# New Technique for Weak Area Clustering in Power System Network

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*Abstract*- Recent development has witnessed blackout incidents in many parts of the world. This can be due to voltage instability phenomena resulted from the stressed situation of the system where large amounts of real and reactive power are transported over long transmission lines. Besides, electric power systems are also exposed to various contingencies which contribute to over-loading of network branches, unsatisfactory voltages, leading to voltage collapse problems. Appropriate precaution can be made if the areas prone to voltage instability are clustered making a continuous monitoring is possible. This paper presents the weak area clustering technique based on sensitive lines and critical line outages in power system network. A new algorithm to automatically perform the line outage contingency analysis and ranking was developed. This technique results in critical line outages in the system. Subsequently, voltage stability analysis which confines the repetitive load flow and voltage stability indices computation revealed the sensitive lines in the system. Outcomes from both techniques will eventually cluster the weak area in the system, representing the resultant cluster deduced from each one. Implementation on the IEEE RTS revealed the effectiveness of the proposed technique, making it feasible to be implemented in a practical system which in turn helping in proper monitoring process to the specified cluster.

*Key-Words* **-** Weak area clustering, voltage stability, contingency, sensitive line clusters, critical line outage cluster, clusters similarity.

## 1 Introduction

**MODERN** power system networks have been operating with its equipment very close to their stability limit. This situation can be termed as stressed condition making the system insecure if an attempt is made to operate beyond this limit. The physical impact of this phenomenon will be the power blackout to the power system network. The stable operation of power system network can turn to unstable condition due to contingency caused by line outage. This situation becomes worst in the absence of reactive power support to maintain normal voltage profiles at the receiving end buses [1]. The unstable area resulted from line outage contingencies and stress condition may occur in the same area, which can be clustered together for proper monitoring purposes. The probability for a system to experience voltage collapse resulted from the voltage instability condition is higher for the weak area. Through clustering process, the power network is partitioned into clusters or group of buses in which each cluster consists of a set of load and generator buses [2, 3]. This is important because the information can be used for voltage control scheme in order to maintain secure power delivery to the utility. In [2], weak area clustering is referred as weak area partitioning, determined based on reduced load flow Jacobian determinant. In this work, the critical bus was first identified. Then, the weak area clustering was identified by encircling the load buses connected closed to the critical bus. All generator buses connected to these buses are belonged to the critical area. On the other hand, in [3] bus clusters were determined utilising the line stability factors. In this work, the line stability factors are ranked from the smallest to the largest values and the lines with large stability factors are eliminated above a certain cut-off value. The bus clusters were then formed, in which all the lines connecting the buses in a cluster have stability factor values of less than the cut-off value, and that the voltages and angles change coherently within the group. A power network can be clustered into smaller networks containing buses that are closely connected [4]. A group of load buses that have similar voltages and angles are considered as electrically close and belonged to the same cluster. On the other hand, for load buses that have voltages and angles not affected by the load variations are considered as electrically distanced or weakly connected and belonged to a different cluster [2]. Several methods have been reported to form the sub-networks in power systems. One of the methods employed the graph theory and arbitrary coherency function technique in order to form the bus clusters [5]. On the other hand, Voltage Control Area (VCA) technique was proposed in [6]. In this technique, VCA was identified based on the weak transmission boundaries in a power system. In this work, it was found that the load and generator buses in a VCA performed in a consistent manner since their voltages responded similarly to any reactive loads and generation changes outside this area due to the rest of the system and inadequate voltage control surrounded by this area. Groups of buses known as control areas which have strong local controllability and observability properties for measurements and controls at buses and generators within a control area was proposed in [7]. The Jacobian of the real and reactive power balance equations with respect to voltage and angle at the network buses was exploited to form the control areas. A power system clustering technique based on electrical distances among buses and interdependent of the system operating condition concept was proposed in [8]. Buses with strong connection were assigned to the same cluster if their voltages and power injections are interdependent and buses with weak connection are assigned to different clusters. Network clustering can also be formed based on voltage variation at each load bus with respect to load variations at other load buses as proposed in [9]. Weak area was identified as the sub-network, which includes the critical buses. On the other hand, bus clustering technique was developed by eliminating the weak lines in power system [10]. The weak lines were identified using the line stability factors and bus clusters were formed by eliminating the weak lines on the coherent behaviour of the buses within a cluster. Factorisation path graph partitioning and equivalent post ordering technique was exploited in [11] to formulate an algorithm for automatic partitioning of a power system network.

