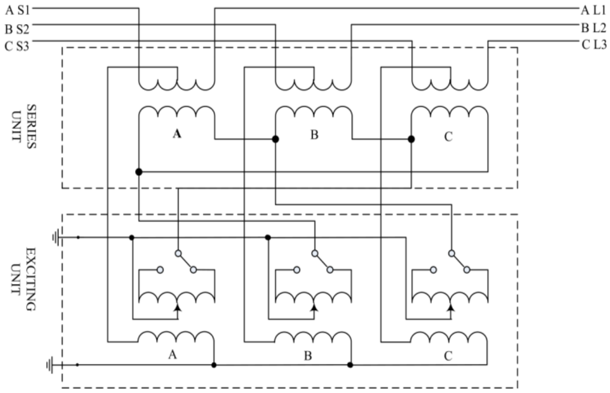


Fig. 1. Indirect Symmetrical Phase Shift Transformer

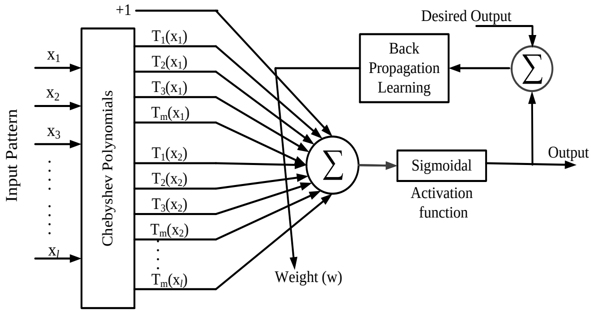


Fig. 2. Basic structure of ChNN

Initially, all of the weights in the matrix are assigned to some arbitrary values. After that, the weighted sum of the improved input is sent through an activation function to produce the desired output. The activation function is represented by a sigmoidal function in this classification issues. Since ChNN is not constrained by any regulating parameters, it consumes less memory when compared to other ANNs [23].

3. METHODOLOGY

The effectiveness of the proposed technique has been investigated for a large number of internal fault and magnetizing inrush cases. The suggested method is illustrated using a three-phase 300MVA, 138kV/138kV, 1255A/1255A, 60Hz ISPST with a maximum phase shift of 30 degrees in total 32 steps (see Appendix-A), which is regarded for illustrative purposes [24]. On both sides of the ISPST, relevant CTs with a ratio of 2000/5A (see Appendix-A), are linked in a star configuration [25, 26].

3.1. Internal Fault

Several types of faults, including turn-to-turn (TT), line-to-ground (LG), line-to-line (LL), double line-to-ground (LLG) as well as triple line-to-ground (LLLG) in series and the excitation unit of an ISPST, have been simulated using the PSCAD/EMTDC platform. According to the literature, TT faults are caused by the degradation of the insulating material as a result of mechanical, thermal, and electrical stressors on the windings. Turn-to-turn insulation failures account for 70 percent to 80 percent of all transformer failures [16]. These TT faults must be differentiated and resolved as soon as possible to prevent triggering an LG fault. Different percentages (ranging from 1 percent to 80 percent) of primary and secondary winding from the neutral terminal of both series and excitation units of an ISPST are simulated to see how TT faults manifest themselves in different situations. With variable fault inception angle and tap location and different percentages of the winding are from the neutral terminal of the winding, several forms of internal faults, including LG, LL, LLG, and LLLG are used to create internal faults in the winding. The effect of load fluctuation from no-load to full-load on different types of fault in both series and excitation units is also considered.

3.2 Magnetizing Inrush

The simulation of the magnetizing inrush situation was carried out by varying the switching angle from 0° to 330° in steps of 30°. It is also considered the load fluctuation from no-load to full-load with varying percentages of full-load. During the modeling of magnetizing inrush, residual flux is also considered, with values ranging from 10 percent to 20 percent, 30 percent to 80 percent of maximum flux at full-load. To improve the accuracy of the suggested method, the case of sympathetic inrush is also taken into consideration for the simulation.

