U.Porto Journal of Engineering, 9:3 (2023) 55-71
ISSN 2183-6493
DOI: 10.24840/2183-6493_009-003_001790

Received: 2 September, 2022
Accepted: 17 October, 2022
Published: 28 April, 2023

A New Multistage Clustering Algorithm for Optimal VAr Planning For Dynamic Voltage Stability Analysis

Bharathi V.[1], Dr. Chandrasekhar Reddy Atla[2], Dr. M. R. Shivakumar[3]
[1]Ph.D. Research Scholar, Department of Power Systems, VTU Research Centre, Power Research and Development Consultants Private Limited, Bengaluru - 560086, Karnataka, India (bharathi.vtu@prdcinfotech.com) ORCID 0000-0002-0378-2728
[2]Deputy General Manager, Power System Solutions, Power Research and Development Consultants Private Limited, Bengaluru - 560086, Karnataka, India (csreddy@prdcinfotech.com) ORCID 0000-0003-0691-1254
[3]Principal, Sri Revana Siddeshwara Institute of Technology, Bengaluru, India (vatsa_mr@yahoo.com) ORCID 0000-0003-2187-2169

Abstract
Power systems need reactive power support to withstand voltage instability issues. The Volt Ampere reactive (VAr) resources are to be optimally determined for location and size. Generally, candidate locations are determined based on the ranking of buses according to sensitivity indices, and the Trajectory Sensitivity Index (TSI) is the most widely used sensitivity index. However, the locations identified by ranking the buses at the system level using the TSI method do not guarantee an optimal VAr solution. The recent methods based on dividing the power system into zones address the issue of optimality. The prevailing zoning methods are based on the computation of the electrical distance between buses and do not address the zoning scenario where the electrical distance between the buses is indeterminable. This paper introduces a new multistage algorithm for grouping the buses into zones even when the electrical distance is indeterminable. The new proposed strategy encompasses applying proposed analytical and parametric techniques after the standard clustering steps. A new index, namely the Bilateral Sensitivity Index (BSI), is introduced to quantify the proximity of buses. The TSI-based zonal level ranking of buses is introduced. The proposed strategy demonstrates that when TSI is employed to rank the buses at the zonal level rather than at the system level, it helps towards an optimal VAr solution. The new multistage clustering strategy is integrated into the generalized Dynamic Voltage Stability Analysis (DVSA) framework for optimal VAr determination and applied to study the voltage collapse phenomenon on a practical 24-bus system in the southern part of India. The results demonstrate the proposed approach's efficacy in mitigating voltage instability issues through optimal VAr support.

Author Keywords. Clustering, sensitivity analysis, voltage collapse, dynamic voltage stability, Dendrogram

Type: Research Article

1. Introduction

Achieving voltage stability is one of the important considerations in planning studies of power systems. The black-out incidents reported throughout the world demand a detailed study of voltage stability issues in the system (IEEE 2002; IEEE 2007). Dynamic voltage stability refers to the ability of the power system to sustain the prescribed voltage limits when subjected to contingencies (Kundur 1994). One of the remedies to voltage instability is to provide Volt

Ampere reactive (VAr) support to the system by installing additional VAr resources. Adding supplementary sources of reactive power adds to the cost of the power system infrastructure. Hence it is important to keep the optimal location and sizing of VAr resources in view while VAr planning. To determine the location of the VAr resources, sensitivity-based methods have been widely employed. In sensitivity methods, a small amount of VAr is injected into buses and the voltage impact on other buses is observed (Saptoka 2010). The buses with the highest sensitivity are selected as candidate locations for installing VAr resources. The Trajectory Sensitivity Index (TSI) is proposed by (Saptoka 2010) to determine the location of dynamic VAr resources. The TSI is also employed by (Paramasivam et al 2013; Liu 2018; Chi and Xu 2020) for candidate selection in dynamic optimization studies. Based on sensitivity analysis, a similar index, Voltage Sensitivity Index (VSI), is employed by (Qi et al 2017; Huang et al 2017) for candidate location selection. The disadvantage of sensitivity-based methods is that the nearby buses are identified as candidate locations. This leads to a concentration of VAr resources and redundant installations (Mao et al 2019). The surplus installations amount to increased expenditure and defeat the purpose of optimality. To overcome these issues, zoning-based methods for candidate locations have been applied in recent studies. In zoning methods, the system is divided into zones employing clustering algorithms. The VAr resources are placed in each zone. The zones are decided based on the dynamic response characteristics of the power system. Dynamic response characteristics are mined employing cohesive voltage performance criteria. Buses with similar characteristics are grouped. In (Guan et al. 2017), zoning-based candidate selection is carried out by employing indices such as Voltage Fluctuation Vector (VFV), Voltage Violation Integral (VVI), and Voltage Control Index (VCI).

The Affinity Propagation Clustering (APC) algorithm is employed. In (Mao et al. 2019), electrical distance-based zoning is carried out by employing the Transient Distance Index (TDI) and Voltage Supporting Index (VSI). Electrical distance is computed using post-contingency voltage response data. The spectral clustering algorithm is applied. In (Chi and Xu 2020), the Voltage Collapse Proximity Indicator (VCPI) and Transient Voltage Stability Indices (TVSI) are used for grouping the buses. The Fuzzy C-mean (FCM) clustering algorithm is applied. In (Mao et al 2021), electrical distance is computed by employing Impedance based method (IM), sensitivity-based method(SM), and Transient Method(TM). The spectral clustering method is employed for grouping the buses into zones. The number of zones is selected based on a guideline formula. The application of TSI for the system-level ranking of buses is analyzed.

From the literature, it is observed that the zoning criteria are developed using the post-fault voltage path data of the buses. This means that buses in the system can be grouped into zones only if the post-contingency path is available for the buses. In practice, there may be a few buses for which post-contingency paths are unavailable. It is because the system may not withstand the application of contingency on some of the buses and may diverge. The existing zoning approaches do not address this scenario. Also, in the existing literature, the approach of employing TSI for the zonal level ranking of the buses is not attempted.

This paper proposes a new multistage clustering algorithm for zoning the power system. Auxiliary techniques are proposed as additional stages of clustering to the standard clustering algorithm. The new approach enables the grouping of even the indeterminable buses in the zoning scheme. The main contributions of the paper are as follows:

1. Development of a new multistage zoning algorithm that enables the inclusion of even the indeterminable buses into zones. Proposed auxiliary techniques employ bus connectivity data and sensitivity parameters for grouping the indeterminable buses.

2. Introduction of a new index, namely the Bilateral Sensitivity Index (BSI) to quantify the mutual sensitivity between the two buses. At the zonal level, TSI - based bus ranking is introduced.
3. Integration of the proposed algorithm into the generalized Dynamic Voltage Stability Analysis (DVSA) framework to study voltage collapse issues.

