Impact of SVC and DG on Voltage Stability Constrained Available Transfer Capability

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***Abstract*— The transmission system loadability is mainly dependent on reactive power support in the system. The imbalance between reactive power generation and consumption in the system causes to voltage drooping in the entire system. This phenomenon will further increase under heavily loaded conditions as well as contingency conditions. In order to avoid blackouts due to lack of reactive power support, most of the current power systems are integrating the emerging technologies like Flexible Ac Transmission Systems (FACTS) devices and Distributed Generation (DG) systems. This paper is addressing the impact of Static Var Compensators (SVC) and Distributed Generation (DG) on Available Transfer Capability (ATC). Using repeated power flow (RPF), the Voltage Stability Constrained Available Transfer Capability (VSATC) has been improved. The case studies are performed on IEEE–14 bus test system and the results are validating the proposed approach for stability margin enhancement in real time applications.**

***Keywords*— Voltage Stability, VSATC, FACTS, DG, RPF**

I. INTRODUCTION

Recent large-scale power system blackouts due to voltage instability, in the worldwide have given us a "wake-up" call on the need of reactive power reserve in the system. The literature on system blackouts due to voltage instability can be found in [1-3]. The investigation report on 2012 INDIA blackout [4] has been quoted as "In order to avoid frequent outages/opening of lines under over voltages and also providing voltage support under steady state and dynamic conditions, installation of adequate static and dynamic reactive power compensators should be planned" and "Intra-State transmission system needs to be planned and strengthened in a better way to avoid problems of frequent congestion". This is an indication of the need of the 'new technologies' for the integration of the system.

The deregulated and competitive energy market systems are also subjected to the increased economic inefficiency due to congestion. The remedial actions for congestion in the network can be found in [5-8]. The literature review has strongly pronounced the need of integration to technical as well as economical benefits of the system with FACTS devices and DG integration to the systems. The impact of FACTS devices on voltage instability in competitive energy market oriented systems can also be addressed in [9]. A novel approach for voltage stability enhancement with adequate corrective actions has been addressed in [10]. The SVC impact can be found on voltage collapse/instability in [11, 17], maximum loadability in [12, 15] and ATC in [13].

The economic schedule in liberalized market environment with DG can be found in [14]. The major advances due to DG systems can also be found in [16]. Keeping all these works in view, this paper has proposed a novel approach for voltage stability enhancement with distributed slack bus (DSB) concept in addition to the FACTS and DG applications at weak buses.

This paper is organized as follows: Following the introduction (section I), distributed slack bus concept is explained briefly in Section II in which the evolution of voltage stability constrained available transfer capability is also presented using repeated power approach. The mathematical modelling of SVC and DG is given in Section III. Then, in section IV, different case studies are carried out and simulation results are discussed briefly. Finally, brief conclusions are made in the section V.

II. DISTRIBUTED SLACK BUS CONCEPT

The scheduling of generators while calculating voltage stability margin should be a considerable issue since the power flow in the network is mainly dependent on residual powers at each bus. The traditional approach to meet excessive load in the system is by slack bus concept or any specified generator bus in voltage stability margin calculations. In this model, if the interface between slack bus and the rest of the network should carry required power balance while increasing the load on system, it causes to more losses as well as reactive power generation.

The reactive power limits at slack bus can also one of the constraints to Newton-Raphson power flow divergence. This can be suppressed by increasing the generation at all generator buses and leads to more loadability on the system in addition to loss minimization as well as voltage drooping nature. In the proposed approach, the adopted Generation Participation Factor (GPF) from [17] is defined as the ratio between the maximum generation limit of a particular bus to the total plant installed capacity i.e. the addition of all the generators' maximum capacities. Mathematically,

$$GPF_i = \frac{P_{g,i}^{\max}}{\sum_{i=1}^{NG} P_{g,i}^{\max}} \tag{1}$$

where NG is the number of generator buses and $P_{g,i}^{\max}$ is the maximum power of the i^{th} generator bus.

1) The energy balance condition

$$P_G = P_D \tag{2}$$

$$P_G = \sum_{i=1}^{NG} P_{g,i} \tag{3}$$

$$P_D = \sum_{i=1}^{NB} P_{d,i} \tag{4}$$

where NB = no. of buses.

