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An Optimal Location of SVC in Power Market

Prof S.Srikanth A.Ramanjaneyulu

Abstract**—** In deregulated power systems participants take their decisions independently. They change their strategies frequently to acquire more information from the market to maximize their benefits. Consumers adjust their loads according to the price signals. Availability of independent power producers is uncertain. Wheeling powers are time varying and affect the nodal prices of the control areas that they pass through. Transmission expansion planning is not coordinated with generation expansion planning. Hence, there is not a specified pattern for load and dispatched power in deregulated power systems. Due to these uncertainties the network is operating closer to critical point in deregulated environments. Therefore, the preventive and corrective control actions for system security are become essential and these can discharge effectively with var supporting devices.

In this paper, the conventional power flow methods are used to determine the proximity to voltage instability and Static VAR Compensator (SVC) is incorporated at critical buses for var support. The optimal location of SVC is determined by voltage rise factors (VRF) and loss fall factors (LFF). The case study is carried out on IEEE 6 bus test system.

Index Terms**—** Voltage Instability, Total Transfer Capability, Available Transfer Capability, Voltage and Loss Benefit Factors, SVC

I. INTRODUCTION

IN a bilateral contract model, the transactions may take place directly between selling and buying entities. These transactions may be in the form of firm power contract or non firm power contracts and they are defined for a particular time interval of the day and its value may be time varying. This model may include different kinds of transactions such as bilateral transactions, multilateral transactions and ancillary services [1-3]. Under this scenario, i.e. *open access power market* the power systems are becoming more vulnerable to operating limit violation and voltage instability problems due to large transmission networks, and utilization of various renewable energy sources as well as different load and generation patterns.

The power system, at this stage, can become insecure and prone to voltage collapse due to lack of reactive power support. Generators have the capability of providing reactive power but are limited to a certain extent. Moreover, the reactive power produced by the generators cannot be effectively utilized if the demand for the reactive power is far from its location. Hence, to prevent the voltage collapse, local var support is an option which is adopted in many countries of the world. In real life, it is always preferable to have optimal location of these devices in the system since it is beneficial to the voltage profile as well as transmission loss. Therefore, it is an important issue to be addressed in the electricity industry. The security of this deregulated power system operation is mainly dependent on the decisions of Independent System Operator (ISO). The optimal decisions under network congestion will maximize social welfare as well as profit of the market participants.

Developments of new and advance devices, which can provide local reactive power support at the load buses, have been becoming the alternative to this type of power system problems. Many of these new apparatuses can be materialized only due to the latest development in high power electronics to be used in the main circuits combined with the control strategies that rely on the modern control systems. By using power electronic controllers a Flexible Alternating Current Transmission System (FACTS) [4-7], have been produced which have a significant impact on the overall power systems performance improvement. Shunt FACTS controllers, such as Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM), are capable of effectively controlling the voltage profile by dynamically adjusting the reactive power output at the point of connection.

Traditionally, the objective of the reactive power (VAR) planning problem is to provide a minimum number of new reactive power supplies to satisfy only the voltage feasibility constraints in normal and post-contingency states. Various researches have been carried out for this subject [8-9]. Work has also been done on optimal reactive power planning strategy against voltage collapse in [10]. Insertion of FACTS devices is found to be highly effective in preventing voltage instability [11]. In [12], a new reactive power spot price index has been suggested to determine the optimal location of SVC in the power system. In [13], SVCs' have been optimally placed in a transmission network in such a manner that its loading margin is maximized. SVCs is used also to provide system stabilization in case of insufficient damped inter area oscillations and improve the power system power quality [14-15]. In most of the previous works on voltage stability improvement, only normal operating condition is considered [16]. The location and size of SVCs have been discussed in details in both transient and steady state [17]. Recently, due to a necessity to include the voltage stability constraints, a few researches have been reported concerning new formulations considering the voltage stability problem [18-19], which provides more realistic solutions for the VAR planning problem. However, the obtained solutions are sometimes too expensive since they satisfy all of the specified feasibility and stability constraints. In [20], a new formulation and solution method are presented for the VAR planning problem including FACTS devices, taking into account the issues just mentioned. Static VAR Compensator is a shunt connected controller capable of all possible benefits of FACTS devices [21]. So this paper is addressing the concept of optimal placement of

SVC for improvement in open access system performance considering bus voltage and line loadability considerations.

