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***Abstract*—The widening gap between energy generation and demand on a global scale, coupled with the imperative to reduce emissions, has necessitated the development of large-scale sustainable energy solutions. Among the various renewable energy options, Wind Power stands out as a viable source capable of generating substantial amounts of electricity. However, the unpredictable nature of wind availability and its fluctuations pose challenges for grid operators in effectively harnessing and distributing the generated wind power. This issue becomes more pronounced when transmitting wind power through local grids to distant load centers. Voltage instability at local buses emerges as a significant concern in wind-integrated power systems. To address these challenges, dynamic compensation at multiple locations has proven to be an effective solution.Various alternative approach to controlling the firing of Static Var Compensators (SVCs) connected to the network is proposed in the present work. The traditional method, which relies on a classical control approach, is computationally intensive and time-consuming. To overcome this limitation, we propose the utilization of a trained Neural Network for simultaneous control of the firing angles of all SVCs, accommodating various system conditions such as change in load and wind generation fluctuations. Porposed method has been evaluated on both a modified IEEE-30 bus system and a 28-bus Indian system.**

***Index Terms*—Distributed Computing, Smart Grid, Restoration, SVC firing, ANN**

I. Introduction

WIND power generation units are typically located in regions with high wind potential, irrespective of their reach from load centers within the system. Consequently, integrating wind power units into the existing grid can give rise to common issues [1], such as congestion in connected area, violation of prescribed grid code limits on bus voltages [2], [3], voltage instability issues and increased system losses. These problems further complicate the evacuation of power produced by these units. In the absence of dedicated corridors for large-scale wind power evacuation, the existing grid is utilized, with wind farms connected at multiple locations to transmit the generated power to different load centers. However, integrating wind power from multiple locations into the same grid amplifies the challenges of voltage regulation. The unpredictable nature of wind availablity, combined with variations in demand at local buses, makes it more difficult to maintain a balance between reactive power supply and demand within the grid. Consequently, grid operators are often compelled to limit the injection of active power from wind farms into the grid, even during peak windy hours.

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To ensure uninterrupted large-scale power evacuation, grid-connected wind generation facilities should be equipped to regulate voltage by providing reactive support as per requirement [4]. Wind farms, consist of numerous distributed [5] wind turbine generators (WTGs) and exhibit behavior that differs significantly from traditional large generators which is mostly inverter based with no reactive support. Nevertheless, wind farms should offer voltage control capabilities consistent with other forms of generation from a power system operational perspective. The voltage regulation capability of Wing Generators varies depending on technology and manufacturer [6].

Wind generation typically incorporate substations at the grid interconnection point, employing various equipment to regulate voltage, such as capacitors, tap-changing transformers, STATCOMs, and SVCs. Predicting the interactions in between these systems can be complex. System operators strive to efficiently utilize this equipment to meet requirements, with conflicting goals. Among the available compensating devices, flexible AC transmission system (FACTs) devices like static compensators and Static Var Compensators are the most desirable for changing reactive power demands [7]. Consequently, it is crucial to identify optimal and suitable locations for the placement and control of such interdependent devices to ensure continuous evacuation of the generated power to the grid.

In the absence of an sufficient reactive power reserves traditional generators, controlling FACTs devices located at different areas in respose to system requirement becomes essential for the well ordered operation of the power system. Among various control strategies, artificial neural networks (ANNs) have garnered interest in numerous applications in power engineering due to their adaptive and parallel computational capabilities. In present paper, we implement a Radial Basis Function (RBF) based neural networks for the control of various SVCs placed at multiple locations in a power system with wind penetration. The goal is to keep the required reactive

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power at their respective places to maintain all bus voltages within the specified limits (within ±5% of their nominal value) under various operating conditions. Here, operating conditions refer to variations in wind power at each wind farm and load.

