A.Ramasamy, R. Verayiah,
H. I. Zainal Abidin, I.Musirin,
A. A. Rahim

Performance of Fast Voltage Stability Index (FVSI) as an indicator for Under Voltage Load Shedding Scheme in a Bulk Power System Network

Abstract— The power system is always exposed to possible risk of instability including voltage stability. Voltage stability can be mitigated by various means which include switching in of reactive power support, tap changing transformers and also increase of generator excitation. However, these mitigating actions could also lead to a more detrimental voltage instability scenario. Hence the last possible mitigating action in this case would be using Under Voltage Load Shedding (UVLS) schemes. The research proposes to utilize an established index called FVSI (Fast Voltage Stability Index) to act as an indicator for Under Voltage Load Shedding (UVLS) locations for a large test system. The research work done shows that the FVSI index can be used as an indicator for UVLS relay location. The FVSI index is capable to identify critical areas in a large power system. Thus, load shedding at these points does improve the stability of the system and it is also shows the improvement of FVSI index during post shed conditions.

Keywords – UVLS, FVSI, Voltage collapse

I. INTRODUCTION

[1]Similar to any utility grid from all over the world, a large power system will be exposed to potential risks of system instability. This would include either frequency related faults and voltage related faults. During fault occurrence, the system may experience a change in frequency or a change in voltage levels or a combination of both. If the system is unable to contain this fault, the power system may experience voltage instability which ultimately leads to a wide area blackout. This study will cover the voltage stability aspect of a large test grid.

There are various methods and approaches that can be used to reduce risks of voltage instability event from occurring [1-4]. They are:

- Improve reactive power resources and its reaction
- Review and maintain line loading limits
- Implementing UVLS Schemes
- Under voltage load shedding (UVLS) is a final mitigating action used to avoid voltage collapse scenarios when all other effective means of mitigation are exhausted. Initiated by low voltage, in combination with other parameters provides the unique characteristics of this type of scheme. Detection of low voltages on the transmission systems may indicate the lack of sufficient reactive power to maintain system stability. If other control actions such as reactive power switching or compensation are not effective in restoring the systems voltages, it is necessary to shed load in order to maintain stable voltage levels hence ensuring voltage stability.

UVLS operates when there is a disturbance and the voltage drops to a certain level for a certain period of time. Systems studies are needed to determine which systems are the potential candidates for a suitable UVLS scheme. UVLS is a low cost yet powerful action to maintain voltage stability for multiple or severe contingencies. In order to benefit from this control action, the analysis requires the information of when, where and how much to load shed.

Several techniques have been proposed [1-3]. Reference [1] introduces the main concepts of this remedial measure. It emphasizes the importance of load characteristics and load models, and predicts the importance of this corrective action in the coming future. In [2], the influence of different load models on the analysis and calculation of the amount of load needed to be shed has been studied. It involved the dynamics simulations of small power system using both static and dynamics load models. Further research in the development of dynamics load models for voltage stability studies have been taken in [3]. The IEEE Task Force on Load Representation for Dynamic Performance Analysis reviewed on the state of the art of representation of power systems load for dynamic performance analysis purposes [4].

An important factor to consider within a UVLS design is the location where load is shed. Notwithstanding the constraints on the type of distribution feeders that should not be considered for UVLS implementation, reactive power relief must be provided at the location of the reactive power deficiency. Small disturbance analysis, coupled with dynamic simulation and in some cases optimal power flow

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[1] A.Ramasamy is with Universiti Tenaga Nasional(UNITEN), Kajang, Malaysia. She can be reached at agileswari@uniten.edu.my
[2] R.Verayiah is with Universiti Tenaga Nasional(UNITEN), Kajang, Malaysia. She can be reached at renuga@uniten.edu.my
[3] H.I.Zainal Abidin is with Universiti Tenaga Nasional(UNITEN), Kajang, Malaysia. He can be reached at Izham@uniten.edu.my
[4] I.Musirin is with Universiti Teknologi Mara Malaysia. He can be reached at i_musirin@yahoo.co.uk.
[5] A.A.Rahim is with Tenaga Nasional Research Sdn. Bhd. He can be reached at azlana@tnbr.com.my

methodology are some tools employed in the determination of the location of load shed [5]. In this case, the load buses are ranked in the order of the weakest to the strongest. The weakest bus tends to have the highest *dQ/dV* component and tends to be most vulnerable to voltage collapse given the relatively large reactive power consumption for a small reduction in bus voltage. Therefore, often it is this bus that is the most appropriate candidate for load shedding initially. In [9], the proposed UVLS scheme detects voltage collapse at every bus in the ten bus system considered. Rather than shedding load at the weakest one through buses ranking, each bus is monitored for voltage collapse and upon detection of this, the UVLS is triggered at that bus.

A major drawback to this approach is that the optimum amount of load will not be shed given that the power-voltage characteristics of the lines would change upon load shed at one bus. Furthermore, this approach does not distinguish between the bus at which the reactive power demand is increased and the adjacent buses whose voltages follow suit. This means that the load at adjacent buses may be shed in the case where load rejection at the weakest bus alone would have arrested voltage collapse. Reference [5] overcomes this approach by pre-determining the weakest buses in the system under various contingencies (N-1, N-2 and N-3).

