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RANKING OF LINE CONTINGENCY FOR VOLTAGE STABILITY ASSESSMENT

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Abstract

Excessive reactive power loading results in bus voltage instability and outage of power transmission lines, which leads to instability of the entire power network. For stable operation, finding the stability margin of buses and lines by identifying and ranking unstable lines under contingency is needed. The aim of contingency ranking is to recommend the stability improvement mechanisms for a secure and stable power network operation. This paper introduces a new line stability index that is used to rank lines to identify unstable lines based on the severity of load contingency. In addition, another new technique called Aggregated-Variance Stability Index (AVSI) in combination with adaptive neuro-fuzzy inference system is used to rank the lines based on the severity of line outage contingency due to excessive reactive power loading. Further, to account for the effect of inductive load on bus voltage and power transmission line stability, only load reactive power is increased up to its maximum stability limit. The line stability index is then determined using Newton Raphson power flow solution and lines are ranked based on the severity of bus loading. In this study, *N*-1 line contingency s used to examine the effect of increased bus loading on line stability and lines are then ranked based on the severity of line outage. The effectiveness of the new stability indices is evaluated against conventional line stability indices based on IEEE-14 bus standard system. Results show that the proposed AVSI-ANFIS performs better in ranking line contingency compared to AVSI.

Keywords: Aggregated-variance, ANFIS, Critical bus ranking, Line stability index, Stability index.

1. Introduction

Due to the exponential growth of energy demand in the recent world, voltage stability analysis emerges as one of the major concerns of power utility companies [1]. Voltage instability occurs if power control devices are unable to maintain the progressive drop in bus voltages before and after the system is being subject to contingencies. Recently, most powerful network buses are operating near to the stability limits within small security margins. Small disturbance results in the bus voltage instability, outage of power transmission lines and partial or total blackout of the network. The line outage on the other hand leads to overall network bus voltage instability [2]. Thus, identifying the loading margin of buses, which results in the stable bus voltage and power transmission line is the main challenge of power engineers. On top of it, analysing the effect of line outages associated with excessive bus loading on overall network bus voltage stability is another concern.

In recent research, different approaches have been used for identifying and ranking voltage unstable buses and power transmission lines based on the voltage and line stability severity indices under load and line contingencies. Techniques such as New Voltage Stability Index (NVSI) [3], Improved Modal Analysis Technique (IMAT) [4], Fast Voltage Stability Index (FVSI) [5], optimal reactive power planning using Differential Evolution (DE) [6], the line stability indices [7], and Voltage Collapse Point Indicators (VCPI) [8] are commonly used. Most of these conventional line and bus voltage stability indices have been developed based on radially connected two-bus power networks. In addition, each of these stability indices is developed as a function of load reactive power, sending end bus voltage and line admittance between two buses. Accordingly, if the stability index approaches unity, the affected bus or line is deemed to be entering into an unstable region. Practically, since modern power networks are highly meshed, considering radially connected two-bus power system and line stability index, as a function of load bus reactive power is not efficient. Because for large interconnected power network, lines reach the stability limit for a line flow, which is less than its end terminal load power. Besides this, line stability not only depends on a single sending end bus voltage and admittance between sending and receiving end buses but also depends on the entire network structures. This necessitates the development of new line stability index.

Conventional techniques have been found to perform fairly well in ranking radially connected networks. However, the modern power network is highly meshed rendering formulation of line stability index as a function of load reactive power based on a two-bus radial system is not feasible. In addition, the stability of an interconnected power network not only depends on sending end bus voltage and impedance between two buses but also depends on the entire network admittances and bus voltages. From the load flow solution, for buses connected through two or more power transmission lines, the load power is equal to the sum of line flow entering into the buses. For a meshed power network, since line flow is always less than the load power, transmission lines reach the stability limit for line power flow less than the bus-end load power. Thus, line stability analysis is more feasible when line reactive power flow is used instead of load power. This necessitates the formulation of a new line stability index. On the other hand, although most conventional stability indices concentrate on finding unstable buses and lines under load contingency, not much research has considered the effect of loading on entire network stability.

Practically, excessive bus loading not only affects bus voltage stability but also affects power transmission line stability. Further bus loading then leads to line outage, which results in entire network instability. This also necessitates the formulation of another stability index called Aggregated-Variance Stability Index (AVSI) that includes the variances of bus voltage, power angle, line stability index, line flow, change in power angle, power loss and deviation inline thermal limit during line outage. Besides this, to reduce the large computational time and maximum errors occur during AVSI, using the combination of AVSI and soft computing techniques like Adaptive Neuro-Fuzzy Inference System (ANFIS) is considered as more appropriate [9]. ANFIS is the combination of artificial neural network and fuzzy if-then logic rules, which comprises the best predicting behaviour of the fuzzy and better adaptive process of neural network for new environment [10].

In this paper, lines are first ranked using new line stability index based on the severity loading. Lines are then ranked using Aggregated-Variance Stability Index (AVSI) and AVSI in combination with Adaptive Neuro-Fuzzy Inference System (AVSI-ANFIS) based on the severity of line outage. The line stability index is used to rank lines based on the severity of load contingency whereas AVSI and AVSI-ANFIS rank lines based on the severity of line outage on overall network voltage stability.

2. Problem formulation

Excessive bus loading affects the power transmission line stability leading to line outages. Thus, identifying and ranking lines using line stability indices based on the severity of load contingency is necessary in order to recommend the stability improvement on the network.

2.1. Developing new line stability index (Lst)

Consider an *N*-bus power network and a load bus *k*, which is connected to buses *i* and *j* through two transmission lines, line-*i*,*k* and *j*,*k*. The apparent power and current at bus *k* are respectively given as:

$$S_k = V_k I_k^* \tag{1}$$

$$I_k = I_{ik} + I_{jk} \tag{2}$$

Using Eqs. (1) and (2) gives:

$$S_k = V_k I_{ik}^* + V_k I_{jk}^* \tag{3}$$

Considering only line apparent power flow, the line stability index for line *ik* is derived as:

$$S_{ik} = V_k I_{ik}^* \tag{4}$$

or

$$S_{ik} = V_k \left(\left(\frac{V_i - V_k}{Z_{ki}}\right)\right)^* \tag{5}$$

where the current I_{ik} is given by:

$$I_{ik} = \frac{V_i - V_k}{Z_{ik}} \tag{6}$$

Considering the phase angle of the bus voltage and line impedance, the apparent power is express as:

$$S_{ik} = V_k \angle \delta_k \left(\frac{V_i \angle \delta_i - V_k \angle \delta_k}{Z_{ik} \angle \theta_{ik}} \right)^* \tag{7}$$