This paper presents the development of weak area clustering technique based on voltage stability analysis and line outage contingency analysis and ranking. A new automatic contingency analysis and ranking (ACAR) algorithm was developed making a fast computation for line outage contingency analysis. Sensitive lines in a system at a given loading condition are identified through the repetitive load flow program. On the other hand, line outage contingency analysis identified from the ACAR process exhibited the critical line outages. A pre-developed voltage stability index was utilised as an indicator to voltage stability condition of the system. The weak areas are formed by the lines which are identified as the weak lines from voltage stability analysis and at the same time the critical line outages identified from line outage contingency analysis. The results show that the lines which are identified as the weak lines from voltage stability analysis would also cause critical outages. Therefore the proposed technique for weak area clustering would help the power system engineers to take extra precautions to these weak areas or system enhancement could be implemented to these weak areas so that voltage instability could be avoided. The proposed technique was implemented on IEEE Reliable Test System (RTS) and the results show that distinct weak areas were identified when the system was closed to the stressed condition.

# 2 Methodology

Weak area clustering technique is performed by firstly performing the repetitive load flow and then followed by the ACAR process. These techniques revealed the sensitive lines cluster and critical line outage cluster. These clusters were formed in the voltage stability and line outage contingency analyses. The resultant of those clusters is extracted to perform the weak area cluster. To perform both clustering techniques, a pre-developed voltage stability index is used as an indicator to voltage stability condition [12]. The mathematical equation for *FVSI* was formulated from a line model given by:-

$$FVSI_{ij} = \frac{4Z_{ij}^{\,2}Q_j}{V_i^{\,2}X_{ij}} \tag{1}$$

where $Z_{ij}$ is the line impedance and $X_{ij}$ is the line reactance connecting bus '$i$' and bus '$j$' while, $V_i$ is the voltage at the sending bus and $Q_j$ is the reactive power at the receiving bus.

## 2.1 Voltage Stability Analysis (VSA) Algorithm

Sensitive lines cluster was implemented by carrying out voltage stability analysis in power system. The purpose of doing this cluster is to identify the lines that encircle the weak boundaries when a load was subjected to the system. In this method, voltage stability analysis was implemented using *FVSI* as a measure of voltage stability condition on the individual line. Sensitive lines cluster was determined based on the most severe lines indicated by their *FVSI* values for a particular load bus. The lines were ranked in descending order based on their severity (*FVSI* values). The most severe lines will have *FVSI* values closed to 1.00 and vice versa for the least severe lines. The lines ranked in the top of the list would be represented graphically on the system. The following procedures were implemented in order to form the sensitive line cluster:-

i. Run voltage stability analysis with the reactive power loading at a selected load bus is increased.
ii. Rank the lines in descending order according to the computed *FVSI* values.
iii. Eliminate the least severe lines below the threshold value.
iv. Represent the most severe lines on the system by highlighting the sensitive lines on the system.

The same process was repeated for other selected load buses.