A total of 19728 cases are simulated by considering the fault at various percentages of faulty winding and variations in other ISPST parameters. Table 1 contains the specifics of all of the instances, as well as their summary information. Table 1 further illustrates the distinction between training and testing scenarios. In this study, 10850 (55 percent of the total cases) instances are used for the training of the ChNN classifier, and 8878 (45 percent of the total cases) cases are utilized for the testing of the ChNN classifier.

Table 1. Detail of training and testing cases

Operating Conditions	No. of cases	Total no. of Cases
Internal fault	(Fault type: TT, LG, LL, LLG, LLLG (5))×(load: no-load, on load (2))×(Mode of operation: Advance mode, Retard mode(2))×(Tap position: 0.1, 0.2, 0.4, 0.6, 0.8, 1.0 (6))×(fault location: 1%, 2%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, (11))×(Fault inception angle(FIA): 0° to 330° in step of 30° (12))	15840
Magnetizing Inrush	(Load: no-load, 10%, 25%, 35%, 40%, 60%, 75%, 90%, 100% (9))×(Mode of operation: Advance mode Retard mode (2))×(Tap position: 0 to 1.0 in step of 0.2 (6))×(Switching angle: 0° to 330° in step of 30° (12))	1296
Residual Inrush	(Load: on-load, no-load (2))×(Mode of operation: Advance mode Retard mode (2))×(Tap position: 0 to 1.0 in step of 0.2 (6))×(Residual flux: 10%, 20%, 30%, 40%, 60%, 80% (6))×(Switching angle: 0° to 330° in step of 30° (12))	1728
Energization during faulty condition	(Load: on-load, no-load (2))×(Mode of operation: Advance mode Retard mode (2))×(Tap position: 0 to 1.0 in step of 0.2 (6))×(Fault type: LG (excitation unit), (LG, LLG(series unit)) (3))×(Fault and Switching angle: 0° to 330° in step of 30° (12))	864
Total no. of cases		19728
Training cases (55% of the above cases)		10850
Testing cases (45% of total cases)		8878

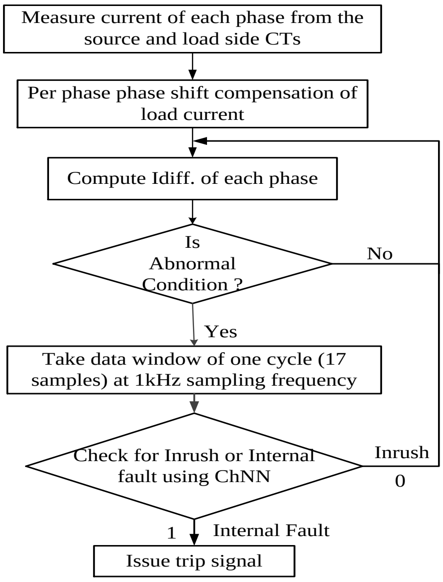


Fig. 3. Schematic flowchart of the proposed algorithm

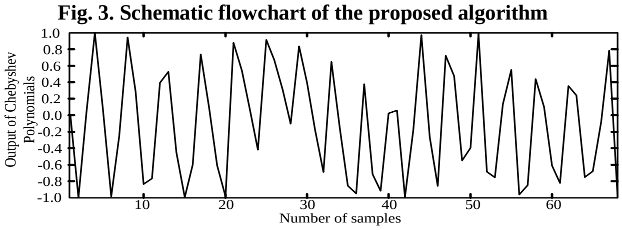


Fig. 4. Chebyshev expansion of one cycle samples of internal fault

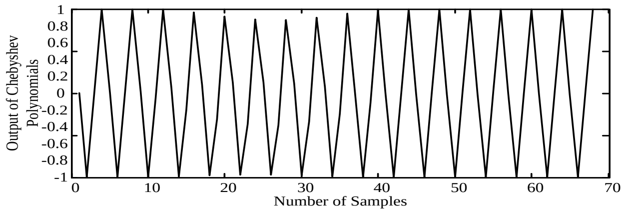


Fig. 5. Chebyshev expansion of one cycle samples of magnetizing Inrush

Table 2. Classification accuracy for the 300 MVA ISPST

Operating Condition	Type of abnormality	No. of test cases	No. of cases detected correctly	No. of cases detected false	Accuracy (%)
Internal fault (7130)	TT	713*+713**	1411	15	98.95
	LG	713*+713**	1426	0	100
	LL	713*+713**	1411	15	98.94
	LLG	713*+713**	1412	14	99.02
	LLLG	713*+713**	1421	05	99.65
Inrush (1360)	Magnetizing Inrush	291*+291**	582	0	100
	Residual Inrush	389*+389**	770	8	98.97
Energization during faulty condition (388)		194*+194**	377	11	97.16
Total Data (8878)		8878	8810	68	99.23

