Optimization Method for Voltage Sag Monitor Placement in Power System

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Abstract – *Voltage sag is one off the severe power quality issues and may cause huge losses to industries. Voltage sag happens frequently and might be caused by random and unpredictable factors. To monitor voltage sag, Voltage Sag Monitoring (VSM) system has been currently implemented to the whole power system. However, implementation of VSM at all buses is not economical. Therefore, the objective of this study is to evaluate the optimal number and placement of voltage sag monitors in IEEE 30-bus system. First, the concept of monitor reach area is used. In this study, voltage sag is represented by balance and unbalance fault with fault impedance,* Z_f *equal to 0Ω. To obtain fault voltage on each bus, IEEE 30-bus system was constructed using PowerWorld software. Then, monitor reach area matrix is formed by comparing fault voltage with selected voltage threshold, α. After that, monitor reach area is analysed by using branch and bound method to evaluate the minimum number and the possible arrangements of VSM. Finally, to optimally place the identified number of VSM, all possible combinations of VSM in the power system were evaluated using sag severity index. To show the effectiveness of the proposed method on the optimal voltage sag monitor placement in power system, the proposed algorithm was implemented and tested on the IEEE 30-bus test system. The proposed method was tested with two different α; i.e. 0.55 p.u. and 0.80 p.u. respectively. The proposed method successfully found the optimal number and its placement for monitoring the whole IEEE 30-bus system with respective α value. Based on the results, for α equal to 0.55, VSM need to be installed on bus 6, 17, 25 and 30 in order to monitor voltage sag on IEEE 30-bus system; and for α equal to 0.80 p.u., VSM are only required to be placed at bus 25 respectively.*

Keywords: *Optimal voltage sag monitor, Monitor reach area, Sag severity index.*

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I. Introduction

Power quality (PQ) issues become more crucial when traditional method is replaced by sophisticated and modern technologies, and the lack of awareness on PQ issues will be a loss to industries [1]. Nowadays, systems such as transportation, manufacturing, military, telecommunication are integrated with computers for a more reliable and efficient system. However, integrating computers into multisystem are expensive and makes the system much complex [2]. For electric companies, detecting and monitoring disturbances in a complete electrical systems are a the challenges [3]. The development of the sophisticated man made machine need to be support by development of power quality means that modern and sophisticated equipment required a good quality power supply [4].

One of the severe and critical power quality issues are voltage sag [5]. Voltage sag happens when the rms voltage decreases between 10% and 90% of nominal voltage for half cycle to one minute [6]. Voltage sag causes huge damage to electronic equipment and bring big losses to industries [7]. Inrush current cause by voltage sag is high in magnitude since voltage will varied in a short period [7]. Missile by military may attack the wrong location if sensors give an incorrect signal due to voltage sag. Telecommunication may not be available for weeks due to equipment damages.

The production cost that is important and affected by voltage sag includes plant downtime, equipment replacement, lost work in process, additional labor, etc. Without the capability to monitor and comprehensive understanding the impact of voltage sag on industrial processes, these production costs will continue to go unaddressed. However, with the knowledge to identify and mitigate voltage sag events, process reliability can be significantly improved. But to place power quality monitor in every bus on power system is not economic. Hence, optimal number and placement of voltage sag monitors need to be determine to reduce voltage sag monitoring installation cost on a complete power system.

II. Monitor Reach Area

Monitor Reach Area (MRA) concept was proposed by Olguin in 2003 which area of network that can be monitor on a given monitoring position. Olguin depicted that if the fault is detected inside MRA, voltage sag meter will be trigger, and vice versa [4][8]. Area of the transmission network for which the meter at bus k is able to capture voltage drops originated by faults that result in residual voltages less than voltage threshold at the meter position [9]. In term of the monitoring of voltage sag, if a fault occurs in MRA, it will trigger the monitor at buses, but if a fault occurs out of the MRA, it will not trigger the monitor [10]. In MRA matrix, each column relates to specific bus which fault occur and in each row refers to a specific bus in the system [11].

