Mansoura Engineering Journal, (MEJ), Vol. 33, No. 4, December 2008.

Economical Insertion of Static Reactive Power Compensators in Power Systems

الإدخال الاقتصادي للمعوض الاستاتيكى للقدرة الغير فعالة في نظم القوى

S.S.Kaddah K.M. Shebl
Dept. of Electrical Engineering
Faculty of Engineering
Mansoura University

E. A. Haikal
Developing Department
Zagazig Branch
Special Studies Academy

ملخص البحث

إن ظهور خطوط النقل المرنة قد غير كلية طريقة التشغيل والتحكم في نظم النقل الكهربية. يعتبر المعوض الاستاتيكي للقدرة غير الفعالة من أهم وأشهر خطوط النقل المرنة حيث يستخدم للعلاج من مشاكل تغير قيمة الجهد و استقرار الجهد ولكنها تؤثر أيضا في قدرة النقل المتاخر وفي معامل زيادة التحميل وكذلك المفاقيد النحاسية في النظام . هذا البحث يقدم طريقة اقتصادية متكاملة لإدخال المعوض الاستاتيكى للقدرة الغير فعالة مبني علي حساب التكاليف الكلية والفوائد الكلية لهذا الإدخال وكذلك يقدم البحث مؤشر موحد لترتيب الأعطال.

هذا الخوارزم المقترح قد تم اختباره علي النظام IEEE-26BUS المتعرض للعديد من المشاكل وكيفية حساب المكان والحجم الأمثل لهذا المعوض في كل حالة

Abstract

The appearance of Flexible AC Transmission System (FACTs) controllers is completely changing the way transmission systems are controlled and operated. Most FACTs controllers are basically based on variable shunt and/or series compensation of transmission systems. One of the most famous type of FACTs is the Static VAr Compensator (SVC), which is basically used as a cure for both voltage and voltage stability problems. However, SVC may also affects the Available Transfer Capability of the system (ATC), Line Overload and Losses. As the power system is economically operated, hence it is important to study the economical effects of SVC on power system operation. This paper presents a construction of a complete Cost Benefit Analysis (CBA) model for SVC insertion into power system to select the best location and size for that insertion. Generally CBA is based on comparison between the cost and benefit for a specific alternative. In our case, the cost components are mainly the cost of the SVC device and its cost of installation and maintenance. While the benefit components are that due to improving voltage stability in terms of increasing the voltage stability margin (VSM), benefits due to extending the ATC, and the benefits as a result of relieving line overloads in the system in terms of reducing the line overload (LO) and finally reducing the system losses. However for the same hardware the cost is the same. So, the most economical alternative is the one with the maximum total benefit. This paper also, introduces a new Unified Index (UI) for ranking contingencies. The proposed CBA algorithm is tested for SVC insertion into the IEEE 26-bus system subject to contingencies.

1. Introduction

Flexible AC transmission systems (FACTS) forms new domain in power system control and operation. FACTS are alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability, stability and increase power transfer capability. They are either pure controlled electronic devices or conventional elements such as resistor, reactor or capacitors controlled by electronic devices. The control here will be either switching out and in or continuous phase angle control, according to these control techniques; they are called switched or controlled devices [1]. The main objectives of such devices can be restated as increase the power transfer capability of the transmission networks, extend stability margin of power system, provide direct control of power flow over designated transmission routes, increase the power system performance by delivering or absorbing reactive power, provide significant benefits in terms of greater flexibility , and finally reduce system losses as it provide the required reactive power so the current is reduced and so the system losses. One of the most famous type of FACTs is the Static VAr Compensator (SVC), which is mainly used as a cure for both voltage and voltage stability problems [2].

As the power systems are always operated from economic point of view, there is a need to perform economic analysis of SVC devices insertion into power systems. The main purpose of this economic analysis is to select the most economical location and size of SVC to be inserted at a specific case. Cost benefit analysis (CBA) is a systematic comparison between the costs and benefits of a proposed (or existing) policy or expenditure and can be used for economic analysis. In this paper, the benefit component due to SVC insertion could be as follows: first, voltage stability improvement; second, available transfer capability improvement; third line

Accepted December 22, 2008

overload relief and finally system losses reduction. The success of CBA practice essentially depends on our ability to correctly account for possible costs and benefits that may be associated with the decision [3-5].

The main contributions of this paper are : First introducing a unified index, UI for ranking the listed contingencies based on the voltage stability margin, available transfer capability, line over load index and system losses; Second constructing a complete cost benefit analysis (CBA) model for economical insertion of SVC into power system. The proposed algorithm includes a complete contingency analysis of the system to identify the ones that need SVC insertion using the unified index. Then for these cases, the location and size of the SVC are selected economically by maximizing the total benefit. The proposed algorithm is tested using IEEE 26-bus system.