This paper is organized as follows: Following the introduction, different voltage instability analysis methods are described in section II. Then in section III, evaluation of Available Transmission Capability (ATC) considering voltage stability constraint and line MVA constraints is explained briefly. The case study with different bilateral transactions between various sources/sink with and without SVC is carried out and simulation results are given in section IV. Finally, brief conclusions are deduced.

II. Static Voltage Instability Analysis

Static voltage instability is mainly associated with reactive power imbalance. This imbalance mainly occurs on a local network or a specified bus in a system. Therefore, the reactive power supports must be locally adequate. With static voltage stability, slowly developing changes in the power system occur that eventually lead to a shortage of reactive power and declining voltage. This phenomenon can be seen in Figure 1, a plot of power transferred versus voltage at the receiving end.

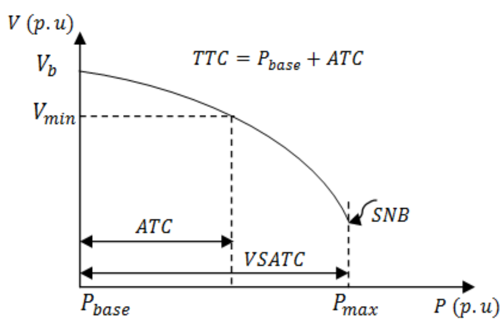

Fig. 1. Typical P-V Curve

These kinds of plots are generally called P - V curves or "nose" curves. As power transfer increases, the voltage at the receiving end decreases. Eventually, a critical (nose) point, the point at which the system reactive power is out of usage, is reached where any further increase in active power transfer will lead to very rapid decrease in voltage magnitude. Before reaching the critical point, a large voltage drop due to heavy reactive power losses is observed. The only way to save the system from voltage collapse is to reduce the reactive power load or add additional reactive power before reaching the point of voltage collapse.

The analysis of static voltage stability can also be possible with conventional load flow methods. In general, the nonlinear power flow equations will solve usually with iterative techniques such as the Gauss-Seidal (GS), Newton-Raphson (NR) and P-Q decoupling or Fast Decoupled (FD) methods [22, 23]. Based on accuracy and time taken for convergence, these methods will play a key role in different studies. The convergence is quite sensitive to the starting values assumed in GS method. Fortunately, in a load flow study a starting vector close to the final solution can be easily identified with previous experience. The NR method is a powerful method of solving non-linear algebraic equations. It works faster and is sure to converge in most cases as compared to the GS method. It is indeed the practical method of load flow solution of large power networks. Its only draw is the large requirement of computer memory which has been overcome through a compact storage scheme. Convergence can be considerably speeded up by performing the first iteration through the GS method and using the values obtained for starting the NR iterations [23]. In conventional NR method, the Jacobean matrix represents the week coupling between *P-δ* and *Q-V*, and therefore will ignore in FD method. Any such approximation reduces the true quadratic convergence to geometric one, but there are compensating computational benefits. In addition to the above approximation, physically justifiable simplifications in FD method causes to improvement in speed without much loss in accuracy of previous methods [24, 25]. The application of these load flow solution methods in present deregulated power system analysis is dependent on its accuracy, speed and capability of handling unequal constraints. To analyze complete system elements' operating status, the NR method has been used exclusively. To permit bilateral contracts, the maximum loading point limited by voltage stability is determined using NR method. In general, the voltage constrained maximum loading limit i.e. nose of the PV curve is determined using continuation method [26, 27].