*Advance mode of operation, **Retard mode of operation

4. IMPLEMENTATION OF ChNN BASED ALGORITHM

The schematic flowchart of the suggested DP method, which is based on ChNN, is shown in Fig. 3. The abnormality detection approach is based on comparison of two successive peaks of differential current [16]. Whenever the abnormal condition is classified, the differential current of one cycle, sampled at frequency of 1 kHz, is considered as an input pattern for training and testing of ChNN. As seen in Figure 2, the input pattern of 17 samples of differential current is enlarged into a pattern of 68 samples by employing fourth-order ChPs in the ChNN.

Figures 4 and 5 depict the 68-dimensional extended pattern obtained by using fourth-order ChPs for one cycle of the internal fault and magnetizing inrush current, respectively, utilizing fourth-order ChPs. If the order of the Chebyshev expansion is raised, the computing burden will become more severe. Consequently, the Chebyshev expansion has been restricted to the fourth order. Using the ChNN and training case data sets, the abnormality detection approach distinguishes between normal and abnormal circumstances after it has been configured (magnetizing inrush and internal fault). In this classification algorithm, ChNN output=1 for internal fault and ChNN output=0 for inrush. Hence the classification accuracy (η) for the test cases is calculated by:

$$\eta(\%) = \frac{No.\,of\;\; cases\; detected\;\; correctly}{Total\, no.of\;\, test\, cases} \times 100\% \qquad (4)$$

5. RESULTS AND DISCUSSION

5.1. Performance Evaluation of Proposed Algorithm

As shown in Table 2, the suggested method achieves internal fault/inrush discrimination accuracy of 99.23 percent when utilizing a complete cycle data window length. This indicates that the proposed algorithm achieves an overall accuracy of 99.23 percent. Following a thorough examination of the various internal faults and inrush situations, it is evident that the LG fault and inrush conditions, which account for 70 percent to 80 percent of transformer failure, have been appropriately recognized 100 percent of the time. The lowest accuracy is found in case of the magnetizing inrush following an internal fault in any unit, which is a very critical condition of abnormality.

5.2. Performance Evaluation of Proposed Algorithm for Different Rating ISPST Performance

The performance of the proposed algorithm is also evaluated for two different sized ISPSTs (1400MVA, 400kV/400kV, 2020A/2020A, ±25°, 60Hz and 480MVA, 230kV/230kV, 1205A/1205A, ±35.1°, 60Hz) (see Appendix-A). Once again the data set is generated for both ISPSTs using PSCAD/EMTDC platform. This data set is tested on the same ChNN model trained by the data set of 300MVA ISPST. The classification accuracy of the proposed ChNN model for both ISPSTs for various cases is shown in Table 3 and found overall accuracy is more than 99%. Hence it is exciting to know that the proposed technique invariant to the rating and parameter of the ISPST.

Table 3. Classification accuracy for the other ratings of ISPST

Operating Condition	No. of test cases	No. of cases detected correctly	No. of cases detected false	%
1400MVA				
Internal Fault	4608	4576	32	99.30
Inrush	576	566	10	98.26
Total cases	5184	5142	42	99.19
480MVA				
Internal Fault	4608	4587	21	99.54
Inrush	576	570	6	98.96
Total cases	5184	5157	27	99.48

Table 4. Effect of Noise on the proposed algorithm

Operating Conditions	No. of test cases	Testing		
		With Noise		
		Detected correctly	Detected false	%
Internal fault	11660	11432	228	98.05
Inrush	1688	1641	47	97.22