Fault voltage need to be calculated before MRA can be built. Fault voltage is determined on every bus by applying various types of short circuit fault on one of the buses [12]. The monitor reach areas of a network's buses can be modelled as a binary matrix of order (N x F), where *N* is the number of buses, and F is the number of fault positions [13]. At first, Y-bus matrix needs to be determined for the specific power system and then convert it to Z-bus matrix. After deriving the Z-bus matrix, fault voltage for every bus are calculated by using equation (1)-(7) [14][15]:

3-phase fault (LLF)

$$V_{\mathrm{ij}} = 1 - \frac{Z_{\mathrm{ij}}}{Z_{\mathrm{ii}}} \tag{1}$$

Single line to ground fault (SLG)

$$V_{\mathrm{ija}} = 1 - \frac{Z_{\mathrm{ij}}^{(1)} + Z_{\mathrm{ij}}^{(2)} + Z_{\mathrm{ij}}^{(0)}}{Z_{\mathrm{ii}}^{(1)} + Z_{\mathrm{ii}}^{(2)} + Z_{\mathrm{ii}}^{(0)}} \tag{2}$$

$$V_{\mathrm{ijb}} = \alpha^2 - \frac{\alpha^2 Z_{\mathrm{ij}}^{(1)} + \alpha Z_{\mathrm{ij}}^{(2)} + Z_{\mathrm{ij}}^{(0)}}{Z_{\mathrm{ii}}^{(1)} + Z_{\mathrm{ii}}^{(2)} + Z_{\mathrm{ii}}^{(0)}} \tag{3}$$

$$V_{\mathrm{ijc}} = \alpha - \frac{\alpha Z_{\mathrm{ij}}^{(1)} + \alpha^2 Z_{\mathrm{ij}}^{(2)} + Z_{\mathrm{ij}}^{(0)}}{Z_{\mathrm{ii}}^{(1)} + Z_{\mathrm{ii}}^{(2)} + Z_{\mathrm{ii}}^{(0)}} \tag{4}$$

Double line to ground fault (DLG)

$$V_{\mathrm{ija}} = 1 - \frac{Z_{\mathrm{ij}}^{(1)} \left(Z_{\mathrm{ii}}^{(2)} + Z_{\mathrm{ii}}^{(0)}\right) - Z_{\mathrm{ij}}^{(2)} Z_{\mathrm{ii}}^{(0)} + Z_{\mathrm{ij}}^{(0)} Z_{\mathrm{ii}}^{(2)}}{Z_{\mathrm{ii}}^{(1)} Z_{\mathrm{ii}}^{(2)} + Z_{\mathrm{ii}}^{(2)} Z_{\mathrm{ii}}^{(0)} + Z_{\mathrm{ii}}^{(0)} Z_{\mathrm{ii}}^{(1)}} \tag{5}$$

$$V_{\mathrm{ijb}} = \alpha^2 - \frac{\alpha^2 Z_{\mathrm{ij}}^{(1)} \left(Z_{\mathrm{ii}}^{(2)} + Z_{\mathrm{ii}}^{(0)}\right) - \alpha Z_{\mathrm{ij}}^{(2)} Z_{\mathrm{ii}}^{(0)} + Z_{\mathrm{ij}}^{(0)} Z_{\mathrm{ii}}^{(2)}}{Z_{\mathrm{ii}}^{(1)} Z_{\mathrm{ii}}^{(2)} + Z_{\mathrm{ii}}^{(2)} Z_{\mathrm{ii}}^{(0)} + Z_{\mathrm{ii}}^{(0)} Z_{\mathrm{ii}}^{(1)}} \tag{6}$$

$$V_{\mathrm{ijc}} = \alpha^2 - \frac{\alpha Z_{\mathrm{ij}}^{(1)} \left(Z_{\mathrm{ii}}^{(2)} + Z_{\mathrm{ii}}^{(0)}\right) - \alpha^2 Z_{\mathrm{ij}}^{(2)} Z_{\mathrm{ii}}^{(0)} + Z_{\mathrm{ij}}^{(0)} Z_{\mathrm{ii}}^{(2)}}{Z_{\mathrm{ii}}^{(1)} Z_{\mathrm{ii}}^{(2)} + Z_{\mathrm{ii}}^{(2)} Z_{\mathrm{ii}}^{(0)} + Z_{\mathrm{ii}}^{(0)} Z_{\mathrm{ii}}^{(1)}} \tag{7}$$

Fault voltage calculated for every types of fault on every bus and then formed a fault voltage matrix. Then, every elements in fault voltage matrix was compared with threshold voltage, α to formed MRA matrix as per below equation (8) – (9) [16]:

Balance fault

$$MRM_{\mathrm{ij}} = \begin{cases} 1, & V_{\mathrm{ij}} \le v_{\mathrm{t}} \\ 0, & V_{\mathrm{ij}} > v_{\mathrm{t}} \end{cases} \tag{8}$$

