**Bathina Venkateswararao[1], Ramesh Devarapalli[2], Łukasz Knypiński[3], R Gowri Sankara Rao[4], Fausto Pedro García Márquez[5]**

Department of EEE, V R Siddhartha Engineering College (1), Department of EEE, Lendi Institute of Engineering and Technology, India (2), Poznan University of Technology (3), Department of EEE, MVGR College of Engineering (4), Ingenium Research Group, University of Castilla-La Mancha (5).
ORCID:1. 0000-0003-4281-8831; 2. 0000-0003-4246-7728; 3. 0000-0001-5741-9548; 5. 0000-0002-9245-440X

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# Shunt capacitor placement under *n*-1 contingency condition: Realization with Mi Power package

***Abstract**, The losses in the power transmission network may increase due to contingency conditions, i.e., contingency analysis is flattering a crucial task for power system scheduling and operation. It is required to forecast the outcome of outages in power system. Contingency may be occurred due to failure of equipment or transmission lines. Single line outage also overloads the other lines, and abrupt voltage drop may cause the outage of other lines. Hence, the contingency analysis plays vital role to handle different system operating conditions. In this paper, n-1 contingency condition is considered to find the impact of shunt capacitor for improvement in voltage profile, where Mi Power package has been used for the conduction of simulation on the considered test network. Voltage Collapse Prediction Index is the method used for finding the optimal placement of shunt capacitor under n-1 contingency. The highest VCPI value indicates the weak bus, therefore, that is the best place for placement of shunt capacitor to improve the voltage profile and reduce the losses. The value of bus voltages, real power losses and real power generation before and after the n-1 transmission line contingency have been examined, where the improvement of voltage profile through optimal location of shunt capacitor has been studied. The usefulness of the shunt capacitor has been verified on 5 bus test system under n-1 contingency condition using MiPower software.*

***Streszczenie,** W artykule przestawiono problematykę łagodzenia skutków stanów awaryjnych w systemach przesyłu energii elektrycznej. W przypadku stanów awaryjnych w systemach przesyłowych występują przeciążenia oraz straty mocy w innych częściach systemu. Dlatego bardzo ważna jest analiza awarii które mogą wystąpić podczas eksploatacji systemu przesyłu energii. Często osoby zarządzające systemem przeprowadzają prognozę skutków wyłączenia poszczególnych linii przesyłowych tworzących system przesyłowy. Stan awaryjny w jednej linii wywołuje spadki napięć w innych punktach systemu przesyłowego. W celu łagodzenia skutków awarii, autorzy zaproponowali zastosowanie kondensatora bocznikującego. W celu wyznaczenia najlepszego miejsca podłączenia kondensatora bocznikującego analizowano wskaźnik zapadów napięcia. Obliczenia symulacyjne zostały wykonane w systemie MiPower. Analizowano system złożony z pięciu linii przesyłowych. Przedstawiono i omówiono wybrane wyniki obliczeń symulacyjnych. (**Wybór punktu umieszczenia kondensatora bocznikującego w stanach awaryjnych systemu przesyłu energii. Realizacja w oprogramowaniu MiPower**)*

**Keywords**: distributed systems, contingency, voltage Collapse Prediction Index (VCPI), optimal placement, shunt capacitor,
**Słowa kluczowe**: rozproszone systemy przesyłowe, awaryjność, optymalne położenie kondensatora bocznikującego, wskaźnik zapadów napięcia

## Introduction

Electricity produced in the power station is transferred over large networks using transformers, overhead lines and cables to reach consumer. But the total amount of power generated at the power stations does not match the total amount of power received by consumers. However, the amount of energy produced and delivered to consumers are different. Some percentage of power mismatches occurred, known as losses. The losses are more with alternating current (AC) lines due to reactance, arcs, surges, resonances, skin effect, etc [1]. All those cause voltage instabilities. Maintaining constant voltage profile is the main challenge in the entire power system network, especially in contingency conditions [2]. Contingencies are mainly classified as generator outages and line outages [3]. Line outages with *n*-1 contingency condition were frequently occurred problem. Under *n*-1 contingency conditions, some of the lines became overloaded, and some other lines became under load, which causes to sudden increase losses. Thereby further voltage profile are sags down. Therefore, it is needed to provide the proper reactive power [4] to the system under *n*-1 contingency condition. In order to improve voltage profile, it is necessary to incorporate the shunt capacitor at appropriate locations [5, 6]. The proper selection of equipment for reactive power and voltage profile improvement problems are the major power system challenges. To overcome above problems, capacitor banks are the best and basic solution [7]. The capacitor requirements can differ extensively from location to location and can change promptly as the location and magnitude of generation and load change. Contingency analysis is the study of the different contingency condition which occurs because of outage of generator, transmission lines, transformers etc. Outage of transmission line, transformer or generator leads to abnormal situation of the power system. Sometimes it may cause the instability of the system, and stable operation is also not possible. Therefore, contingency analysis plays a vital role in a stable and reliable power system, and many researchers work on *n*-1 contingency condition.

The novelty of this paper is to reduce losses and improvement of voltage profile by injecting the reactive power into the system by placing shunt capacitors at optimal location given by Voltage Collapse Prediction Index (VCPI) in *n*-1 contingency condition. In this paper, the effectiveness of the shunt capacitor has been tested on 5-bus test system under *n*-1 contingency condition using MiPower software, developed by Power Research and Development Consultants Pvt. Ltd. Bangalore (PRDC). It has been employed for various studious, for example [8], use the Mipower for transient stability analysis. They applied on 5-bus system and observed that results were obtained with Mipower compared with other available tools. It is shown that Mipower is more accurate, takes less number of iterations and consumes less time to compute. Jamnani and Pandy [9] used the MiPower software for comparison Newton Raphson (NR), Gauss-Seidel (GS) and fast decoupled methods of load flow studies. They use 3-bus system to validate the fast computation of MiPower compared to MATLAB and Power World Simulator environments [10], propose the shunt capacitor for improvement of voltage profile under overload condition in power system with MiPower software. They observed the enhancement of voltage magnitude under overload conditions with shunt capacitor [11], applied the MiPower for symmetrical fault analysis studies in power system. They compared the obtained results with other power system tools and found that MiPower produce better results [12], applied the MiPower for load flow studies using GS method. Thus, they observed that obtained results for 3-bus system are more convincing and suggested using the NR method with higher order bus systems [13], using the new technique to find the impact of contingencies in the power system.