2. Problem Formulation

Aiming at constructing a complete cost benefit analysis (CBA) model for insertion of SVC into power system, both benefit and cost components should be identified, calculated and then valued. Mainly the cost component in this case is the cost of the SVC device and its cost of installation and maintenance. While the benefit components resulting from this insertion are benefits due to improving voltage stability in terms of increasing the voltage stability margin defined in MVAr, benefits due to extending the available transfer capability defined in MW, benefits as a result of relieving line overloads in the system in terms of reducing the line overload defined in MVA and finally reducing the system losses defined in MW.

2.1. Flexible AC Transmission Systems (FACTS)

FACTS are alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability. They are either pure controlled electronic devices or conventional elements such as resistor, reactor or capacitors, controlled by electronic devices. In general, FACTS controllers can be classified as follows: Series, Shunt, Combined Series-Series, and Combined Series-Shunt Controllers [6].

The series controllers could be variable impedance, such as capacitor, reactor, etc., or power electronics based variable source of main frequency, sub synchronous and harmonic frequencies (or a combination) to serve the desired need. All series controllers inject voltage in series with the line. The shunt controllers may be variable impedance, variable source, or a combination of both. In principle, all shunt controllers inject current into the system at the point of connection. Combined series-series controllers could be a combination of separate series controllers or it could be a unified controller, in which series controllers provide independent series reactive compensation for each line but also transfer real power among the lines via the power link. Combined series-shunt controllers could be a combination of separate shunt and series controllers or a Unified Power Flow Controller with series and shunt elements. In principle, combined shunt and series controllers inject current into the system with the shunt part of the controller. However, when the shunt and series controllers are unified, there can be a real power exchange between the series and shunt controllers via the power link [7-9]. In this paper, SVC is introduced as an example of the shunt connected FACTs.

2.2. Static VAr Compensator (SVC)

SVC is a shunt connected static reactive power generator/load whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific power system variables. SVC is similar to a synchronous compensator in that it is used to supply or absorb reactive power but without rotating part. It operates similar to an automatic voltage regulator system to set and maintain a target voltage level.

The two most popular configurations of the SVC are the fixed capacitor (FC) with a thyristor controlled reactor (TCR), and the thyristor switched capacitor (TSC) with (TCR). Of these two setups, the second (TCR-TSC) minimizes standby losses; however, from a steady-state perspective, this is equivalent to the FC-TCR structure as shown in Figure 1. The TCR consists of a fixed reactor of inductance L and a bi-directional thyristor valve.

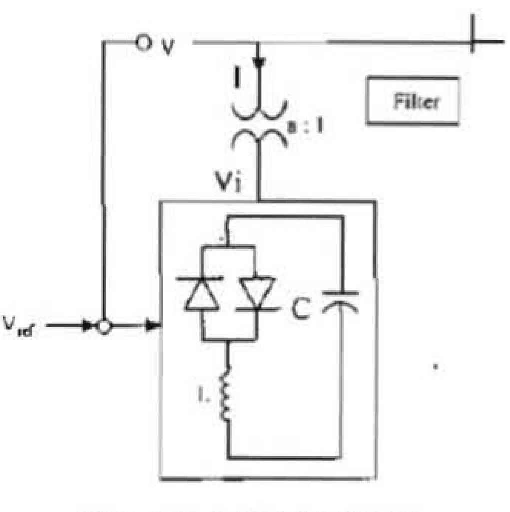

Figure 1. Basic Structure of SVC

The thyristor valves are fired symmetrically in an angle α with a control range of 90° to 180°, with respect to the capacitor (inductor) voltage. The valves automatically turn off at approximately the zero crossing of the AC current. Equation (1) accurately describes the steady-state behavior of the SVC when connected to a system bus K.

$$\begin{aligned} & V_i - V_{ref} + X_{sl} V_k B_e = 0 \\ & Q_{svc} - V_k^2 B_e = 0 \qquad (1) \\ & \pi X_c X_l B_e + \sin(2\alpha) + \pi\left(2 - \frac{X_l}{X_c}\right) = 0 \end{aligned}$$

The initialization of the SVC variables is done either from a "flat start" or from a user defined initial guess. This flat start is based on the initial values of AC variables and the characteristic of the equivalent reactance. The SVC control limits are basically represented as limits on the firing angle α, i.e., $\alpha \in (\alpha_m \ , \ \alpha_M)$

where

α_m : is the minimum firing angle and

α_M is the maximum firing angle

So, a specific SVC may work in a continuous wide range of reactive power compensation by changing the firing angle. When we refer to the cost of the SVC, we assume it is the cost of the hardware but the corresponding reactive power varies with changing the firing angle as long as it is working in the range between the minimum and the maximum firing angle. When more reactive power than the one corresponds to the maximum firing angle, another SVC is needed. The steady state circuit representation of the SVC is shown in Figure 2.