Decomposing into real and reactive power:

$$P_{ik} = -V_k^2 Y_{ik} \cos\theta_{ik} + V_{ik} V_i Y_{ik} \cos(\delta_k - \delta_i + \theta_{ik}) \tag{8}$$

$$Q_{ik} = -V_k^2 Y_{ik} \sin\theta_{ik} + V_k V_i Y_{ik} \sin(\delta_k - \delta_i + \theta_{ik}) \tag{9}$$

Considering the reactive part only due to its adverse effect on bus voltage and line stability, the quadratic equation for the bus voltage at the receiving end is:

$$V_k^2 - \frac{V_k V_i \sin(\delta_k - \delta_i + \theta_{ik})}{\sin\theta_{ik}} + \frac{Q_{ik}}{Y_{ik} \sin\theta_{ik}} = 0 \tag{10}$$

From the general quadratic equation, the voltage at bus k is given as:

$$V_k = \left(\frac{V_i \sin(\delta_k - \delta_i + \theta_{ik})}{\sin\theta_{ik}}\right) \frac{\pm\sqrt{\left(\frac{V_i \sin(\delta_k - \delta_i + \theta_{ik})}{\sin\theta_{ik}}\right)^2 - 4\left(\frac{Q_{ik}}{Y_{ik}\sin\theta_{ik}}\right)}}{2} \tag{11}$$

For a stable and non-imaginary voltage at the load bus, the discriminant should be greater or equal to zero and is given as:

$$\left(\frac{V_i \sin(\delta_k - \delta_i + \theta_{ik})}{\sin\theta_{ik}}\right)^2 - 4\left(\frac{Q_{ik}}{Y_{ik}\sin\theta_{ik}}\right) >= 0 \tag{12}$$

The line stability index L_{st} at bus k is thus, given by:

$$L_{st} = \left(\frac{4Q_{ik}\sin\theta_{ik}}{(Y_{ik}(V_i \sin(\delta_k - \delta_i + \theta_{ik}))^2)} <= 1\right) \tag{13}$$

From Eq. (13), the maximum reactive power loading, Q_{ik} of the power transmission line is given as:

$$Q_{ik} \leq \frac{(Y_{ik}(V_i \sin(\delta_k - \delta_i + \theta_{ik}))^2)}{4Q_{ik}\sin\theta_{ik}} \tag{14}$$

For stable operation, the line stability index should be less or equal to unity. The lines are then identified and ranked based on the severity of bus loading. Thus, if L_{st} approaches unity, the power transmission line is considered unstable and more prone to the outage.

Based on studies by Quaia [11], the adverse effect of line outage on the entire network bus voltage stability calls for formulation of another stability index. In general line outage leads to violation of bus voltage stability, line power flow limits, bus angle stability limits, thermal limit of power transmission lines and line stability limits, hence resulting in excessive power loss. Violation in one of these variables affects the entire network bus voltage stability. Thus, to account for these effects, a new technique called aggregated-variance stability index is developed in the next section.

2.2. Developing aggregated-variance stability index (AVSI)

The aim of aggregated-variance stability index is to find the deviation of power system parameters from their base-case or mean value during line outage and also to observe the effect of line outage on network bus voltage stability. The aggregated stability index comprises the sum of six stability variances, that is, voltage stability limit variance, variance of power angle, variance power stability limit violation, the variance of line thermal limit, the variance of power loss and variance of line stability index. By using the different stability variances, the line outage, which results in the most severe network bus voltage instability, can be identified based on the aggregated-variance stability index.

2.2.1. Voltage stability limit variance

The performance index of voltage (PIV) is one of the techniques used in finding the variance of bus voltage from the expected mean in the presence of a contingency. It uses base-case load flow bus voltage as an expected mean and determines its variance during contingency [12]. This technique performs well in finding voltage unstable buses, however, it needs modification due to the loading effect on base-case bus voltage and its limited variance during a contingency. In this paper, 1 p.u. the bus voltage is considered as the expected mean as expressed in Eq. (15) and the variance of voltage during contingency is calculated as given in Eq. (16).

$$\bar{V_i} = \sum_{i=1}^{N} \frac{V_i}{N} = 1 \tag{15}$$

$$\rho_V = \sum_{i=1}^{N} \left(\frac{\left(\bar{V_i} - V_i \right)^2}{N} \right) \tag{16}$$

2.2.2. Variances of power angle

Outage in a power transmission line affects the power angle and the network bus voltage stability. Diamenu]13] mentioned that the power stability equation for two interconnected buses is given as:

$$P_j = P_{\max} \sin \delta \tag{17}$$

$$P_{\max} = \frac{V_i V_j}{X_{ij}} \tag{18}$$

For stable operation, the power angle δ, which must not exceed 90^0 [14] is given by:

$$\sin \delta = \left(\frac{P_j}{P_{\max}} \right) \tag{19}$$

For the no-load condition, the sending and receiving end bus voltages are almost equal and the phase shift is small ($\sin\delta \approx 0$). Thus, the variance ρ_δ of the power angle during contingency is given by:

$$\rho_\delta = \sum_{j=1}^{N} \frac{(\delta_{nl} - \delta_j)^2}{N} \tag{20}$$

2.2.3. Power stability limit violation

For stable operation, the line power flow should be less than given maximum power and the power stability index P_{st} under contingency is given by:

$$P_{st} = \frac{P_{ij}}{P_{ij}^{\max}} \tag{21}$$

This power stability index should be less than unity. The power stability index should be less than unity.

Considering the no-load condition of power stability index considering that the no-load power stability index P_{st}^{no} is approximately equal to zero as an expected mean, the variance in power stability index $\rho_{P_{st}}$ during contingency is given by

$$\rho_{P_{st}} = \sum_{i,\, j=1}^{N} \left[\frac{P_{st}^{\ no} - P_{st})}{N} \right]^2 \tag{22}$$

2.2.4. Variances of line thermal limit

The power flow of a short transmission line is limited by the line thermal limit while medium and long transmission lines are limited by Surge Impedance Loading (SIL). According to Pentayya et al. [15], SIL is defined as the reactive power generated by the line capacitance and is equal to the reactive power consumed by the line inductance. Due to inductive loading, most transmission lines are loaded beyond the SIL limit. This necessitates consideration of line SIL as defined by the following Eq. (23) [16]:

$$SIL = \frac{V^2}{Z_c} \tag{23}$$

$$Z_c = \frac{V}{I} = \sqrt{\frac{L}{C}}\ \ \Omega \tag{24}$$

For short and medium-length transmission lines, the maximum thermal limit is defined as.