The continuation power flow (CPF) analysis is robust and flexible and suited for solving load flow problems with convergence difficulties. However, the method is very slow and time consuming. Hence the better approach is to use combination of conventional load flow method i.e. NR or FD and continuation method. Starting from the base case, load flow is solved using a conventional method to compute power flow solutions for successively increasing load levels until a solution cannot be obtained. Hereafter, the continuation method is restored to obtain the load flow solutions. Normally, the continuation method is required only if solutions are required exactly at and past the critical point [23]. The detailed information about CPF can be obtained from [26, 27]. The aim of load flow solution is limited to identify critical load point; hence in this paper we have used NR method only.

III. Sensitivity Analysis for SVC Placement

Sensitivity indices have been used in this work to optimally place a SVC controller to increase power system security. The purpose of the voltage sensitivity analysis is to improve the voltage profile and to minimize system real power losses through the optimal reactive power controls (i.e., adding VAR supports). These goals are achieved by proper adjustments of VAR variables in power networks through seeking the weak buses in the system. Therefore, if the voltage magnitude at generator buses, VAR compensation (VAR support), and transformer tap position are chosen as the control variables, the optimal VAR control model can be represented as:

$$Min \quad P_{Loss}\left(Q_{support}, V_{Gen}, a_{tap}\right) \qquad (1)$$

Such that

$$Q\left(Q_{support}, V_{Gen}, a_{tap}, V_{Load}\right) = 0 \qquad (2)$$

$$Q_{Gen,min} \leq Q_{Gen}\left(Q_{support}, V_{Gen}, a_{tap}\right) \leq Q_{Gen,max} \qquad (3)$$

$$V_{Load,min} \leq V_{Load}(Q_{support}, V_{Gen}, a_{tap}) \leq V_{Load,max} \quad (4)$$

$$Q_{support,min} \leq Q_{support} \leq Q_{support,max} \quad (5)$$

$$V_{Gen,min} \leq V_{Gen} \leq V_{Gen,max} \quad (6)$$

$$a_{tap,min} \leq a_{tap} \leq a_{tap,max} \quad (7)$$

Here P_{Loss} is the real power loss in the system, $Q_{support}$ is the VAR support in the system, V_{Gen} is a voltage magnitude of the generator buses, Q_{Gen} is the reactive power generation in the system, a_{tap} is the tap position of the transformer and V_{Load} is the voltage magnitude of load buses. In the subscripts "min" and "max" represent the lower and upper limits of the constraint, respectively.

Two kinds of sensitivity - related factors can be computed through equations (1) to (7). Here they are called *voltage benefit factors* (VBF) and *loss benefit factors* (LBF), which are expressed as follows [28]:

$$LBF_p = \frac{\sum_p \left(P_{Loss,b} - P_{Loss(Q_{support,p})}\right)}{Q_{support,p}} \times 100\% \;\; p \in NL \quad (8)$$

$$VBF_p = \frac{\sum_p \left(V_{p(Q_{support,p})} - V_{p,b}\right)}{Q_{support,p}} \times 100\% \;\; p \in NL \quad (9)$$

Here $V_{p,b}$ and $P_{Loss,b}$ are the base case voltage at bus *p* and the real power loss in the system in base case respectively. Similarly $V_{p(Q_{support,p})}$ and $P_{Loss(Q_{support,p})}$ are the voltage at bus p and the real power loss in the system after VAR support i.e., $Q_{support,p}$ at bus *p* respectively.

IV. TRANSFER CAPABILITY CALCULATIONS

A. Mathematical Model for TTC Calculation

The total transfer capability (TTC) is defined as "the amount of electric power that can be transferred over the interconnected transmission network in a reliable manner while meeting all of a specific set of defined pre and post contingency system conditions"[29]. Mathematically

$$TTC = min\{P_{max,I_{Limit}}, P_{max,V_{Limit}}, P_{max,S_{Limit}}\} \quad (10)$$

The above equation can also valid for determination of security constrained TTC. This paper is focusing mainly on voltage instability due to lack of var support, hence $P_{max,V_{Limit}}$ is the maximum transferable power through the interface between seller and buyer buses and it is consider as the point of proximity to voltage instability.