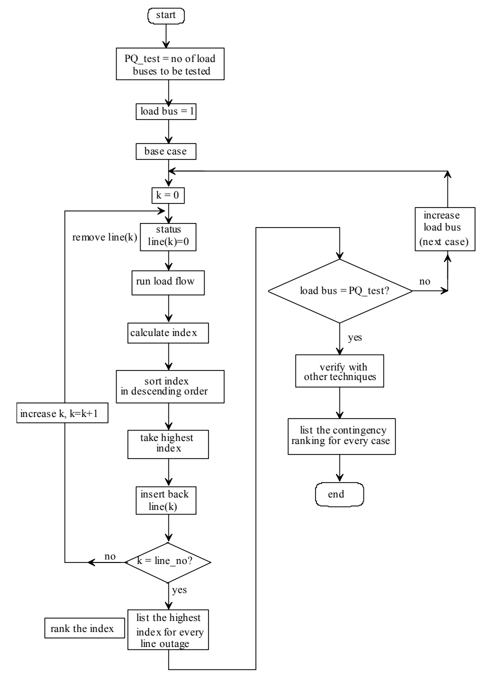


Fig. 1: Flow chart for automatic line outage contingency analysis

## 2.2 Automatic Contingency Analysis and Ranking (ACAR) Algorithm

It is important to perform contingency analysis to a power system since the results can be used to notify the power system operators for any potential occurrence of system violation due to any contingency. Conventional contingency analysis technique has known to be time-consuming especially for a large power system. If a single line outage contingency required 1 minute of computation time to be simulated, therefore for a 57-bus system it may require 1 hour 20 minutes of computation time to simulate all possible line outage contingencies. Those are human factors required to be considered. Therefore, a new algorithm is required to speed up the contingency analysis process hence the computation time is reduced. The proposed automatic line outage contingency analysis incorporated the line outage simulation and voltage stability analysis together. For any line outage simulated which leads to non-convergence of the load flow, the proposed technique will assign an *FVSI* value of unity for the outage. This would indicate that voltage collapse has occurred in the system due to the outage. The steps of the algorithm can be represented in the form of flow chart as appeared in Fig. 1.

Critical line outage clustering technique was conducted in order to identify the cluster, which includes the most critical line outages in a system. A post-outage voltage stability analysis was conducted and the *FVSI* values were calculated on each line in the system. The highest *FVSI* values from each line outage were sorted in descending order with the largest value was ranked highest. The line outages ranked in the top of the list were identified as the critical line outages. These line outages were graphically highlighted on the system in order to form the critical line outage cluster. The following procedures were implemented to form the critical line outage cluster:-

i. Perform post-outage contingency analysis.
ii. Rank the post-outage contingency results in descending order according to the computed *FVSI*.
iii. Eliminate the least severe contingencies.
iv. Represent the critical line outages on the system by highlighting the lines categorised as the critical line outages.

## 2.3 Weak Area Cluster

In order to perform the comparison correctly, the results from the sensitive lines cluster and the critical line outage cluster were compared in order to identify the common lines forming both clusters. The voltage stability analysis (VSA) and ACAR were performed at similar loading conditions. The common lines were highlighted on the system to indicate the weak area in which resultant cluster is obtained.

# 3 Simulation Results and Discussion

The results from the clustering techniques based on VSA and ACAR tested on the IEEE 57-bus RTS are included to demonstrate the effectiveness of the proposed technique. The results for two participating buses namely bus 10 and bus 16 for each clustering technique are included and discussed separately.

Table 1: VSA ranking for bus 10 and bus 16

| $Q_{10}$ = 1.20 p.u. | | | | | $Q_{16}$ = 2.50 p.u. | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Rank | line | Bus | | *FVSI* | Rank | line | Bus | | *FVSI* |
| | | from | to | | | | from | to | |
| 1 | 23 | 10 | 12 | 0.5871 | 1 | 26 | 12 | 16 | 0.6180 |
| 2 | 9 | 9 | 10 | 0.2910 | 2 | 16 | 1 | 16 | 0.6110 |
| 3 | 66 | 13 | 49 | 0.1985 | 3 | 66 | 13 | 49 | 0.1412 |
| 4 | 11 | 9 | 12 | 0.1655 | 4 | 54 | 11 | 41 | 0.1402 |
| 5 | 54 | 11 | 41 | 0.1404 | 5 | 46 | 34 | 32 | 0.1302 |
| 6 | 63 | 49 | 50 | 0.1398 | 6 | 56 | 41 | 43 | 0.1238 |
| 7 | 46 | 34 | 32 | 0.1311 | 7 | 43 | 30 | 31 | 0.1162 |
| 8 | 56 | 41 | 43 | 0.1248 | 8 | 55 | 41 | 42 | 0.1061 |
| 9 | 43 | 30 | 31 | 0.1187 | 9 | 76 | 39 | 57 | 0.1033 |
| 10 | 76 | 39 | 57 | 0.1104 | | | | | |
| 11 | 25 | 12 | 13 | 0.1087 | | | | | |
| 12 | 29 | 18 | 19 | 0.1078 | | | | | |
| 13 | 55 | 41 | 42 | 0.1063 | | | | | |

### 3.1 Sensitive Lines Cluster

Sensitive lines cluster was formed by identifying the most severe lines from the VSA results. A threshold value was identified so that the lines with *FVSI* lower than the threshold value will be discarded. The chosen lines to form the cluster were then highlighted in the system so that the formed cluster can be clearly distinguished. The weak line clusters for the IEEE 57-bus RTS were identified by implementing the procedures explained in section 2.1. An *FVSI* threshold value of 0.1000 was chosen in order to identify the lines, which form the weak clusters. This value was chosen because this is the possible *FVSI* value in which its loading condition will give correct ranking during ACAR. Higher threshold *FVSI* value from VSA reflects higher loading condition is required to perform ACAR which in turns making several lines will be evaluated with unity *FVSI* values leading inaccurate line outage ranking. Two load buses were randomly chosen in order to perform the tests using the proposed clustering technique.