Zimmerman et al.[14], used the MATPOWER tool to plan and analysis of power system. They observe that both AC and Direct Current (DC) load flows in various loading and contingency conditions. Dong et al .[15], determined the parameters of the network using different methods. Moreover, Musirin et al. [16] proposed various simulation techniques for identifying the weak buses in the system, and also gives the ranking for system based on contingency condition. All the above authors used the MiPower for load flow studies for various bus systems and compare the with different tools like MATLAB, PWS, etc. Some authors concluded that MiPower was more accurate and computation time is less but did not use this software package for contingency condition. Therefore, authors use the MiPower software package in this paper for load flow studies under *n*-1 contingency condition with placement of shunt capacitor. In this paper voltage instability analysis in MiPower is used to find the VCPI values and load flow analysis using NR method used also in [17, 18] to find the power flow solution.

The paper's main aim is to identify the effect of *n*-1 contingency condition on 5- bus system using MiPower software tool, and find the weak bus using VCPI technique to place the shunt capacitor into the system for injection of the reactive power. The procedure has been tested on five bus system.

In this paper, *n*-1 contingency condition is investigated to find the impact of shunt capacitor for improvement in voltage profile. The approach is based on the VCPI method and is applied to finding the optimal placement of shunt capacitor condition under *n*-1 contingency. Section 2 discusses the various voltage stability indices and contingency analysis. Next, in Section 3 highlights the method for optimal placement of shunt capacitor presented in this paper, i.e., VCPI technique. The case study data and simulation results with and without shunt capacitor under normal and *n*-1 contingency condition is presented and discussed in Section 4. Finally, Section 5 presents the conclusions drawn from the given investigations.

## Voltage Stability Indices and contingency analysis

### *Voltage Stability Indices*

There are many voltage stability indices available in literature, out of which some of best indices are: (a) P-V and Q-V curves, (b) modal analysis, (c) V/V0 index, (d) L-index, (e) VCPI, (f) Line Stability Index LQP, (g) Line Stability Index FVSI, and (h) Line Stability Index [19]. Power stability index (PSI) and fast voltage stability index (FVSI) has been introduced for placement of shunt connected reactive power devices in [20]. In this these indices are calculated from the data obtained after performing load flow analysis in interconnected transmission networks by using Newton Rapson's method in MIPOWER software. Load analysis using MATLAB presented in [21], in this Newton Rapson's method excecuted with MATLAB. Aziz et al. [22] proposed the sensitivity index for placement of shunt FACTS controllers. The contingency-based selection of placement of reactive power compensation devices was proposed in [23]. Whereas, Karbalaei et al. [24] reviewed the various voltage collapse proximity indicator for placement of capacitors, FACTS controllers. They study and analyze these techniques in IEEE14 bus system. Some authors, e.g., [25], studied different stability analysis techniques for identifying the weak location in terms of stability point of view. They also discuss about line outage conditions. Some other authors, e.g., [26], applied the L-index technique for congestion management in power system, and [27] assessed various voltage stability methods for placement shunt reactive power devices in the power system. The various indexes for placement of series devices in the power system were introduced in [28]. From all the above literature, it is observed that some of the indices are used for placement of series compensating devices and some other indices used placement of shunt compensation devices. Modal analysis method eigenvalues are associated with a mode of voltage and reactive power variation. Stability of the system based on eigenvalues shows that if all are positive system is stable, otherwise unstable. The line stability index based on the power transmission concept in this voltage quadratic equation is set to be greater or equal to zero to achieve stability. Fast Voltage Stability Index (FVSI) is referred to a line initiated from the voltage quadratic equation at the sending end of a representation of a 2-bus system. If this value is closed to zero indicates that the line has more stable; otherwise, the system leads to instability. The VCPI index is calculated based on variation of small change in loads. If this value is big indicates the unstable condition, i.e., it is more flexible. Therefore, in this paper authors apply the bus-based voltage stability index, called VCPI, for placement of shunt capacitor, because it is easy to compute and provides reliable results.

### *Contingency analysis*

Contingencies are well-defined as theoretically dangerous troubles that happen during the steady state operation of the power system. Load flow establishes the significant study in a power system for planning, operation and expansion. The persistence of load flow study is to calculate operating conditions of the power system under steady state. A future event, or circumstance, which is possible, but cannot be anticipated with certainty, is known as a contingency [29]. The possible uncertain events that will happen in a power system are overloading or loss of line due to some fault. If a fault has been encountered in a transmission line, the corresponding circuit breaker will safeguard the whole system from the fault by isolating the faulted line from the rest of the power system. It will take some time to take that line into service, then the system needs to operate on *n*-1 lines properly. There comes the condition for contingency [30, 31]. Under contingency conditions, some lines may be overloaded, while others may be under-loaded. If outage of one line happens in the power system, it is termed as *n*-1 contingency. There may be some other critical situation where it is n-2 criteria. Weak elements are those which will be overloaded during contingency condition. But online contingency analysis is difficult because of the conflict between the accuracy in solution of the power system problem and the speed required to simulate all the contingencies. The simulation of contingency is complex since it results in change in configuration of the system. Therefore, in this paper, for the purpose of study the contingency analysis authors use the MiPower software tool. Mipower software tool also used for economic load dispatch problems in [32], authors use four thermal generating units with different performance functions and generator limits are considered for the analysis and simulation is conducted in Mipower software for ELD problem.

Phase I: Load the data related to 5 bus system.

Phase II: Perform the load flow using Mipower and tabulate the results obtained for base case.

Phase III: Consider the one line outage and compute the load flow

Phase IV: determine the VCPI index values

Phase V: Place the shunt capacitor at highest VCPI indexed bus.

Phase VI: Perform the load flow using Mipower and tabulate the results obtained for *n*-1 contingency condition.

Phase VII: Consider succeeding line outage and duplication of steps IV,V, VI for each consequent outages.

Phase VII: Identify the worst line outage condition and observe the impact of the placement of shunt capacitor.