The rest of the document is arranged as follows. Section 2 presents the detailed methodology. Section 3 presents results and analysis of applying the new multistage clustering algorithm on a practical 24-bus system in Southern India (MiPower 2022®). Section 4 presents the conclusion and scope for further research.

2. Methodology

This section presents the high-level approach, electrical distance concept, the criteria for selecting the number of clusters, the proposed auxiliary techniques, the new multistage clustering algorithm, and the corresponding flowchart.

2.1. High-level Approach

High-level program flow is presented in (Figure 1). The system data is fed into the proposed multistage clustering algorithm. The proposed algorithm allocates the buses into the zones and determines potential locations for installing the VAr resources. The candidate buses identified by the algorithm are employed by the generalized DVSA framework developed in our previous work (Bharathi, C.R. Atla, and Shivakumar 2022) to determine the optimal VAr to mitigate voltage instability issues. The generalized DVSA framework involves an optimization tool and a generic Differential and Algebraic Equations (DAE) solver for VAr determination.

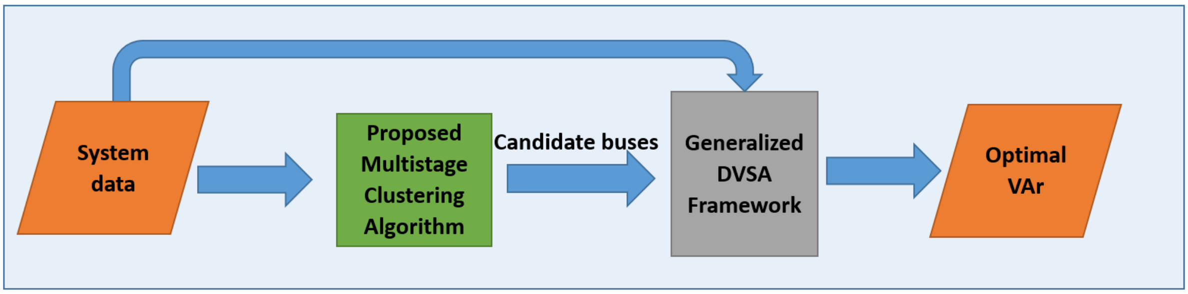

Figure 1. High-level program flow

The electrical distance concept (Mao et al. 2021) employed in the clustering algorithm is presented in the next section.

2.2. Electrical Distance Computation

The ability of buses to mutually impact the voltage level is treated as the electrical distance (Mao et al 2021). There is no standardized definition for electrical distance in academia (Mao et al 2021). In the Transient Method (TM) method (Mao et al 2021) of electrical distance computing, a three-phase to-ground contingency is applied on each bus. The extent to which the post-contingency voltage path of the faulted bus and the other buses match determines the electrical distance between the buses. If a bus is at a farther electrical distance from the faulted bus, the voltage path of that bus will not be impacted by the faulted bus. Hence the voltage curves of the two buses will not be similar. Whereas, if the bus is at a closer electrical distance from the faulted bus, it gets impacted by the faulted bus and the voltage curves of the two buses will have a degree of similarity (Mao et al 2019). Based on the degree of similarity, the buses are grouped into zones. (Figure 2) illustrates the voltage waveform of faulted bus and impacted bus. If j is the faulted bus and i is the impacted bus, the normalized voltages $v(t)'_j$ at the faulted bus and $v(t)'_i$ at the impacted bus are computed as given by (Equation 1) and (Equation 2), respectively.

$$v(t)'_j = \frac{\boldsymbol{V(t)_j}}{V0} \tag{1}$$

$$v(t)'_i = \frac{V(t)_i}{V0} \tag{2}$$

Where

$V(t)_j$ => Post contingency voltage at faulted bus j at time t

$V(t)_i$ => Voltage at impacted bus i at time t due to fault at bus j

$V0$ => Steady state voltage at respective buses

The gap between two voltage paths is given by (Equation 3)

$$\sum_{t=1}^{T} \boldsymbol{v}((t)'_i - \boldsymbol{v}(t)'_j)^2 \tag{3}$$

Where T refers to the post-fault time duration considered. Generally, it is taken as 5 seconds (Mao et al 2019).

If the impacted bus i is far from the faulted bus, then the normalized voltage becomes

$$v(t)'_i = \frac{Vi(t)}{V0} = 1 \tag{4}$$

After substituting (Equation 4) in (Equation 3), the maximum gap between the impacted bus and the faulted bus is given by (Equation 5)

$$\sum_{t=1}^{T} 1 - v(t)'_j)^2 \tag{5}$$

The gap ratio is defined by (Equation 6).

$$Gap\ Ratio_{ij} = \frac{Actual\ gap_{ij}}{Maximum\ gap_{ij}} \tag{6}$$

The index that defines the similarity between the impacted bus and the faulted bus is given by (Equation 7)

$$\textit{Similarity Index= (1- Gap Ratio)} \tag{7}$$

The similarity index varies between 0 and 1.

$Similarity\ index_{ij}$=> Close to 0, if the impacted bus i is far from the faulted bus j

$Similarity\ index_{ij}$ => Close to 1, if the impacted bus i is close to the faulted bus j

$$\text{However, } Similarity\ index_{ij} \neq Similarity\ index_{ji} \tag{8}$$

To achieve symmetry, the Similarity Index is transformed into a Distance Index using (Equation 9)

$$\text{Distance index} = -\log\left(Similarity\ index_{ij} * Similarity\ index_{ji}\right) \tag{9}$$

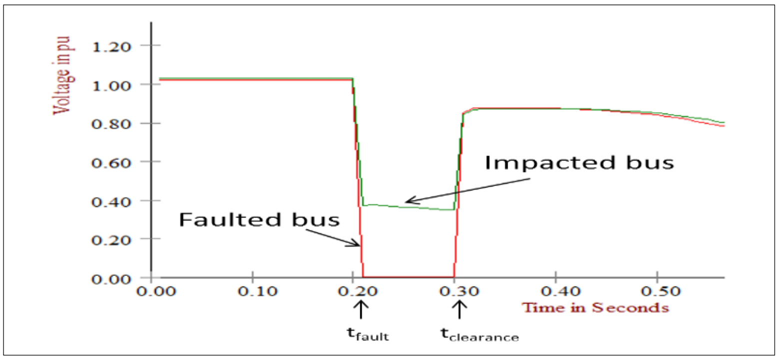

Figure 2.The gap between the waveforms based on (Mao et al. 2021)

Then the distance index satisfies (Equation 10)

$$Distance\ index_{ij} = Distance\ index_{ji} \tag{10}$$

The computation of the distance index for all the buses will form the symmetric distance matrix. The symmetric distance matrix is used to divide the system into zones.

The approach to determining the number of clusters is presented in the following section.