The ability of power systems to remain bus voltages within certain acceptable intervals either if it is operated under normal conditions or undergo some contingencies has to be considered seriously owing to the consequences of voltage stability fails that can lead to blackouts. Therefore, it is essential to understand those basic concepts and tools related to this phenomenon. Thus, it would be possible to use these analyses to enhance the new energy management environment.

A loading parameter, λ is used in power system analyses in order to apply a general mathematical theory to classify instabilities, namely, bifurcation theory [30]. Moreover, this methodology reports quantitative information in the neighborhood of particular points, such as collapse points and unstable points. Therefore, system equations need to include, besides state variables *x*, a new set of parameters, λ, as follows:

$$f(x, \lambda) = 0 \quad (11)$$

The classical approach for optimizing the loading parameter λ could be the following one:

$$P_{Gi} = (1 + \lambda)P_{Gi,0} \quad (12)$$

$$P_{SG,i} = P_{Gi} - P_{Gi,0} = \lambda P_{Gi,0} \quad (13)$$

$$P_{Di} = (1 + \lambda)P_{Di,0} \quad (14)$$

$$P_{BD,i} = P_{Di} - P_{Di,0} = \lambda P_{Di,0} \quad (15)$$

where P_{Gi} and $P_{Gi,0}$ are generations at voltage instability point and at current operating point respectively. Similarly P_{Di} and $P_{Di,0}$ are system demands at voltage instability point and at current operating point respectively. The $P_{SG,i}$, $P_{BD,i}$ are the available generation and demand at seller bus and at buyer buses respectively. The generation and load multiplied by λ, in (12) and (15) depend only on the market participants, being this formulation appropriated to determine the impact of on security and to maximize that effect. Nevertheless, (3) and (4) optimizes the auction results and the transaction outside the bid process to improve the system security.

According to the mathematical theory introduced previously, it is possible to distinguish two types of singular points associated to the condition of Jacobian matrix, namely, SNB (*Saddle Node Bifurcation*) and LIB (*Limit Induced Bifurcation*) [31-33]. The latter is related to the disappearance of steady-state solutions when system control limits are reached, for example maximum generator reactive power limits. The former is characterized by two equilibriums, one stable and one unstable, being the maximum power transfer capacity when not other boundaries get active before. Therefore, both of them might lead to voltage collapse.

The SVC is installed at the critical bus for var support, i.e. the load bus which has gone through under voltage constrained. The compensation level of installed SVC in the system is determined such that to transfer the required amount of transaction level from seller bus to buyer bus without compromising in voltage stability.

B. Available Transfer Capability Calculation

According to [34], "ATC is a measure of the transfer capability remaining in the physical transmission network for further commercial activity over and above already committed users". This term is defined through the *Total Transfer*

Capability (TTC), *Transmission Reliability Margin* (TRM), *Existing Transmission Commitments* (ETC) and *Capacity Benefit Margin* (CBM). Mathematically

$$ATC = TTC - TRM - ETC \quad (16)$$

In the case study, we have considered as ETC as equal to base case load and TRM is zero since the loading of the network is limited to 95% only.

C. Enhancement of ATC using SVC

The ATC value obtained in the previous section is enhanced to a small range using SVC placement at optimal location. The location of SVC is decided based on sensitivity factors as mentioned in section III. The optimal values of SVC are determined for the network congestion free. In this work, to focus on the SVC application for congestion management, we have not limited the range of SVC.

D. Static Model of SVC

The shunt compensator SVC is simply a static capacitor/reactor with susceptance B_{SVC} [35]. Fig. 1 shows the equivalent circuit of the SVC can be modeled as a shunt-connected variable susceptance B_{SVC} at bus-*p*.