**Problem formulation and VCPI calculation**

Voltage instability of a power system is a result of increasing in load up to certain limit on a power system any further increase in load caused to voltage collapse [33]. Voltage collapse mainly depends on the load behavior. In order to assess the voltage instability margin during sudden disturbances under steady state condition, the voltage instability program is designed according to reference [34]. In this approach, the load buses are ranked based on VCPI value, where the highest VCPI value represents the nearer to voltage collapse point [35]. The value of VCPI is zero at no load and unity at verge of the collapse point [36]. In this paper, voltage instability analysis in the MiPower software is used to find the VCPI values. The bus having uppermost VCPI value is the finest location for employment of shunt capacitor [37, 38].

For the resident network, power flow equation inscribed at node *j* gives:

(1) $$V_j [Y]_j [V] = S_j$$

where, $[Y]_j$ , row j-th admittance matrix,

(2) $$[Y]_j = [-Y_{j1} - Y_{j2} + Y_{jj} ....... - Y_{jn}]$$

$Y_{ji}$ is admittance between node *j* and node *i*:

(3) $$Y_{ji} = G_{ji} + iB_{ji} = Y_{ji} e^{i\delta_{ji}} \text{ , } i = 1...n, i \neq j$$

where $Y_{jj}$ is self-admittance at node j:

(4) $$Y_{jj} = \sum_{\substack{i=1 \\ i \neq j}}^{n} Y_{ji} = Y_{jj} e^{i\delta_{jj}}$$

In general VCPI at any bus k can be computed using Equations 5 and 6 are taken from [39].

(5) $$\mathrm{VCPI}_k = \left| 1 - \frac{\sum_{m=1}^{n} V'_m}{V_k} \right|, \text{ where } m \neq k$$

(6) $$V'_m = \frac{Y_{km}}{\sum_{j=1}^{n} Y_{kj}}, \text{ where } j \neq k$$

where $V_k$ is the *k*-th bus voltage, $V_m$ is the *m*-th bus voltage, $Y_{km}$ is the admittance between bus *k* and *m*, $Y_{kj}$ is the admittance between bus *k* and *j*, *n* is the of buses in the system.

**Results and discussions**

The persistence of contingency analysis is to control the voltage stability limit of the power system. In such case, enhancement of voltage profile through optimal placement of shunt capacitor under *n*-1 contingency condition has been examined using the VCPI method. The size of the shunt capacitor is obtained using MiPower software. After placing the shunt capacitor at particular bus its voltage magnitude enhanced to 1.0 p.u based on that its size has been computed. The contingencies verified based on transmission line outage. The six different scenarios were investigated. Numerous situations were simulated to express the impact of shunt capacitor under *n*-1 contingency each condition, namely:

- Case I: Base case, without outage, without and with shunt capacitor.
- Case II: Considering line 2-3 outage, without and with shunt capacitor.
- Case III: Considering line 2-4 outage, without and with shunt capacitor.
- Case IV: Considering line 2-5 outage, without and with shunt capacitor.
- Case V: Considering line 3-4 outage, without and with shunt capacitor.
- Case VI: Considering line 4-5 outage, without and with shunt capacitor.

In this paper, 5-bus test system is considered for contingency analysis. It consists of 2 PV buses and 3 PQ buses interconnected with seven transmission lines. MiPower software package is used for VCPI calculations and to perform the load flow analysis. Table 1 provides the line data, Table 2 shows the voltage values and Table 3 presents the load data.

Table 1. The 5-bus system line data

| S. No | From bus | To bus | *R* [p.u] | *X* [p.u] | *B*/2 *[p.u]* |
|---|---|---|---|---|---|
| I | 1 | 3 | 0.080 | 0.240 | 0.0250 |
| II | 1 | 2 | 0.020 | 0.060 | 0.0300 |
| III | 2 | 3 | 0.060 | 0.250 | 0.0200 |
| IV | 2 | 4 | 0.060 | 0.180 | 0.0200 |
| V | 2 | 5 | 0.040 | 0.120 | 0.0150 |
| VI | 3 | 4 | 0.010 | 0.030 | 0.0100 |
| VII | 4 | 5 | 0.080 | 0.240 | 0.0250 |

Table 2. The 5-bus system line data

| S. No | Bus voltages | |
|---|---|---|
| | Magnitude [p.u] | Angle [degrees] |
| I | 1.06 | 0.0 |
| II | 1.00 | 0.0 |
| III | 1.00 | 0.0 |
| IV | 1.00 | 0.0 |
| V | 1.00 | 0.0 |

Table 3. The 5-bus system load data

| S. No | Bus number | Real load [MW] | Reactive load [MVAR] |
|---|---|---|---|
| I | 2 | 20 | 10 |
| II | 3 | 45 | 25 |
| III | 4 | 40 | 25 |
| IV | 5 | 60 | 30 |

***Case I: Base case, considering 5-bus system without and with shunt capacitor***

Fig. 1 shows the bus-5 system having 2 generators, 7 lines and 4 loads as per the give data. After executed of load flow analysis in the MiPower, the following parameters were obtained in the system: a total generation of 170.930 MW and 79.204 MVar, total load equal 165 MW and 90 MVar and total losses of 5.9303 MW and -10.7956 MVar. Using the voltage instability analysis in MiPower software, VCPI values were obtained, which are presented in Table 4. To analyze the data contained in this table, it can be observed that bus number 5 has highest VCPI value therefore that is the finest location for the employment of shunt capacitor. To reduce the losses and improve the voltage magnitude shunt capacitor has been incorporated based on the VCPI calculation under normal conditions. In this case VCPI value is highest for bus 5 i.e 0.112, than the shun capacitor has been placed in bus 5 to enhance the voltage magnitude at bus 5 to 1.0 p.u based on that capacitor size obtained as 38.672 MVAR.

In the Fig. 2 the 5-bus system layout with shunt capacitor is presented. Subsequently, the shunt capacitor was added at bus number 5, and calculation of load flow analysis in the MiPower was performed. The results are presented in Table 5. From this table, it has been observed that real power losses reduced to 4.657 MW from 5.93 MW.