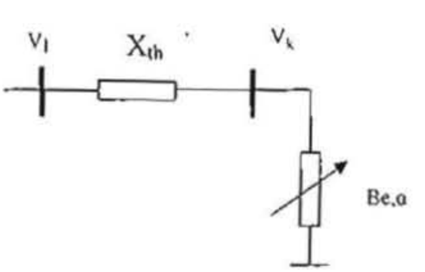

Figure 2. SVC Steady-State Circuit Representation

2.3. Voltage Stability

Voltage stability is defined as the ability of the power system to maintain acceptable voltage at all nodes of the system under normal conditions and after being subjected to a disturbance. Voltage stability is measured by the distance that the operating point is far from the collapse point in terms of active or reactive power using the PV curve or QV curve. In this paper, QV curve is used as there is a strong relationship between the reactive power and the voltage.

The influence of reactive power characteristics of devices at the receiving end (loads or compensating devices) is more apparent in the QV Curves relationship as shown in Figure 3 that shows the voltage stability limit at the point where the derivative dQ/dV is zero. An increase in reactive power will lead to an increase in voltage during normal operating conditions. Hence, if the operating point is on the right side of the curve, the system is said to be stable. Conversely, operating points in the left side of the graph are deemed to be unstable[10-12].

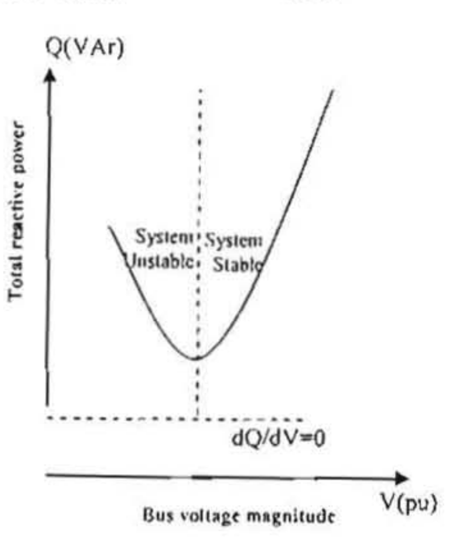

Figure 3. Typical Q – V Curve

2.4. Available Transfer Capability (ATC)

Available Transfer Capability is a measure of the transfer capability remaining in the physical transmission network for further commercial activity over and above already committed uses. Mathematically, ATC is defined as the Total Transfer Capability (TTC) less the summation of the Transmission Reliability Margin (TRM) and the Capacity Benefit Margin (CBM) as shown in Equation (2):

$$ATC = TTC - TRM - CBM \qquad (2)$$

Total Transfer Capability (TTC) is the amount of electric power that can be moved or transferred reliably from one area to another area of the interconnected transmission system over transmission lines (or paths) between those areas under specific system conditions more than the transmission commitment. Transmission Reliability Margin (TRM) is the amount of transmission transfer capability necessary to ensure that the interconnected transmission network is secure under a reasonable range of uncertainties in system conditions. Capacity Benefit Margin (CBM) is the amount of transmission transfer capability reserved by load-serving entities to ensure access to generation from interconnected systems to meet generation reliability requirements [13-16].

2.5. Line Overload

Another parameter used to measure the system performance and the effect of the SVC insertion is the line overload, LO, that measures the System overload and expressed as follows [17]:

$$LO = \sum_{k=1}^{NL} MVA_k - MVA_k^{base} \qquad (3)$$

Where:

MVA_k: Apparent power flowing at bus k,

MVA_k^{base} : Base Apparent power flowing at bus k,

K: Line index

NL: Total number of lines in the system

3. Proposed Algorithm

The proposed algorithm for selecting the most economical SVC is represented in the following steps:

Step 1: Read System Data
Step 2: Perform base case power flow
Step 3: If there is any violation go to step 1. if not, continue
Step 4: Read list of contingencies, Nc
Step 5: Calculate performance indices of each contingency
Step 6: Rank contingencies using Unified Index (Sub-algorithm A)
Step 7: Identify the contingencies that need support, Nr
Step 8: For first ranked contingency
Step 9: Select SVC location using Sub-algorithm B.
Step 10: Select the SVC size using Sub-algorithm C.
Step 11: Identify the economical location and size of SVC
Step12: IF last ranked contingency, end, else choose next contingency and go to step 9 .
Step13: Display Results
Step 14: End