Table 5. Performance evaluation considering CT saturation

Operating Conditions	No. of test cases	Detected correctly	Detected false	%
Internal fault	2880	2829	51	98.23
Inrush	389	384	5	98.71
Total accuracy (3269)				98.28

Table 6. Comparison of various Neural Networks

Type of NN	Type of architecture	No. of weight required	No. of epoch	No. of test case	No. of failure cases	Classification Accuracy	No. of post disturbance samples
ChNN	17-69-1	69	5000	13738	121	99.12	13
MLP	17-10-1	191	5000	13738	302	97.80	16
RBFNN	17-946-1	17975	1000	13738	625	95.45	15
PNN	17-15888-1	301873	1	13738	1051	92.35	16

5.3. Effect of Noisy Signal on Proposed Algorithm

With the application of electronic components in transmission and distribution systems, it is necessary to study the effect of noise on AI techniques. To analyze the performance of ChNN with noisy input signals vectors, Gaussian noise of SNR 15dB is added to simulated differential current signal samples [27]. It can be noticed from the Table 4 results that ChNN can classify the internal faults and inrush conditions efficiently even in a noisy atmosphere.

5.4. Performance Evaluation Considering CT Saturation

The proposed technique is also evaluated for the effect of CT saturation during internal fault and inrush. Source side CT is forced to saturate by considering remanent flux (up to 80%) and boosting the CT burden [28]. Table 5 shows the performance of the proposed technique, and it is found that overall accuracy is greater than 98% hence it is observed that CT saturation negligibly influences the overall classification.

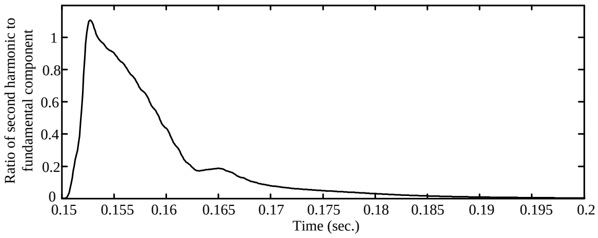
5.5. Comparisons of MLP, RBFNN, PNN, ChNN and other methods

Neural network classifiers such as MLP, RBFNN and PNN are most widely used for the classification problem. These classifiers have been applied to the same problem for the comparison with the proposed ChNN based approach. The comparison has been made on the basis of architecture, number of required weight and classification accuracy. In addition to that based on the literature, the discrimination time is an important parameter of relay operation which have also been considered for comparison. All neural network simulation studies have been carried out on MATLAB environment using an Intel(R) Core(TM) i7-2600 CPU 3.40 GHz with 16.0 GB RAM machine. No optimization technique is used in any neural network for the purpose of making the actual comparison among the various classifiers.

It is clear from Table 6 that ChNN gives better classification accuracy and takes less computation time due to less number of required weights as compare to others neural network. The proposed ChNN is capable to discriminate internal fault and inrush condition in about 3/4 cycle whereas other technique ANN network taking more time. In addition to that in recent few years some research papers have been published based on the conventional method which has also been compared. [10] presents a technique for the protection of PST based on the conventional method. Time taken for the protection is less than two cycle which is more than the proposed technique. Disadvantage of the proposed technique is that second harmonics component is used to restraint from inrush condition which causes mal-operation of relay as discussed in [3]. [8] has done the hardware implementation of the previously published technique which is based on the Kirchhoff’s current law and magnetic coupling, however the technique fails to operate in case of turn-to-turn fault because it follow Kirchhoff’s current low even in case of inter turn fault. On addition to that it requires 18 CT’s for the protection which is quite costly. Hence the proposed technique provides the better results and stability against the unfaulty conditions as compare to other methods.

5.6 Advantage of the Proposed Algorithm over Harmonic Restraint (HR) Method

As part of this study, a DFT-based harmonic restrained method using phase shift compensation was implemented to compare its performance with the proposed ChNN algorithm for discriminating internal fault from inrush condition. Figs. 6a and 6b show the ratio of the second harmonic component of the differential current to its fundamental component under typical internal fault condition and during a magnetizing inrush condition respectively. Fig. 6 reveals that in an internal fault condition during first cycle, the ratio of second harmonic to fundamental is quite greater than that during a magnetic inrush condition. Therefore, the conventional relay with harmonic restraint will malfunction in this condition. Furthermore, it can also be seen that the magnitude of the ratio varies, which makes setting a threshold difficult. Moreover, HR based technique is capable to make this classification in more than one cycle. The proposed algorithm is also immune from the different harmonics contents in operating signals which makes it simpler and robust than conventional differential techniques.