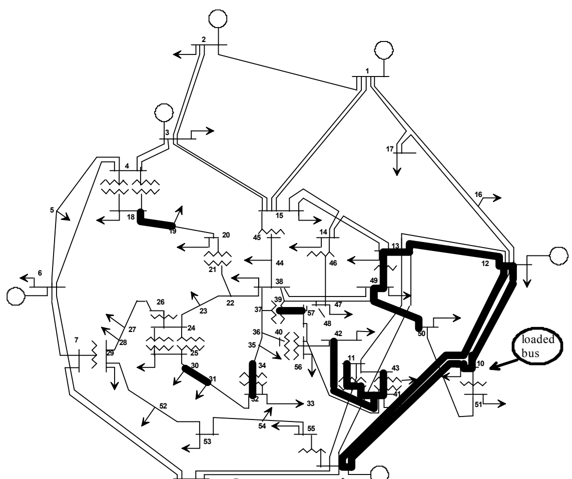


Fig. 2: Sensitive lines cluster when bus 10 was loaded with 1.20 p.u.

The participating buses are buses 10 are 16. Table 1 tabulates the sensitive lines, which are chosen to form the weak clusters when reactive power loadings are increased at buses 10 and 16. From Table 1, thirteen lines with their *FVSI* values higher than 0.1000 were chosen to form the clusters when bus 10 was reactively loaded with 1.20 p.u.. The sensitive lines are highlighted in the single line diagram of the test system to form the sensitive line clusters as shown in Fig. 2. From the figure, it is observed that six isolated clusters are formed by the results tabulated in Table 1. The main cluster is formed by the lines, which are directly connected to the loaded bus. Other clusters contain isolated lines and they are normally connected closed to transformer. The results for the sensitive lines as bus 16 loaded with 2.50 p.u. are also tabulated in Table 1. Nine lines are chosen to form the weak clusters as their *FVSI* values are higher than 0.1000. The selected lines are highlighted in the system to form the clusters as they appeared graphically in Fig. 3. From the figure, it is observed that six clusters are formed by the results tabulated in Table 6.1. The main cluster that includes most of the sensitive lines are directly connected to bus 16 i.e., the loaded bus. Other clusters are isolated and they are formed by the lines, which are connected closed to transformer.

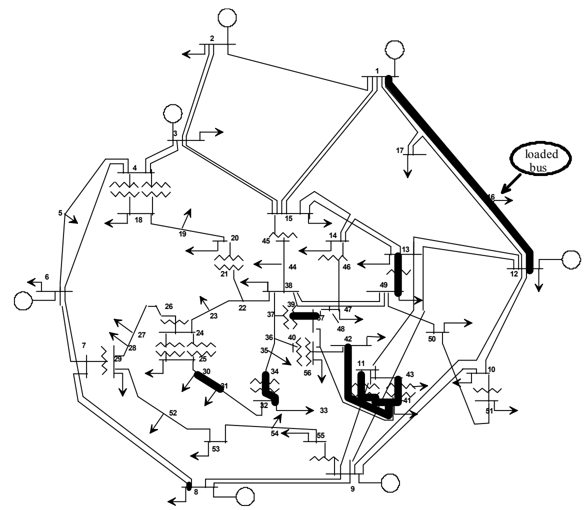


Fig. 3: Sensitive lines cluster when bus 16 was loaded with 2.50 p.u.