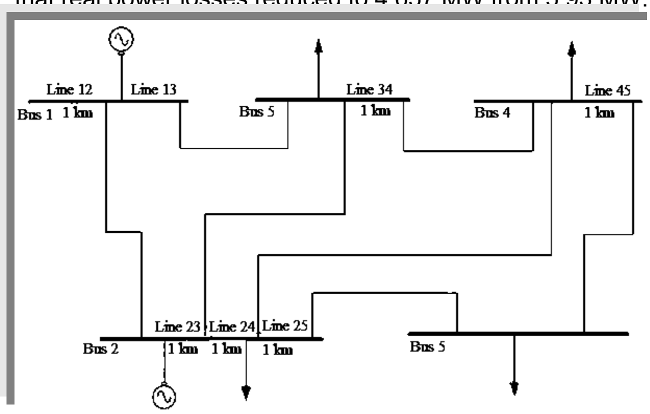


Fig. 1. The 5-bus system base case layout

Table 4. The 5-th bus system VCPI results

| S. No | Bus number | VCPI value |
|---|---|---|
| 1 | 3 | 0.080659 |
| 2 | 4 | 0.095530 |
| 3 | 5 | 0.112069 |

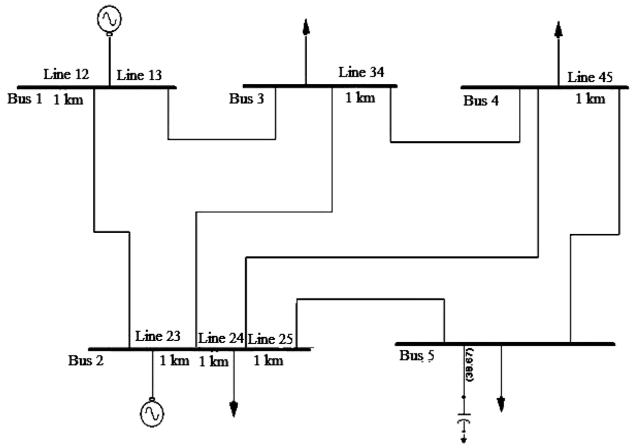


Fig. 2. The 5-bus system with shunt capacitor at bus number 5

Table 5. Generated total real power and total real power losses

| Parameter | Without employing shunt capacitor | With containing of shunt capacitor |
|---|---|---|
| Over-all real power generation [MW] | 170.9303 | 169.657 |
| Over-all reactive power generation [ MVAR] | 79.204 | 35.394 |
| Over-all real power load [MW] | 165 | 165 |
| Over-all reactive power load [ MVAR ] | 90 | 90 |
| Over-all real power losses [MW] | 5.930 | 4.65711 |
| Over-all reactive power losses [ MVAR ] | -10.7955 | -15.9340 |
| Capacitor size [ MVAR ] | -- | **38.672** |

***Case II: Considering line 2-3 outage, without and with shunt capacitor***

Figure 3 shows the 5-bus system after removing the line connected between bus 2 and bus 3. In this case, the highest VCPI value, i.e., 0.115206 p.u, finds at bus 3, than bus 3 is the best location for the placement of shun capacitor to enhance the voltage magnitude. To increase the bus 3 voltage magnitude to 1.0 p.u, 56.285 MVAR size capacitor is required. The sizing of the capacitor is done based enhancement of the voltage magnitude at bus 3 to 1.0 p.u. The results of computation are presented in Table 6. After placing the capacitor at bus 3, system is represented in Fig. 4. After placing the shunt capacitor at bus 3, once again the load flow analysis is performed in the MiPower, and the results are presented in Table 7. From this table, it has been observed that real power losses were reduced to 5.23 MW from 6.96 MW.

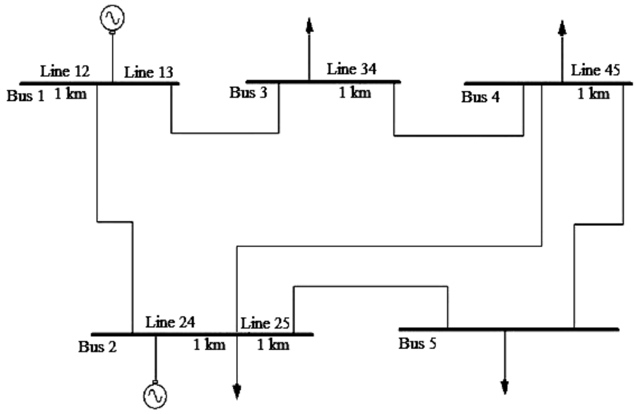


Fig. 3. The 5-bus system layout under line 2-3 outage

Table 6. The 5-bus system VCPI results under line 2-3 outage condition

| S. No | Bus number | VCPI value |
|---|---|---|
| 1 | 3 | 0.115206 |
| 2 | 4 | 0.111759 |
| 3 | 5 | 0.099824 |

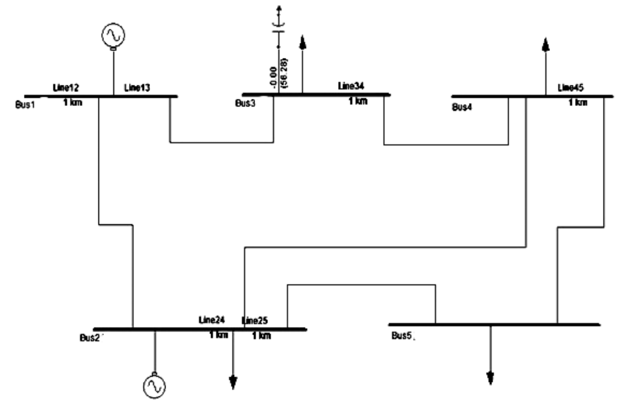


Fig. 4. The 5-bus system layout under line 2-3 outage with shunt capacitor at bus number 3

Table 7. Generated total real power and total real power losses

| Parameter | Without employing shunt capacitor | With containing of shunt capacitor |
|---|---|---|
| Over-all real power generation [MW] | 171.968 | 170.230 |
| Over-all reactive power generation [ MVAR] | 86.219 | 23.093 |
| Over-all real power load [MW] | 165 | 165 |
| Over-all reactive power load [ MVAR ] | 90 | 90 |
| Over-all real power losses [MW] | 6.9676 | 5.230 |
| Over-all reactive power losses [ MVAR ] | -3.7812 | -10.622437 |
| Capacitor size [ MVAR ] | --- | **56.285** |

***Case III: considering line 2-4 outage, without and with shunt capacitor***

In this case, line 2-4 is removed from the base case. Figure 5 represents the 5-bus system having 2 generators, 6 lines and 4 loads as per the give data. VCPI results were obtained from the voltage instability analysis in the MiPower software, which are presented in Table 8. From this table, it is observed that bus number 4 have highest VCPI value, therefore, that is the best location for the placement of the shunt capacitor. Figure 6 shows the 5-bus system layout with shunt capacitor. After placing the shunt capacitor at bus number 4, once again is improved the load flow analysis in the MiPower. To increase the bus 4 voltage magnitude to 1.0 p.u, the 42.946 MVAR size capacitor is required. The sizing of the capacitor is done based on enhancement of the voltage magnitude at bus 4 to 1.0 p.u. The results are presented in Table 9. From this Table, it has been observed that real power losses are reduced to 5.56 MW from 7.38 MW, and after placement of shunt capacitor the voltage profile has been improved, which is observed in Fig. 11.