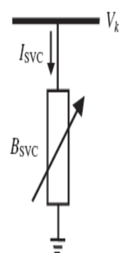

Fig. 2: Shunt Variable Susceptance Model

With reference to Figure 2, the current drawn by the SVC is:

$$I_{svc} = jB_{svc}E_p \quad (17)$$

and the reactive power drawn by the *SVC*, which is also the reactive power injected at bus *p*, is

$$Q_{svc} = Q_p = -E_p^2 B_{svc} \quad (18)$$

The Linearized equation is given by Equation (5.6), where the equivalent susceptance B_{svc} is taken to be the state variable:

$$\begin{bmatrix} \Delta P_p \\ \Delta Q_p \end{bmatrix}^{(k)} = \begin{bmatrix} 0 & 0 \\ 0 & Q_p \end{bmatrix}^{(k)} \begin{bmatrix} \Delta\theta_k \\ \dfrac{\Delta B_{svc}}{B_{svc}} \end{bmatrix}^{(k)} \quad (19)$$

At the end of iteration (*k*), the variable shunt susceptance B_{SVC} is updated according to

$$B_{svc}^{(k)} = B_{svc}^{(k-1)} + \left(\frac{\Delta B_{svc}}{B_{svc}}\right)^{(k)} B_{svc}^{(k-1)} \quad (20)$$

The changing susceptance represents the total SVC susceptance necessary to maintain the nodal voltage magnitude at the specified value. Once the level of compensation has been computed then the thyristor firing angle can be calculated. After adding SVC at bus-*p* of a general power system, the new system admittance matrix Y'_{bus} can be updated as:

$$Y'_{bus} = Y_{bus} + \begin{bmatrix} 0 & 0 & 0 & \dots & 0 & 0 & 0 \\ 0 & Y_{shunt} & 0 & \dots & 0 & 0 & 0 \\ 0 & 0 & 0 & \dots & 0 & 0 & 0 \\ \dots & \dots & \dots & \dots & 0 & \dots & 0 \\ 0 & 0 & 0 & \dots & 0 & 0 & 0 \\ 0 & 0 & 0 & \dots & 0 & 0 & 0 \\ 0 & 0 & 0 & \dots & 0 & 0 & 0 \end{bmatrix} \begin{matrix} \\ row-i \\ \\ \\ \\ row-j \\ \\ \end{matrix}$$

$$\qquad col-i \qquad\qquad col-j$$

For constant active power flow and supply voltage of E_p, the required capacitive VAR is the difference between the pre compensation VAR and the required compensated VAR as given by equation (18):

$$Q_{svc} = Q_{Required} - Q_{Uncompensated} \quad (21)$$

V. Case Study and Results

A. Results and Discussions without SVC Installation

For validation purpose, IEEE 6-bus system with its base case solution is shown in Figure 3 and will be applied to the proposed methodology. The system bus data and line data can be found in [36]. The power flow solutions are performed using PowerWorld® Simulator [37].

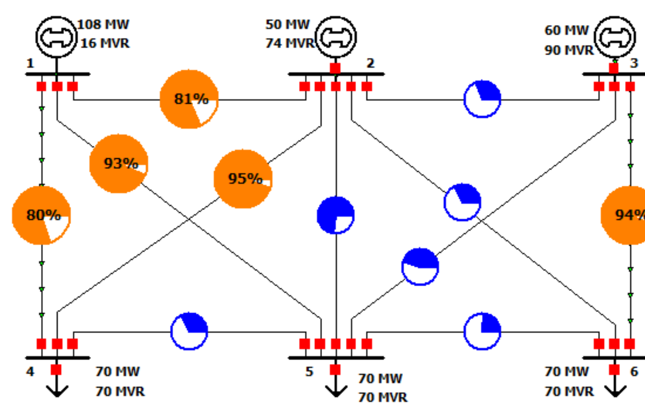

Fig. 3: IEEE 6bus System base case solution

From the base case solution given in Fig 3, out of 11 transmission lines, 5 lines are loaded more than 80% to their respective MVA limit. The increment in loading factor λ is zero for the system wide available transfer capability. It means a small increment in load will also causes to overloading of the transmission system. Under such type of operating conditions, it is worthwhile to evaluate available transmission capacity for bilateral contracts in open access.