$$S^{Th} = 3SIL \tag{25}$$

For long transmission line:

$$S^{Th} = 0.5SIL \tag{26}$$

For the line apparent power flow S_{ij} under contingency, the thermal stability index of the power transmission line is given as:

$$S_{ind}^{Th} = (\frac{S_{ij}}{S_{ij}^{Th}}) \tag{27}$$

For stable operation, the line thermal index should be less than unity. If the thermal stability index of a line approaches unity for a given line outage, the line is said to be unstable and more prone to the outage. Thus, considering the no-load case, the line thermal index $S_{ind}^{Th(no)}$ approaches zero and the thermal limit variance $\rho_{S^{Th}}$ during contingency is given by:

$$\rho_{S^{Th}} = \sum_{i,\,j=1}^{M} \frac{\left(S_{ind}{}^{Th(no)} - \frac{S_{ij}}{S_{ij}^{Th}} \right)^2}{M} \tag{28}$$

2.2.5. Variances of power loss

Increased inductive loading results in the increased flow of line current, which leads to large power loss along a transmission line as given by [17]:

$$P_{ij}^{L} = R_{ij} I_{ij}^{2} \tag{29}$$

For a lossless power transmission line, the power loss is approximately equal to zero. Considering the power loss of a lossless transmission line as the expected mean, the variance in power loss ρ_{PL} under contingency is given by:

$$\rho_{P^L} = \sum_{i,\,j=1}^{M} \frac{(0 - P_{ij}^{L})^2}{M} \tag{30}$$

2.2.6. Variances of line stability indices

Line outage associated with excessive loading results in the violation of line stability limits. For the no-load condition, since there is no line reactive power flow, the line stability index L_{st} is zero. Assuming the no-load line stability index as the expected mean, the variance of line stability index ρ_{Lst} during contingency is given by:

$$\rho_{L_{st}} = \sum_{i,\,j=1}^{N} (\frac{0 - L_{st}^{ij}}{M})^2 \tag{31}$$

$$\rho_{L_{st}} = \sum_{i,\,j=1}^{N} (\frac{0 - L_{st,ij}}{M})^2 \tag{32}$$

2.2.7. Aggregated-variance Stability Index (AVSI)

The variance of two or more independent variables is equal to the summation of individual variances [18]. Accordingly, the aggregated-variance ρ_{agr} of the power system parameters is given as:

$$\rho_{agr} = (\rho_V + \rho_\delta + \rho_{P_{st}} + \rho_{S^{Th}} + \rho_{PL} + \rho_{L_{st}}) \quad (33$$

The lines are ranked using aggregated-variance stability index based on the severity of line outage on the entire network bus voltage stability. The line outage, which yields the largest aggregated-variance stability index, is ranked at the top as the most severely affected and hence unstable line.

2.3. Adaptive Neuro-fuzzy model for ranking line contingency

Neuro-fuzzy is the combination of an artificial neural network (ANN) and fuzzy inference system, commonly known as the Adaptive Neuro-Fuzzy Inference System (ANFIS). ANN is designed in a way that human neuron behaves. It assigns a membership function to check the strength and weakens of the input-output parameters based on its input, hidden and output layers relationship. It can easily adapt to the artificial environment for modelling the new system. However, ANN is very weak in predicting the output within a short period of time, needs largely hidden layers that require large computer memory for storage and needs a good background knowledge of the new system when assigning the memberships functions. The combination of ANN with the fuzzy if-then rule, commonly known as Adaptive Neuro-fuzzy Inference System (ANFIS) solves the drawback of ANN. A fuzzy system is very good in predicting an output compared to ANN though it is very weak in adapting to the new environment. Haidar et al. [19] proposed that ANFIS needs a small number of hidden layers and does not need any background knowledge compared to ANN.

ANFIS is designed in a manner to comprises accurate learning and adapting the new environment technique of neural network and fast output prediction of a fuzzy system. It uses the Takagi-Sugeno Fuzzy Inference System (FIS) with a neural network. ANFIS uses the hybrid-learning rule of gradient descent in combination with least square estimation, which is more efficient, fast and reliable than using a simple gradient descent method. Adaptive neuro-fuzzy inference system has five layers. The five layers starting from first to the fifth layer are fuzzification of input parameters, aggregating the degree of membership, normalization of the aggregated membership function, defuzzification of the input and output function [20].

The two-input, single-output, two-membership function each and five-layer ANFIS structure is given in Fig. 1. Each layer is connected through weight function, which measures the strength and weakness of input parameters. Thus, the first layer receives the input data and maps the input data into the membership functions, and hence gives it into the second layer based on their respective weight functions. The output is then normalized in the third layer and given into the fourth layer. The fourth layer unnormalizes the output based on the leaner function of input variables using pre-determined fuzzy rules. The single-valued output is then extracted from the fifth layer. In general, the fuzzy system needs prior knowledge in order to define input-output rules. However, ANFIS overcomes this using programmed parameters tuned by ANN fixed inside a fuzzy system to replace the prior knowledge needed in fuzzy rule layer [21].

In this paper, the six components of AVSI index is used as input for adaptive neuro-fuzzy inference system and the output is extracted from ANFIS using neuro-fuzzy rules. Lines are then ranked using the AVSI and AVSI-ANFIS based on the severity of line outage.

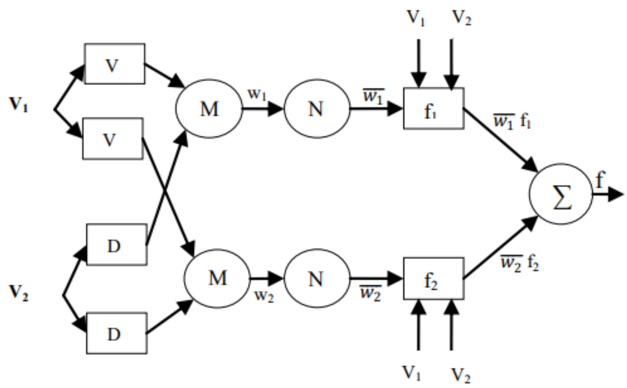


Fig. 1. Basic structure of ANFIS.

Classifying and selecting input-output membership

In this paper, the triangular membership function is used due to its best conformity and predicting an output near to the expected value. Accordingly, the membership parameter is given as shown in Table 1.

Table 1. Classifying the six input and output membership functions of ANFIS.