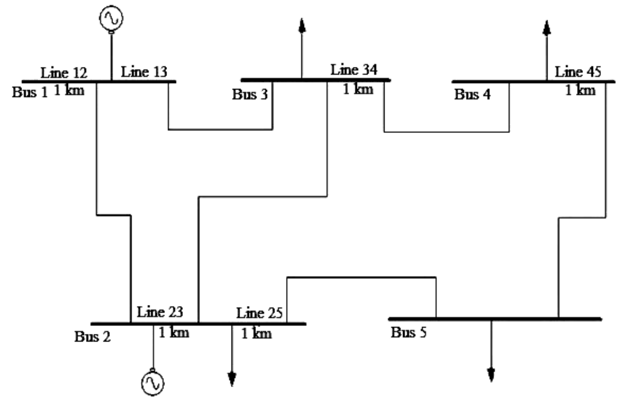


Fig. 5. The 5-Bus system layout under line 2-4 outage

Table 8. The 5-bus system VCPI results under 2-4 line outage

| S. No | Bus number | VCPI value |
|---|---|---|
| 1 | 3 | 0.126554 |
| 2 | 4 | 0.141158 |
| 3 | 5 | 0.109943 |

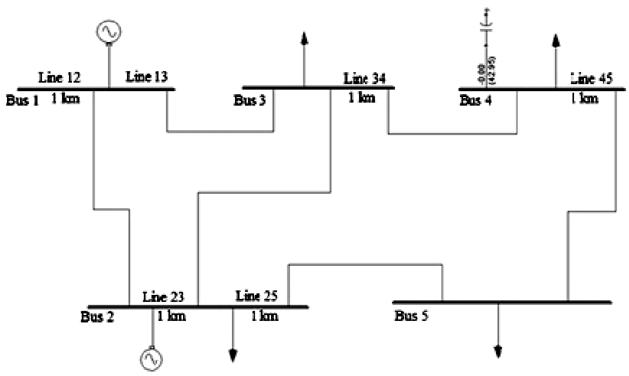


Fig. 6. 5-bus system layout under line 2-4 outage with shunt capacitor at bus number 4

***Case IV: considering line 2-5 outage, without and with shunt capacitor***

In this subsection the line connected between bus 2 and bus 5 is removed (see Fig. 7). From the voltage instability analysis in the MiPower software, VCPI results were obtained and presented in Table 10. It was observed that losses are more for outage of line 2-5, this indicates that line 2-5 is the more crucial line in the analyzed system. To reduce the losses and improve the voltage magnitude shunt capacitor has been incorporated based on the VCPI calculation under line 2-5 outage conditions. In this case VCPI value is highest for bus 5 i.e 0.553687, than the shun capacitor has been placed in bus 5 to enhance the voltage magnitude at bus 5 to 1.0 p.u based on that capacitor size obtained as 35.0447 MVAR.

Table 9. The 5-bus system load flow results under 2–4-line outage

| Parameter | Without employing shunt capacitor | With containing of shunt capacitor |
|---|---|---|
| Over-all real power generation [MW] | 172.387 | 170.5612 |
| Over-all reactive power generation [ MVAR] | 88.614 | 38.5326 |
| Over-all real power load [MW] | 165 | 165 |
| Over-all reactive power load [ MVAR ] | 90 | 90 |
| Over-all real power losses [MW] | 7.38745 | 5.5613 |
| Over-all reactive power losses [ MVAR ] | -1.3855 | -8.5214 |
| Capacitor size [ MVAR ] | -- | **42.946** |

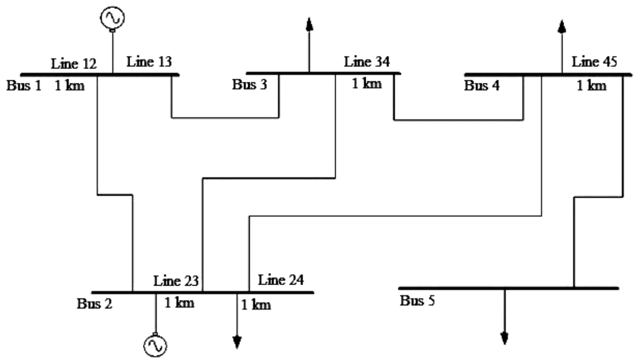


Fig. 7. 5-bus system layout under line 2-5 outage

Table 10. The 5-bus system VCPI results under 2-4 line outage

| S. No | Bus number | VCPI value |
|---|---|---|
| 1 | 3 | 0.161407 |
| 2 | 4 | 0.185151 |
| 3 | 5 | 0.553687 |

Figure 8 shows the bus 5 system layout with shunt capacitor. After placing the shunt capacitor at bus 5, the flow load analysis by the use MiPower was performed. The results of computer simulation are presented in Table 11. It has been observed, that real power losses reduced to 10.92 MW from 17.76 MW, and after placement of shunt capacitor voltage profile has been improved.

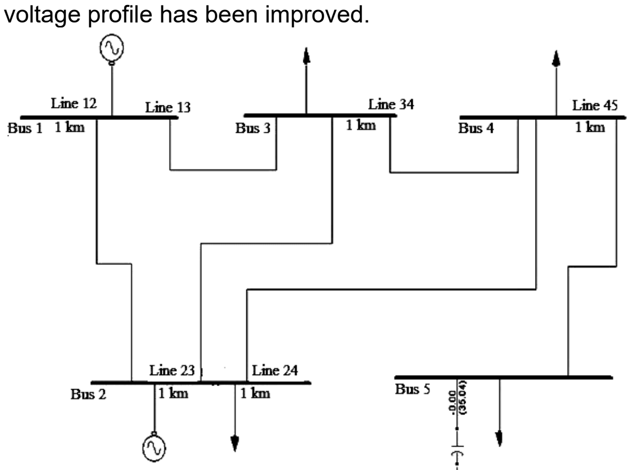


Fig. 8. The 5-bus system layout under line 2-5 outage with shunt capacitor at bus number 5