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Static voltage constrained ATC is determined using NR method convergence. The load on the system is increased with constant power factor up to NR method fails to converge. With this step, the system wide total transfer capability (VSTTC) or maximum loading point i.e. SNB point is determined for analysis of voltage instability. The voltage security constrained ATC using Equation (16) is determined without SVC installation and the results are given in Table 1.

The PV curves for three cases as mentioned in Table 1 are shown in Figures 4, 5 and 6 respectively. From the figures, we can conclude that the optimal location of MVR support for voltage stability margin enhancement in the network is varying depending upon V_{min} constrained bus. The various bilateral transactions and corresponding ATC values in open market are evaluated and the results are given in Table 2. The observable information from the same table is, the ATC is determined and limited by transmission line constraint also. This indicates clearly the need of optimal location of FACTS devices in real deregulated system [38].

TABLE. I. VOLTAGE STABILITY ANALYSIS

Source Bus	λ (p.u)	VSTTC	VSATC	Loss (MW)	V_{min} bus
1	1.8	378	168	163.109	6
2	2.3	483	273	155.939	5
3	1.9	399	189	184.720	4

TABLE. II. OPEN MARKET ANALYSIS

Source /Sink	λ (p.u)	ATC (MW)	TTC (MW)	Loss (MW)	S_{max} line
1-4	1.03	5.076	215.076	7.300	1-5
1-5	1.02	2.135	212.135	7.103	1-5
1-6	1.03	5.076	215.076	7.274	1-5
2-4	0	0	210	6.128	2-4
2-5	0	0	210	6.128	2-4
2-6	0	0	210	6.128	2-4
3-4	0	0	210	6.157	3-6
3-5	0	0	210	6.157	3-6
3-6	0	0	210	6.157	3-6