Input	Indices	Severity of indices		
	$\rho_{L_{st}}$	Low	Moderate	High
	ρ_v^{sum}	Low	Moderate	High
	ρ_δ	Low	Moderate	High
	$\rho_{P_{st}}$	Low	Moderate	High
	ρ_S^{Th}	Low	Moderate	High
	ρ_{PL}	Low	Moderate	High
Output	AVSI-ANFIS	No risk	Less risk	High risk

3. Contingency ranking using AVSI and AVSI-ANFIS

In this paper, MATLAB is used to rank lines using the Aggregated-Variance Stability Index (AVSI) and, its combination with ANFIS based on 14 standard bus system. The steady-state condition of the power network is checked using Newton Raphson (NR) power flow solution. Considering the adverse effect of inductive loading on bus voltage and line stability, only the load reactive power is increased up to its maximum stability limit and line stability index is determined. Lines are then ranked from the most to the least unstable, based on the severity of line outage. The proposed line stability index is validated by comparing the effectiveness of using line reactive power overload reactive power inline ranking. To observe the adverse effect of line outage on the entire network bus voltage stability, another stability index called aggregated-variance stability index is determined. AVSI comprises the variances of bus voltage, power angle, line flow limit, line thermal limit, power loess and line stability index. In addition, AVSI in combination with ANFIS is also used for ranking the contingency to reduce the large computational time and error occur using AVSI. To account for the effect of line outage, N-1 line contingency is applied if Q_{ij} exceeds the maximum stability limit as given in Eq. (14) and the AVSI and AVSI-ANFIS are determined using the NR power flow and adaptive neuro-fuzzy inference input-output relationship. Lines are then ranked using AVSI and AVSI-ANFIS combination based on the severity of line outage on entire network bus voltage stability. The flowchart for contingency ranking is given by Fig. 2.

Step 1: Start.
Step 2: Read the line, bus, generation and load data of IEEE-14 bus standard system.
Step 3: Apply Newton Raphson (NR) and observe base-case solutions.
Step 4: Increase a load reactive power up to maximum stability limit and apply NR again.
Step 5: Find line stability index.
Step 6: Go back to step four and increase load reactive power in another load bus.
Step 7: Rank lines using line stability index based on the load severity.
Step 8: Apply *N*-1 line contingency when Q_{ij} exceeds the maximum stability limit as given in Eq. (14).
Step 9: Find AVSI and also generate an output based on (AVSI-ANFIS) combination using six components of AVSI as the ANFIS input.
Step 10: Repeat steps 8 and 9 for another line outage.
Step 11: Rank lines using AVSI and AVSI-ANFIS combination.
Step 12: Compare the results.

Fig. 2. MATLAB flow chart for ranking line contingency.

4. Results and Discussions

The results of ranking lines based on the severity of bus loading and line outage are given in this section.

4.1. Comparing the new line stability index (*Lst*) with the conventional line stability index, Lmn [22]

IEEE-6 and 14 bus standard system are used for validating and checking the effectiveness of the proposed line stability index in ranking lines based on the severity of load contingency. Its effectiveness when compared to the conventional line stability index. The base-case line and load reactive power are increased up to the maximum stability limit, $Q_{ij(max)}$ that observed in Tables 2 and 3, and the line stability indices are determined. The results in Tables 2 and 3 show both the conventional and proposed line stability indices are effective in ranking unstable lines. The top-ranked unstable line is the same in both cases however, lines attain the stability limit at lower maximum reactive power loadings under the proposed line stability index. The reduction in loading is as a result of using the line reactive power flow for ranking the stability of meshed transmission lines, which is less than the reactive power loading at the bus-end of the lines that used in conventional line stability index. Thus, for the highly meshed network, the reactive power at a load bus is equal to the sum of the parallel-connected line reactive power flow. The stability indices and maximum loading limits for the two cases are also compared in Figs. 3 and 4, respectively.

As observed from Figs. 3 and 4, in case of the conventional line stability index, the meshed lines that connected to the same end-terminal load bus attain the stability limit for the same magnitude of maximum reactive power loading. However, due to the variation in line current and types of the transformer connected between the sending and receiving end buses, parallel-connected power transmission line do not attain the maximum stability limit for the same magnitude of maximum reactive power loading [23], as observed in the proposed line stability index result.

Table 2. Line ranking of IEEE-6 bus standard system using (L_{st}) and conventional line stability index (L_{mn}).

Line [i,j]	ID	Q_{ij} (base)	Q_{ij} (max)	L_{st}	Rank	Line [i, j]	ID	Q_d (base)	Q_d (max)	Lmn	Rank
4,5	6	0.740	1.169	2.871	1	1,5	3	0.70	1.365	4.079	1
5,6	9	0.727	1.247	1.896	2	4,5	6	0.70	1.365	3.857	2
3,5	5	0.452	0.985	1.698	3	3,5	5	0.70	1.365	2.501	3
2,5	4	0.693	0.914	1.395	4	2,5	4	0.70	1.365	2.200	4
1,5	3	1.412	1.458	1.287	5	5,6	9	0.70	1.260	2.008	5
2,6	7	0.666	0.930	0.957	6	2,6	7	0.70	1.260	1.367	6
1,4	1	0.679	0.776	0.598	7	1,4	1	0.70	1.225	0.975	7
3,6	8	0.770	1.046	0.539	8	2,4	2	0.70	1.225	0.766	8
2,4	2	0.643	0.783	0.448	9	3,6	8	0.70	1.260	0.656	9

Table 3. Line ranking of IEEE-14 bus standard system using (L_{st}) and conventional line stability index (L_{mn}).

Using the proposed line stability indices						Conventional line stability index					
Line	ID	$Q_{ij(base)}$	$Q_{ij(max)}$	L_{st}	Rank	Line	ID	$Q_{d(base)}$	$Q_{d(max)}$	L_{mn}	Rank
4,9	6	0.232	0.278	0.644	1	4,9	6	0.166	2.160	5.358	1
1,5	1	0.634	0.675	0.568	2	12,13	12	0.058	0.585	1.281	2
13,14	14	0.046	0.242	0.475	3	7,9	11	0.166	2.160	1.114	3
12,13	12	0.056	0.222	0.443	4	13,14	14	0.050	0.256	0.961	4
2,4	2	0.455	0.491	0.366	5	6,13	13	0.058	0.585	0.765	5
2,5	3	0.339	0.360	0.264	6	9,14	10	0.050	0.256	0.744	6
7,9	11	0.323	0.497	0.233	7	3,4	4	0.039	0.233	0.527	7
3,4	4	0.280	0.286	0.230	8	2,4	2	0.039	0.233	0.411	8
9,14	10	0.074	0.098	0.144	9	9,10	9	0.058	0.136	0.290	9
4,5	5	0.532	0.599	0.116	10	6,12	7	0.016	0.063	0.167	10
6,13	13	0.104	0.116	0.083	11	10.11	15	0.018	0.06	0.142	11
10,11	15	0.025	0.071	0.073	12	6,11	8	0.018	0.041	0.126	12
6,12	7	0.052	0.053	0.072	13	1,5	1	0.016	0.036	0.079	13
9,10	9	0.061	0.109	0.047	14	2,5	3	0.016	0.036	0.067	14
6,11	8	0.030	0.041	0.044	15	4,5	5	0.016	0.036	0.024	15

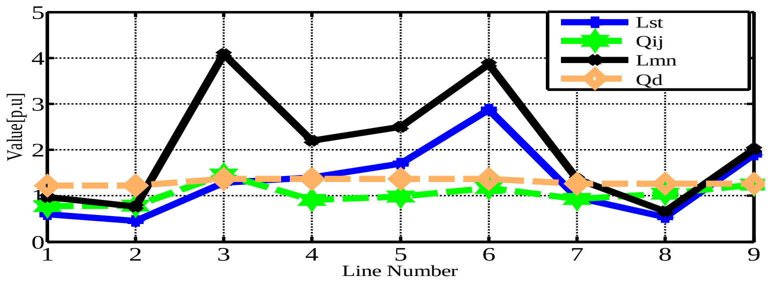


Fig. 3. IEEE-6 bus Q_{ij} vs. Q_d in case of L_{st} and L_{mn} stability indices.