II. VAR Compensation by SVC

The early SVCs were adapted for dynamic compensation in electric power transmission systems by combining TCRs with TSCs. However, until the 1990s, there were no suitable high-power applications for GTO devices. The Electric Power Research Institute (EPRI) recognized the potential of power electronic devices in power transmission systems and promoted their use through the Flexible AC Transmission System Program (FACTS). As a result, the static VAR compensator has evolved into a mature technology widely employed in transmission applications. Its high-speed control capability allows power system operators to take advantage of steady-state modes that may be considered unstable or insecure in mechanical control systems. Additionally, it can respond rapidly to address stability and security concerns [8].

The generation of harmonics is inherent to any phase angle control application. To meet the required performance, SVCs are equipped with a voltage regulator that allows adjustment of the gain and other parameters. Properly placed SVCs in the network ensure a favorable voltage profile under all operating conditions. When these devices exhibit rapid response capabilities, they contribute to enhanced transient stability and can help prevent voltage collapse. The well-established SVC, when accompanied by appropriate control strategies, becomes an appealing tool for enhancing transmission systems. With the increasing integration of renewable energy sources into existing grids, widespread utilization of SVCs is crucial for effective management of reactive power and ensuring secure and reliable operation of power systems.

III. Reactive Power Compensation by Multiple SVC Placements

Managing voltage stability issues at a local bus through the dynamic supply of reactive power using SVCs is a reliable and robust method. However, when it comes to properly compensating the reactive power of the local network responsible for evacuating wind power to a distant grid with wind farms connected at multiple locations, the task becomes significantly more challenging. This difficulty arises because the voltage profile of most local buses varies in terms of criticality under different system operating conditions. These issues are comprehensively elucidated through simulation studies conducted on various test systems [9]. In such situations, the use of a single SVC may not be sufficient to mitigate voltage instability problems. Therefore, dynamic reactive power compensation is required at multiple locations within the network.

The effectiveness of reactive power compensation strongly relies on the placement and size of the compensators being added. However, Due to economic contraints we have to determine the optimal location for VAR compensators with steady-state network conditions. Numerous studies have been conducted and documented in the literature on the utilization of these controllers for voltage and angle stability applications. Various methods are employed to optimize the allocation of these devices in power systems [10].

In [11], an approach is introduced to identify the locations where the number of SVCs can be installed can be minimized with their necessary ratings. This approach ensures that none of the buses violates the specified grid code regarding voltage deviations (±5%) under all operating conditions

IV. Simultaneous Control of Multiple SVCs

FACTs encompass a range of innovative devices that have the capability to modify voltage, phase angle, and impedance at specific points within power systems. These devices offer fast response times and hold great potential for enhancing power system stability. Furthermore, the SVC aids in damping power swings and minimizing system losses through optimized control of reactive power. The performance of transmission corridors, whether between interconnected power systems or within national transmission networks, often imposes limitations on network operations and market activities. Transfer limits, determined based on voltage stability limits, are typically calculated offline and must be conservative enough to account for all plausible operating conditions.

In [11], [12], the focus is on steady state modeling and determining the firing angles of multiple SVCs connected at necessary locations in a inter connected system to maintain the required voltages at different buses via PMUs. Monitoring and operating transmission corridors become more robust and reliable with the assistance of PMU information obtained from various PMUs placed at strategic locations. Figure-1 illustrates the schematic diagram for controlling the firing angles of all SVCs connected to the network from the control center. This centralized control aims to maintain optimal reactive power support and ensure that all bus voltages remain within the specified grid code limits.

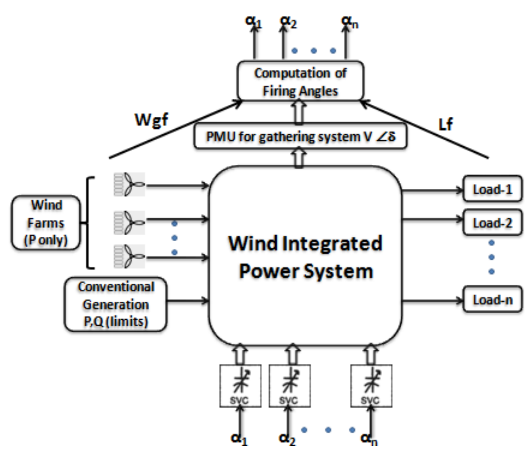


Fig. 1: Schematic diagram for control of SVCs without ANN

$'L_f'$ refers to the percentage of load and $'W_{gf}'$ refers to wind penetration level at any instant for which firing angles of all SVCs need to be computed.