2.3. Selection of Number of Clusters

In our proposed approach, we have employed an analytical approach based on similarity level data available in the amalgamation table (Minitab® 2022) to determine the number of clusters.

The abrupt change in similarity levels provided by the amalgamation table gives an insight into the number of clusters to be formed (Minitab® 2022). The proposed auxiliary techniques to supplement the clustering capabilities of the standard algorithms are presented in the next section.

2.4. Proposed Auxiliary Techniques

The auxiliary techniques are proposed to be included as subsequent stages to the standard clustering algorithm. The techniques utilize the bus connectivity data and the bus sensitivity data to allocate the indeterminate buses to the appropriate zones. The indeterminable buses are the buses that do not have the post contingency voltage profile due to post-fault system divergence issues. The buses having the post contingency voltage path are referred to as determinable buses.

2.4.1. Analytical technique based on bus connectivity data

Bus connectivity data utilizes the physical connectivity data of two buses to allocate the indeterminable bus to the appropriate zone. If the indeterminable bus is connected to a single determinable bus, then the indeterminable bus is allocated to the zone of the determinable bus. If the indeterminable bus is connected to multiple determinable buses, then the BSI-based strategy is applied to allocate indeterminable buses.

The BSI-based allocation strategy is presented in the next section.

2.4.2. Bilateral Sensitivity Index (BSI)

The Bilateral Sensitivity Index (BSI) is proposed in this paper to measure the mutual sensitivity between the two buses. Buses with the highest BSI are grouped. Consider an indeterminate bus ‘a’. Consider a determinable bus ‘b’ that has already been allocated to a zone. The sensitivity parameters for bus ‘a’ and bus ‘b’ are computed using (Equation 11) and (Equation 12).

$$\textit{Sensitivity of bus 'a' due to injection of reactive power at bus 'b'} = \frac{\partial Va}{\partial Qb} \quad (11)$$

$$\text{Sensitivity of bus 'b' due to injection of reactive power at bus 'a'} = \frac{\partial Vb}{\partial Qa} \quad (12)$$

Bilateral sensitivity between bus ‘a’ and bus ‘b’ is defined as:

$$\text{BSI (a, b)} = \left(\frac{\partial Va}{\partial Qb} * \frac{\partial Vb}{\partial Qa}\right) \quad (13)$$

Consider a bus ‘c’ that is determinable and belongs to a different zone than the bus ‘b’. The BSI between bus ‘a’ and bus ‘c’ can be defined as:

$$\text{BSI (a, c)} = \left(\frac{\partial Va}{\partial Qc} * \frac{\partial Vc}{\partial Qa}\right) \quad (14)$$

If the BSI (a, b) > BSI (a, c), then the bus ‘a’ is allocated to the zone of bus ‘b’.

If the BSI (a, c) > BSI (a, b), then the bus ‘a’ is allocated to the zone of bus ‘c’.

The proposed multistage clustering algorithm incorporating the auxiliary techniques is presented in the next section.

2.5. The Proposed Multistage Clustering Algorithm

The existing zoning techniques (Mao et al 2021) are based on the presumption that the electrical distance data between the buses is available. Electrical distance is computed based on post contingency voltage data. Hence these methods cannot be applied in scenarios with indeterminate buses. The proposed multistage clustering algorithm overcomes this limitation. The proposed auxiliary techniques bolster the capability of the existing clustering techniques to include indeterminate buses in the clustering scheme. The proposed approach employs a standard clustering algorithm in the first stage to group the determinable buses. Proposed auxiliary techniques are applied in subsequent stages to group the indeterminate buses. We have employed the standard Dendrogram algorithm (Minitab® 2022), an unsupervised hierarchical clustering technique in machine learning to group the determinable buses in the first stage. The Dendrogram provides the visual representation of the clusters. The correctness of the Dendrogram is validated by employing the cophenetic correlation coefficient, an index that measures how well the Dendrogram models the original data set. The cophenetic correlation coefficient values close to 1 indicate the most faithful data modeling (Minitab® 2022). After allocating buses to zones, the buses are ranked at zonal levels based on TSI. The buses with the highest TSI values are selected as candidate buses from each zone. Generally, it is sufficient to place one VAr resource in each zone (Guan et al. 2017).

The algorithm and the flowchart for the proposed approach are presented in this section

2.5.1. Multistage Clustering Algorithm

a) Prepare the system data
b) Compute the TSI of the load buses
c) Inject fault to the load buses and observe the voltage trajectory impact
d) Compute the distance matrix
e) determine the number of clusters
f) Form the clusters employing a standard clustering technique and allocate the buses to the zones
g) If the distance matrix is computable for all buses, go to step (q)
h) If there are indeterminate buses for which the distance matrix is not computable, note the bus numbers of the indeterminate buses.
i) Form the clusters employing a standard clustering technique and allocate the determinable buses to the zones
j) Analyze the connectivity features of the indeterminable buses.
k) If they are connected to a bus allocated to the same zone, then allocate the bus to the same zone
l) If they are connected to buses belonging to different zones, compute the BSI for the indeterminable buses and the connected determinable buses.
m) Compare the BSIs.
n) Note the connected determinable bus that contributes to the highest BSI. Consider the zone of that bus as the target zone
o) Allocate the indeterminable bus to the target zone
p) Repeat the steps (j) to (o) for all indeterminate buses
q) Rank the buses within the zone according to TSI
r) Select the highest TSI valued bus from each zone as the candidate bus
s) Carry out DVSA with the candidate location obtained from step (r)
t) Stop

2.5.2. Flowchart

The flowchart for the proposed multistage clustering algorithm is presented in (Figure 3).