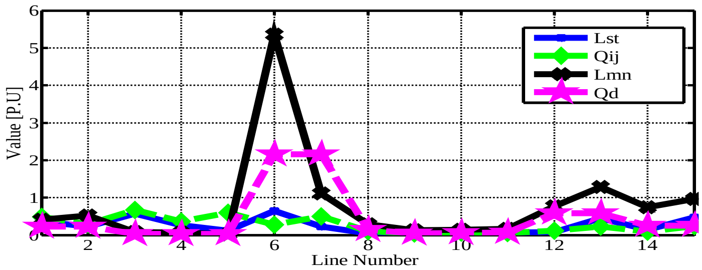


Fig. 4. IEEE-14 bus Q_{ij} vs. Q_d in case of L_{st} and L_{mn} stability indices.

4.2. Comparison of the proposed voltage variance and performance index of voltage, PIV

The results in Fig. 5 show the IEEE-14 bus standard system voltage profiles using the proposed and PIV techniques. The PIV technique considers the base-case load flow solution of the bus voltage as the expected mean whereas, the proposed variance considers 1 p.u. bus voltage as the expected mean and determines the deviation in bus voltage under contingency. Practically, voltage profile at some buses approach the stability limits even for the base-case load and only a small additional loading is possible.

Thus, change in the bus voltage is very small though buses are entering voltage unstable regions, which is a drawback of the PIV technique as shown in the results.

The PIV results show that the variances in the bus voltage are approximately zero except the variance at bus 14, which is also too small. On the other hand, the proposed variance of the bus voltage shows that not only this bus is subjected to voltage variance but also other buses too. However, as shown by the results given in Table 3, not only the lines connected to bus 14 for is subjected to voltage stability problems but also lines connected to other buses. Thus, the proposed variance of bus voltage is much more compliant to the line stability index results compared to PIV.

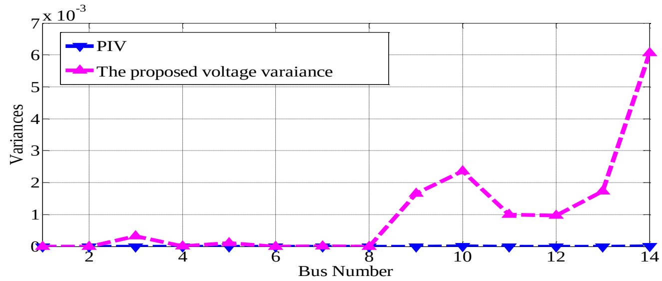


Fig. 5. IEEE-14 standard bus per unit bus voltage profile comparison.

4.3. Contingency ranking of IEEE-14 bus standard using aggregated-variance stability index (AVSI)

The line outage occurs when the line reactive power flow exceeds the maximum allowable line reactive power flow limit ($Q_{ij(max)}$) based on the severity of increased bus loading at the line end-terminal load bus. The results in Table 4 show the line ranking of IEEE-14 standard system using aggregated-variance stability index based on the severity of line outage. The line outage, which results in the severe overall network instability is ranked at the top. The results in Table 4 show the outage of lines 6-13 and 13-14 results in the severe network bus voltage instability. The effect of line outage on bus voltage stability is also observed in Figs. 6 to 9. The result in Fig. 6 shows the base-case bus voltage profile, without the line outage whereas the results in Figs. 7 to 9 respectively show the voltage profiles of an IEEE-14 bus system based on the severity of line outage. The results in Figs. 7 to 9 respectively show the voltage profiles of an IEEE-14 bus system based on the severity of line outage. It can be observed that outage of the most severely affected line due to excessive bus loading results in overall network bus voltage instability. On the other hand, outage of the least affected line has little impact on network bus voltage stability, which is similar to the base-case result of bus voltage.

Generally, the line outage results in higher variances of power loss, bus voltage and line thermal limit compared to the other three variances, which is observed in Table 4. Thus, the variances of power loss, bus voltage and line terminal limit are the most dominant factor that affects the aggregated-variance stability index compared to others.

The overall results show that aggregated-variance stability index is an efficient and effective way of ranking the lines based on the severity of line outage.

Table 4. Line contingency ranking of IEEE-14 bus standard system using aggregated-variance stability index.

Line-out	***Id***	Q_{ij}	ρ_{PL}	$\rho_{P_{st}}$	$\rho_{S^{Th}}$	ρ_{δ}	$\rho_{L_{st}}$	ρ_{V}	ρ_{agr}	**Rank**
6,13	13	0.165	0.182	0.0007	0.726	0.0007	0.004	0.003	0.917	1
13,14	14	0.140	0.161	0.0004	0.300	0.0004	0.0006	0.003	0.464	2
6,12	7	0.046	0.017	0.0008	0.071	0.0005	0.0023	0.002	0.093	3
2,5	2	0.046	0.018	0.0009	0.066	0.0006	0.0026	0.002	0.091	4
9,10	9	0.162	0.017	0.0008	0.068	0.0005	0.0024	0.002	0.090	5
3,4	4	0.111	0.017	0.0009	0.064	0.0006	0.0025	0.002	0.088	6
12,13	12	0.162	0.016	0.0008	0.060	0.0005	0.0023	0.002	0.081	7
9,14	10	0.140	0.017	0.0013	0.032	0.0006	0.0207	0.003	0.075	8
1,5	1	0.046	0.028	0.0013	0.037	0.0007	0.0030	0.004	0.073	9
2.4	3	0.111	0.020	0.0010	0.046	0.0006	0.0029	0.003	0.073	10
4,9	6	0.465	0.017	0.0011	0.040	0.0006	0.0037	0.003	0.065	11
7,9	11	0.465	0.017	0.0012	0.032	0.0006	0.0065	0.003	0.060	12
4,5	5	0.045	0.017	0.0010	0.033	0.0005	0.0028	0.002	0.056	13
6,11	8	0.050	0.021	0.0012	0.022	0.0006	0.0054	0.002	0.026	14