V. ANN based firing angle control

In [11], a novel approach is presented for determining the size and location of Static VAR Compensators (SVCs) in a wind-integrated power system. The objective is to ensure that the bus voltages remain within permissible limits, considering the varying wind power penetration levels and load variations at the load buses. However, it is equally important to have simultaneous control of all the SVCs to maintain a balance of reactive power within the network, supplying or absorbing the required reactive power. The paper proposes a conventional technique for computing the firing angle of each SVC. However, this conventional method is found to be complex, time-consuming, and prone to convergence issues under certain system conditions.

To overcome these challenges, this paper suggests utilizing the control method based on Artificial Neural Networks (ANN), which has shown successful applications in different areas of power engineering [13]. Implementing ANN control requires the development of a comprehensive input dataset that represents the parameters associated with different conditions for the operation of the system which includes control parameters and state variables. In the present study, operating conditions of the system refer to simultaneous change in wind power generation from all wind farms and change in load at all load buses. Figure.2 illustrates the block diagram depicting computation of firing angles of SVCs using ANN-based control. This approach enables effective management of reactive power requirements within the system, ensuring that the bus voltages remain within the specified limits.

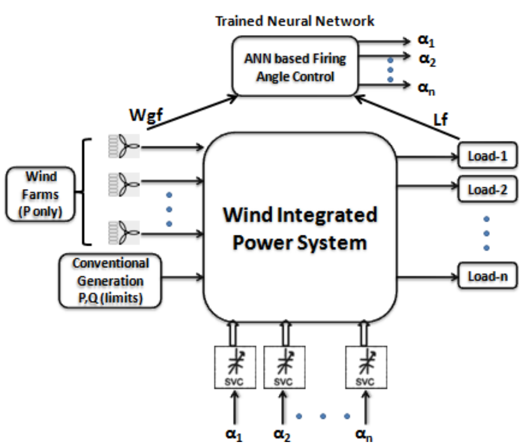


Fig. 2: Schematic diagramfor control of SVCs based on ANN

In this setup, the trained ANN-based controller receives information about the wind power generation (P_{wind}) of the wind farms, represented as a ratio of their installed capacity ($W_{gf} = P_{wind}$/Installed capacity of the wind farm) as wind generation factor, and the load at each bus, represented as a ratio of the connected load Lf = (P+jQ)/($P_{connected} + jQ_{connected}$) as the load factor. This information is transmitted to the ANN controller through a communication channel. Unlike traditional methods of computing firing angles, the PMU data of bus voltages is not required in this arrangement. The ANN controller processes the input data and calculates the firing angles for all SVCs. The resulting information is then transmitted to the respective SVCs, enabling them to supply or absorb the necessary reactive power to or from the grid.

VI. Determination of Firing Angles of SVCs

The present methodology has been proposed and implemented on modified IEEE 30-bus system and 28-bus Indian system. The method has two parts.

- Training the ANN for computation for angles of SVCs depending on specific conditions
- Use the trained controller on the system for various conditions

Steps implemented for the training of ANN are:

Step 1: Formation of system conditions with respect to the wind generation factor and load factor.

These data for training the neural network includes two factors: 'W_{gf}' and 'L_f.' 'W_{gf}' varies from 0.1 to 1 in steps of 1%, while 'L_f' varies from 0.7 to 1.3 in steps of 1%. These factors are used as input data during the ANN training process.

Step 2: Perform a load flow analysis for each 'W_{gf}' and 'L_f' using the given system condition.