Unbalance fault

$$MRM_{\mathrm{ij}} = \begin{cases} 1, & \min(v_{\mathrm{ija}}, v_{\mathrm{ijb}}, v_{\mathrm{ijc}}) \le v_{\mathrm{t}} \\ 0, & \min(v_{\mathrm{ija}}, v_{\mathrm{ijb}}, v_{\mathrm{ijc}}) > v_{\mathrm{t}} \end{cases} \tag{9}$$

III. Branch and Bound Method

In real world optimization share commons properties; i.e. easy to determine the problem and have a finite but usually very large number of feasible solutions [17]. While some of the optimization problems such as Shortest Path problem and Minimum Spanning Tree problem have polynomial algorithms, the majority of the problems share the same difficulty; polynomial method for their solution is unknown, e.g. vehicle routing, crew scheduling, and production planning.

Several methods were tested for optimization of road travels, which was to solve Traveling Salesman Problem (TSP) [18]. Branch and Bound method (B&B) was introduce by Little, Murty, Sweeny and Karel in conjunction with TSP algorithm [18]. Enumerative B&B method answer discrete optimization problem by breaking up its feasible set into smaller subsets, computing bounds on the objective function value over each subset and using them to remove certain subsets from further consideration. The bounds are obtained by changing the problem over a given subset with an easier problem, such that the solution value of the later bound that of the former. The procedure ends when each subset has either produced a feasible solution or was shown to contain no better solution from current value [19].

Figure 1 shows example of B&B method for optimization solution. The solution may differ according to the rules, strategy and requirement choose when it bound to the next process. If the selection of next sub problem is based on the bound value of the sub problems, then the first operation of an iteration after choosing the node is branching, i.e. subdivision of the solution space of the node into two or more subspaces to be investigated in a subsequent iteration. Figure 1 (b) shows the B&B was branch out to S1, S2, S3 and S4 after bound process found value of S got potential of studying the optimal solution. For each of these, it is checked whether the subspace consists of a single solution, in which case it is compared to the current best solution keeping the best of these. Otherwise the bounding function for the subspace is calculated and compared to the current best solution. If it can be established that the subspace cannot contain the optimal solution, the whole subspace is discarded, else it is stored in the pool of live nodes together with its bound. Figure 1 (c) shows that element S1 and S4 not branching out since bound process found element S1 and S4 does not contain optimal solution. This called the eager strategy for node evaluation, since bounds are calculated as soon as nodes are available. The alternative is to start by calculating the bound of the selected node and then branch on the node if necessary. The nodes created are then stored together with the bound of the processed node. This strategy is called lazy and is often used when the next node to be processed is chosen to be a live node of maximal depth in the search tree. The optimization process end and objective is achieved when there is no unexplored part or the termination requirement achieve.

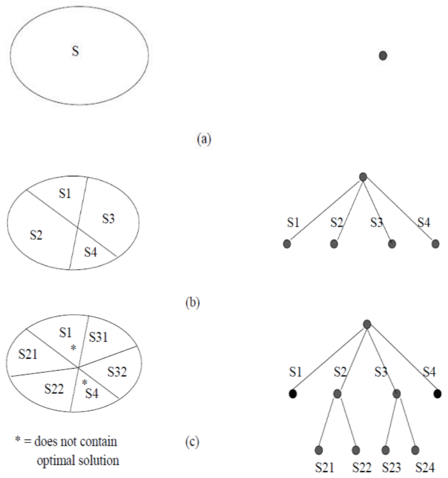

Figure 1. Illustration of the search space of B&B (a) 1st step of B&B (b) B&B branch out (c) S1 and S4 not branch out

IV. Sag Severity Index

Since voltage sag is a type of PQ issue which has a severe effect and cause huge loss to industries, sag severity assessment is an important study [20]. Before engineer can mitigate the voltage sag issues, it is important to evaluate the severity of voltage sag precisely.

The severity of voltage sag is measure by the relation between voltage sag to the response of monitoring equipment [20]. Sag Severity Index (SSI), derived with respect to equipment sensitivity to voltage sag [20]. In other word, it is the relationship between uncertainties/variation in equipment response to voltage sag to the existing single-event characteristics. By changing the parameter settings, the index appropriately accounts for sag duration and adequately addresses the variation in equipment sensitivity. The value of the index changes continuously at the joining regions of different sag severity levels and reflects realistically the sensitivity trend of equipment embedded in voltage tolerance curves [21].