Table 2: Critical line outage for bus 10 and bus 16

| $Q_{10}$ = 1.20 p.u. | | | | | $Q_{16}$ = 2.50 p.u. | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Rank | line | Bus from | Bus to | *FVSI* | Rank | line | Bus from | to | *FVSI* |
| 1 | 51 | 37 | 39 | 1.0000 | 1 | 45 | 32 | 33 | 1.0000 |
| 2 | 45 | 32 | 33 | 1.0000 | 2 | 48 | 35 | 36 | 1.0000 |
| 3 | 38 | 26 | 27 | 1.0000 | 3 | 47 | 34 | 35 | 1.0000 |
| 4 | 9 | 9 | 10 | 1.0000 | 4 | 46 | 34 | 32 | 1.0000 |
| 5 | 48 | 35 | 36 | 1.0000 | 5 | 42 | 25 | 30 | 1.0000 |
| 6 | 47 | 34 | 35 | 1.0000 | 6 | 26 | 12 | 16 | 1.0000 |
| 7 | 46 | 34 | 32 | 1.0000 | 7 | 16 | 1 | 16 | 0.9127 |
| 8 | 42 | 25 | 30 | 1.0000 | 8 | 15 | 1 | 15 | 0.6544 |
| 9 | 23 | 10 | 12 | 0.8015 | 9 | 17 | 1 | 17 | 0.6515 |
| 10 | 41 | 7 | 29 | 0.7673 | | | | | |
| 11 | 63 | 49 | 50 | 0.6893 | | | | | |
| 12 | 8 | 8 | 9 | 0.6469 | | | | | |
| 13 | 25 | 12 | 13 | 0.6457 | | | | | |

### 3.2 Critical Line Outage Cluster

Identification of critical line outage cluster is important, as this cluster enable the weak area identification, which is very critical in line outage contingencies. The critical line outages, which form the weak clusters, are determined by extracting the top ranks contingencies according to the severity of the voltage stability condition in the system. This can be identified by the maximum *FVSI* value evaluated during each contingency. The number of line outages to be selected in forming the weak clusters equals to the number of sensitive lines selected to form the weak clusters. In other words, if the number of sensitive lines selected to form the sensitive lines clusters is seven, therefore the first seven contingencies according to the ranking will be grouped together to form the critical line outage cluster. The same IEEE 57-bus RTS was utilised in the test with similar load buses i.e., buses 10 and 16. For each loading condition, the clusters due to critical line outages were identified by selecting the critical line outage contingencies. The results for critical line outages for buses 10 and 16 are tabulated in Table 2. From this table, it is observed that thirteen lines are identified as critical line outages when bus 10 was reactively loaded up to 1.20 p.u.; while nine lines are identified as critical line outages when bus 16 was reactively loaded up to 2.50 p.u.. Apparently, the *FVSI* values for the post-outage condition of all the contingencies are higher than 0.6000, which implies that the system is closed to its voltage instability condition during post-outage in both cases. These lines are highlighted in the system to form the critical line outages clusters.

Fig. 4 shows seven clusters formed by the chosen critical line outages as given in Table 2 when bus 10 was reactively loaded up to 1.20 p.u.. It can be observed that the main cluster includes the lines, which are closely connected to bus 10. The other six clusters are isolated from the main cluster, and they are connected closed to transformer. Fig. 5 on the other hand, illustrates the critical line outage clusters for the case of bus 16. From the figure, three clusters are formed by the lines tabulated in Table 2. The main cluster consists of the lines, which are closely connected to bus 16; while the other two clusters are isolated from the main cluster, and they are connected closed to transformer.

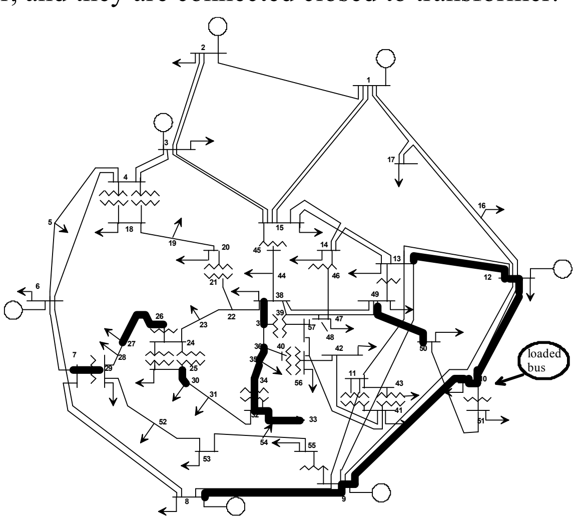


Fig. 4: Critical line outage cluster when bus 10 was loaded with 1.20 p.u.