Step 3: Calculate the susceptances of each SVC based on the required reactive power at their respective locations for a given set of 'W_{gf}' and 'L_f'.

Step 4: Calculate the firing angles (α_1, α_2, ..., α_n) for each SVC corresponding to the set of 'W_{gf}' and 'L_f'. These firing angles (α_1, α_2, ..., α_n) are used as target outputs for the ANN training.

Step 5: Select an appropriate neural network structure for the training process. In this study, a Radial Basis Function (RBF) based artificial neural network is utilized.

Step 6: Initialize the epochs, error tolerance (ϵ), weights, and bias for training the network.

Step 7: Calculate the neural network output using Equation 6.

Step 8: Calculate the error (e), which represents the deviation of the output from the specified target.

Step 9: Check for convergence. Training is considered to have converged if the error (e) is less than or equal to the specified tolerance (ϵ).

Step 10: If convergence is not achieved, repeat steps 5 to 8.

Step 11: Stop the training process if convergence is achieved. Otherwise, restart the training process from step 4.

After successfully training the ANN we tested the systems for ensuring all the bus voltages to remain within the stipulated grid code limit for any system operating conditions when the firing angles of all SVCs are controlled by ANN based controller. The testing is done based on the flow chart given at Figure.3

VII. Results and Discussion

The objective of this research is to train the ANN using a comprehensive set of data to determine the firing angles

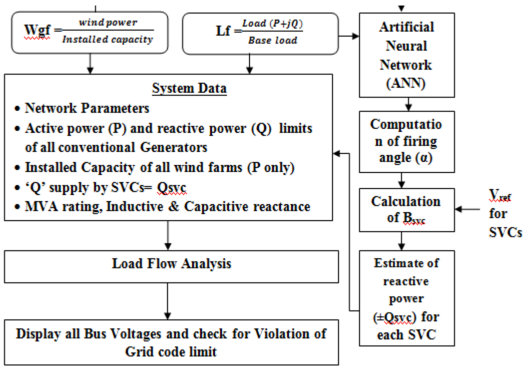


Fig. 3: Flowchart for verification of grid code compliance with ANN based firing angle control of SVCs of artificial neural network from the test data

TABLE I: IEEE 30-bus system modification for wind generation

Line no	From	To	Capcity (MW)	Line Parameter(p.u.)		
				R	X	B
42	30	31	56	0.0159	0.0725	0.0306
43	26	32	21	0.0165	0.12574	0.0255
44	24	33	14	0.0343	0.11098	0.0714
45	29	34	49	0.0183	0.09539	0.03366

of all static VAR compensators in different practical scenarios involving load variations and wind power penetration at different wind farms. The firing angles were obtained using conventional methods such as Newton-Raphson's load flow analysis and other mathematical computations described in [10].

To validate the proposed methodology, the study was conducted on two test systems: the IEEE 30-bus test system and a practical 28-bus Indian test system. The 28-bus system, which includes four wind farms supplying power to the grid at bus number 1 through the local network. The system data for the IEEE 30-bus test system was modified for this specific application which includes four generators that is connected via a line through a transformer. The generator bus voltages in both systems are fixed at 1.05 p.u, to ensure that the load bus voltages remain within the grid code range under the given load conditions. For the IEEE 30-bus system, the line specifications are provided in Table I.

Optimal location for placement of the SVCs is already discussed in [11]. The same locations are considered for placement of SVCs for this study. For generating training input and target data for the proposed ANN controller, load flow and consequently the firing angle computation of SVCs as described in [11] is carried out for both test systems with following system operating conditions. In view of Table.II and Table.III, 707 operating conditions (in terms of Wgf and Lf) have been framed for formation of input dataset and the respective target (Firing angles $\alpha 1$, $\alpha 2 ...$ $\alpha 1_n$) dataset in order to perform the proposed training analysis.