In this study, SSI was used in order to determine the best location of VSM to be installed. SSI is defined as ratio between summations of phases experiencing voltage sag with magnitude lower than voltage threshold, β for all buses over total number of phases in the whole system as expressed with Equation 10 [11]. The higher value of SSI for specific bus meaning that voltage sag impact of the bus toward the system is higher. For easy understanding, the SSI value is 1 when the whole system experiencing voltage sag when fault occur at that bus. So, bus with higher SSI value should be the priority to install Voltage Sag Monitor (VSM) as shown in equation (10).

$$SSI_{\beta}^{F} = \frac{\sum N_{\mathrm{SPB}}}{\sum N_{\mathrm{TPB}}} \qquad (10)$$

where F is a type of fault, β is a voltage threshold, N_{SPB} is a number of affected phases by voltage sag for all buses, N_{TPB} is a total number of phases for all buses in the whole system.

V. Implementation of Proposed Method

This research used *PowerWorld* software to obtained voltage sag which is represented by balance and unbalance faults. The Monitor Reach Area (MRA) matrix will be constructed before B&B method, in order to analyze the MRA matrix and to study the minimum number of VSM and its possible arrangements. Finally, the best arrangement of VSM will be determine by calculating SSI for every VSM arrangement possibilities. The highest values of SSI will be the best location to place the VSM. Figure 2 give a better understanding of method used in this study.

B&B method needs rules for the method to branch or bound. Rules for B&B method used in this study were determined with caution because incorrect assignment of the rule to B&B method will cause it to not converge and final optimization unattainable. Figure 3 shows Branch and Bound method rules and strategy for this study to determine the minimum number of VSM and its arrangement possibilities. For every VSM arrangement possibilities, the SSI value will be calculated. By using *Powerworld* software, balance and unbalance fault is applied on buses and fault voltage recorded. Value of all phase fault voltage for balance and unbalance faults will be compared with voltage threshold, β. The SSI will be calculated by dividing number of affected phases by voltage sag for all buses with total number of phases for all buses in the whole system.

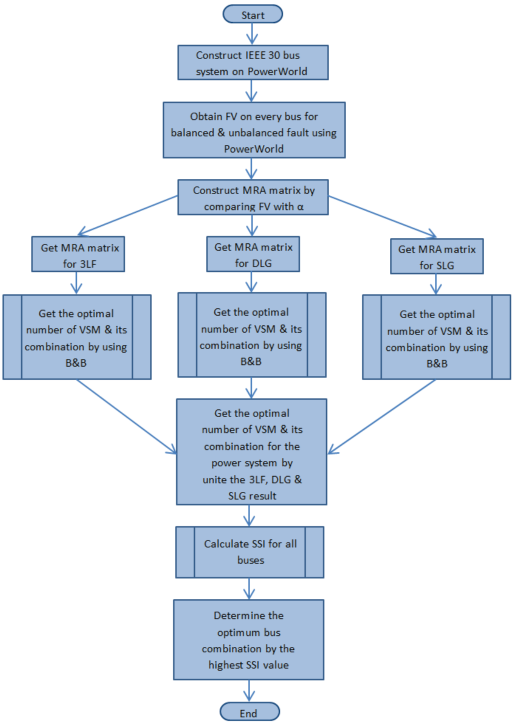

Figure 2. Flow chart of methodology

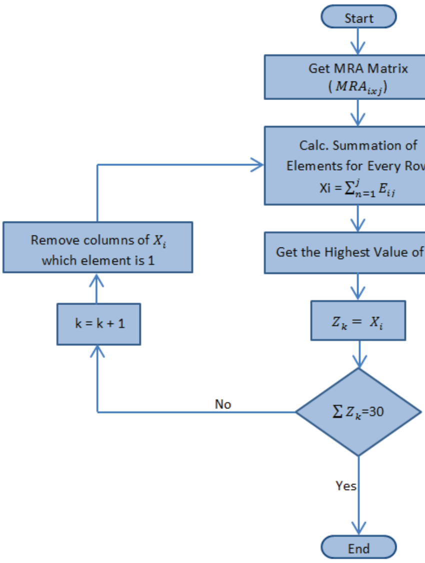

Figure 3: B&B rules and strategy

VI. Results and Discussion

IEEE 30 bus power system was used for verifying the effectiveness of proposed method. IEEE 30 bus power system was constructed on *PowerWorld* software using data taken from [22]. This power system consists of 30 buses, two voltage levels-132kV and 33kV, four step-down transformers and 35 transmission lines, six power generators and 21 loads.