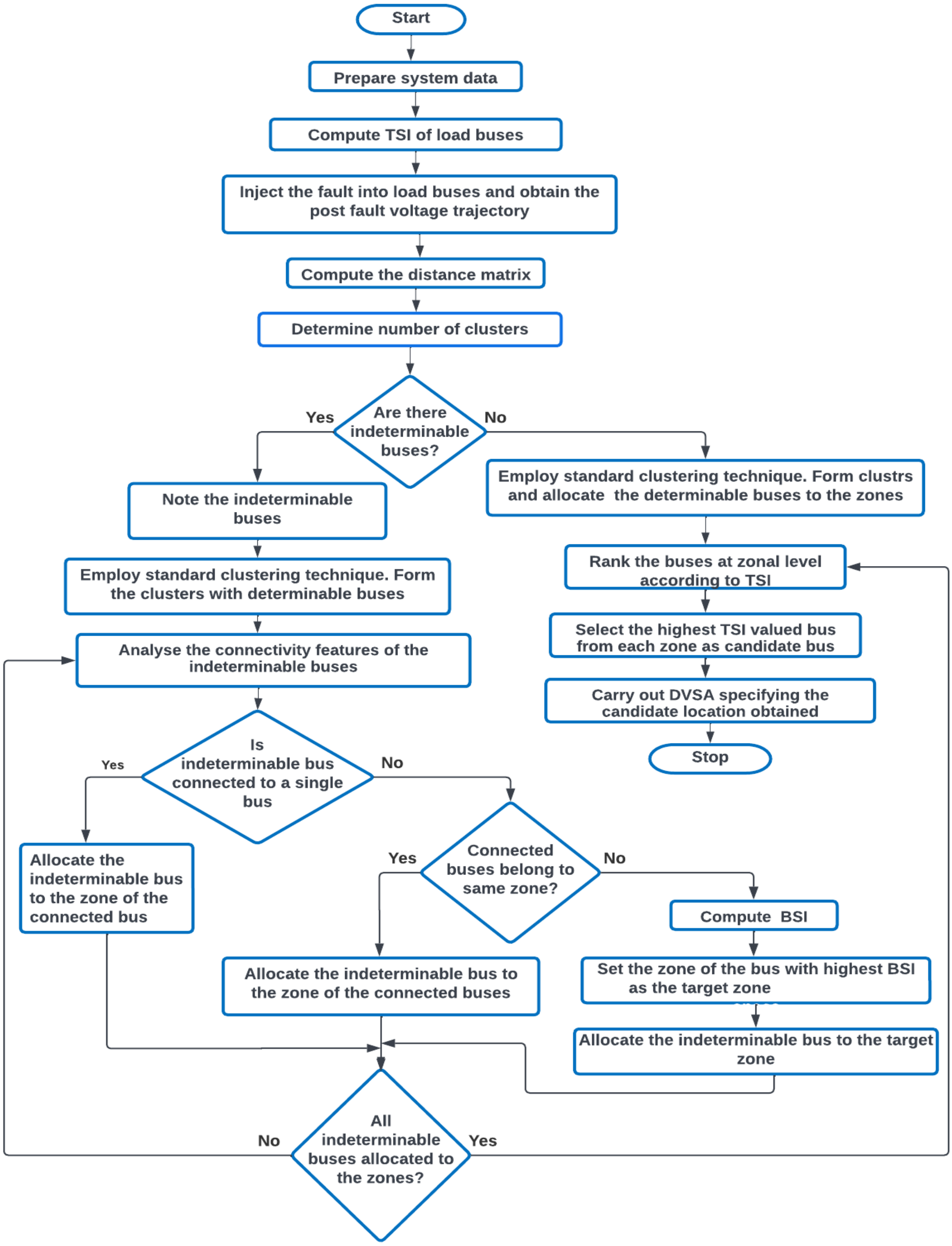

Figure 3. Flowchart for the proposed multistage clustering algorithm

3. Results and Discussions

The methodology presented in section 2 is applied to a practical 24-bus system in Southern India (MiPower 2022®). Candidate buses are selected employing the proposed multistage clustering algorithm. The DVSA is performed based on our previous work (Bharathi, C.R. Atla, and Shivakumar 2022). Results obtained with the proposed multistage clustering algorithm are compared with those obtained from the existing TSI method i.e., TSI-based ranking at the system level without clustering.

The single-line diagram of the 24-bus system is represented in (Figure 4) (MiPower® 2022). It has four generators and 14 load buses with the total specified MW load and MVAr load of 1343 MW and 603 MVAr, respectively.

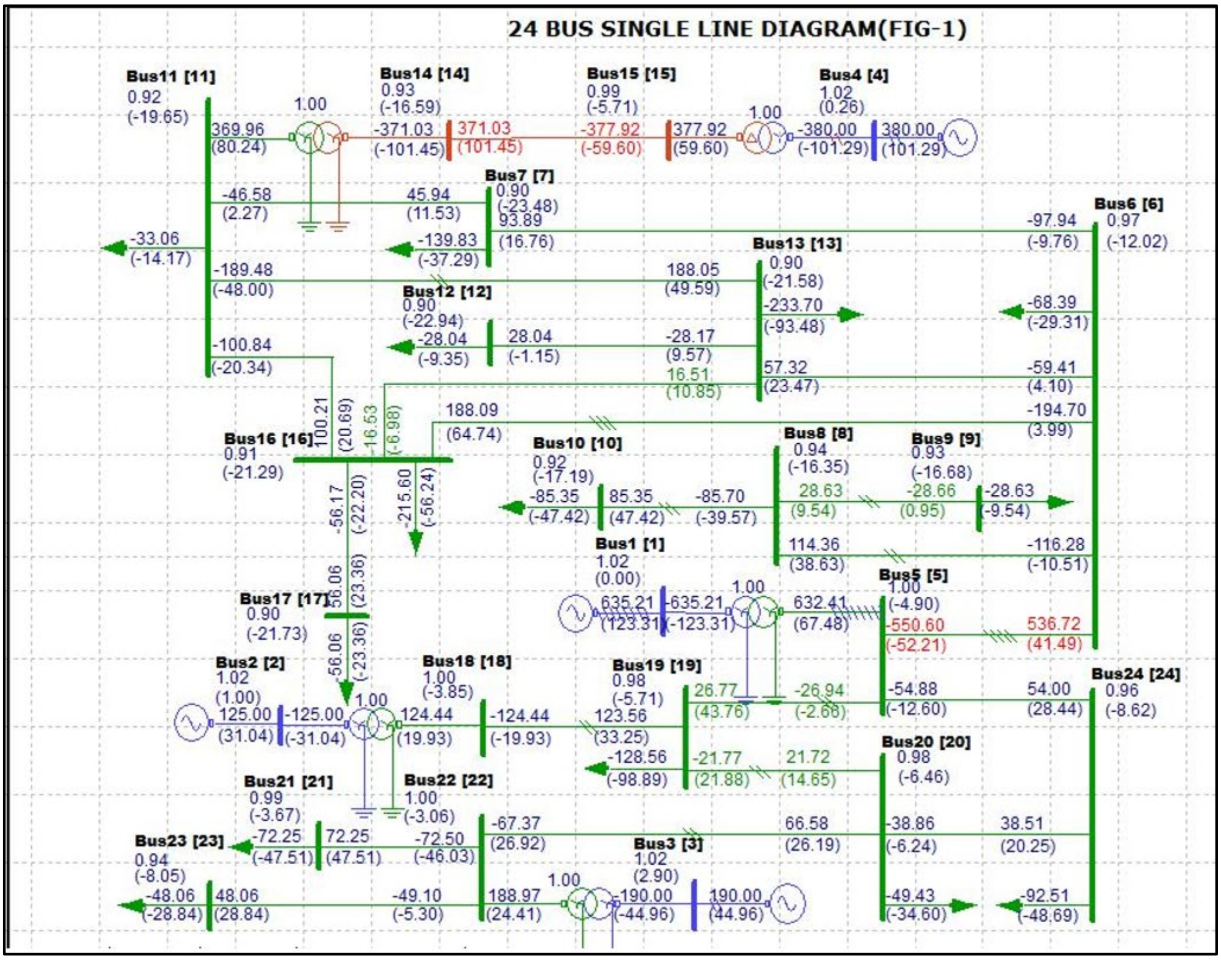

Figure 4: Single line diagram of 24 bus system (MiPower® 2022).