Table 11. The 5-bus system load flow results with capacitor under line 2-5 outage

| Parameter | Without employing shunt capacitor | With containing of shunt capacitor |
|---|---|---|
| Over-all real power generation [MW] | 181.6028 | 175.9297 |
| Over-all reactive power generation [ MVAR] | 120.7902 | 63.1510 |
| Over-all real power load [MW] | 165 | 165 |
| Over-all reactive power load [ MVAR ] | 90 | 90 |
| Over-all real power losses [MW] | 17.7660 | 10.9299 |
| Over-all reactive power losses [ MVAR ] | -31.3718 | -8.1961 |
| Capacitor size [ MVAR ] | -- | **35.0447** |

***Case V: considering line 3-4 outage, without and with shunt capacitor***

In the next scenario, the line 3-4 outage is considered. The configuration of analyzed power system is presented in Fig. 9. The computed VCPI values are listed in Table 12. The VCPI value is maximum at bus 4 and is equal 0.099915 p.u. therefore to increase the bus 4 voltage magnitude to 1.0 p.u, 35.906 MVAR size capacitor is required. The sizing of the capacitor is done based enhancement of the voltage magnitude at bus 4 to 1.0 p.u. After placing 35.906 MVR size capacitor at bus 4, the loses is decreased to 5.119375 MW from 6.588348 MW. The obtained results are shown in Table 13. After placement of shunt capacitor, it has been noted improvement of voltage magnitude. The results are presented in Fig. 16. It has been observed that voltage magnitude at bus 4 improved to 1.0086 p.u from 0.9405 p.u.

***Case VI: considering line 4-5 outage, without and with shunt capacitor***

Case VI considers the outage of the line connected between bus 4 and bus 5. The configuration of the power system is shown in Fig. 10. The VCPI values are calculated using MiPower software and presented in Table 14. The VCPI value equal 0.095102 is highest at bus 5. It is a suitable location for the placement of the shunt capacitor. In this case to increase the bus 5 voltage magnitude to 1.0 p.u 33.23 MVAR size capacitor is required. The sizing of the capacitor is done based on the enhancement of the voltage magnitude at bus 5 to 1.0 p.u. The comparison of obtained results for systems with and without shunt capacitor are listed in Table 15.

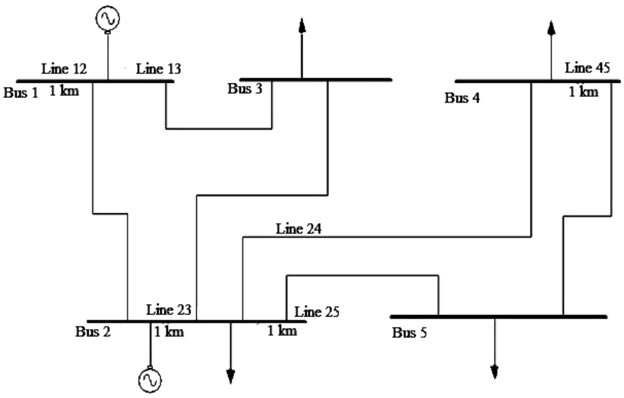


Fig. 9. The 5-bus system layout under line 2-5 outage with shunt capacitor at bus number 5

Table 12. The 5-bus system layout under line 3-4 outage

| S. No | Bus number | VCPI value |
|---|---|---|
| 1 | 3 | 0.067442 |
| 2 | 4 | 0.099915 |
| 3 | 5 | 0.097007 |

Table 13. The 5-bus system load flow results with capacitor under line 3-4 outage

| Parameter | Without employing shunt capacitor | With containing of shunt capacitor |
|---|---|---|
| Over-all real power generation [MW] | 171.583 | 170.119 |
| Over-all reactive power generation [ MVAR] | 83.145 | 41.503 |
| Over-all real power load [MW] | 165 | 165 |
| Over-all reactive power load [ MVAR ] | 90 | 90 |
| Over-all real power losses [MW] | 6.588348 | 5.119375 |
| Over-all reactive power losses [ MVAR ] | -6.854231 | -12.590983 |
| Capacitor size [ MVAR ] | -- | **35.906** |

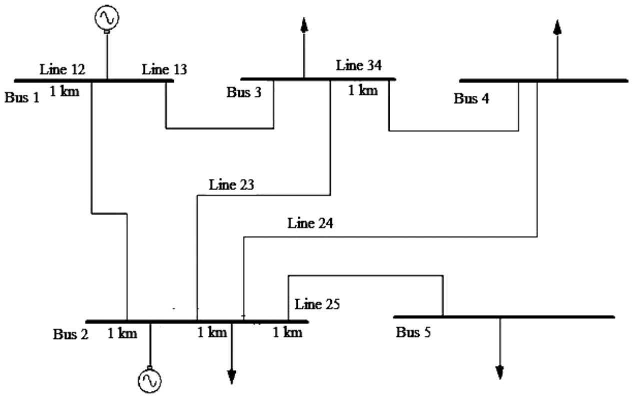


Fig. 10. The 5-bus system layout under line 4-5 outage

Table 14. The 5-bus system VCPI results under line 4-5 outage

| S. No | Bus number | VCPI value |
|---|---|---|
| 1 | 3 | 0.079162 |
| 2 | 4 | 0.081828 |
| 3 | 5 | 0.095102 |

Table 15. The 5-bus system load flow results with capacitor under line 4-5 outage

| Parameter | Without employing shunt capacitor | With containing of shunt capacitor |
|---|---|---|
| Over-all real power generation [MW] | 171.279 | 169.9791 |
| Over-all reactive power generation [ MVAR] | 84.9494 | 47.1066 |
| Over-all real power load [MW] | 165 | 165 |
| Over-all reactive power load [ MVAR ] | 90 | 90 |
| Over-all real power losses [MW] | 6.279489 | 4.9793 |
| Over-all reactive power losses [ MVAR ] | -5.050610 | -9.6569 |
| Capacitor size [ MVAR ] | -- | **33.2366** |

Analyzing the results presented in Table 15, it has been observed that real power losses were reduced to 4.97 MW from 6.27 MW, and after placement of the shunt capacitor, the voltage at bus 5 was increased to 1.007 p.u from 0.9454 p.u.