In terms of the UVLS Schemes for a large test system, UVLS relays are placed with the purpose to reduce Voltage Instability based upon a series of contingency scenarios. The location and strategy of these schemes are based upon the system engineer's expert knowledge of the system grid behavior. However, effectiveness of installing relays at these locations has not been proven empirically due to the limited resources of the planners.

Usually such UVLS schemes can be examined through simulations, but voltage collapse analysis require analysis which are neither steady state nor transient type simulations as it takes minutes (in real time) for collapse to occur. Thus simulations on the voltage collapse phenomenon require tremendous amounts of time. In addition, these simulations require very detailed and numerous data which are not readily available. Given the fact that the power system has not gone through an exhaustive search for new possible UVLS schemes, it means there are still possibilities of new UVLS schemes that could be more effective as compared to present schemes.

Apart from the above, it would be expected that the grid would experience changes over time i.e. load levels, line loading, line expansion and system upgrades, hence there is a need to review existing schemes and verify whether new UVLS schemes is required and also whether the existing schemes is sufficient and the relays are placed at the most strategic place. If these changes are to be considered, it will require considerable efforts on the planners to determine a new UVLS scheme, assuming that the barriers in the above paragraph can be surmounted.

If the maximum loadability can be indicated and weakest point in large system can be indentified quickly, then it will facilitate the placement of UVLS relays.

The slow variation in reactive power loading towards its maximum point causes the traditional load flow to reach its non- convergence point. Beyond this point, the ordinary load flow solution does not converge, which in turn forces the system to reach the voltage stability limit prior to bifurcation in the system. The margin measured from the base case solution to the maximum convergence point in the load flow computation determines the maximum loadability at a particular bus in the system. This is in agreement with most literature that maximum loadability depends on the solvability margin of load flow when the Jacobian matrix becomes singular [6-9].

Fast Voltage Stability Index (FVSI) is an instrument used to analyze the voltage stability condition in a power system [10]. This index is basically used to determine the maximum loadability in a power system.

The study has incorporated the use of FVSI index as an indicator for critical bus in a large power system network. Hence, from the location of the critical bus, the placement of UVLS relays in a particular area can be determined.

II. METHODOLOGY

This paper focuses on a 793 test bus system and all simulations were carried out using PSSE Simulation Tool.

A. FVSI Index

Fast Voltage Stability Index, FVSI [5] is given as follows:

$$FVSI_{ij} = \frac{4Z^2 Q_j}{V_i^2 X} \tag{1}$$

The symbols 'i' represents the sending bus while 'j' represents the receiving bus whereas Z is the line impedance, X is the line reactance, R is line resistance, Q_j is the reactive power at the receiving end, and V_i is the sending end voltage. The FVSI index was derived based on the following single line diagram:-

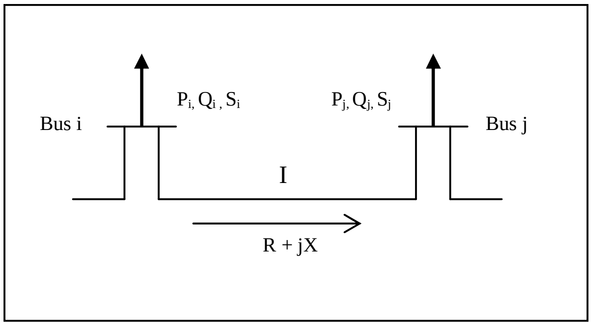


Fig. 1: Two- Bus Power System Model [5]

P_i, Q_i = Active and reactive power on the Sending Bus
S_i, S_j = Apparent power on the Sending and Receiving Bus

The line that gives index value closest to 1 will be the most critical line of the bus and may lead to system wide instability scenario. This index can also be used to determine the weakest bus on the system. The determination of the weakest bus is based on the maximum load allowed on a load bus. The most vulnerable bus in the system corresponds to the bus with the smallest maximum permissible load.

B. Determination of Maximum Loadability at load bus

The process of maximum loadability estimation at each load bus is conducted by looking at the variation of real and reactive power loading with load flow analysis using PSSE tool. FVSI values are computed utilizing the load flow solutions at each load flow cycle. A template in Microsoft Excel is configured in order to perform the FVSI calculations for the buses. Basically, the algorithm for the maximum loadability estimation is given in the following procedural steps:

i. Performed load flow analysis using Newton-Raphson technique for base case.
ii. Evaluate the *FVSI* value for every line in the system.
iii. Gradually increase the reactive power loading at a chosen load bus until one of the connecting lines has *FVSI* value close to 0.95.
iv. Extract the line with *FVSI* value close to 0.95, this line is called as the most sensitive line with respect to a bus.
v. Choose other load bus and repeat steps i to iv.
vi. Extract the maximum reactive power loading (Q_{max}) at *FVSI* = 0.95 for each tested bus i.e., when the sensitive line referred to a bus gives an *FVSI* value close to 0.95.
vii. Sort the maximum loadability (Qmax) obtained from step vi in ascending order. The smallest maximum loadability is ranked the highest implying the weakest bus in the system.

The whole process for maximum loadability estimation and the determination of weak load bus are represented in the flowchart in Fig. 2.