2) Load Up-gradation

$$P_{d,i}^{new} = P_{d,i}^{base} + \Delta P_{d,i} = (1+\lambda) P_{d,i}^{base} \tag{5}$$

$$\Delta P_{d,i} = \lambda \times P_{d,i}^{base} \tag{6}$$

$$P_D^{new} = \sum_{i=1}^{NB} P_{d,i}^{new} \tag{7}$$

3) New Generation Schedule

$$P_{g,i}^{new} = P_{g,i}^{old} + \Delta P_{g,i} \tag{8}$$

$$\Delta P_{g,i} = GPF_i \times \Delta P_D \tag{9}$$

$$\Delta P_D = P_D^{new} - \sum_{i=1}^{NB} P_{d,i}^{base} \tag{10}$$

4) Maximum Loading Capability

$$MLC = P_D^{cri} - P_D^{base} \tag{11}$$

$$P_D^{cri} = (1+\lambda^{cri}) P_D^{base} \tag{12}$$

In the above approach, the loading parameter will be increased till the NR method fails to converge [18] and at this condition, the loadability is treated as voltage stability constrained available transfer capability (VSATC) or critical loading margin of the system. The important note is that, this margin is mainly dependent on the increment of type of load, i.e. only real power increment, only reactive power increment or combination. In general, the combined real and reactive power increment will be employed in the literature.

III. Static Modelling of SVC and DG

A. SVC Modelling [19]

At stable operating conditions, the shunt compensator SVC can be considered simply as a static capacitor/reactor. It is modeled as an ideal reactive power injection/withdrawal at bus *p*. The range of injected VAR with SVC is taken as [0, 100]. The modified residual reactive power at the SVC installed load bus is given by

$$\Delta Q_p = \left\{ \left(Q_{p,g} - Q_{p,d} \right) - Q_p^{cal} \right\} + Q_{svc,p} \tag{13}$$

B. DG Modelling [20]

The DG is simply a generator which can produce a minimum of 5MW real power to distribute locally.

In this approach, the load bus which is opted for DG installation, is modified as a PV bus and its reactive power limits are considered as [-50, 50]. The 100 MW power is considered as its maximum real power capacity. If the DG is met 100 MW load on the system, the remaining load is shared to all the generators as explained in previous section.

IV. CASE STUDIES & DISCUSSIONS

The IEEE–14 bus test system [21] has been considered for case studies. The list of maximum generation limits of the generators and their respective generation participation factors (GPF) are tabulated in Table-I. According to these factors, the schedules are also given for a total load of 259 MW. The base case with this schedule is suffered with a real power loss of 4.534 MW.

TABLE I
GENERATION SCHEDULE FOR BASE CASE

Gen #	Capacity (MW)	GPF	Generation (MW)
1	332.4	0.430347	111.4599
2	140.0	0.181253	46.94459
3	100.0	0.129467	33.53185
4	100.0	0.129467	33.53185
5	100.0	0.129467	33.53185

The critical loading margin has been determined by increasing the load with a constant power factor at all the buses and the excessive load from base case is shared among all the generators according to their GPF. The NR method fails to converge at a loading factor of 4.866. At this case, the load bus 14 is subjected to minimum voltage of 0.543 p.u. The new real and reactive power generations at all the buses can be observed in Table II.

In order to understand more clearly the concept of DSB, the critical loading margin is also computed by traditional slack bus concept. In this approach, the entire excessive load will be compensated at only one generator bus. Still the loss will be met by actual slack bus only. For various choices of generator buses, the critical loading parameter has been changed and the corresponding generation schedules are given in Table III - VII. The constrained load bus which is subjected to minimum voltage under NR method fails to converge is also mentioned. From this, we can conclude that the critical load bus in the system is bus-14 and is best suitable for SVC as well as DG installation.

From all the above case studies, the critical loading parameter is high when the load is shared among all the generators. So in the following case studies, the impact of SVC and DG is also observed on the loading margin.