## Conclusions

In this paper, the VCPI method is used to determine the optimal position for employment of shunt capacitor under *n*-1 contingency condition. The analysis has executed done using MiPower software for 5-bus test system. The software is applied to arrangement the power flows without and with shunt capacitor in power system under *n*-1 contingency condition. Integration of shunt capacitor into power flow studies and verified their enactment on 5-bus test system. The obtained results proved, that voltage profile of power system was enhanced with shunt capacitor under *n*-1 contingency condition, and the losses are also reduced in the system by employing the shunt capacitor.

The over-all real power losses at normal condition are 5.930 MW, at line 2-3 outage losses are 6.9676 MW, at line 2-4 the loses are 7.38745 MW, line 2-5 the loses are 17.7660 MW, line 3-4 the loses are 6.588348 MW, and line 4-5 are 6.279489 MW. It was observed that the losses are more for outage of line 2-5, i.e., this indicates that line 2-5 is the more crucial line in the system. After that to reduce the losses and improve the voltage magnitude shunt capacitor has been incorporated based on the VCPI calculation under different contingency conditions. For example under 2-5 line outage condition VCPI value is highest for bus 5, than the shun capacitor has been placed in bus 5 to enhance the voltage magnitude at bus 5 to 1.0 p.u based on that capacitor size obtained as 35.0447 MVAR and then the losses has been reduced to 10.9299 MW. Similarly, losses have been reduced in different line outage conditions.

Finally, it is concluded that to enhance the performance of the power network, shunt capacitor has been integrated to the system. Based on the VCPI calculation, shunt capacitor is incorporated into the system to advance the enactment of the system in terms of the voltage profile. As future works, it can be used to perform larger systems, e.g., IEEE 30, 57, and 118 bus systems. It can be further extended to applications like the placement of FACTS devices in power systems.

## Nomenclature

VCPI – Voltage collapse prediction index
AC – Alternating current
NR – Newton Raphson
GS – Gauss-Siedel
DC – Direct current
FVSI – Fast voltage stability index
FACTS – Flexible alternating current transmission system
$V_k$ – *k*-th bus voltage
$V_m$ – *m*-th bus voltage
$Y_{km}$ – Admittance between bus *k* and *m*
$Y_{kj}$ – Admittance between bus *k* and *j*
*n* – Number of buses in the system
GUI – Graphical user interface
*R* – Resistance
*X* – Reactance
*B* – Susceptance
*P* – Real power
Q – Reactive power

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***Authors**: Associate professor Bathina Venkateswararao, Siddhartha Engineering College, Vijayawada-520007, India; e-mail: bvrao.eee@gmail.com; Associate professor Ramesh Devarapalli, Lendi Institute of Engineering and Technology, Vizianagaram-535005, India e-mail: Dr.R.Devarapalli@gmail.com; Assistant professor Łukasz Knypiński, Poznan University of Technology, ul, Piotrowo 3a, 60-965 Poznan, Poland, e-mail: lukasz,knypiński@put,poznan,pl; dr R Gowri Sankara Rao, MVGR College of Engineering Vizianagaram, India, e-mail: gowrisankaree@gmail.com; Professor Fausto Pedro García Márquez, Ingenium Research Group, University of Castilla-La Mancha, Spain, E-mail: FaustoPedro.Garcia@uclm.es;*

## REFERENCES

[1] HEIKO T., ADELA M., CHERVYAKOV A., STÜCKRAD S., RUBBIA C., "Efficiency of superconducting transmission lines: An analysis with respect to the load factor and capacity rating", Electric Power Systems Research, vol. 141, pp. 381 - 391, 2016.
[2] DUTTA S., ROY P. K., NANDI D., "Optimal location of UPFC controller in transmission network using hybrid chemical reaction optimization", Energy Systems, vol. 64, pp. 194–211, 2015.
[3] LO K. L., LUAN W. P., GIVEN M., BRADLEY M., WAN H. B., "ANN based automatic contingency selection for electric power system", COMPEL, vol. 21, no. 221, pp. 193–207, 2002.
[4] BALAMURUGAN K., MUTHUKUMAR K., "Differential evolution algorithm for contingency analysis-based optimal location of FACTS controllers in deregulated electricity market", Soft Computing, vol. 23, no. 1, pp. 163–179, 2019.
[5] AFFONSO C. M., DA SILVA L. C. P., "Potential benefits of implementing load management to improve power system security", International Journal of Electrical Power and Energy Systems, vol. 36, no. 6, ,704–710, 2010.
[6] DASHTI R., GORD E., NAJAFI M., REZA SHAKE H., "An intelligent and cost-effective method for single-phase fault location in conventional distribution systems", Electrical Engineering, vol. 102, no. 4, pp. 1975 – 1991, 2020.
[7] ZHOU M., FENG D., "Parallel Contingency Analysis for Multi-CPU/Core Computing Environment", IFAC-PapersOnLine, vol. 52, no. 4, pp. 105–110, 2019.
[8] ILANGO D. R., "Load flow and transient stability analysis for IEEE 5 bus system using UPFC", International Journal of Scientific and Technology, vol. 9, no. 4, pp. 1349 – 1352, 2020.
[9] JAMNANI J. G., PANDYA M., "Coordination of SVC and TCSC for management of power flow by particle swarm optimization", Energy Procedia, vol. 156, pp. 321–326, 2019.
[10] VENKATESH R., VENKATESWARARAO B., GOUTHAMKUMAR N., "Impact of shunt capacitor on voltage profile improvement at over load conditions using MiPower software", International Journal of Electronics, vol. 6, vol. 6, pp. 115 – 121, 2017.
[11] MAHAPATRA S., SINGH M., "Analysis of symmetrical fault in IEEE 14 bus system for enhancing over current protection scheme", International Journal of Future Generation Communication and Networking, vol. 9, no. 4, pp. 51–62, 2016.
[12] DEVARAPALLI R.; KUMAR SINH, N.; VENKATESWARARAO B.; KNYPIŃSKI Ł.; JAYA NAGA N; MARQUEZ, F. P G., "Allocation of real power generation based on computing over all generation cost: An approach of Salp Swarm Algorithm", Archives of Electrical. Engineering, vol. 70, no. 2, 337–349 2021.
[13] MASOUD FATEMI S., ABEDI M., VAHIDI B., ABEDI S., RASTEGAR H., "A novel and fast voltage estimation scheme for assessment of power system component outages", COMPEL, vol. 33, no. 4, pp. 1296–1328, 2014.[14]
[14] ZIMMERMAN R. D., MURILLO-SANCHEZ C. E., THOMAS R. J., "MATPOWER Steady-State Operations, Planning, and Analysis Tools for Power Systems Research and Education", IEEE Transactions on Power Systems, vol. 26, no. 1, pp. 12–19, 2011.
[15] YANG J., BAO X., YANG Z., "Load Identification for the More Electric Aircraft Distribution System Based on Intelligent Algorithm", Aerospace, vol. 9, no. 7, pp. 1 -15, 2022.
[16] MUSIRIN I., KHAWA T., RAHMAN A., "Simulation technique for voltage collapse prediction and contingency ranking in