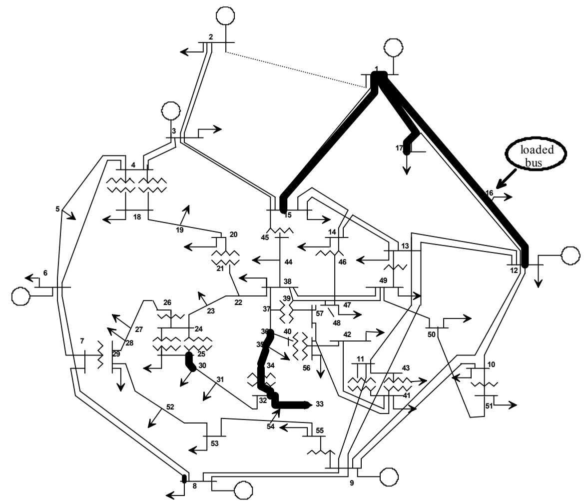


Fig. 5: Critical line outage cluster when bus 16 was loaded with 2.50 p.u.

Table 3: Cluster similarities for $Q_{10}$ = 1.20 p.u. in IEEE 57-bus RTS

| Sensitive lines | | | | | Critical line outages | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Rank | line | Bus from | Bus to | *FVSI* | Rank | line | Bus from | Bus to | *FVSI* |
| 1 | 23* | 10 | 12 | 0.5871 | 1 | 51 | 37 | 39 | 1.0000 |
| 2 | 9* | 9 | 10 | 0.2910 | 2 | 45 | 32 | 33 | 1.0000 |
| 3 | 66 | 13 | 49 | 0.1985 | 3 | 38 | 26 | 27 | 1.0000 |
| 4 | 11 | 9 | 12 | 0.1655 | 4 | 9* | 9 | 10 | 1.0000 |
| 5 | 54 | 11 | 41 | 0.1404 | 5 | 48 | 35 | 36 | 1.0000 |
| 6 | 63* | 49 | 50 | 0.1398 | 6 | 47 | 34 | 35 | 1.0000 |
| 7 | 46* | 34 | 32 | 0.1311 | 7 | 46* | 34 | 32 | 1.0000 |
| 8 | 56 | 41 | 43 | 0.1248 | 8 | 42 | 25 | 30 | 1.0000 |
| 9 | 43 | 30 | 31 | 0.1187 | 9 | 23* | 10 | 12 | 0.8015 |
| 10 | 76 | 39 | 57 | 0.1104 | 10 | 41 | 7 | 29 | 0.7673 |
| 11 | 25* | 12 | 13 | 0.1087 | 11 | 63* | 49 | 50 | 0.6893 |
| 12 | 29 | 18 | 19 | 0.1078 | 12 | 8 | 8 | 9 | 0.6469 |
| 13 | 55 | 41 | 42 | 0.1063 | 13 | 25* | 12 | 13 | 0.6457 |

Note: * = common lines in cluster similarities

### 3.3 Weak Area Cluster

Similarities between the clusters formed by the sensitive lines and critical line outages were investigated to form the resultant cluster known as the weak area cluster. This is to identify the correlation between the clusters formed by the sensitive lines and critical line outages; and hence the common weak areas are identified. The clusters from the sensitive lines and critical line outages for the IEEE 57-bus RTS are compared and the common lines, which formed both clusters are identified. The results for the cluster similarities when reactive power loading at bus 10 was increased to 1.20 p.u. are tabulated in Table 3.From the table, five lines namely lines 23, 9, 63, 46 and

25 are the common lines, which formed the weak clusters based on sensitive lines and critical line outages. Fig. 6 shows the resultant clusters formed by the sensitive lines and critical line outages when reactive power loading at bus 10 was increased up to 1.20 p.u..