The methodology consists of 3 main processes which are constructing MRA matrix, Branch and Bound method and sag severity index concept. IEEE 30-bus system was constructed on *PowerWorld* software and fault voltage for every bus obtained by *PowerWorld* analysis tools. Then, by using Branch and Bound method, minimum number of VSM required and its arrangement possibilities was obtained. Finally, sag severity index was calculated in order to determine the best VSM arrangement in IEEE 30 bus system. Proposed method was successfully obtained the optimal VSM placement for IEEE 30 bus system.

Table 1 shows SSI value for all arrangement possibilities for α = 0.55 p.u. From Table 1, arrangement of bus 25, 17, 30 and 6 give the highest value of SSI which is 2.6037. So, the best location for installing VSM in IEEE 30 bus test system is at bus 25, 17, 30 and 6 for α = 0.55 p.u..

TABLE 1

SSI VALUE OF VSM ARRANGEMENT ON IEEE 30-BUS SYSTEM FOR A = 0.55 AND B = 0.9

	VSM Location				
No.	Bus				SSI
1.	25	17	30	1	2.57778
2.	25	17	30	2	2.58889
3.	25	17	30	3	2.55556
4.	25	17	30	4	2.59259
5.	25	17	30	5	2.53333
6.	25	17	30	6	2.60370
7.	25	17	30	7	2.54074
8.	25	17	30	8	2.57778
9.	25	17	30	28	2.55185
10.	25	20	30	1	2.57407
11.	25	20	30	2	2.58519
12.	25	20	30	3	2.55185
13.	25	20	30	4	2.58889
14.	25	20	30	5	2.52963
15.	25	20	30	6	2.60000
16.	25	20	30	7	2.53704
17.	25	20	30	8	2.57407
18.	25	20	30	28	2.54815
19.	26	17	30	1	2.48519
20.	26	17	30	2	2.49630

21.	26	17	30	3	2.46296
22.	26	17	30	4	2.50000
23.	26	17	30	5	2.44074
24.	26	17	30	6	2.51111
25.	26	17	30	7	2.44815
26.	26	17	30	8	2.48519
27.	26	17	30	28	2.45926
28.	26	20	30	1	2.48148
29.	26	20	30	2	2.49259
30.	26	20	30	3	2.45926
31.	26	20	30	4	2.49630
32.	26	20	30	5	2.43704
33.	26	20	30	6	2.50741
34.	26	20	30	7	2.44444
35.	26	20	30	8	2.48148
36.	26	20	30	28	2.45556

The process was repeated for α value equal to 0.80. Table 2 shows SSI value for all possible bus to place the VSM for α = 0.80 p.u. After comparing SSI value for all possibilities, found that bus 25 is the best location to place the VSM for monitor the whole IEEE 30-bus system with α = 0.80 p.u..

TABLE 2

SSI VALUE OF VSM LOCATION ON IEEE 30-BUS SYSTEM FOR B = 0.9, A = 0.80 P.U.

No.	VSM Location	SSI
1	Bus 25	0.633333
2	Bus 26	0.540741
3	Bus 27	0.629630
4	Bus 29	0.581481
5	Bus 30	0.555556

Table 3 shows result obtained for optimal placement of voltage sag monitor on IEEE 30 bus with different voltage threshold, α value. From the table, higher α value required less VSM to monitor. This due to vulnerability of VSM is bigger for the higher α value. However, sag voltage range able to be monitor by VSM for higher α is small.

Voltage sag due to faults can be severe and therefore are a major concern to use fault voltage for representing voltage sag [23]. Therefore, voltage sag was represented by balance and unbalance fault with fault impedance 0Ω meaning that voltage sag was represented by fault bus voltage which is 0V. If fault impedance is not 0Ω, fault bus voltage value is not going to be 0V. This will cause VSM installed on the system might not be able to detect the voltage sag occur on the system. This issue can be overcome by reducing α value but number of monitoring unit will be increase. As a result, value of α need to be choose carefully so that optimum voltage sag monitoring system with less VSM can be implemented.

TABLE 3

OPTIMAL PLACEMENT RESULT ON IEEE 30-BUS SYSTEM

α value (p.u.)	VSM Location (Bus)
0.55	6, 17, 25, 30
0.80	25

In order to confirm the result obtained by the proposed method, result obtained was tested by simulate voltage sag for every bus and at least one of the proposed VSM location should be able to detect the voltage sag event. To verify results obtained from this study, voltage sag was simulated again using balance and unbalance faults on *PowerWorld* software to see residue voltage on bus installed with VSM. If the residue voltage on bus installed VSM below α value, mean that VSM installed able to detect the voltage sag event.