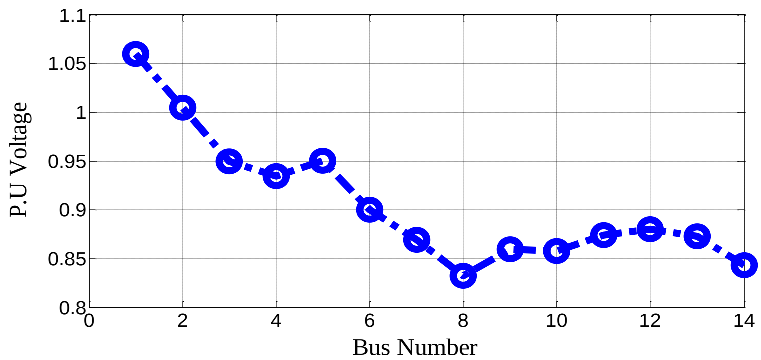


Fig. 6. IEEE-14 standard bus voltage profile for base-case load flow.

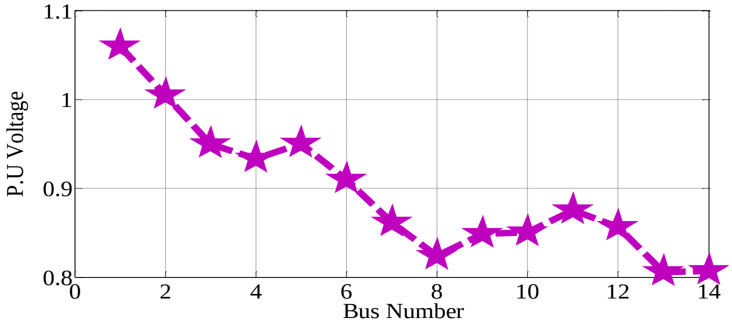


Fig. 7. IEEE-14 standard bus voltage profile with outage of line 6-13.

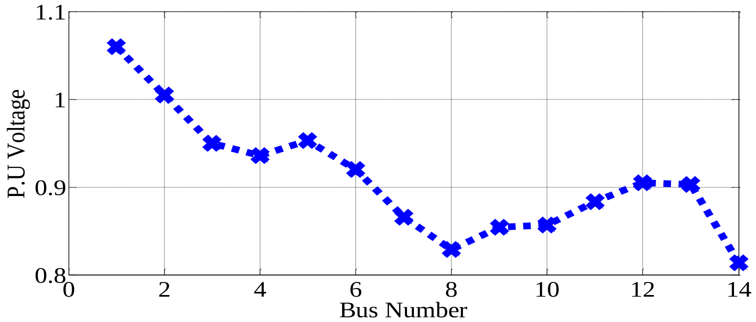


Fig. 8. IEEE-14 bus voltage profile with outage of line 13-14.

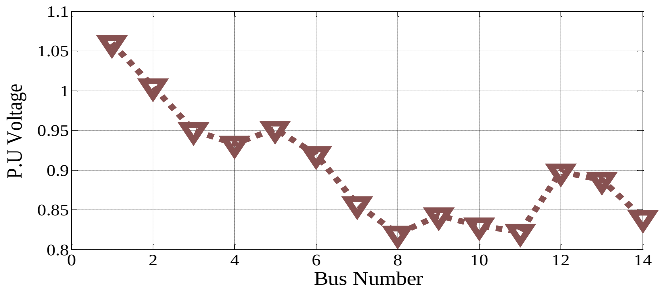


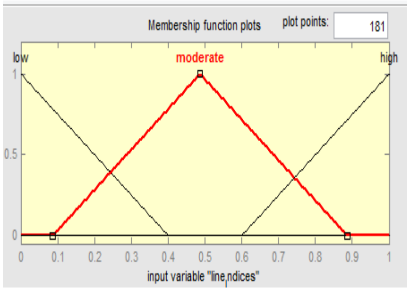
Fig. 9. IEEE-14 standard bus voltage profile with outage of line 6-116.

4.4. Contingency ranking of IEEE-14 standard bus using AVSI in combination with ANFIS

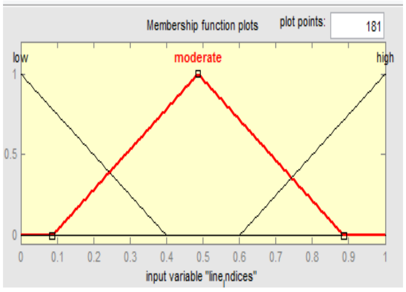
The six components of (AVSI) or variances in power system parameters under contingency are used as the input for ANFIS and ranking the line outage contingency is done using AVSI-ANFIS combination.

Training ANFIS and selecting its structure

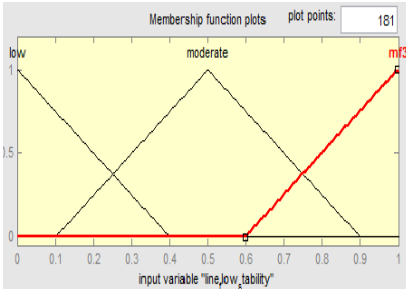
The graphical representations of six input one output triangular membership function and Takagi-Sugeno type structure of ANFIS are given in Figs. 10 and 11. Figure 10 comprises the six input and single output ANFIS membership functions under contingency as given in sub-figures from Figs. 10(a) to (f).



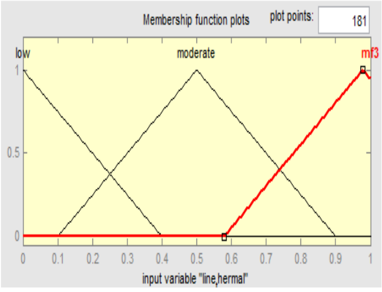
(a) Line stability index variance.



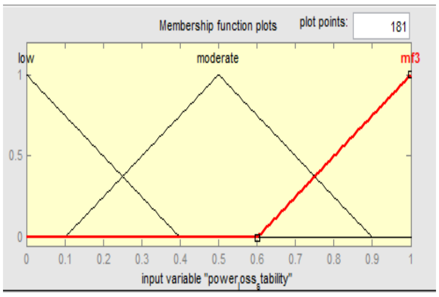
(b) Power angle variance.