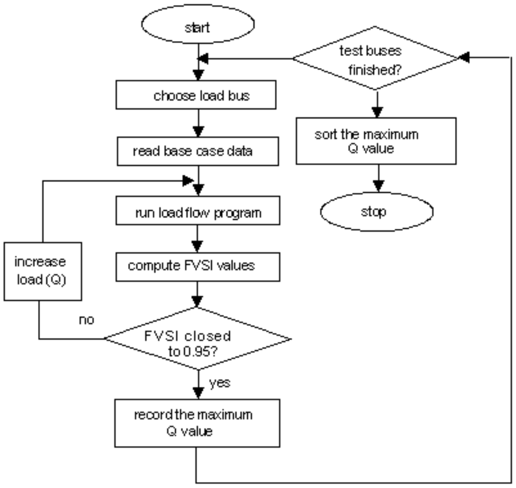


Fig. 2: Flowchart for maximum loadability estimation and determination of weak load bus.

From the implemented procedures above, the results of maximum loadability for each load bus can be used to rank the weak load bus of the system by sorting the value of maximum loadability for each bus in ascending order. The bus which has smallest value of maximum loadability is identified as the weakest bus.

C. Identication of Critical Bus in the 793 Test Bus System

FVSI index was evaluated for the test bus system. The test bus systems were categorized to three main areas based on geographical location. The areas are:

- Area1
- Area 2
- Area 3

Generally, high FVSI value indicates critical busses in a base case. FVSI value of the base case was used as a point of reference for the other contingency scenarios.

D. Contigency Scenarios for the 793 Test Bus System

The following scenarios were created to analyze the system.

a) Transmission line stressed

The load demand is increased gradually from 1% up to 7% in Area 1, Area 2 and Area 3. The transmission line was stressed until the system does not converge and for this system, the verge of instability is at maximum loading of 7%.

b) Load shedding analysis

Loads that are placed near and further from the critical busses indentified in a) was shed.

c) QV analysis

QV analysis was carried for Area 1, Area 2 and Area 3 to investigate and verify the correlation between FVSI and reactive power flow.

d) Single load stressed

This test and simulation is done in order to push the tested points in the network to achieve maximum reactive power (Q) flow in the branch tested. For this test, Bus 1662 and Bus 2466, which are among the critical buses in Area 1, are selected and the reactive power demand of the system was increased. The FVSI is then computed for this case

e) Multiple contingency

To further stress the large system and to analyze the FVSI index, multiple contingency were carried out. This contingency includes generation outage, transmission line outage and load demand increase. Bus 2752 which is a critical bus in Area 1 and has interconnections with other critical buses such as Bus 1752, Bus 2342, Bus 2436 and Bus 2467 is selected for analysis and observation.

f) Appropriate location to load shed

FVSI index can also be used to indicate suitable location to be load shed. FVSI index was computed for different locations of load shed and comparison was carried out.

All the results obtained for the scenarios described above are presented in the following section.

III. RESULTS AND ANALYSIS

FVSI value was computed for all the scenarios explained above. Sample of results for each case is presented here.

A. FVSI For Base Case

Simulations done for base case indicate that the test system is stable due to very low FVSI values. The FVSI results for base case were used for comparison purpose for all other cases analyzed. The sample of the FVSI calculation for base case is as shown in TABLE I.

TABLE I
FVSI CALCULATION FOR BASE CASE

From Bus No	To Bus No	MVAR(p.u)	VOLTAGE	Z	FVSI
19		MVAR(p.u)	1.0331		
	1106	0.139		0.005668	0.00299441
	1294	0.024		0.014949	0.00136365
	1440	0.163		0.008033	0.00497675
20		MVAR(p.u)	1.0325		
	1107	0.22		0.005668	0.00474487
	1294	0.005		0.014949	0.00028442
	1440	0.215		0.008033	0.00657205
25		MVAR(p.u)	1.0426		
	40	0.116		0.001491	0.00064563
	1128	0.176		0.019391	0.01273637
	1236	0.06		0.000257	5.8376E-05
26		MVAR(p.u)	1.0401		
	1238	0.008		0.003143	9.4278E-05
	1238	0.008		0.003143	9.4278E-05
	1408	0.05		0.081213	0.01522684
	1580	0.034		0.001419	0.00018075

It can be observed that the FVSI value does not exceed 0.1 for all the 793 buses for the system in base case.

B. FVSI for Transmission Line Stressed

In the simulation, the load demand in Area 1 is increased gradually to 2% from base case by taking into consideration of the machine limits. Generations at Bus 1436 (one of major generator bus in Area 1) were adjusted to honour the machine limit of the stressed system. As expected, the corresponding FVSI value increases due to increase in real and reactive power demand. The FVSI values for the system are at the highest as compared to the base case. Bus 1226 is selected for analysis due to high FVSI value observed in the Base Case and also in the stressed case. Bus 1226 is also interconnected to many other buses. It can be said that this particular bus has heavy interconnections. In general, it was observed that some buses were experiencing increase in the FVSI value when the system is stressed. This is due to the nature of the system, where the load flow is adjusted accordingly in the overall large system. The sample results for Bus 1226 are shown in TABLE II.

It can be clearly seen that FVSI value at Bus 1226 decreases, indicating the stability of the system improves when load is shed at Bus 1860. It can be concluded that Bus 1860 is the appropriate location for the UVLS relay placement for Bus 1226.