A three-phase to ground fault is applied at bus 13 at 0.2 seconds. The fault is cleared by opening the transmission line 6-13. The resulting voltage response of the system is shown in (Figure 5). It is observed that post-fault bus voltages recover to above 0.75 p.u. and below 1.2 p.u. levels initially. Bus voltages continue to fluctuate between these levels till around 19 seconds. After 19 seconds, bus voltages continue to hover at unacceptable levels, resulting in voltage collapse at around 26 seconds. To solve the voltage collapse problem, VAr compensation is required to be provided at suitable locations. The VAr support should be such that it is economical and improves the voltage level of the system to meet the specified voltage criteria. The optimal VAr required to improve the bus voltages is determined by employing the DVSA optimization technique presented in our previous work (Bharathi, C.R.Atla, and Shivakumar 2022). The criteria specified by WECC/NERC (Western Electricity Coordinating Council, North American Electric Reliability Corporation) (Bharathi, C.R. Atla, and Shivakumar 2022) and the Indian Electricity Grid Code (CERC 2010) are applied. From the voltage waveform (Figure 5), it is observed that the post-fault bus voltages recover to levels between 0.75 p.u. and below 1.2 p.u. and meets the specified criteria of the T1 timeframe (Bharathi, C.R. Atla, and Shivakumar 2022). Hence VAr support is not required during the T1 timeframe that corresponds initial few seconds post fault clearance. However, the criteria are not satisfied for T2 and T3 timeframes. The time duration of T2 and T3 timeframes are presented in (Table 1). The WECC/NERC criteria are applied for the T2 timeframe as the (CERC 2010) does not have the criteria defined for the T2 timeframe.

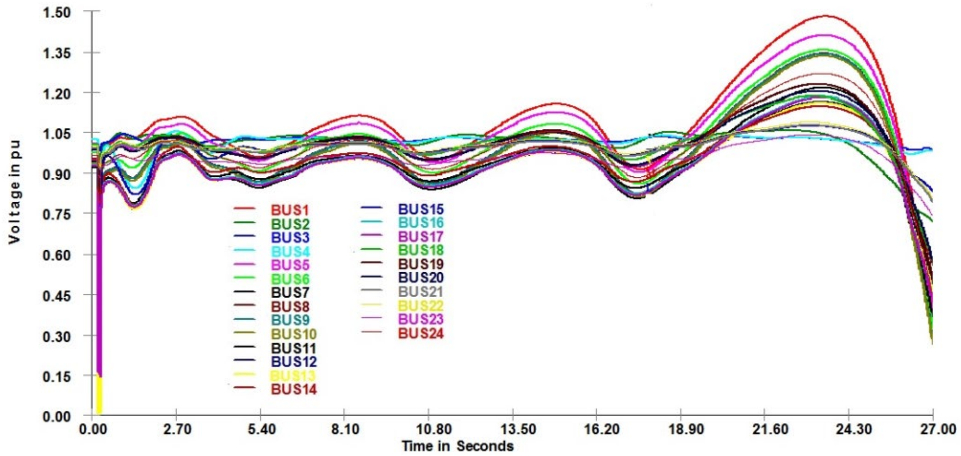

Figure 5: Voltage profile after 3 phase fault at bus 13 without VAR support

Timeframe	Voltage criteria
T2 (1.45 seconds to 3.3 seconds)	WECC/NERC
T3 (3.31 seconds to 20s)	Indian Electricity Grid Code

Table 1. Voltage criteria for 24 bus system

3.1. DVSA with the Proposed Multistage Clustering Algorithm

The proposed algorithm is implemented by employing MiPower®, Minitab®, and MATLAB® tools. Power system analysis is carried out employing MiPower® as a DAE solver. Clustering is carried out employing Minitab® and MATLAB®.

3.1.1. Selection of number of clusters

The number of clusters is selected based on the approach presented in section 2.3. The amalgamation table obtained for the test system is presented in (Table 2).

The amalgamation table represents the Similarity levels corresponding to the number of clusters. It can be observed that the Similarity level smoothly varies from steps 1 to 8. But in step 9, there is an abrupt change from 92.42 levels to 44.28 levels. This indicates that 3 clusters are appropriate for this system.

Step	Number of clusters	Similarity level
1	10	99.9354
2	9	99.5865
3	8	98.7757
4	7	98.6551
5	6	98.5719
6	5	97.1473
7	4	96.8223
8	3	92.4229
9	2	44.2875
10	1	1.7711

Table 2. Amalgamation table for zoning of 24-bus system

3.1.2. Dendrogram for clustering the determinable buses

The distance matrix is computed as presented in section 2.2 and the Dendrogram is established based on the distance matrix for the determinable buses. The clusters determined by the Dendrogram are depicted in (Figure 6). The cophenetic coefficient value is 0.9959 which indicates that the Dendrogram has provided a good representation of the distance matrix.

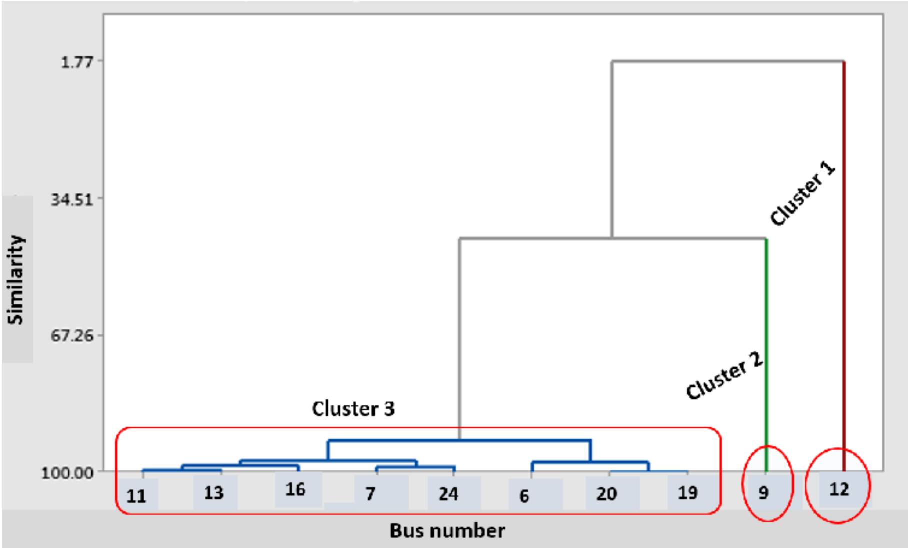

Figure 6. Dendrogram for 24-bus system

It can be observed from (Figure 6) that the load buses viz., bus 10, bus 17, bus 21, and bus 23 are not included in the zoning scheme as they are indeterminable buses. The allocation scheme for indeterminable buses is discussed in the following section.