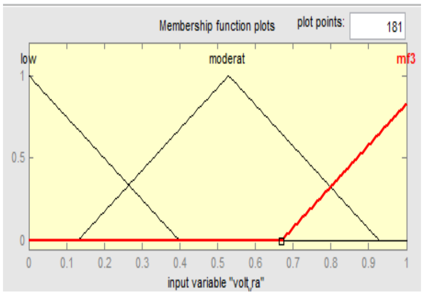
(c) Line flow stability index variance.



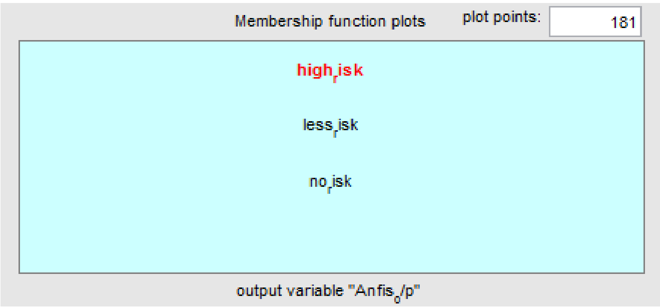
(d) Line thermal stability limit variance.



(e) Power loss variance.



(f) Bus voltage variance.



(g) Output membership function.

Fig. 10. Six input single output ANFIS membership functions.

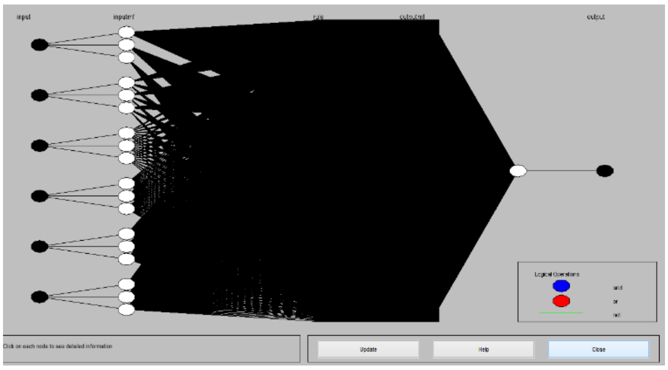


Fig. 11. Takagi-Sugeno type six-input, single-output ANFIS structure.

For the implementation of ANFIS, first the data are trained, tested and checked using the hybrid approach and the output is generated based on the severity of line outage. For IEEE-14 bus test system, ANFIS has 1503 nodes, 729 linear, 54 non-linear and 783 total number of parameters. Each ANFIS is trained for a maximum of 100 iterations. Thus, the fuzzy rules of 729 are used based on the number of input and output membership functions. After training, the final result is generated based on neuro-fuzzy input and output, mapping functions and rules.

Table 5 shows the line contingency ranking of IEEE-14 bus standard system using AVSI-ANFIS combination based on the severity of line. The line outage assumed to occur when line reactive power flow exceeds its maximum reactive power line flow limit (Q_{ij}) *as* given in the results. The change in six input power system parameters under contingency are then given into ANFIS input and the output is extracted from ANFIS considering 0.0001 tolerance. The results show that ANFIS reaches the predicted output within a short period of time for iterations less than 10. Table 5 shows increasing reactive power load at bus 14, 13 and 12 results in the worst overall network bus voltage instability. Excessive reactive power loading of these buses then leads to the outage of lines connected to the intended buses, which results in the overall network bus voltage instability.

Table 5. Contingency ranking of IEEE-14 Standard bus system using AVSI-ANFIS combination.

Line out [*I*, *j*]	Line ID	Error	AVSI-ANFIS output	Rank
13-14	14	0.000019	1.690	1
6-13	13	0.000017	1.630	2
6-12	7	0.000015	0.152	3
9-10	9	0.000015	0.145	4
6-11	8	0.000016	0.127	5
4-9	6	0.000020	0.120	6
1-5	1	0.000025	0.082	7
12-13	12	0.000019	0.056	9
9-14	10	0.000014	0.052	10
3-4	4	0.000021	0.042	11
2-5	2	0.000024	0.039	12
4-5	5	0.000017	0.031	13
2-4	3	0.000016	0.031	14
7-9	11	0.000014	0.021	15

4.5. Comparing the AVSI and AVSI-ANFIS combination results

The results in Fig. 12 shows the comparison of AVSI and AVSI-ANFIS combination results given in Tables 4 and 5, respectively. It shows both techniques work properly in ranking lines based on the severity of line outage. However, AVSI-ANFIS performs better in predicting the accurate result with minimum error and reduced computational time. The AVSI-ANFIS combination improves the simple summation used in AVSI techniques in computing six power system parameter variances and the aggregated-variance stability index, using ANFIS self-generated weight functions based on the severity of change in parameters from the expected mean. In addition, using hybrid learning rule with combined gradient and least square estimation in ANFIS reduces the error.

The overall results show that the aggregated-variance stability index and AVSI-ANFIS combination are an efficient and effective way of ranking the line based on the severity of line outage.

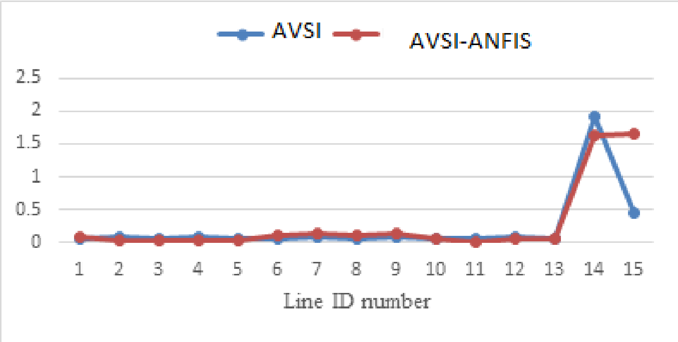


Fig. 12. Comparing AVSI and AVSI-ANFIS results for IEEE-14 bus system.

5. Conclusion

In this paper, the ranking of line contingency is performed using aggregated-variance stability index and AVSI-ANFIS combination based on the severity of line outage. First, based on the severity of inductive loading on the power transmission line, lines are ranked using the proposed line stability index. The line ranking using aggregated-variance stability index and AVSI-ANFIS combination under N-1 contingency indicated that the most severely loaded network lines can be more readily identified. In addition, the effect of reactive power loading on power transmission lines, and hence the effect of line outage on entire network stability, can be easily determined. The results show that both techniques are very good in ranking lines but AVSI and ANFIS combination is more superior in predicting the output within a short period of time for better accuracy.