power system", Student Conference on Research and Development, Shah Alam, Malaysia, pp 188 – 191, 2002.
[17] PRADEEP KUMAR S.K.B., BAAMURUGAN G., BUTCHI RAJU Y., "Optimal Infusion and Grading of Combined DGs and Capacitor Banks for Line Loss Minimization and Enhancement of Voltages in Radial Circuit System", Przegląd Elektrotechniczny, vol. 98, no. 12, pp. 14 – 22, 2021.
[18] BITEW AEGGEGN D., OLALEKAN A., GEBRU Y., "Load flow and contingency analysis for transmission line outage", Archives of Electrical Engineering, vol. 69, no. 3, pp. 581 – 549, 2020.
[19] KIANI E., DOAGOU-MOJARRAD H., RAZMI H., "Multi-objective optimal power flow considering voltage stability index and emergency demand response program", Electrical Engineering, vol. 102, no. 4, pp. 2493–2508, 2020.
[20] MISHRA S., BRARY. S., "Load Flow Analysis Using MATLAB",2022 IEEE International Students' Conference on Electrical, Electronics and Computer Science (SCEECS), pp. 1-4, 2022, doi: 10.1109/SCEECS54111.2022.9741005.
[21] KMAK J., NOWAK W. TARKO R., "Statistical assessment of shock hazard during earth faults in medium voltage substations", Przegląd Elektrotechniczny, vol 98, no. 10, pp. 99 – 102, 2022, doi: 10.15199/48.2022.10.19.
[22] KARBALAEI F., SOLEYMANI H., AFSHARNIA S., "A comparison of voltage collapse proximity indicators", Conference Proceedings IPEC, 2010, pp. 429–432.
[23] AZAD S., AMIRI M. M., AMELI M. T., "Contingency ranking for timely power system security assessment using a new voltage-angle index and based on the PMU data", Journal of Energy Management and Technology, vol. 4, no. 1, pp. 1 -10, 2020.
[24] SINGH P., TIWARI R., SHAH M. K., NIAZI K. R., MEENA N. K., RATRA S., "Voltage stability index and APFC for performance improvement of modern power systems with intense renewable", The Journal of Engineering, vol. 18, pp. 5187–5192., 2019.
[25] MATSUKAWA Y., WATANABE M., WAHAB N. I., OTHMAN M., "Voltage stability index calculation by hybrid state estimation based on multi-objective optimal phasor measurement unit placement", Energies, vol. 12, no. 14, 2688, 2019.
[26] OUKENNOU A., SANDALI A., "Novel voltage stability index for electric power system monitoring", International Journal of Electrical and Computer Engineering Systems, vol. 10, no. 1, pp. 1–9, 2019.
[27] AIROBOMAN A. E., JAMES P., ARAGA I. A., WAMDEO C. L., OKAKWU I. K., "Contingency analysis on the Nigerian power systems network", IEEE PES/IAS Power Africa, pp.70–75, 2019.
[28] ÁLVAREZ-ROMERO G., CASTRO L. M., RONCERO-SÁNCHEZ P., "Effective sensitivity-based method for *N*-1 contingency analysis of VSC-based MTDC power grids considering power generation droop speed controls", International Journal of Electrical Power and Energy Systems, vol. 122, 106175, 2020.
[29] IZUMI S., KARAKAWA Y., XIN X., "Analysis of small-signal stability of power systems with photovoltaic generator", Electrical Engineering, vol. 110, no. 2, pp. 321–331, 2019.
[30] IQBAL M. S., SUJATHA B.C., Multiple contingency analysis for optimal placement and estimate the value of SVC for power loss reduction employing genetic algorithm, International Journal of Electrical Engineering and Technology, vol. 10, no. 4, pp. 60 – 69, 2019.
[31] ADEBAYO I. G., SUN Y., "A Comparison of Voltage Stability Indices for Critical Node Identification in a Power System", 2021 International Conference on Sustainable Energy and Future Electric Transportation (SEFET), pp. 1-5, 2021, doi: 10.1109/SeFet48154.2021.9375674.
[32] S. M. C, "Analysis And Simulation Of Economic Load Dispatch in Power System", 2022 Second International Conference on Advances in Electrical, Computing, Communication and Sustainable Technologies (ICAECT), pp. 1-6, 2022, doi: 10.1109/ICAECT54875.2022.9808026.
[33] ZAHEB H., DANISH M. S. S., SENJYU T., "A contemporary novel classification of voltage stability indices", Applied Sciences, vol. 10, no. 5, pp. 1 -15, 2020.
[34] KYOMUGISHA R., MURIITHI C. M., NYAKOE G. N., "Performance of Various Voltage Stability Indices in a Stochastic Multiobjective Optimal Power Flow Using Mayfly Algorithm", Journal of Electrical and Computer Engineering, 7456333, 2022, doi: 10.1155/2022/7456333.
[35] AMULYAVALLI K, VENKATESWARA RAO B., GOUTHAM KUMAR N., "MiPower based optimal location and sizing of shunt capacitor with *L*-index to improve voltage magnitude in IEEE 14 bus system", International Journal of Pure and Applied Mathematics, vol. 114, no. 7, 2017, pp. 259-269.
[36] UPENDRA PRASAD, NIKHIL KUMAR SINHA, BATHINA VENKATESWARA RAO, NARAHARISETTI JAYA NAGA LAKSHMI, RAMESH DEVARAPALLI, "Optimal placement of shunt capacitor with VCPI to improve voltage profile using Mi power", IOP Conf. Series: Materials Science and Engineering, vol. 981, 042061, 2020,doi:10.1088/1757-899X/981/4/042061.