Table 4: Cluster similarities for $Q_{16} = 2.50$ p.u.

| Rank | line | Bus | | *FVSI* | Rank | line | Bus | | *FVSI* |
|---|---|---|---|---|---|---|---|---|---|
| | | from | to | | | | from | to | |
| 1 | 26* | 12 | 16 | 0.6180 | 1 | 45 | 32 | 33 | 1.0000 |
| 2 | 16* | 1 | 16 | 0.6110 | 2 | 48 | 35 | 36 | 1.0000 |
| 3 | 66 | 13 | 49 | 0.1412 | 3 | 47 | 34 | 35 | 1.0000 |
| 4 | 54 | 11 | 41 | 0.1402 | 4 | 46* | 34 | 32 | 1.0000 |
| 5 | 46* | 34 | 32 | 0.1302 | 5 | 42 | 25 | 30 | 1.0000 |
| 6 | 56 | 41 | 43 | 0.1238 | 6 | 26* | 12 | 16 | 1.0000 |
| 7 | 43 | 30 | 31 | 0.1162 | 7 | 16* | 1 | 16 | 0.9127 |
| 8 | 55 | 41 | 42 | 0.1061 | 8 | 15 | 1 | 15 | 0.6544 |
| 9 | 76 | 39 | 57 | 0.1033 | 9 | 17 | 1 | 17 | 0.6515 |

Note: * = common lines in cluster similarities

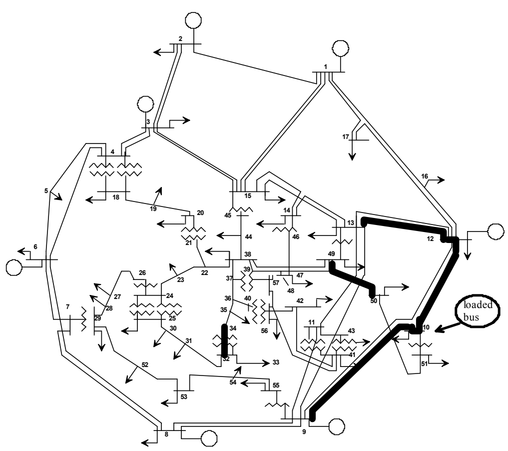


Fig. 6 Weak Area cluster when bus 10 was loaded with 1.20 p.u.

From the figure, it is observed that three clusters are formed. The main cluster includes the lines connected directly and closed to bus 10. The second cluster is connected from bus 49 and bus 50, which is closed to a transformer while the third cluster is connected between bus 32 and bus 34 via a transformer.

The results for the cluster similarities when reactive power loading at bus 16 was increased to 2.50 p.u. are tabulated in Table 4. From the table, three lines namely lines 26, 16 and 46 are the common lines, which formed the weak clusters based on sensitive lines and critical line outages. Fig. 7 shows the resultant clusters formed by the sensitive lines and critical line outages when reactive power loading at bus 16 was increased up to 2.50 p.u.. From the figure, it is observed that two clusters are formed. The main cluster includes the lines connected directly and closed to bus 16. The second cluster consists only one line connecting bus 34 and 32 through a transformer.

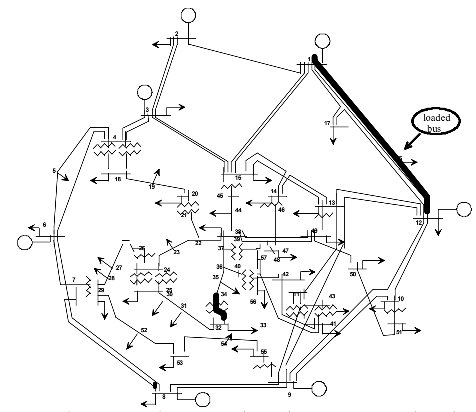


Fig. 7 Weak Area cluster when bus 16 was loaded with 2.50 p.u.

## 4. Conclusion

This paper has presented the identification of weak clusters based on sensitive lines and critical line outages. New automatic contingency analysis and ranking (ACAR) algorithm was developed for critical, line outage identification. As a result of weak clusters based on both techniques, common weak clusters are then identified. The most sensitive lines resulted from the VSA were extracted and sensitive lines clusters were formed from this list. The same case happen for the critical line outages clusters formation. The lines resulted in critical line outages were selected based on the ranking to form the weak cluster. The common lines formed both clusters were identified and they reflect that most of the sensitive lines, which are also the critical line in terms of line outages; are closely connected to the loaded bus. The other common clusters, isolated from the main clusters are normally the lines connected to transformer. This information could be utilised by power system operators to perform necessary precaution and close monitoring could be conducted to these areas.

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