Tables 4, 5 and 6 show that during any fault occur at any bus for α = 0.55 p.u.. At least one VSM will sense there is fault occurring in the test system. This verify that result obtained from the proposed method was successfully covered the whole IEEE 30-bus system for voltage threshold, α = 0.55 p.u. For example, based on Table 4, voltage sag happen at bus 13, VSM at bus 17 and 25 detected voltage sag occur on the power system. Another example, voltage sag happen at bus 26, only VSM at bus 25 detected there is voltage sag was occurred on the power system. Figures 4, 5 and 6 show locations of VSM on IEEE 30-bus system obtained from the result for α = 0.55 where VSM was placed at bus 6, 17, 25 and 30 and it vulnerability area. From the figures, all the buses for IEEE 30-bus system was covered by the VSMs installed at buses 6, 17, 25 and 30 for 3LF, SLG and DLG fault.

TABLE 4

VSM VOLTAGE VALUE WHEN VOLTAGE SAG OCCUR ON THE IEEE 30-BUS SYSTEM FOR 3LF FAULT AND A = 0.55 P.U.

Fault/Voltage sag Location	Voltage at VSM Location (pu)			
	6	17	25	30
Bus 1	0.30642	0.39499	0.35222	0.32941
Bus 2	0.20180	0.30704	0.25875	0.23489
Bus 3	0.24334	0.32828	0.28937	0.26946
Bus 4	0.12461	0.21487	0.17504	0.15678
Bus 5	0.37091	0.47212	0.42603	0.39998
Bus 6	0.00000	0.15858	0.09153	0.06184
Bus 7	0.27319	0.39268	0.33973	0.31196

Bus 8	0.15645	0.29042	0.21236	0.17668
Bus 9	0.40128	0.19935	0.30440	0.33392
Bus 10	0.42487	0.05871	0.24799	0.30785
Bus 11	0.65413	0.54262	0.59704	0.60474
Bus 12	0.46258	0.26692	0.34599	0.38263
Bus 13	0.63220	0.49509	0.54715	0.56631
Bus 14	0.64991	0.54483	0.56698	0.58753
Bus 15	0.54484	0.37693	0.39565	0.44239
Bus 16	0.58439	0.27818	0.48482	0.51245
Bus 17	0.52508	0.00000	0.39268	0.43415
Bus 18	0.65171	0.50441	0.54674	0.57459
Bus 19	0.64656	0.47949	0.54292	0.57053
Bus 20	0.62649	0.43821	0.51770	0.54783
Bus 21	0.50270	0.21966	0.30080	0.36847
Bus 22	0.50505	0.23031	0.28659	0.36033
Bus 23	0.64656	0.52307	0.44151	0.50603
Bus 24	0.59302	0.44338	0.22125	0.34946
Bus 25	0.68580	0.64849	0.00000	0.24115
Bus 26	0.84492	0.84405	0.50918	0.61775
Bus 27	0.66002	0.65785	0.18950	0.00000
Bus 28	0.22122	0.33197	0.17208	0.10638
Bus 29	0.80921	0.82394	0.55225	0.18921
Bus 30	0.82563	0.84168	0.59047	0.00000

Figure 4: Area covered by the installed VSMs when voltage sag occur on the IEEE 30-bus system for 3LF fault and α = 0.55 p.u.

TABLE 5

VSM VOLTAGE VALUE WHEN VOLTAGE SAG OCCUR ON THE IEEE 30-BUS SYSTEM FOR DLG FAULT AND Α = 0.55 P.U.