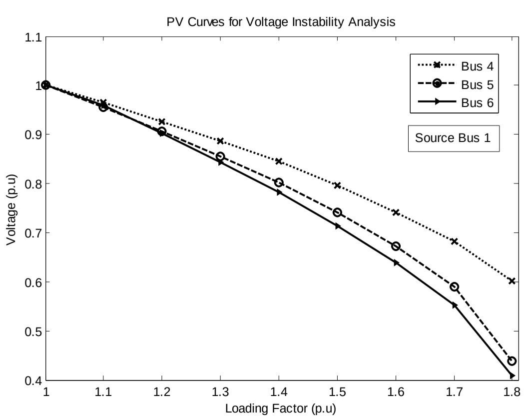

Fig. 4. PV Curves when Bus 1 is as a Source

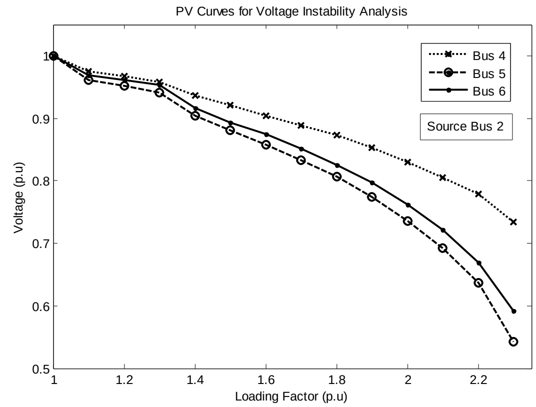

Fig. 5: PV Curves when Bus 2 is as a Source

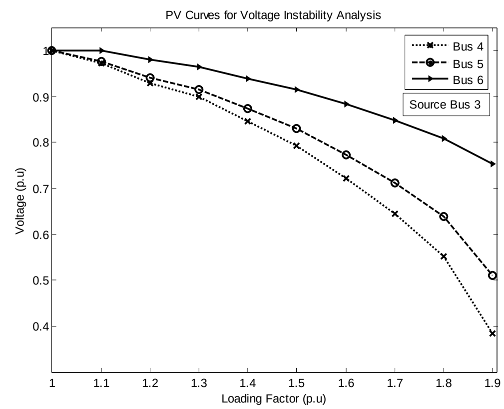

Fig. 6: PV Curves when Bus 3 is as a Source

B. Results and Discussions with SVC Installation

The location for SVC installation is considered at the three load buses i.e., buses 4, 5 & 6. The SVC with 10MVR is placed at each bus and the corresponding VRF & LFF are determined for the selection of optimal bus. The graph for various factors with different SVC locations is given in Figure 4. From the results, the location of SVC at bus 5 having higher values of benefit factors compare with other locations. This indicates that if SVC is placed at bus 5 results in system loss reduction and voltage depressions at critical points. Hence, the final SVC location for installation is bus 5 favored in all the aspects.

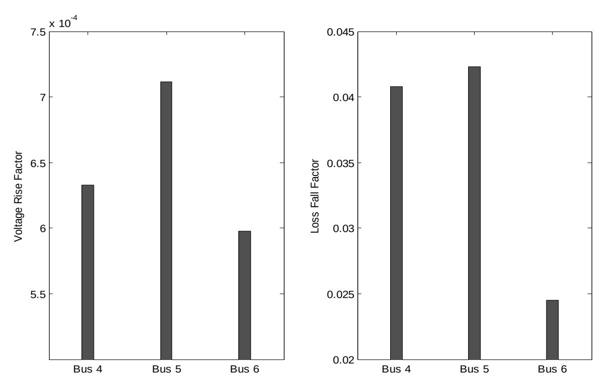

Fig. 7. Voltage Rise & Loss Fall Factors with various SVC locations

C. Results and Discussions of Open Market with SVC Support

The case studies carried out in the previous section are once again repeated with SVC support. Various point-to-point transactions with SVC support by satisfying all system operating constraints are given in Table III. For better understanding, we have provided the simulation models of PowerWorld® Software as a Figures 8, 9, 10 and 11 for different cases. It can also be eye-catching of congestion elevation by SVC support in all the cases.

TABLE. III. OPEN MARKET ANALYSIS WITH SVC

Source /Sink	λ (p.u)	ATC (MW)	Loss (MW)	S_{max} line	Loss with SVC (MW)
1-4	1.043	3	7.96	2-4	7.55
1-5	1.114	8	8.66	1-5	8.19
1-6	1.086	6	8.25	3-6	7.83
2-4	1.057	4	8.14	2-4	7.74
2-5	1.143	10	8.72	1-5	8.27
2-6	1.086	6	8.23	3-6	7.83
3-4	1.043	3	7.94	2-4	7.55
3-5	1.214	15	8.98	1-5	8.50
3-6	1.079	5.5	8.04	3-6	7.65