3.1.3. Allocation of indeterminable buses to zones

The proposed auxiliary techniques presented in section 2.4 are employed to allocate the indeterminable buses to appropriate zones.

3.1.4. Analytical techniques employing bus connectivity data

The analytical technique presented in section 2.4.1 is employed to group the indeterminate buses. The outcome of the analysis is presented in (Table 3). It can be inferred that bus 17, bus 23, and bus 21 belong to zone 3 as they are connected to a bus of zone 3. Whereas bus 10 is connected to two buses that belong to different zones. Bus 10 is connected to bus 9, which is in zone 2, and to bus 6, which is in zone 3. To allocate bus 10 to an appropriate zone, the BSI-based strategy is applied.

Bus Number	Analysis	Inference	Decision
17	Connected to the load bus 16 and not to any other buses	Allocate to the zone of bus 16	Allocate to zone 3
10	Connected to the load bus 9 and load bus 6 through the switching bus 8	Allocate to the zone of bus 9 or bus 6	Allocate to zone 2 or zone 3
23	Connected to the load bus 20 through the switching bus 22 and not to any other buses	Allocate to the zone of bus 20	Allocate to zone 3
21	Connected to the load bus 20 through the switching bus 22 and not to any other buses	Allocate to the zone of bus 20	Allocate to zone 3

Table 3: Allocation of indeterminable buses based on analytical technique

3.1.5. BSI based technique

The BSI-based strategy is applied in the scenario where an indeterminable bus is connected to determinable buses of different zones. Bus 10 is the indeterminable bus. Bus 6 and bus 9 are the determinable buses belonging to zone 1 and zone 2, respectively. The voltage sensitivity of bus 10 is computed with respect to reactive power injection at bus 9 and bus 6. Also, the voltage sensitivity of bus 9 and bus 6 with respect to reactive power injection at bus 10 is determined. The BSI is computed based on sensitivity parameters. The results are presented in (Table 4).

Indeterminable bus	Determinable bus	Sensitivity parameter	Sensitivity value	BSI
10	6	$\frac{\partial V10}{\partial Q6}$	0.177461	0.029943
		$\frac{\partial V6}{\partial Q10}$	0.168733	
	9	$\frac{\partial V10}{\partial Q9}$	0.297535	0.088685
		$\frac{\partial V9}{\partial Q10}$	0.298067	

Table 4. BSI for bus 10, bus 6, and bus 9

The BSI between bus 10 and bus 9 is 0.088685. The BSI between bus 10 and bus 6 is 0.029943. Comparing the BSIs, it can be noted that the mutual sensitivity between bus 10 and bus 9 is greater than that of bus 10 and bus 6. Hence it can be inferred that bus 10 and bus 9 are located closer and bus 10 belongs to the zone of bus 9. After the buses are allocated to the zones, buses are to be ranked. The ranking of the buses based on zonal level TSI values is discussed in the following section.

3.1.6. Ranking of buses at zonal levels based on TSI

Candidate buses are ranked in each zone after the allocation of buses to the zones. The top three ranked buses based at the zonal level TSI are indicated in (Table 5). It can be noted that zone-1 has only bus 12. Hence bus 12 can be taken as the location.

Zone	Bus Number	TSI	Within-Zone ranking
1	12	0.906795	1
2	9	0.766043	2
	10	0.767891	1
3	13	0.868919	1
	17	0.853856	2
	16	0.842526	3
	11	0.833789	
	7	0.823485	
	6	0.689046	
	23	0.629149	
	24	0.600696	
	21	0.593459	
	20	0.578058	
	19	0.56226	

Table 5. Re-ordered ranking of buses at zonal levels based on TSI

In zone 2, the TSI of bus 10 is 0.767891 and that of bus 9 is 0.766043. Since the TSI of bus 10 is greater than that of bus 9, bus 10 is considered as the candidate from zone 2. In zone 3, the TSI of bus 13 is the highest among all buses. Hence, bus 13 is chosen as a location from zone 3.

3.1.7. Optimal VAr determined with the proposed multistage clustering algorithm

With candidate locations such as bus 12, bus 13, and bus 10, DVSA is carried out. The optimal values of VAr obtained are presented in (Table 6). After supporting the system with the obtained VAr, the resulting voltage profile of the system is shown in (Figure 7). It can be observed that the voltage profile meets the specified criteria. The results obtained with the existing method i.e., TSI at the system level without zoning, are presented in the next section.

VAr at buses	Minimum MVAr	Maximum MVAr
Bus 12(Q12)	-51.9498	-2.32
Bus 13(Q13)	68.41	166.37
Bus 10(Q10)	-60.76	9.5

Table 6. Optimal VAr obtained with the proposed multistage clustering algorithm

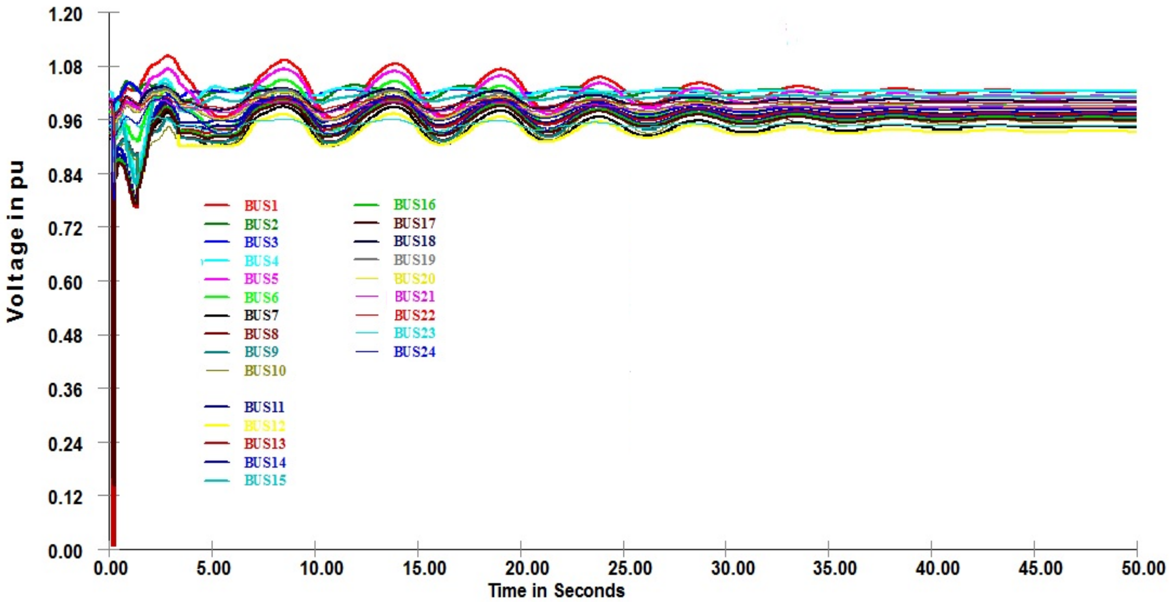

Figure 7: Voltage profile of the system with VAr support determined from the proposed algorithm

3.2. DVSA with the TSI-based ranking at the System Level Without Clustering

(Table 7) presents the ranking of the buses at the system level based on TSI.