Fault/Voltage sag Location	Voltage at VSM Location (pu)			
	6	17	25	30
Bus 1	0.28736	0.48656	0.45277	0.43193
Bus 2	0.17783	0.46666	0.43648	0.41760
Bus 3	0.23046	0.50587	0.48149	0.46424
Bus 4	0.11883	0.46217	0.44405	0.43005
Bus 5	0.34801	0.60970	0.56908	0.54334
Bus 6	0.00000	0.45572	0.42925	0.40885
Bus 7	0.25651	0.56686	0.52393	0.49804
Bus 8	0.14100	0.50618	0.45242	0.42461
Bus 9	0.49929	0.15954	0.24192	0.25486
Bus 10	0.52582	0.04862	0.19700	0.23507
Bus 11	0.67302	0.47240	0.51584	0.51305
Bus 12	0.55483	0.21566	0.26938	0.28645
Bus 13	0.66130	0.41383	0.45477	0.46065
Bus 14	0.72832	0.48058	0.47758	0.47968
Bus 15	0.63568	0.32398	0.32544	0.35083
Bus 16	0.65832	0.23954	0.40371	0.41284
Bus 17	0.60895	0.00000	0.32199	0.34249
Bus 18	0.71973	0.44782	0.46753	0.47713
Bus 19	0.71441	0.42710	0.46487	0.47403
Bus 20	0.69703	0.38843	0.43981	0.45083
Bus 21	0.59671	0.19370	0.24679	0.29011
Bus 22	0.59993	0.20296	0.23543	0.28415
Bus 23	0.71849	0.46470	0.37693	0.41814
Bus 24	0.67990	0.39869	0.19174	0.28768
Bus 25	0.74599	0.61012	0.00000	0.19348
Bus 26	0.87985	0.80649	0.47037	0.54785
Bus 27	0.71093	0.62468	0.17653	0.02250
Bus 28	0.20915	0.53777	0.44085	0.40283
Bus 29	0.84358	0.79000	0.51754	0.16350
Bus 30	0.85735	0.80914	0.55737	0.00000

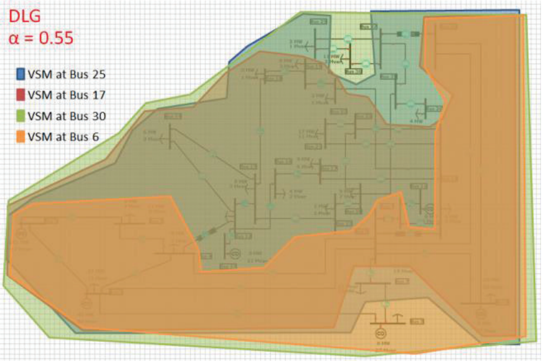

Figure 5: Area covered by the installed VSMs when voltage sag occur on the IEEE 30-bus system for DLG fault and α = 0.55 p.u.

TABLE 6

VSM VOLTAGE VALUE WHEN VOLTAGE SAG OCCUR ON THE IEEE 30-BUS SYSTEM FOR SLG FAULT AND Α = 0.55 P.U.

Fault/Voltage sag Location (Bus)	Voltage at VSM Location (pu)			
	6	17	25	30
Bus 1	0.33259	0.68847	0.65495	0.63088
Bus 2	0.21017	0.65262	0.61725	0.59290
Bus 3	0.26868	0.69678	0.66707	0.64456
Bus 4	0.14537	0.64911	0.61946	0.59781
Bus 5	0.37948	0.75653	0.72283	0.69732
Bus 6	0.00000	0.62194	0.57958	0.55250
Bus 7	0.28587	0.73161	0.69514	0.66881
Bus 8	0.15555	0.67832	0.62965	0.59938
Bus 9	0.80438	0.18143	0.21980	0.21672
Bus 10	0.81348	0.05737	0.12886	0.14054
Bus 11	0.84140	0.42254	0.44689	0.43756
Bus 12	0.81382	0.23729	0.23798	0.24217
Bus 13	0.83828	0.39219	0.39365	0.39106
Bus 14	0.86947	0.49950	0.46860	0.46806
Bus 15	0.84003	0.32917	0.26755	0.27613
Bus 16	0.85091	0.23631	0.36267	0.36303
Bus 17	0.83798	0.00000	0.26414	0.26927
Bus 18	0.87409	0.44720	0.42746	0.42805
Bus 19	0.87386	0.42303	0.42312	0.42333
Bus 20	0.86771	0.38324	0.39521	0.39637
Bus 21	0.83611	0.19492	0.17009	0.18516
Bus 22	0.83661	0.20427	0.15268	0.17037
Bus 23	0.87398	0.47033	0.29976	0.31440
Bus 24	0.86558	0.41363	0.07530	0.11323
Bus 25	0.91355	0.67144	0.00000	0.06471
Bus 26	0.95229	0.82456	0.41440	0.43960
Bus 27	0.92391	0.73108	0.20630	0.03682
Bus 28	0.24201	0.71235	0.62735	0.58286
Bus 29	0.95094	0.82582	0.45309	0.12033
Bus 30	0.95528	0.83886	0.48760	0.00000

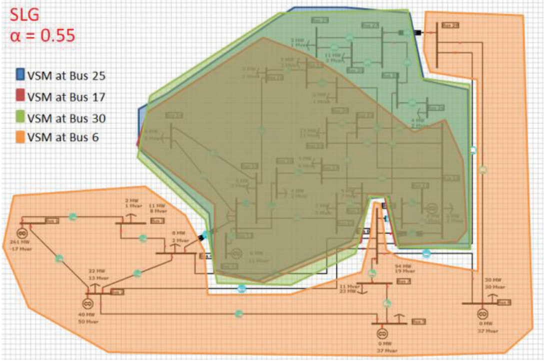

Figure 6: Area covered by the installed VSMs when voltage sag occurs on the IEEE 30-bus system for SLG fault and α = 0.55 p.u.