TABLE II
FVSI CALCULATION FOR STRESSED CASE

From Bus No	To Bus No	FVSI BASE CASE	FVSI STRESSED	% Difference
1226				
	LOAD-P			
	1130	0.000152638	0.000174676	14.43827684
	1130	0.000152638	0.000174676	14.43827684
	1458	0.004000776	0.004144259	3.586371281
	1459	0.004000776	0.004144259	3.586371281
	2226	0	0	0
	2226	0	0	0
	2226	0	0	0

TABLE III
FVSI CALCULATION FOR STRESSED CASE AFTER LOAD SHED

From Bus No	To Bus No	FVSI (Load shed)	FVSI STRESSED	% Difference
1226				
	LOAD-P			
	1130	0.000173913	0.000174676	0.437033347
	1130	0.000173913	0.000174676	0.437033347
	1458	0.00408685	0.004144259	1.385252077
	1459	0.00408685	0.004144259	1.385252077
	2226	0	0	0
	2226	0	0	0
	2226	0	0	0

* Note that positive percentage difference in TABLE III indicates the FVSI values decreases from the stressed case after load is shed at Bus 1860.

Generally load shed is carried out at location near to critical busses in a particular area. This is because load shedding at a bus that is located further from the critical area in a large system only shows minimal improvement to the FVSI value and the overall system stability. Thus, in order to secure a bulk system from voltage collapse, some loads needs to be shed nearby the critical area in order to prevent the wide spread effect of voltage collapse and wide system blackout.

D. QV analyses

QV analyses were done for all the three main regions. It is observed that the reactive power margin decreases as the system become more stressed. As an example, QV curves were plotted for Bus 1226 Area 1. In the base case, the particular bus has the most the reactive power margin. The reactive power margin decreases drastically when the system is stressed and it improves when load is shed at Bus 1860. The QV curves obtained are shown in Fig. 3a, Fig. 3b and Fig. 3c. Table IV shows the reactive power and FVSI for all the three main areas.

In Fig. 3a, the QV curve for base case intercept the 1.00 p.u at reactive power of -175.95MVAR while for stressed case the QV curve intercepts at reactive power of -164.93 MVAR. Load shedding has improved the QV curve where the intercept takes place at reactive power of -180.12 MVAR. It can be observed from Table IV that FVSI value increases when the system is stressed and improves when load shed is carried out on the stressed system. This correlates perfectly with the QV curves plotted.

TABLE IV
FVSI CALCULATION FOR BASE CASE, STRESSED CASE AND AFTER LOAD SHED

Area	Case	Base Case	Stressed Case	Stressed Case after Load Shed
Area1	Reactive Power (Q, MVAR)	-175.95	-164.93	-180.12
	FVSI	0.0039	0.0043	0.0042
Area2	Reactive Power (Q, MVAR)	3.3	7.29	5.15
	FVSI	0.11184	0.1247	0.124
Area3	Reactive Power (Q, MVAR)	-139.11	-125.07	-132.45
	FVSI	0.0051	0.0065	0.0062

E. Single Load Stressed

Results are shown in Table V and Table VI. The following summarises the findings:

- Based upon TABLE V, the following values for "From bus 1662 to bus 1780" is observed:

  Voltage = 0.4726 pu
  MVAR flow = 338.9 MVAr
  FVSI = 0.236301084

- Based upon TABLE VI, the following values for "From bus 2466 to bus 2752" is observed:

  Voltage = 0.7724 pu
  MVAR flow = 1200.6 MVAr
  FVSI = 0.25982712

Based upon this test, it is observed that increasing Q demand at the test branch does promote very high Q flow. This would further increase the FVSI index although its increase is still not considered to be high if compared to "IEEE 30" test bus system simulation cases. From here and looking back at the FVSI formulation, the main reason for this low values is due low impedances of lines. When comparing this test system with the "IEEE 30" test bus system, it is found that the branch impedances are relatively small.

F. FVSI for Multiple Contingency

FVSI value observed for all the cases above are very small compared to values that are obtained for "IEEE 30" test bus system in specific. (Earlier simulations were carried on IEEE 30 Bus Test System). Therefore, multiple contingency were carried out at Bus 2752. Bus 2752 has among the highest FVSI value in this large test system.

TABLE V
FVSI RESULTS FOR LOAD INCREASE AT BUS 1662 (MONITORING CONNECTIONS FROM BUS 1662 TO BUS 1780)

From Bus No	To Bus No	MVAr (pu)	Voltage	Z	FVSI Stressed	FVSI at Base
1662			**0.4726**			
	LOAD-P	5.615		0		
	1144	0.201		0.002045	0.007563028	0.001964
	1200	0.103		0.00253	0.004798818	0.001111
	1663	0		0.0001	0	0
	1780	3.389		0.001367	**0.236301084**	**0.00367**
	2662	2.529		0		

TABLE VI
FVSI RESULTS FOR LOAD INCREASE AT BUS 2466 (MONITORING BUS 1466, BUS 2662 AND BUS 2752)

From Bus No	To Bus No	MVAr (pu)	Voltage	Z	FVSI Stressed	FVSI at Base
2466		0	**0.7724**	0		
	1466	4.461		0		
	1466	4.461		0		
	1466	4.461		0		
	2662	1.376		0.000532	0.004933077	0.000575
	2752	12.006		0.003204	**0.25982712**	**0.008993**