Sub-algorithm A (Ranking Algorithm Using the Unified Index)

Step 1: Read contingency number
Step 2: For first contingency, get performance indices VSM, ATC, LO and Ploss.
Step 3: If last contingency, continue. Otherwise, choose next contingency and go to step2.
Step 4: Normalize performance indices for the listed contingencies as follows:

$$NVSM_i = VSM_i / VSM_{max}$$
$$NATC_i = ATC_i / ATC_{max}$$
$$NLO_i = LO_i / LO_{max}$$
$$NLosses_i = Losses_i / max\ Losse$$

Step 5: Calculate Unified Index,UI at each contingency as follows:

$$UI = W_1 * NVSM_i + W_2 * NATC_i + W_3 *(1 - NLO_i) + W_4 * (1 - Nlosses_i)$$

Step 6: Rank the contingencies according to the values of UI from the lower to higher as the one with lowest UI is the one that need support most.
Step 7: End
Step 8: Return

Sub-algorithm B (SVC *Location Selection Algorithm*)

Step 1: For first location.
Step 2: Model the congested system with the SVC at the selected location.
Step 3: Calculate performance indices, VSM^{new}, ATC^{new}, LO^{new}, $P_{loss}{}^{new}$.
Step 4: Calculate improvement in performance indices as following:

$$\Delta\ VSM = VSM^{new} - VSM^{old}.$$
$$\Delta\ ATC = ATC^{new} - ATC^{old}.$$
$$\Delta\ LO = LO^{old} - LO^{new}.$$
$$\Delta\ Ploss = P_{loss}{}^{old} - P_{loss}{}^{new}$$

Step 5: Calculate total benefit due to installing SVC at the specific location.

$$TB = B_{VSM} * \Delta VSM + B_{ATC} * \Delta AT + B_{LO} * \Delta LO + B_{loss} * \Delta P_{loss}$$

Step 6: If last location done go to next step. Otherwise, choose next location and go to step 2.
Step 7: Select the location that maximizes TB.
Step 8: End.
Step 9: Return.

Sub-algorithm C (SVC *Location Selection Algorithm*)

Step 1: For first size.
Step 2: Model the congested system with the SVC at the selected location.
Step 3: Calculate performance indices, VSM^{new}, ATC^{new}, LO^{new}, $P_{loss}{}^{new}$.
Step 4: Calculate improvement in performance indices as following:

$$\Delta\ VSM = VSM^{new} - VSM^{old}.$$
$$\Delta\ ATC = ATC^{new} - ATC^{old}.$$
$$\Delta\ LO = LO^{old} - LO^{new}.$$
$$\Delta\ Ploss = P_{loss}{}^{old} - P_{loss}{}^{new}.$$

size of *Step 5:* Calculate total benefit due to specific SVC at the specific location:

$$TB = B_{VSM} * \Delta VSM + B_{ATC} * \Delta AT + B_{LO} * \Delta LO + B_{loss} * \Delta P_{loss}$$

Step 6: If last size done go to next step. Otherwise, choose next size and go to step 2.
Step 7: Select the location that maximizes TB.
Step 8: End.
Step 9: Return.

4. Case Study and Results

4.1. System Description

The proposed algorithm is tested using the IEEE.26-Bus system that's shown in Figure 4. This system consists of 6 generating units and 20 load buses; total active power generation excluding the slack bus of the system is 559 MW. The total load of the entire system equals 1263 MW and 637 MVAr, the base power of the test system is taken as 100 MVA and the total compensation reactive power is 22 MVAr. The system has 7 transformer and 46 transmission lines. Bus 1 is considered as the slack bus [18]. The system is divided into two areas. For base case result, there are no any line overload or voltage problems.

4.2. Contingency Analysis

The IEEE 26-Bus system is subjected to many contingencies. In this paper, seven of these contingencies are introduced. The list of these contingencies is as follows:

Contingency no 1: Loss of Line (1-2)
Contingency no.2: Loss of Line (1-18)
Contingency no.3: Loss of Line (3-13)
Contingency no.4: Loss of Line (5-6)
Contingency no.5: Loss of Line (6-19)
Contingency no.6: Loss of Line (12-14)
Contingency no.7: Loss of generator 5.