It can be observed that buses 12, 13, and 17 are the top three buses having the highest TSI values. Hence they are considered as the candidate buses for performing the DVSA. The optimal VAr results obtained with DVSA are presented in (Table 8). After proving the system with this reactive power, the bus voltages have improved. The resulting voltage profile of the system is shown in (Figure 8). It can be observed that bus voltages have complied with the defined criteria.

Bus Number	TSI	Rank
Bus 12	0.906795	1
Bus 13	0.868919	2
Bus 17	0.853856	3
Bus 16	0.842526	
Bus 11	0.833789	
Bus 7	0.823485	
Bus 10	0.767891	
Bus 9	0.766043	
Bus 6	0.689046	
Bus 23	0.629149	
Bus 24	0.600696	
Bus 21	0.593459	
Bus 20	0.578058	
Bus 19	0.56226	

Table 7: Ranking of buses without zoning scheme

VAr at buses	Minimum MVAr	Maximum MVAr
Bus 13(Q13)	-281.02	262.33
Bus 12(Q12)	-61.27	0.00
Bus 17(Q10)	-126.21	460.05

Table 8: Optimal VAr obtained with the TSI method at system level without zoning

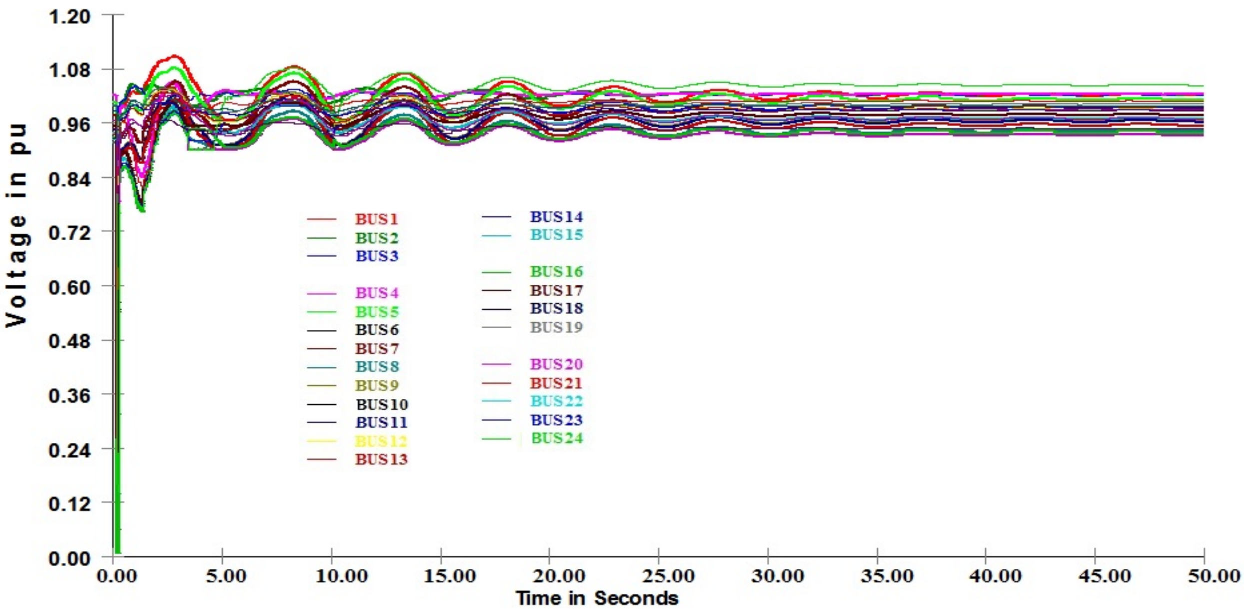

Figure 8: Voltage profile of the system with VAr support determined from the TSI method at system level without zoning

3.3. Comparison of Results

The results obtained with the proposed multistage clustering algorithm are compared with the existing TSI method i.e., TSI-based ranking at the system level without clustering. It can be observed that both methods are successful in uplifting the voltage profile to acceptable levels after providing the VAr support. However, it can be observed that the amount of VAr determined by the TSI method is not optimal. The VAr size determined by the two methods is compared in (Table 9). It can be observed from (Table 10) that the total amount of VAr determined by the proposed algorithm is 288.58 MVAr whereas the total VAr determined by the TSI method is 1190.86 MVAr. That is, the amount determined by the proposed method is 25% of that of the TSI method.

Method	Locations identified	Total MVAr (Capacitive)	Total MVAr (Inductive)
The proposed multistage clustering algorithm	Bus 13, Bus 12, and Bus 10	175.87	-112.71
TSI method at system level without clustering	Bus 13, Bus 12, and Bus 17	722.37	-468.49

Table 9: Comparison of VAr between the proposed method and the TSI method

This demonstrates that the proposed algorithm is more efficient in determining the optimal VAr requirement to improve the voltage profile of the system.

Method	Total VAr (MVAr)	Voltage criteria
TSI method at system level without clustering	1190.86	Voltage Criteria are satisfied
The proposed multistage clustering algorithm	288.58	Voltage Criteria are satisfied.

Table 10: Comparison of total VAr determined between the proposed method and the TSI ranking method at the system level without zoning

(Table 11) and (Table 12) present a summary of the comparison between the proposed method and the existing methods.

As stated in (Table 11) though the TSI method enables the performance of DVSA, the results obtained are not optimal. At the identified locations, the VAr resources of higher capacity are required to sustain the required voltage levels. As the system is not divided into zones, buses cannot be ranked at the zonal level.

Method	DVSA possible?	Zone-based?	VAr is optimal?	Zonal level bus ranking with TSI?
The proposed multistage clustering algorithm	✓	✓	✓	✓
TSI method at system level without clustering	✓	X	X	X

Table 11: Comparison between the proposed method and the TSI method

As summarized in (Table 12) though the existing TM clustering method divides the system into zones, it does not support the zoning with indeterminable buses. Since the indeterminable buses are not allocated, the candidate buses for VAr support cannot be finalized at zonal level. This hinders the performance of DVSA and the determination of optimal VAr.