TABLE VII
FVSI RESULTS FOR MULTIPLE CONTINGENCY CREATED AT BUS 2752 WITH SHUNT CAPACITORS IN AREA 1 ARE SWITCHED OFF

From Bus No	To Bus No	MVAR(p.u)	Voltage	FVSI
2752			0.9558	
	1752	0.265		
	1752	0.265		
	1752	0.265		
	2342	3.32		0.07183249
	2436	2.007		0.04342404
	2436	2.007		0.17583812
	2467	6.541		0.91164649

- Contingency 1 were created as below:
  - Generation at Bus 2298 is out of service
  - Shunt Capacitors in Area 1 OFF
  - One transmission line outage from Bus 2752 to Bus 2467
  - One transmission line outage from Bus 2342 to Bus 2752.
  - Load MVar increased for Bus 2466 (50 Mvar) and Bus 1780 (20Mvar)

It can be seen clearly that for a large system, multiple contingency is needed to make the FVSI value to reach close to 1. TABLE VII shows the simulation result when the shunt capacitors were switched off.

- Contingency 2 were created as below:
  - *Generation at Bus 2298 is out of service*
  - *Shunt Capacitors in Area 1 ON*
  - *One transmission line outage from Bus 2752 to Bus 2467*
  - *One transmission line outage from Bus 2342 to Bus 2752.*
  - *Load MVar increased for Bus 2466 (50 Mvar) and Bus 1780 (20Mvar)*

It was observed that the system voltage is improved when the shunt capacitors in Area 1 were switched on. FVSI value also decreases. Table VIII shows the simulation result when the shunt capacitors were on.

TABLE VIII
FVSI RESULTS FOR MULTIPLE CONTINGENCY CREATED AT BUS 2752 WITH SHUNT CAPACITORS IN AREA 1 ARE SWITCHED ON

From Bus No	To Bus No	MVAR(p.u)	Voltage	FVSI
2752			0.9917	
	1752	0.001		
	1752	0.001		
	1752	0.001		
	2342	3.138		0.063068
	2436	1.292		0.025967
	2436	1.292		0.105148
	2467	5.725		0.741193

G. Appropriate Location to Load Shed

The following illustrates an example of optimising load shed scenarios using high FVSI values. For this case, Bus 2752 is found to have high FVSI values. The following looks into UVLS relay locations and the determination of the best load shed strategy for that particular bus. Note that these simulations are whilst monitoring interconnection for Bus 2752 values.

a) Load Shed at Bus 1260

Table IX tabulates the results for FVSI value for interconnections to bus 2752 with bus 1260 load shed.

b) Load Shed at Bus 1260, Bus 1860 and Bus 1790

Referring to the FVSI values presented before and after load shed (Table IX, Table X, Table XI, Table XII), it is observed that load shedding at Bus 1260 is seen present the best possible solution.

TABLE IX
FVSI INDEX FOR INTERCONNECTIONS TO BUS 1752 WITH BUS 1260 LOAD SHEDDED

From Bus No	To Bus No	MVAR (p.u.)	Voltage (p.u.)	FVSI_Load Shed	FVSI_ Stressed
1752			1.0438		
	1261	0.273		0.001916	0.003508
	1261	0.273		0.001916	0.003508
	1522	0.364		0.005335	0.000271
	1522	0.364		0.005335	0.000271
	2752	0.061	1		
	2752	0.061	1		
	2752	0.061	1		