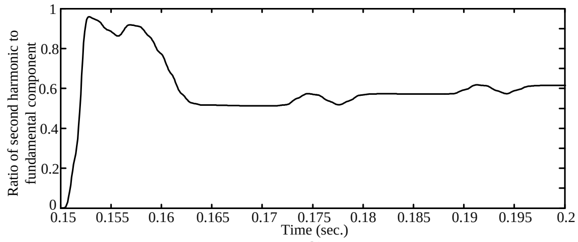


Fig. 6. Ratio of second harmonic to fundamental of the differential current under typical (a) internal fault condition (b) magnetizing inrush condition occurs at 0.15 sec

6. CONCLUSIONS

In the paper, an intelligent Differential Protection method for the protection of an ISPST is developed. The differentiation between internal fault and magnetizing inrush has been accomplished through the use of a ChNN-based classification system. Following the occurrence of an anomaly, the discrimination is carried out using complete cycle data with a sample frequency of 1kHz. All of the aspects that might have an impact on the correctness of the suggested algorithm have been taken into consideration in the current study. The suggested algorithm achieves an overall accuracy of better than 99 percent and demonstrates that it is accurate even when signal noise and varied ratings of the ISPSTs are taken into consideration.

Appendix A.

This appendix presents technical specification of simulated Indirect Symmetrical Phase Shift Transformer (ISPST) with source. The technical specifications of 300, 480 and 1400MVA ISPSTs are as follows:

A.1 Technical Specifications of 300 MVA ISPST [24]

Parameters	Value
3-phase MVA	300MVA
Rated Voltage(Line-line, RMS) 3-phase	138kV/138kV
Rated Current	1255A/1255A
Rated Frequency	60Hz
Maximum phase shift	±30°
No. of steps	32
Positive sequence impedance (at max. phase shift)	5.56Ω
Positive sequence impedance (at zero phase shift)	3.43Ω
Series Unit	
3-phase MVA	156.545
Primary winding voltage	41.579kV
Secondary winding no. of turns	61.783kV
Excitation Unit	
3-phase MVA	150 MVA
Primary winding no. of turns	76.959kV
Secondary winding no. of turns	35.69kV

A.2 Technical Specifications of 480 MVA ISPST [29]

Parameters	Value
3-phase MVA	480MVA
Rated Voltage(Line-line, RMS) 3-phase	230kV/230kV
Rated Current	1205A/1205A
Rated Frequency	60Hz
Maximum phase shift	±35.1°
No. of steps	32
Positive sequence impedance (at max. phase shift)	11.44Ω
Positive sequence impedance (at zero phase shift)	7.48Ω
Series Unit	
3-phase MVA	289.45 MVA
Primary winding no. of turns	80.1kV
Secondary winding no. of turns	99 kV
Excitation Unit	
3-phase MVA	276 MVA
Primary winding voltage	126.61 kV
Secondary winding voltage	57.23 kV

A.3 Technical Specifications of 1400 MVA ISPST [30]

Parameters	Value
3-phase MVA	1400MVA
Rated Voltage(Line-line, RMS) 3-phase	400kV/400kV
Rated Current	2020.7A/2020.7A
Rated Frequency	60Hz
Maximum phase shift	±25°
Series Unit	
3-phase MVA	609.10 MVA
Primary winding voltage	100 kV
Secondary winding voltage	138.6 kV
Excitation Unit	
3-phase MVA	594.7 MVA
Primary winding voltage	225 kV
Secondary winding voltage	80 kV

A.4 Technical Specifications of 2000/5A CT [26]

Parameters	Value
Primary current	2000 A
Secondary Current	5 A
Class	C800
Resistance	4Ω
Inductance	18.4mH

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