Method	Zone-based?	Indeterminable buses grouped?	DVSA possible?	Optimal VAr?
The proposed multistage clustering algorithm	✓	✓	✓	✓
Existing clustering algorithms based on TM electrical distance	✓	X	Not possible for the systems with indeterminable buses	Not computable for the systems with indeterminable buses

Table 12: Comparison between the proposed method and the existing clustering methods

The proposed method fares better than the existing methods with respect to the factors as stated in (Table 11) and (Table 12). The proposed method supports the inclusion of even the indeterminable buses in the zoning scheme. The zonal level ranking of buses helps to determine the candidate locations that provide desired voltage support functionality with a lesser cost to improve the dynamic voltage stability of the system.

4. Conclusions and Future Scope

This research proposes a new multistage clustering algorithm to allocate the buses into zones. The proposed auxiliary techniques effectively allocate the indeterminable buses to appropriate zones. The new clustering strategy is integrated into the generalized DVSA framework for performing the DVSA. The integrated strategy is verified on a practical 24-bus system in Southern India (MiPower® 2022). It is observed that with the application of VAr determined by the proposed approach, the voltage collapse issue is effectively addressed. Compared with the existing method employing TSI at the system level, it has been established that the proposed method is more efficient in determining the optimal VAr requirement to maintain the bus voltages according to the defined criteria. The comparison with the existing clustering techniques based on the TM method demonstrates that the proposed algorithm has enabled the allocation of even the indeterminable buses into the zones.

As a part of the future scope, the proposed algorithm along with the DVSA framework will be applied to a power system with renewable energy sources.

References

Bharathi V., C. R. Atla, and M. R. Shivakumar. 2022. “Power System Voltage Collapse Mitigation Employing Optimization Based Dynamic Voltage Stability Analysis”, U.Porto Journal of Engineering, “Manuscript Accepted”.

Chi, Yuan, and Yan Xu. 2020. “Zoning-based Candidate Bus Selection for Dynamic VAR Planning in Power System towards Voltage Resilience.” IET Generation, Transmission & Distribution 14 (6): 1012–20. https://doi.org/10.1049/iet-gtd.2019.1049.

Chi, Yuan, Yan Xu, and Rui Zhang. 2021. “Many-Objective Robust Optimization for Dynamic VAR Planning to Enhance Voltage Stability of a Wind-Energy Power System.” IEEE Transactions on Power Delivery 36 (1): 30–42. https://doi.org/10.1109/TPWRD.2020.2982471.

Guan, Lin, Liang Wu, Feng Li, and Qi Zhao. 2017. “Heuristic Planning for Dynamic VAR Compensation Using Zoning Approach.” IET Generation, Transmission & Distribution 11 (11): 2852–61. https://doi.org/10.1049/iet-gtd.2016.2113.

Hathaway, Richard J., James C. Bezdek, and Yingkang Hu. 2000. “Generalized Fuzzy C-Means Clustering Strategies Using L/Sub p/ Norm Distances.” IEEE Transactions on Fuzzy Systems 8 (5): 576–82. https://doi.org/10.1109/91.873580.

Huang, Weihong, Kai Sun, Junjian Qi, and Jiaxin Ning. 2017. “Optimal Allocation of Dynamic Var Sources Using the Voronoi Diagram Method Integrating Linear Programing.” IEEE Transactions on Power Systems 32 (6): 4644–55. https://doi.org/10.1109/TPWRS.2017.2681459.

Huang, Weihong, Kai Sun, Junjian Qi, and Yan Xu. 2014. “A New Approach to Optimization of Dynamic Reactive Power Sources Addressing FIDVR Issues.” In 2014 IEEE PES General Meeting | Conference & Exposition, 1–5. National Harbor, MD, USA: IEEE. https://doi.org/10.1109/PESGM.2014.6939809.

Huang, Weihong, Kai Sun, Junjian Qi, and Yan Xu. 2015. "Voronoi Diagram Based Optimization of Dynamic Reactive Power Sources." In 2015 IEEE Power & Energy Society General Meeting, 1–5. Denver, CO, USA: IEEE. https://doi.org/10.1109/PESGM.2015.7286263.

IEEE (Institute of Electrical and Electronics Engineers). 2002. "PES-TR9 Voltage Stability Assessment: Concepts, Practices and Tools."

IEEE (Institute of Electrical and Electronics Engineers). 2007. "PES-TR12 Blackout Experiences and Lessons, Best Practices for System Dynamic Performance, and the Role of New Technologies."

Kundur, P. 1994. Power System Stability and Control. New York: McGraw-Hill.

Liu, Junwei, Yan Xu, Zhao Yang Dong, and Kit Po Wong. 2018. "Retirement-Driven Dynamic VAR Planning for Voltage Stability Enhancement of Power Systems With High-Level Wind Power." IEEE Transactions on Power Systems 33 (2): 2282–91. https://doi.org/10.1109/TPWRS.2017.2732441.

Mao, Xiaoming, Weifeng Zhu, Liang Wu, and Baorong Zhou. 2019. "Optimal Allocation of Dynamic VAR Sources Using Zoning-Based Distributed Optimization Algorithm." International Journal of Electrical Power & Energy Systems 113 (December): 952–62. https://doi.org/10.1016/j.ijepes.2019.06.025.

Mao, Xiaoming, Weifeng Zhu, Liang Wu, and Baorong Zhou. 2021. "Comparative Study on Methods for Computing Electrical Distance." International Journal of Electrical Power & Energy Systems 130 (September): 106923. https://doi.org/10.1016/j.ijepes.2021.106923.

"Minitab® Statistical Software" 21.2. Accessed August 1, 2022. https://www.minitab.com/.

"MiPower® Software Tool Box.". Accessed August 1, 2022. http://www.prdcinfotech.com/.

Paramasivam, Magesh, Ahmed Salloum, Venkataramana Ajjarapu, Vijay Vittal, Navin B. Bhatt, and Shanshan Liu. 2013. "Dynamic Optimization Based Reactive Power Planning to Mitigate Slow Voltage Recovery and Short Term Voltage Instability." IEEE Transactions on Power Systems 28 (4): 3865–73. https://doi.org/10.1109/TPWRS.2013.2271260.

Qi, Junjian, Weihong Huang, Kai Sun, and Wei Kang. 2017. "Optimal Placement of Dynamic Var Sources by Using Empirical Controllability Covariance." IEEE Transactions on Power Systems 32 (1): 240–49. https://doi.org/10.1109/TPWRS.2016.2552481.

Sapkota, B., and V. Vittal. 2010. "Dynamic VAr Planning in a Large Power System Using Trajectory Sensitivities." IEEE Transactions on Power Systems 25 (1): 461–69. https://doi.org/10.1109/TPWRS.2009.2030356.