To generate the training input and target data for the proposed ANN controller, load flow analysis and firing angle computations for the SVCs are performed on both test systems under various system operating conditions. Based on the information provided in Table II and Table III,represented by variations in the wind generation factor (W_{gf}) and load factor (L_f), are selected. These operating conditions are used to create the input dataset and the corresponding target dataset (Firing angles $\alpha 1$, $\alpha 2 ...$ $\alpha 1_n$) for the training analysis proposed in this study.

TABLE II: Evaluation of firing angles of SVC in modified IEEE-30 bus with 70% to 130% with a step of 10% & 0% to 100% with a step of 1%

Location of Wind	Calculated Parameters of SVC/TCR			X_l of SVC	X_c of SVC
	Location	Q_{max}	Q_{min}		
24	30	6.4755	-9.94	0.28 p.u.	1.4 p.u.
26	26	4.2367	-23.0	0.28 p.u.	1.4 p.u.
29	19	15.108	-10.25	0.28 p.u.	1.4 p.u.
30	27	32.7395	-16.87	0.28 p.u.	1.4 p.u.

TABLE III: Evaluation of firing angles of SVC in modified IEEE-28 bus Indian System with 70% to 130% with a step of 10% & 0% to 100% with a step of 1%

Location of Wind	Calculated Parameters of SVC/TCR			X_l of SVC	X_c of SVC
	Location	Q_{max}	Q_{min}		
25	25	-8.9	-20.52	0.28 p.u.	1.4 p.u.
26	8	45.82-	-0.582-	0.28 p.u.	1.4 p.u.
27	28	6.44	-18.17	0.28 p.u.	1.4 p.u.
28	20	55.58	2.84	0.28 p.u.	NA (TCR)

With the given considerations, the proposed methodology has been applied and tested on the two mentioned test systems, following the steps outlined below:

Step 1: Formation of Input Data: The N-R load flow analysis is conducted, and the firing angles for all SVCs are computed for each case. The system operating conditions, such as "W_{gf}" and "L_f," are organized into a matrix, resulting in an input data matrix with dimensions of 707 × 02.

Step 2: Formation of Target Data: For each operating scenario, the firing angles obtained in Step 1 are monitored, and a corresponding target value is generated . The target data are arranged in a matrix with dimensions of 707 × 04. In both test cases, four SVCs are placed at optimal locations.

Step 3: ANN Approach: Two different types of neural networks (NNs) have been considered by the researchers: a multilayer feed-forward neural network (MFFN) with a backpropagation training algorithm and a radial basis function network (RBFN). The RBFN model is utilized in this study for SVC control. All the aforementioned steps are implemented in Matlab simulation to achieve successful training of the neural networks. The convergence results obtained from these simulations are presented in plots are shown in Figure 4 and Figure 5, respectively.

The test results of the trained network is compared with the conventional method mentioned in [11] for determination of firing angles of multiple SVCs, the results of which is available