For α = 0.80 p.u., only 1 VSM is enough to monitor the whole IEEE 30 bus system. Table 7 and Figure 7 shows that during any fault occur at any bus for α=0.80 p.u., VSM at bus 25 able to sense fault occur in the IEEE 30 bus system.

TABLE 7

VSM VOLTAGE VALUE WHEN FAULT OCCUR ON THE IEEE 30-BUS SYSTEM AND Α=0.80 P.U.

Fault/Voltage sag Location	Voltage at VSM Location (pu)		
	Bus 25		
	3LF	DLG	SLG
Bus 1	0.35222	0.45277	0.65495
Bus 2	0.25875	0.43648	0.61725
Bus 3	0.28937	0.48149	0.66707
Bus 4	0.17504	0.44405	0.61946
Bus 5	0.42603	0.56908	0.72283
Bus 6	0.09153	0.42925	0.57958
Bus 7	0.33973	0.52393	0.69514
Bus 8	0.21236	0.45242	0.62965
Bus 9	0.30440	0.24192	0.21980
Bus 10	0.24799	0.19700	0.12886
Bus 11	0.59704	0.51584	0.44689
Bus 12	0.34599	0.26938	0.23798
Bus 13	0.54715	0.45477	0.39365

Bus 14	0.56698	0.47758	0.46860
Bus 15	0.39565	0.32544	0.26755
Bus 16	0.48482	0.40371	0.36267
Bus 17	0.39268	0.32199	0.26414
Bus 18	0.54674	0.46753	0.42746
Bus 19	0.54292	0.46487	0.42312
Bus 20	0.51770	0.43981	0.39521
Bus 21	0.30080	0.24679	0.17009
Bus 22	0.28659	0.23543	0.15268
Bus 23	0.44151	0.37693	0.29976
Bus 24	0.22125	0.19174	0.07530
Bus 25	0.00000	0.00000	0.00000
Bus 26	0.50918	0.47037	0.41440
Bus 27	0.18950	0.17653	0.20630
Bus 28	0.17208	0.44085	0.62735
Bus 29	0.55225	0.51754	0.45309
Bus 30	0.59047	0.55737	0.48760

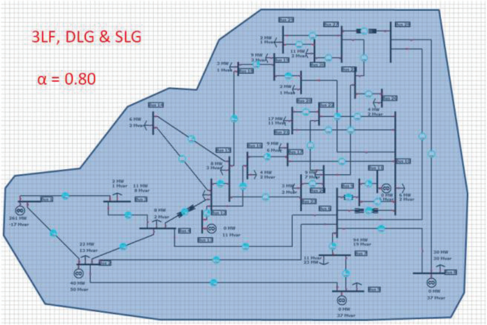

Figure 7: Area covered by the installed VSMs when voltage sag occur on the IEEE 30-bus system for SLG fault and α = 0.80 p.u.

VII. Conclusion

In this paper, the proposed non-heuristic method successfully discussed the optimum number and location of Voltage Sag Monitor (VSM) to monitor whole system of IEEE 30 bus system. The proposed method based on analyzing MRA matrix using Branch and Bound method to study the minimum VSM require and calculating Sag Severity Index (SSI) to get the best arrangement of VSM. Result shows that it is not necessary to install VSM on all Bus to monitor overall IEEE 30 bus system. So, proposed method may help engineer to design voltage sag monitor on power system and then, cost for monitor the power system can be reduce without reducing it performance. Minimum number of VSM for IEEE 30-bus system are 4 units for α = 0.55 p.u. and 1 unit for α = 0.8. VSM should be place on bus 6, 17, 25 and 30 for IEEE 30-bus system with α = 0.55 and for IEEE 30-bus system with α = 0.8, VSM should be place at bus 25. From result, it is obvious that smaller voltage threshold, α required less VSM number to monitor the whole IEEE 30 bus system.

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