The system is subjected to different contingencies (outage of transmission line or generating unit), the system may have some problems such as voltage problem. When voltage magnitude at any bus of the system violates the acceptable limits (0.95 p.u $\leq |V| \leq$ 1.05 p.u). Voltage stability problem is noticed by calculating voltage stability margin. Stability margin determine how far the system is operating from the voltage collapse point. Also, VSM represents the distance, in MVAr or percentage, from the base case operating point to the maximum power transfer capability point of the system (QV-Curve nose point). System overload is measured by line overload (LO). For the listed contingencies, Table 1 summarizes the voltage problems, voltage stability margin, and the weakest buses. However, available transfer capability, and line overload and system losses for the listed contingencies are summarized in Table 2.

Table 1. Summary of Voltage Problems and VSM for the Listed Contingencies

Cont.#	Description	Voltage Problem	Voltage Stability Margin	Weakest buses
1	LOL (1-2)	None	337.5 MVAr 22.5 p.u	19,23,22, 13,10,6
2	LOL (1-18)	Slight	558 MVAr 18 p.u	15,17,16, 24,18,6
3	LOL (3-13)	None	456 MVAr 12 p.u	17,16,15, 10,6
4	LOL (5-6)	Islanding		
5	LOL (6-19)	Slight	202.5 MVAr 13.5 p.u	19,25,23,24 22,20,10,6
6	LOL (12-14)	None	152 MVAr	
7	LOG5	None	195 MVAr 15 p.u	25,23,24, 22,10

Table 2. Summary of ATC, LO and System Losses for the Listed Contingencies

Cont.#	Description	ATC (MW)	LO (MVA	System Losses (MW)
1	LOL (1-2)	59.2	350.3	36.1
2	LOL (1-18)	113.1	738.6	34.6
3	LOL (3-13)	81.1	-719.3	17.3
4	LOL (5-6)	Islanding		
5	LOL (6-19)	38.3	-211.5	21.3
6	LOL (12-14)	236.3	-691.9	15.4
7	LOG5	58.5	-127.2	19.3

4.3. Contingency Ranking

For ranking purposes, the performance indices are normalized using the following formula:

Normalized Voltage Stability Margin,

$$NVSM_i = VSM_i / VSM_{max}$$

Normalized Available Transfer Capability, N

$$ATC_i = ATC_i / ATC_{max}$$

Normalized Line Overload ,

$$NLO_i = LO_i / LO_{max}$$

Normalized System Losses,

$$NLosses_i = Losses_i / max\ Losses$$

Then, the unified index is calculated as:

$$UI = W_1 * NVSM_i + W_2 * NATC_i + W_3 * (1 - NLO_i) + W_4 * (1 - Nlosses_i)$$

Where W_1, W_2, W_3, W_4 are weighting factors, where the summation of W_1, W_2, W_3, and W_4 equals unity. The values of W's are varying from utility to utility and from system to another based on the importance of one performance index over another one. *In our case we select:* $[W_1, W_2, W_3, W_4] = [0.4, 0.3, 0.2, 0.1]$. Table 3 lists the normalized performance indices, unified index of the listed contingencies.

Table 3. Normalized Performance Indices and UI for Different Contingencies.

Cont.#	Desc	NVSM	NATC	NLO	NLos	UI
1	LOL (1-2)	0.682	0.682	-0.309	2.34	0.42
2	LOL (1-18)	0.75	0.906	-1.06	2.25	0.54
3	LOL (3-13)	0.941	0.675	1.04	1.12	0.89
4	LOL (5-6)	Islanding				
5	LOL (6-19)	0.45	0.85	0.305	1.38	0.49
6	LOL (12-14)	0.944	0.793	0.999	1	0.85
7	LOG5	0.906	0.825	0.183	1.25	0.49

The contingencies that ranked first (low unified index) are the ones that need support. As shown from Table 3, contingencies # 1, 2, 7 are the most serious ones and there is a support needed.

4.4. Economical Insertion of SVC for Contingency Ranked#1

The selected SVC is chosen from the available standards that satisfies the range of the required reactive power in the test system. The chosen SVC has the following data: $X_C = 5.43$, $X_L = 2.32$, $\alpha_{min} = 120°$, $Q_{min} = 15.8$ MVAr, $\alpha_{max} = 180°$, $Q_{max} = 200$ MVAr [13], Equation (1) governs the SVC behavior. The economical insertion of the SVC in the system has 2 folds: First, economical location selection; second, economical size selection.