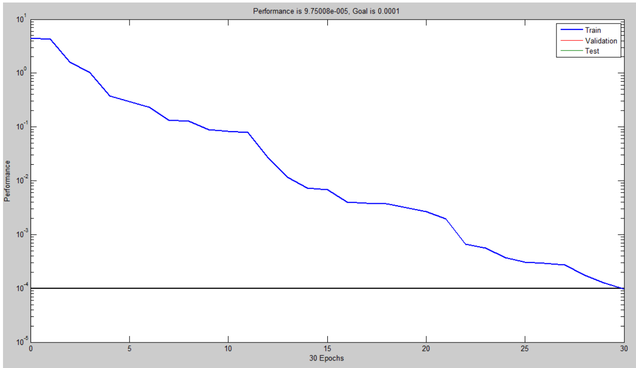


Fig. 4: Graph of convergence for Training of IEEE-30 Bus system

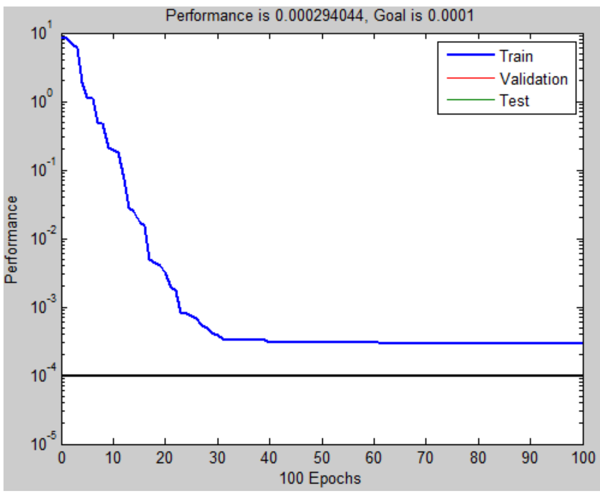


Fig. 5: Convergence Graph for Training of 28 Bus Indian systems

in Figure.6a to Figure.6d (For Wind-Integrated IEEE 30-bus system).

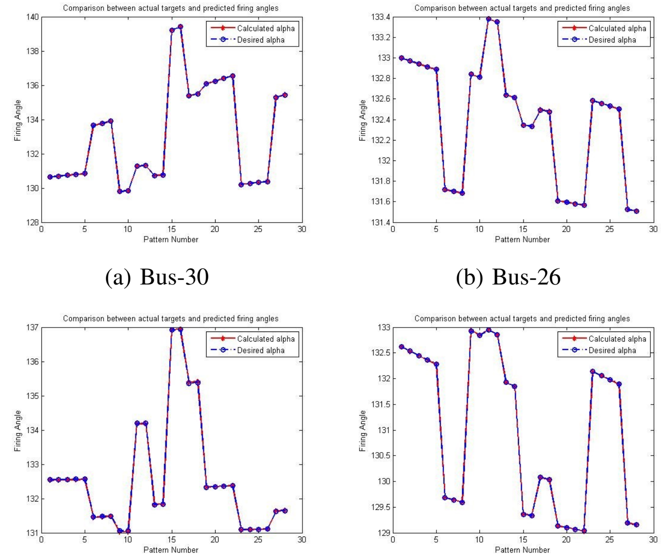
Similar ANN training is performed for 28-bus Indian system results of which are presented in Figure.7a to Figure.7d.

Once the ANN is successfully trained, the proposed scheme is tested on both systems to verify compliance with the grid code in terms of the bus voltages under various operating conditions. Random operating conditions are selected by assigning values to "W_{gf}" (ranging from 0 to 1) and "L_f" (ranging from 0.7 to 1.3). The N-R load flow analysis is performed on the wind integrated networks with the firing angle control based on the trained ANN. The results of these tests are presented in Table IV and Table V.

The results ensures that ANN based firing angle control of SVCs in both systems compliances the grid code limits in violation of bus voltages for possible system operating conditions.

VIII. Conclusion

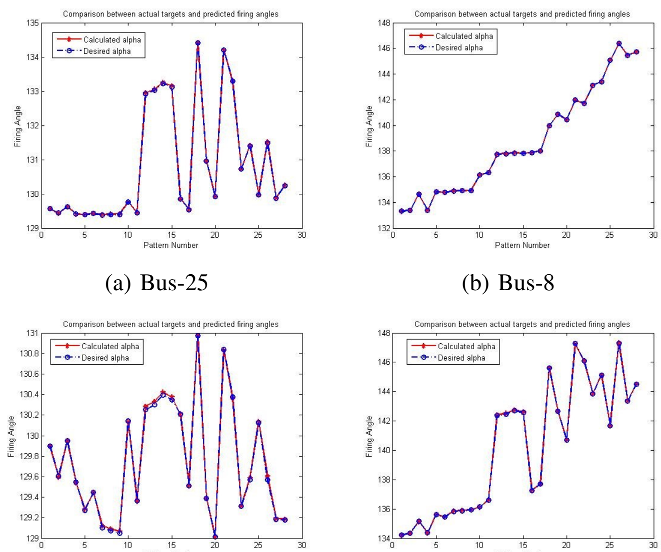
The main objective of this paper was to evaluate the effectiveness of an ANN-based firing angle controller for