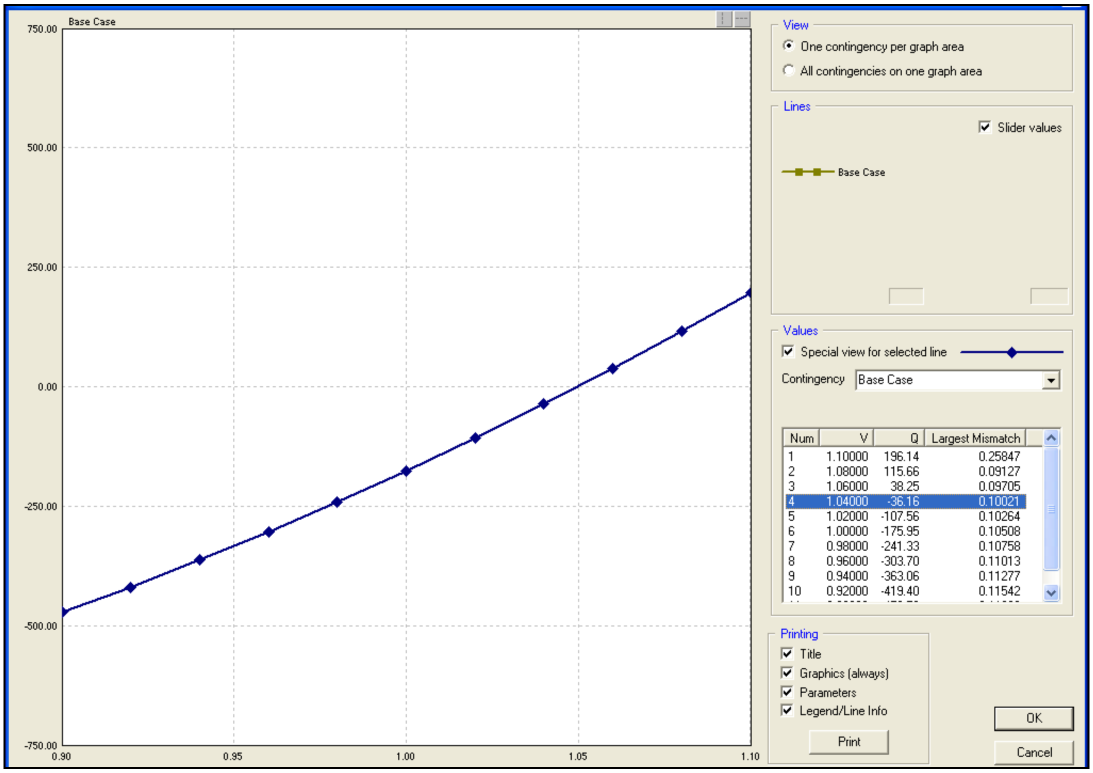
TABLE X
FVSI VALUE FOR INTERCONNECTIONS TO BUS 2752 WITH BUS 1260 LOAD SHEDDED

From Bus No	To Bus No	MVAR (p.u.)	Voltage	FVSI_Load Shed	FVSI_ Stressed
2752			1.0294		
	1752	0.021	0.9633		
	1752	0.021	0.9633		
	1752	0.021	0.9633		
	2342	0.243		0.004533	0.016654
	2342	0.243		0.004533	0.016654
	2436	0.034		0.002568	0.041819
	2466	0.293		0.00357	0.009522
	2467	0.222		0.002705	0.007751
	2956	0.059		0.004456	0.03956

TABLE XI
FVSI INDEX FOR INTERCONNECTIONS TO BUS 1752 WITH BUS 1260, BUS 1860 AND BUS 1790 LOAD SHEDDED

From Bus No	To Bus No	MVAR (p.u.)	Voltage	FVSI_Load Shed	FVSI_ Stressed
1752			1.0553		
	1261	0.272		0.001868	0.003508
	1261	0.272		0.001868	0.003508
	1522	0.501		0.007184	0.000271
	1522	0.501		0.007184	0.000271
	2752	0.153	1		
	2752	0.153	1		
	2752	0.153	1		

Although load shedding at these area (Bus 1260, Bus 1860 and Bus 1790) improves the load point FVSI value, but load shedding in these area increase the FVSI value for lines from Bus 1752 to Bus 1522 whilst improving the FVSI value on the 275kV interconnection. Hence load shedding at Bus 1260 is chosen because not only it improves the FVSI value on the 275kV interconnection, it also minimizes the increase of



● One contingency per graph area
○ All contingencies on one graph area
☑ Slider values
☑ Special view for selected line
Contingency: Base Case

Num	V	Q	Largest Mismatch
1	1.10000	196.14	0.25847
2	1.08000	115.66	0.09127
3	1.06000	38.25	0.09705
4	1.04000	-36.16	0.10021
5	1.02000	-107.56	0.10264
6	1.00000	-175.95	0.10508
7	0.98000	-241.33	0.10758
8	0.96000	-303.70	0.11013
9	0.94000	-363.06	0.11277
10	0.92000	-419.40	0.11542

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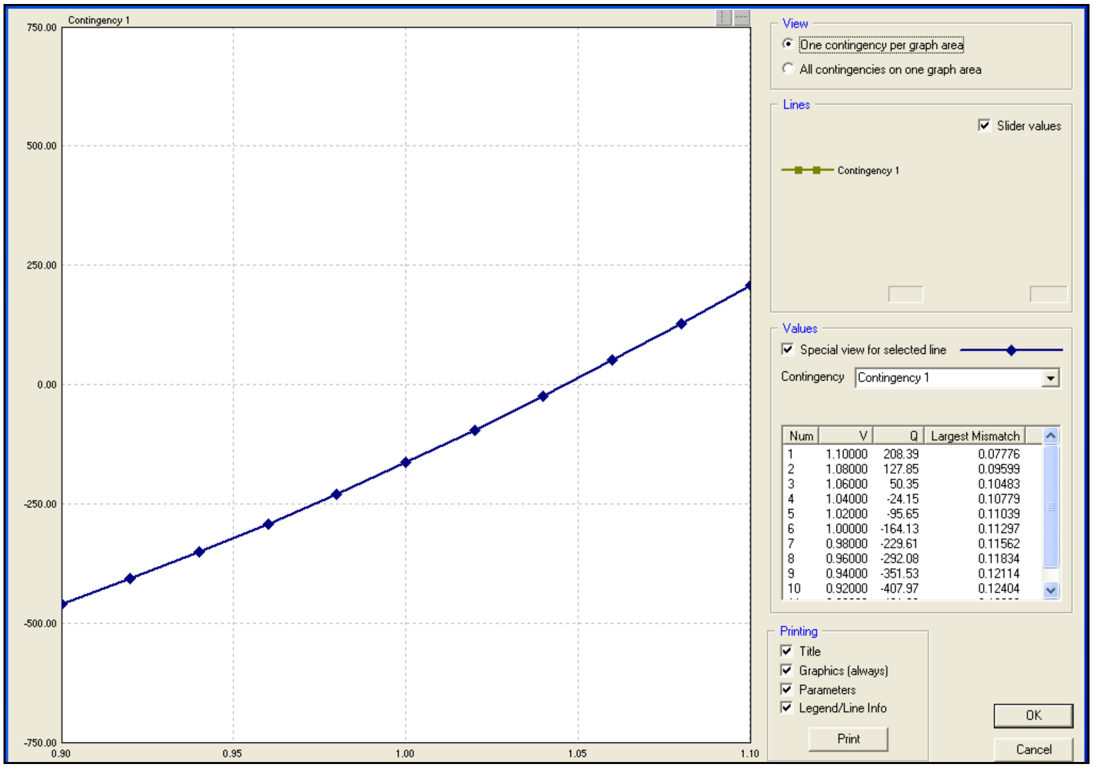
Fig. 3a: QV curve for Bus 1226 in Area 1(base case)