4.4.1 Location Selection of SVC at the Case of Contingency Ranked #1

For contingency ranked no.1 *(Loss of Line (1-2))*, SVC with specific size (Q_{svc}= 58.4 MVAr) is inserted at the weakest buses (19, 23, 22, 13, 10, 6). The task now is to search for the optimum location among these buses. Table 4 shows a summary of the performance indices when the system is subjected to the loss of line 1-2.

As shown in Table 4, bus #19 is considered the best location for SVC considering the voltage stability margin only. However, bus #22 is considered the best location if the available transfer capability is considered alone. Considering line overload is the only index, then bus #23 is the best location for insertion SVC and finally, buses 22 and 19 are the best locations if we consider the system losses as the only index. So, to decide properly the best location of inserting the SVC economically, ***Cost Benefit Analysis*** is introduced. The first step in performing this is to evaluate the improvement in the performance indices and then valuing this improvement and calculate the total benefit due to insertion of SVC. Since, it is only one SVC we are taking about. So, the total cost is the same and the choice that maximizes the total benefit is the most economical choice. Improvements in VSM, ATC, LO and Losses after using SVC at different locations are shown in Table 5.

Table 4. Summary of Performance Indices of the System Subjected to Contingency Ranked #1 and SVC Installed at Different Locations.

Inde	Static VAr Compensator Location					
	Bus (19)	**Bus (23**	**Bus (22**	**Bus (13**	**Bus (10)**	**Bus (6)**
V.S.M. (MVAr) VSM (p.u)	405 (27)	382.5 (25.5)	382.5 (25.5)	382.5 (25.5)	360 (24)	360 (24)
ATC (MW)	75.7	62.6	**97.4**	60.1	53.7	60
LO (MVA)	279.4	**252.3**	268.2	323.8	281.4	306.5
P_{Losses} (MW)	35	35.1	35	36.4	35.2	35.3

Table 5. Improvements of Performance Indices When Inserting SVC at Different Locations for Contingency Ranked #1.

Improvement in Indices	**Static VAr Compensator Location**					
	Bus (19)	**Bus (23**	**Bus (22)**	**Bus(3)**	**Bus (10)**	**Bus(6**
ΔVSM (MVAr)	67.5	45	45	22.5	22.5	22.5
ΔATC (MW)	16.5	3.4	38.2	0.9	-5.5	0.8
ΔLO (MVA)	70.9	98	82.1	26.5	68.9	43.8
ΔP_{loss} (MW)	1.1	1.0	1.1	-0.3	0.9	0.8

Aiming to estimate the benefit of inserting the SVC into the system, we have to value the improvement of different indices. Of course these values are different from system to another. The chosen value are 20$ / KVAr for VSM, 15$ / KW for ATC, 5$ / KVA for LO and with respect to system losses 0.01$ / KWh. After calculating the total benefits, the most economical location for inserting SVC at case of contingency ranked no.1 *(outage of line (1-2))* is bus #19.

4.4.2. Size Selection for insertion of SVC for Contingency Ranked #1

Now, after selecting the location of SVC, the proper size of reactive power inserted from SVC has to be chosen, especially changing the reactive power occurs by changing the firing angle only at no cost. Table 6 shows a summary of the performance indices when inserting SVC with different sizes at bus #19 for contingency ranked 1.

Table 6. Summary of Performance Indices when Inserting SVC with Different Sizes for Contingency Ranked #1

Indices	Befor SVC	Static VAr Compensator Size, MVAr				
		32.7	58.4	87.4	130.6	147.9
VSM (MVAr VSM (p.u	337.5 (22.5	382.5 (25.5)	405 (27)	427.5 (28.5)	472.5 (31.5)	495 (33)
ATC (MW)	59.2	77.1	75.7	61.4	67	75.6
LO (MVA)	350.3	310.5	279.4	260.5	248.1	246
P_{Loss} (MW)	36.1	35.6	35	34.9	35	35.1

To select the economical size of the SVC, improvement in VSM, ATC, LO and losses after inserting SVC with different sizes are calculated and listed in Table 7.

Table 7. Performance Indices Improvements when Inserting SVC with Different Sizes for Contingency Ranked no.1.

SVC Size, MVAr	Static VAr Compensator Size, MVAr				
	32.7	58.4	87.4	130.6	147.9
ΔVSM (MVAr)	45	67.5	90	135	157.5
ΔATC (MW)	17.9	16.5	2.2	7.8	16.4
ΔLO (MVA)	39.8	70.9	89.8	102.2	104
ΔP_{loss} (MW)	0.5	1.1	1.2	1.1	1.0

After calculating the improvement of the performance indices and valuing these improvements, the total benefit is calculated at different sizes of SVC as shown in Table 8.