(a) Bus-30 (b) Bus-26

(c) Bus-19 (d) Bus-27

Fig. 6: Comparison of firing angles for SVC at different buses Bus-a.30 b.26 c.19 d.27 (IEEE-30 bus)



(a) Bus-25 (b) Bus-8

(c) Bus-28 (d) Bus-20

Fig. 7: Comparison of firing angles for SVC at different buses (28-bus Indian System)

optimally located SVCs in order to mitigate bus voltage violations and ensure compliance with grid code limits during the integration of wind power into the grid. The study utilized a conventional approach involving load flow simulations and mathematical computations to create an extensive dataset consisting of various operating conditions (707 situations/events) and corresponding target dataset containing firing angles for SVCs in each situation. The obtained datasets were used to train RBFNN neural networks successfully. The study confirms that the employed neural networks are capable of

TABLE IV: Testing of System Voltages for Wind Integrated IEEE-30 bus test System with ANN based SVC control

Sl. No.	System Conditions L_f	W_{gf}	Bus No.	Voltage without SVCs	Voltage With SVCs
1	0.8	0.74	6	1.053	1.042
			8	1.058	1.043
			24	1.051	1.015
			25	1.069	1.0
			26	1.101	1.002
			27	1.068	0.998
			28	1.061	1.043
			29	1.142	1.035
			30	1.149	1.005
2	0.9	0.95	26	1.072	1.001
			29	1.111	1.036
			30	1.12	1.004
3	0.7	0.94	3	1.052	1.046
			4	1.051	1.045
			6	1.055	1.046
			8	1.061	1.05
			25	1.054	0.998
			26	1.096	1.003
			28	1.06	1.047
			29	1.132	1.038
			30	1.143	1.005
4	1.1	0.5	26	1.062	1
			27	1.053	0.999
			29	1.104	1.027
			30	1.104	1.002
4	1.3	0.9	29	1.057	1.036
			30	1.061	1.005

achieving successful training. The trained ANN is then utilized to control the firing angles of all optimally located SVCs, effectively balancing the reactive power demand and supply in the network to adhere to grid code limits for bus voltages under different wind generation and loading conditions. Case studies were conducted on two systems: the wind-integrated IEEE 30-bus test system and the 28-bus Indian system. The simulation results demonstrate that the RBFNN is a compact and robust network, offering fast convergence to attain the required firing angles for effective reactive power management of all SVCs.

TABLE V: Testing of System Voltages for Wind Integrated 28 bus Indian System with ANN based SVC control

Sl. No.	System Conditions L_f	W_{gf}	Bus No.	Voltage without SVCs	Voltage With SVCs
1	0.76	0.32	9	1.051	1.014
			10	1.082	1.012
			11	1.084	1.010
			12	1.089	1.011
			13	1.082	1.011
			14	1.071	1.019
			15	1.059	1.018
			16	1.052	1.016
2	0.9	0.6	8	0.94	0.998
			11	1.052	1.007
			12	1.059	1.011
			20	0.949	0.997
3	0.92	0.53	8	0.941	0.998
			10	1.057	1.008
			11	1.06	1.008
			12	1.067	1.011
			13	1.057	1.007
4	1.2	0.9	5	0.888	0.983
			6	0.864	0.993
			7	0.838	1.000
			8	0.805	0.993
			15	0.949	0.990
			16	0.947	0.982
			17	0.948	0.976
			19	0.858	0.973
			20	0.841	0.991
			21	0.869	0.975
			22	0.949	0.968
4	1.3	0.9	5	0.886	0.982
			6	0.855	0.992
			7	0.824	0.998
			8	0.788	0.992
			19	0.872	0.974
			20	0.850	0.991
			21	0.869	0.975

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