● One contingency per graph area
○ All contingencies on one graph area
☑ Slider values
☑ Special view for selected line
Contingency: Contingency 1

Num	V	Q	Largest Mismatch
1	1.10000	208.39	0.07776
2	1.08000	127.85	0.09599
3	1.06000	50.35	0.10483
4	1.04000	-24.15	0.10779
5	1.02000	-95.65	0.11039
6	1.00000	-164.13	0.11297
7	0.98000	-229.61	0.11562
8	0.96000	-292.08	0.11834
9	0.94000	-351.53	0.12114
10	0.92000	-407.97	0.12404

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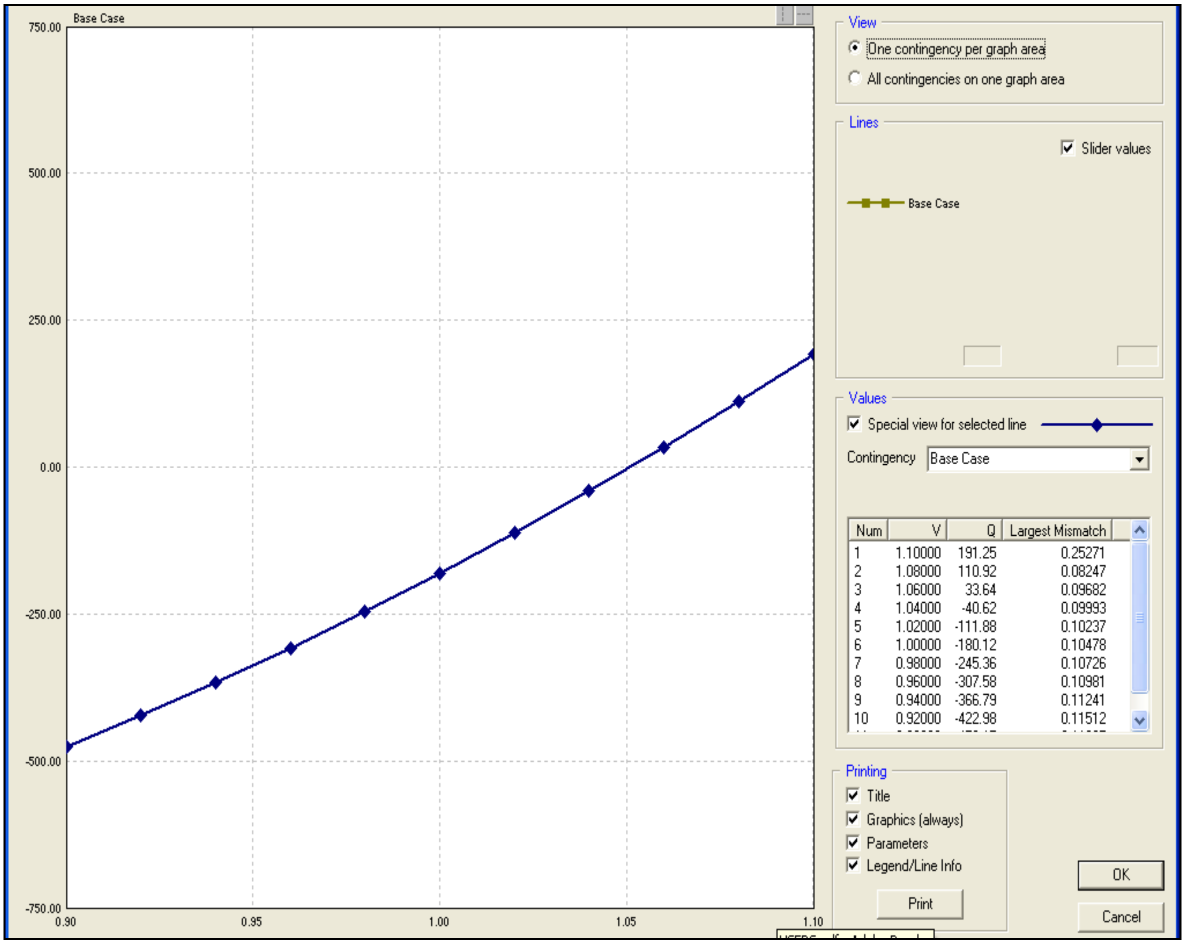
☑ Parameters
☑ Legend/Line Info

Fig. 3b: QV curve for Bus 1226 in Area 1(stressed case)



View
● One contingency per graph area
○ All contingencies on one graph area

☑ Slider values

Values
☑ Special view for selected line

Contingency: Base Case

Num	V	Q	Largest Mismatch
1	1.10000	191.25	0.25271
2	1.08000	110.92	0.08247
3	1.06000	33.64	0.09682
4	1.04000	-40.62	0.09993
5	1.02000	-111.88	0.10237
6	1.00000	-180.12	0.10478
7	0.98000	-245.36	0.10726
8	0.96000	-307.58	0.10981
9	0.94000	-366.79	0.11241
10	0.92000	-422.98	0.11512

Printing
☑ Title
☑ Graphics (always)
☑ Parameters
☑ Legend/Line Info

Fig. 3c: QV curve for Bus 1226 in Area 1(after load shed case)

recursive load flow to optimize load shed strategy to improve FVSI value during stressed conditions.