A. *Impact of SVC at Bus-14*

When SVC is at 14, the voltage profile has been increased and simultaneously at bus 10, it is decreased rapidly and the result has been given in Table VIII.

B. *Impact of SVC at Bus-14 and DG at Bus-10*

In the above case study, the ATC was limited due to bus 10. Hence, the DG is placed at bus 10 with 100 MW. The loading margin is increased significantly and the result has been given in Table IX.

TABLE II
GENERATION SCHEDULE WHEN $\lambda^{cri} = 4.866$

Gen #	1	2	3	4	5
P_{gen}	757.278	228.432	163.166	163.166	163.166
Q_{gen}	110.176	308.618	309.265	295.639	186.994

TABLE III
GENERATION SCHEDULE WHEN $\lambda^{cri} = 4.128$
SOURCE BUS: GEN # 1, CRITICAL LOAD BUS: 14 (0.624 P.U)

Gen #	1	2	3	4	5
P_{gen}	1482.619	46.9446	33.5319	33.5319	33.5319
Q_{gen}	377.416	1005.227	490.974	398.372	162.569

TABLE IV
GENERATION SCHEDULE WHEN $\lambda^{cri} = 4.284$
SOURCE BUS: GEN # 2, CRITICAL LOAD BUS: 14 (0.596 P.U)

Gen #	1	2	3	4	5
P_{gen}	449.888	897.501	33.53185	33.53185	33.53185
Q_{gen}	225.389	428.319	524.225	399.712	167.793

TABLE V
GENERATION SCHEDULE WHEN $\lambda^{cri} = 4.468$
SOURCE BUS: GEN # 3, CRITICAL LOAD BUS: 14 (0.559 P.U)

Gen #	1	2	3	4	5
P_{gen}	318.069	46.94459	931.774	33.53185	33.53185

Q_{gen}	179.659	310.749	169.129	386.217	173.189

TABLE VI

GENERATION SCHEDULE WHEN $\lambda^{cri} = 3.434$

SOURCE BUS: GEN # 4, CRITICAL LOAD BUS: 14 (0.515 P.U)

Gen #	1	2	3	4	5
P_{gen}	293.243	46.94459	33.53185	663.938	33.53185
Q_{gen}	98.314	126.535	237.647	373.233	132.593

TABLE VII

GENERATION SCHEDULE WHEN $\lambda^{cri} = 2.154$

SOURCE BUS: GEN # 5, CRITICAL LOAD BUS: 7 (0.807 P.U)

Gen #	1	2	3	4	5
P_{gen}	141.758	46.94459	33.53185	33.53185	332.418
Q_{gen}	111.99	111.885	104.777	120.813	272.854

TABLE VIII

GENERATION SCHEDULE WHEN $\lambda^{cri} = 5.567$

SOURCE BUS: ALL GENERATORS, CRITICAL LOAD BUS: 10 (0.653 P.U)

Gen #	1	2	3	4	5
P_{gen}	910.976	261.340	186.672	186.672	186.672
Q_{gen}	144.355	451.203	392.564	282.999	210.121

TABLE IX

GENERATION SCHEDULE WHEN $\lambda^{cri} = 7.219$

SOURCE BUS: ALL GENERATORS, CRITICAL LOAD BUS: 5 (0.717 P.U)

Gen #	1	2	3	4	5
P_{gen}	1381.618	320.767	229.120	229.120	229.120
Q_{gen}	320.819	1008.026	693.996	247.793	182.533

V. CONCLUSION

In this paper, Distributed Slack Bus Concept is used and the loading parameter is increased till the NR method fails to converge. SVC is considered simply as a static capacitor/reactor and is modeled as an ideal reactive power injection/withdrawal at bus *p*. The DG is considered as to produce a minimum of 5MW real power to distribute locally and a maximum of 100MW.In this approach, the load bus which is opted for DG installation, is modified as a PV bus.

And the IEEE-14 bus is considered as a test case and it is of maximum generation limits of the generators and their respective generation participation factors (GPF) are tabulated in Table-I. The constrained load bus is found out by subjecting it to minimum voltage under NR method till it fails to converge. From this, it is concluded that the critical load bus in the system is 14 and is best suitable for SVC as well as DG installation.

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