Nomenclatures

I_{ik}	Line current flow between bus *i* and *k*
I_{jk}	Line current flow between bus *j* and *k*
$L_{st,ij}$	The line stability index between two buses during contingency

P_{ij}	The line flow between two buses in p.u during continency
$P_{ij}^{\max}$	The maximum line flow in p.u
P_{ik}	Line real power flow
P_j	the receiving end load bus real power
P_{st}	The power stability index under contingency
Q_{ik}	Line reactive power flow
S^{Th}	The maximum thermal limit of power transmission line in MW
S_{ind}^{Th}	The thermal stability index of power transmission line
V_i	The sending end bus voltage
V_k	Load bus voltage
X_{ij}	The line admittance between two bus
Y_{ik}	The line admittance
Greek Symbols	
δ	The phase angle of sending end bus voltage in degree
δ_i	The power angle in degree
δ_k	The phase angle of the load bus voltage
δ_{nl}	Power angle variance
θ_{ik}	The phase angle of line admittance in degree
ρ_{agr}	The aggregated-variance of the power system parameters
ρ_{Lst}	The variance of line stability index during contingency
ρ_{PL}	The variance in power loss under contingency
$\rho_{S^{Th}}$	The thermal limit variance during contingency
ρ_v	The variance of voltage during contingency
ρ_δ	The variance of power angle during contingency
Abbreviations	
ANFIS	Adaptive Neuro-Fuzzy Interface System
AVSI	Aggregated-Variance Stability Index
AVSI-ANFIS	Aggregated-Variance Stability Index in combination with Adaptive Neuro-Fuzzy Interface System

References

1. Amroune, M.; Bouktir, T.; and Musirin, I. (2018). Power system voltage stability assessment using a hybrid approach combining dragonfly optimization algorithm and support vector regression. *Arabian Journal for Science and Engineering*, 43(6), 3023-3036.
2. Amroune, M.; Bourzami, A.; and Bouktir. T. (2014). Weakest buses identification and ranking in large power transmission network by optimal location of reactive power supports. *TELKOMNIKA Indonesian Journal of Electrical Engineering*, 12(10), 7123-7130.
3. Kanimozhi, R.; and Selvi, K. (2015). An efficient method for contingency ranking using voltage stability index in power system. *Journal of Electrical Systems*, 11(3), 353-366.
4. Adebayo, I.; and Sun, Y. (2017). New performance indices for voltage stability analysis in a power system. *Energies*, 10(12), 1-18.

5. Bouchoucha, C.; Abdelaziz, S.; Mansouri, M.N.; and Mimouni, F. (2012). Voltage stability: Effect of the load and contingency ranking. *Trends in Applied Sciences*, 7(10), 792-812.
6. Vadivelu, R.; and Marutheswar, G.V.(2014). Fast voltage stability index based optimal reactive power planning using differential evolution. *Electrical and Electronics Engineering: An International Journal (ELELIJ)*, 3(1), 51-60.
7. Goh, H.H.; Chua, Q.S.; Lee, S.W.; Kok, B. C.; Goh, K.C.; and Teo K.T.K. (2011). Comparative study of line voltage stability indices for voltage collapse forecasting in power transmission system. *International Journal of Civil and Environmental Engineering*, 9(2), 132-137.
8. Kanimozhi, R; and Selvi, K. (2013). A novel line stability index for voltage stability analysis and contingency ranking in power system using fuzzy based load flow. *Journal of Electrical Engineering and Technology (JEET)*, 8(4), 694-703.
9. Shaikh, F.A.; Zaheeruddin.; and Asghar, M.S.J. (2011). Computational intelligence and voltage stability analysis for mitigation of blackout. *International Journal of Computer Applications*, 16(2), 6-11.
10. Jebaraj, L.; Rajan, C.C.A.; and Shakthivel, S. (2012). Real power loss and voltage stability limit optimization incorporating TCSC and SVC through DE algorithm under different operating conditions of a power system. *IOSR Journal of Electrical and Electronics Engineering (IOSRJEEE)*, 1(5), 16-25.
11. Quaia, S. (2018). Critical analysis of line loadability constraints. *International Transactions on Electrical Energy System*, 28(6), 1-11.
12. Burada, S., Joshi, D.; and Mistry, K.D. (2016). Contingency analysis of power system by using voltage and active power performance index. *Proceedings of the IEEE International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*. Delhi, India, 1-5.
13. Diamenu, G. (2017). A review on stability improvement of electric power transmission systems using shunt and series compensation techniques. *Journals of Electronics and Communication Engineering* (*IOSR-JECE*), 12(4), 62-70.
14. Lin, H.; Jia, C.; Guerrero, J.M.; and Vasquez, J.C. (2017). Angle stability analysis for voltage-controlled converters. *IEEE Transactions on Industrial Electronics*, 64(8), 6265-6275.
15. Pentayya, P.; Verma, U.K.; Mukhopadhyay, P.; Mitra, G.; Bannerjee, S.; Thakur, M.; and Sahay, S. (2008). Line loadability in indian perspective. 5 pages.
16. Kumar, A.; and Vyas, S. (2013). Reactive power control in electrical power transmission system. *International Journal of Engineering Trends and Technology (IJETT)*, 4(5), 1707-1717.
17. Jianying, Z.; Bo, Z.; Yujing, G.; Yongqi, Y.; Yao, Y.; Zhijun, W.; and Hao, Z. (2017). Research on power loss calculation and temperature rise simulation of AC high voltage GIS busbar. *Proceedings of the International Conference on Electric Power Equipment – Switching Technology (ICEPE-ST).* Xi'an, China, 720-725.
18. Khartov, A. (2017). Stochastic compactness of distributions of sums of independent random variables with finite variances. *Lithuanian Mathematical Journal*, 57(2), 196-203.

19. Haidar, A.M.A., Mohamed, A.; Jaalam, N.; Khalidin, Z.; and Kamali, M.S. (2009). A neuro-fuzzy application to power system. *Proceedings of the International Conference on Machine Learning and Computing*. Singapore, 131-135.
20. Suganyadevi, M.V.; and Babulal, C.K. (2014). Fast assessment of voltage stability margin of a power system. *Journal of Electrical System*, 10(3), 305-316.
21. Nor, A.F.M.; Sulaiman, M.; Kadir, A.F.A.; and Omar, R. (2017). Voltage stability analysis of load buses in electric power system using adaptive neuro-fuzzy inference system (ANFIS) and probabilistic neural network (PNN). *ARPN Journal of Engineering and Applied Sciences*, 12(5), 1406-1412.
22. Goh, H.H.; Chua, Q.S.; Lee, S.W.; Kok, B.C.; Goh, K.C.; and Teo, K.T.K. (2015). Comparative study of line voltage stability indices for voltage collapse forecasting in power transmission system. *International Journal of Civil and Environmental Engineering*, 9(2), 132-137.
23. Wenzel, T.; and Leibfried, T. (2008). Simulation of load displacement in parallel lines using series connected tapped reactor. *Proceedings of the International Conference on High Voltage Engineering and Application*. Chongqing, China, 4 pages.