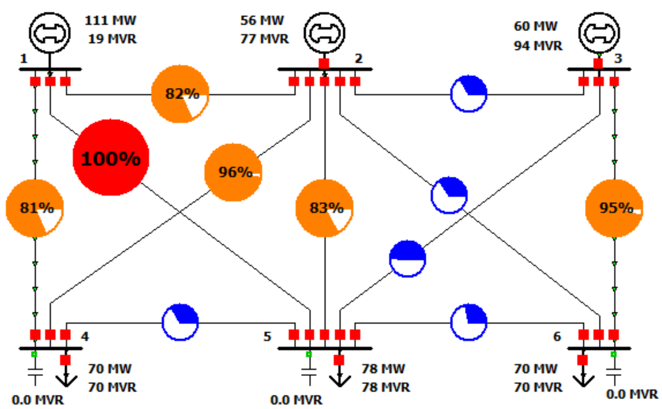

Fig. 8. ATC Calculation from Bus 1 to Bus 5

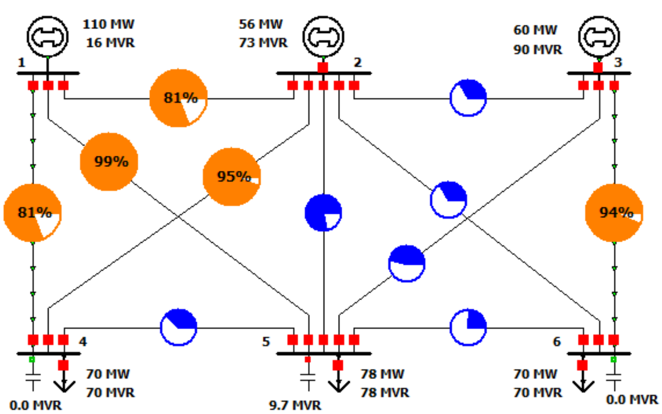

Fig. 9. Congestion Relief by SVC at Bus 5 for the case of Fig. 8

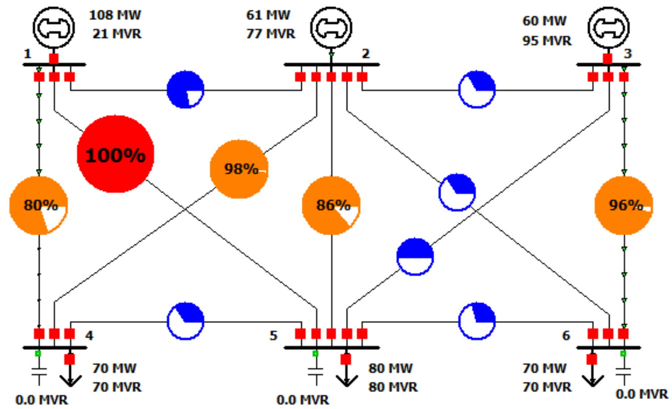

Fig. 10. ATC Calculation from Bus 2 to Bus 5

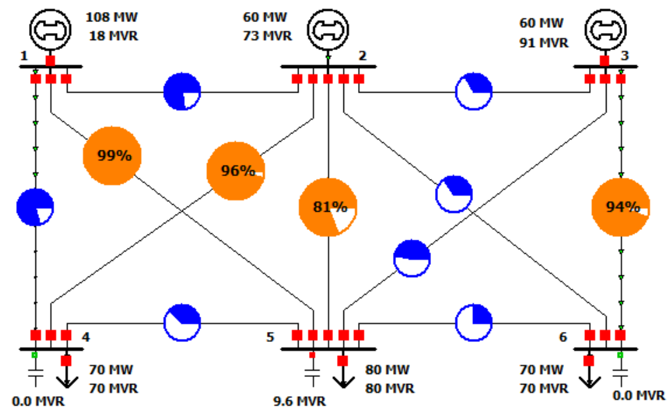

Fig. 11. Congestion Relief by SVC at Bus 5 for the case of Fig. 10

VI. CONCLUSIONS

This paper reviews the necessity of reactive power support in the present open access power market. One of the FACTS devices SVC is placed optimally based on sensitivity indices. The minimum amount of VAR support by SVC for network security is obtained and consequently the location of SVC is finalized based on MVAR required for congestion relief. Enhanced ATC values with congestion free network are obtained by suitable SVC location and its compensation level. The voltage and loss benefit factors can easily gives the solution for SVC optimal location. A simple 4 bus system has been used and the results obtained in the case study are validating the proposed methodology for SVC location to improve the system performance in the presence of point to point transactions in the system. The optimal location of SVC improves the security margin in terms of enhanced ATC in the network.

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