TABLE XII
FVSI INDEX FOR INTERCONNECTIONS TO BUS 2752 WITH BUS 1260, BUS 1860 AND BUS 1790 LOAD SHEDDED

From Bus No	*To Bus No*	*MVAR (p.u.)*	*Voltage*	*FVSI_Load Shed*	*FVSI_ Stressed*
2752			1.0347		
	1752	0.101	0.9633		
	1752	0.101	0.9633		
	1752	0.101	0.9633		
	2342	0.116		0.002142	0.016654
	2342	0.116		0.002142	0.016654
	2436	0.037		0.002766	0.041819
	2466	0.284		0.003425	0.009522
	2467	0.214		0.002581	0.007751
	2956	0		0	0.03956

H. Variation of FVSI Value for Large Power System

Based upon the results shown, it can be seen that FVSI values for the large system will not reach a high index value (close to 1) even though the system is already stressed. This value can only be reached if multiple contingency is carried out. The following list down the reasons to this:

- FVSI value is not high in large system due to multiple load increase in the system which is interconnected. Hence the branch may not be able to reach maximum reactive power, Q.
- The system has low impedance as most of the lines are short and connected in radial.
- Apart from that it is found that this large test system can be considered to be a voltage stable system if looking from load increase point of view. This is because the only way to collapse the system is to create multiple contingencies after the system is already stressed.

I.CONCLUSION

Simulation studies conducted to the system shows that an FVSI index increases as the system becomes stressed. Although the FVSI value obtained is very small compared to the value of 1(critical bus) but it gives a clear indication of critical busses whereby the FVSI value is relatively higher at the critical buses. Simulation results also verify that the FVSI value improves after load is shed. The clearly indicates that FVSI index can be used as an indicator for Under Voltage Load Shedding (UVLS) relay placement in a bulk power system network.

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I.BIOGRAPHIES

Dr. Agileswari Ramasamy, was born in 1974 in Perak, Malaysia. She received her BSc in Electrical Engineering from Purdue University U.S.A in 1999, MSc in Control System from Imperial College, UK in 2001 and PhD in Electrical Engineering from Universiti Tenaga Nasional (UNITEN), Malaysia in 2008 in Electrical Engineering. Dr. Agileswari is currently a Senior Lecturer in the Department of Electronics and Communication Engineering at UNITEN in Malaysia. Dr. Agileswari is a Graduate Member of the Institution of Electrical Engineers (IET). Her field of interest includes Power Quality, Power System Stability and control system.

Renuga Verayiah was born in 1980 in Perak, Malaysia. She received her B. Eng. (Hons). in Electrical & Electronics Engineering from Universiti Tenaga Nasional (UNITEN), Malaysia in 2002 and M. Eng in Electrical Engineering from Universiti Tenaga Nasional (UNITEN), Malaysia in 2008. Renuga Verayiah is currently a Lecturer in the Department of Electrical Power Engineering at UNITEN in Malaysia. Renuga Verayiah is a Graduate Member of the Institution of Electrical Engineers (IET). Her field of interest includes Power System Stability, Voltage Collapse Study and Control System.

Dr. Izham Zainal Abidin received his Bachelor in Electrical Engineering degree from Southampton University, UK in 1997. He obtained his PhD in Electrical Engineering from the University of Strathclyde, Scotland, UK in 2002. Currently, he is an academic staff at Department of Electrical Power Engineering, Universiti Tenaga Nasional Malaysia. His research interests include voltage stability studies, artificial intelligence and fuzzy logic application to Power Systems problems, and robotics

Dr. Ismail Musirin obtained Diploma of Electrical Power Engineering in 1987, Bachelor of Electrical Engineering (Hons) in 1990; both from Universiti Teknologi Malaysia, MSc in Pulsed Power Technology in 1992 from University of Strathclyde, United Kingdom and PhD in Electrical Engineering in 2005 from Universiti Teknologi MARA, Malaysia. He is currently an Associate Professor and Deputy Dean Research and Industrial Networking at the Faculty of Electrical Engineering, Universiti Teknologi MARA, Shah Alam, Malaysia. He has published 2 books and more than 100 technical papers in the international and national, conferences and journals. He is a reviewer for the IEEE Transaction of Power System, IEEE Transaction of Energy Conversion, IEEE Transaction of Power Delivery and, WSEAS Transaction and conferences. His research interest includes power system stability, optimization techniques, distributed generator, biological computing, computational intelligence and artificial intelligence.

Azlan Abdul Rahim received his Bachelor in Electrical & Electronic Engineering from University Science of Malaysia in 1996. Currently, he is a senior researcher at Power System Group, TNB Research Sdn. Bhd. His research areas include dynamic thermal ratings of electrical equipment, power system wide area measurement, fault detection and location.