Table 8. Total Benefits when Inserting SVC with Different Sizes for contingency Ranked#1

	Static VAr Compensator Size, MVAr				
	32.7	**58.4**	**87.4**	**130.6**	**147.9**
TB . (*1000$)	5941	8623	10049	14416	16486

Based on the above results, it is clear that the most economical size for this contingency is Q_{svc} = 147.9 MVAr at bus #19.

The same procedure were repeated for contingency ranked #2 *(Outage of generator G5) and the proposed algorithm results that the* most economical location is bus #25 and the optimum size Q_{svc} equals to 110.5 MVAr. However for the contingency ranked#3 (Outage of line (1-18)), the most economical location for inserting SVC is proved to be bus #15 and the most economical size is Q_{svc} = 190.4 MVAr.

5. Conclusions

This paper presented a construction of a complete cost benefit analysis (CBA) model for SVC insertion in power systems to select the best location and economical size for that insertion. . The cost components are mainly the cost of the SVC device and its cost of installation and maintenance. While the benefits are: that due to improving voltage stability, increasing the available power transfer capability, relieving line overloads in the system and reducing the system losses. All these benefits are calculated and valued to represent the total benefit. However for the same hardware the cost is the same and the benefit is varied according to the SVC size and location. So, the most economical alternative is the one with the maximum total benefit. The proposed algorithm is applied to give the best location and economical size selection of the SVC. The proposed CBA algorithm is tested through its application on the IEEE 26-bus system subjected to 7 contingencies. The result ensures simplicity and accuracy for identifying the most economical location and size of SVC.. Also, this paper suggested a unified index for contingency ranking. This index is based on the Voltage Stability Margin, Available Transfer Capability, Line Overload and System Losses.

Also, the Proposed algorithm is very general and can be used for different types of FACTs and even can be used for type selection among available types of FACTS.

6. References

[1] H.K.Tyll, SM IEEE "FACTs Technology for Reactive Power Compensation and System Control" IEEE /PES Panel Session on FACTs, Nov.8-11-2004.

[2] Power System Voltage Stability and Power Quality " Mohamed. Z .EL-Sadek, book, El-Mukhtar Press, 1999.

[3] Sugden, R. and Wiliems, A., "The Principles of Practical Cost-Benefit Analysis", Book, Oxford University Press, 1978.

[4] Dompere, K.K., "The theory of social costs and costing for cost-benefit analysis in a fuzzy decision space", Journal of Fuzzy Sets and Systems 76, Elsevier Science, Oct. 1994, pp. 1-24.

[5] Anthony E. Boardman, David H. Greenberg, Aidan R. Vining, David L. Weimer, "Cost-benefit Analysis: Concepts and Practice," book, Pearson/Prentice Hall, 2006.

[6] H. Narian and G.Laszio, "Understanding FACTs: Concepts& technology of Flexible AC Transmission Systems," book, IEEE Series, John Wiley Press, Dec.1999.

[7] N. Mithalananthan, A. Sode-Yome and N. Acharya, "Applications of FACTS Controllers in Thailand Power Systems", Report, RTG Budget-Joint Research Project, Fiscal- Year 2005.

[8] Claudio A. Canizares and Zeno T. Faur, "Analysis of SVC and TCSC Controllers in Voltage Collapse." IEEE trans. Power Systems, VoL.14, No.1, February 1999, PP. 158-165.

[9] L. Gyugyi, "Power electronic in electric utilities: Static VAr compensators," Proceeding of the IEEE, Vol.76, No.4, April 1988, PP. 483-494.

[10] C.W. Taylor, "*Power Systems Voltage Stability*", book, McGraw-Hill Education - Europe 1994.

[11] C. A. Canizares, "Voltage Stability Assessment, Procedures and Guides ", IEEE/PES Power Systems Stability Subcommittee, January 1999, available at: *http://www.power.uwaterloo.ca*

[12] J. A. Momoh and M. E. El-Hawary, "Electric System Dynamics and Stability with Artificial Intelligence Applications", book, Marcel Dekker Inc., New York, 1999.

[13] Transmission Transfer Capability Task Force, "Available Transmission Capability Definitions and Determination," Report, North American Reliability Council, Princeton, New Jersey, June 1996.

[14] K. Narasimha Rao, J. Amarnath and K.Arun Kumar, "Voltage Constrained Available Transfer Capability Enhancement with FACTS Devices " ARPN Journal of Engineering and Applied Sciences, Vol.2, No.6, December 2007.

[15] G.C.Ejebe J. Tong J.G. Frame X.Wang W.F.Tinney " Available Transfer Capability Calculation " IEEE Transaction on Power Systems, Vol. 13, No.4, November 1998.

[16] Yan Ou and Shanan Singh ," Assessment of Available Transfer Capability and Margins", IEEE Transaction on Power Systems, Vol.17, No.2, May 2002.

[17] Y. Dai, J.D. McCalley, N. Abi-Samra, Vittal, "Annual risk assessment for overload security," IEEE Transactions on Power Systems, Volume 16, Issue 4, Nov 2001, PP. 616-623.

[18] H. Saadat, "Power System Analysis", book, McGraw Hill WCB, 2nd Edition, 2002.

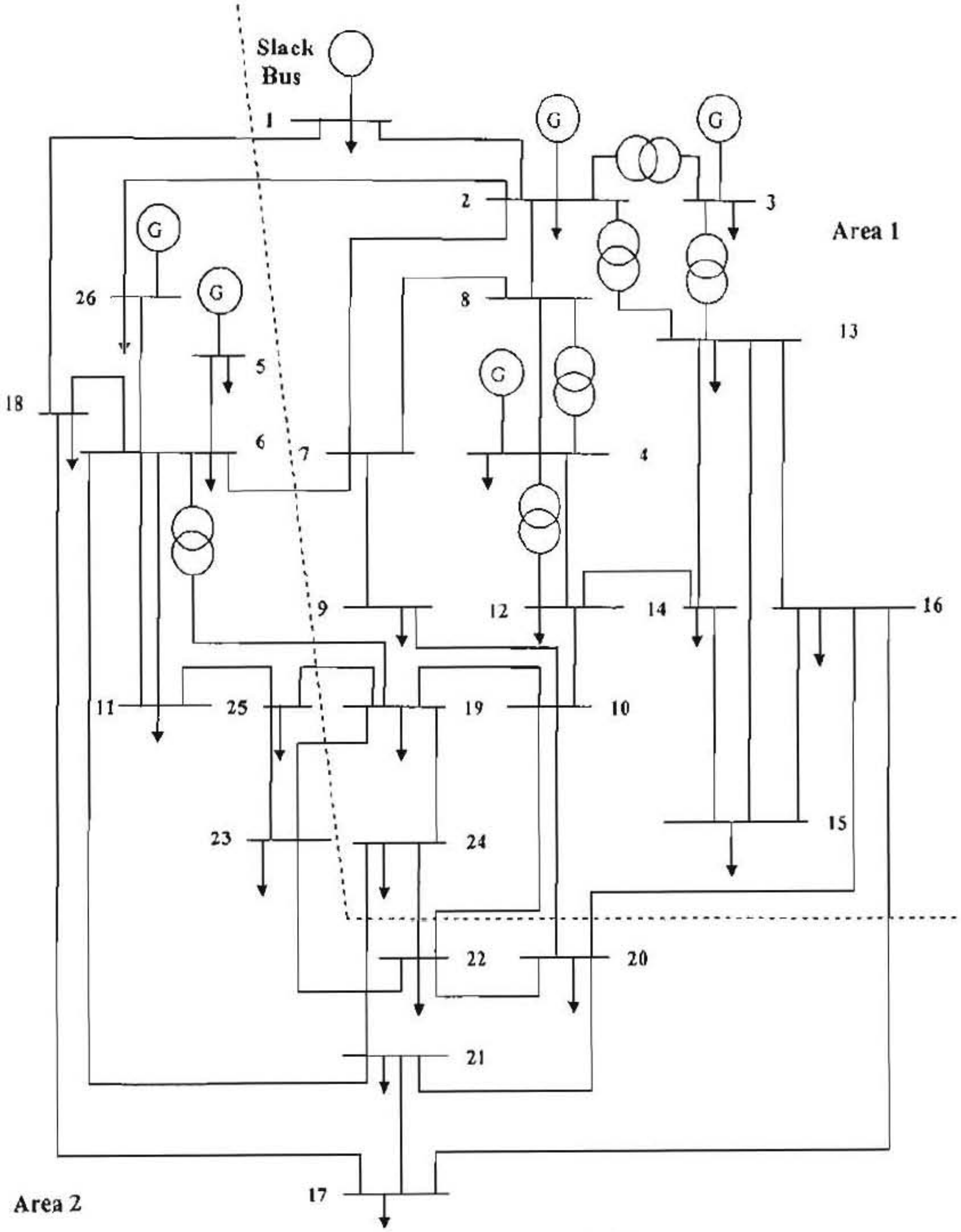

Figure 4. One-line diagram for 26-Bus System