Proceedings of the 5th WSEAS Int. Conf. on Power Systems and Electromagnetic Compatibility, Corfu, Greece, August 23-25, 2005 (pp347-352)

The Role of SVC on Power Quality and Suppressing the Possible Resonance inside the SVC by Active Filters in Distribution Systems

AHAD KAZEMI ROUZBEH SARAFRAZ
Electrical Engineering Department
Iran University of Science and Technology
IRAN

Abstract: In this paper, a new method for reactive power compensation by an SVC and an active filter is described and used for suppressing unbalanced three-phase distribution feeder with harmonic distortion. Here the classic SVC used for load balancing and power factor correction; also the small rating active filter is used to improve filtering characteristics of the passive filters inside the classic SVC. To control the firing angle of thyristors that used both in SVC and active filter, control signals are derived from the computation of active and reactive powers of the distribution feeders in the system. The results show this small rating of active filter makes the hybrid compensator a possible option inside the classic SVC. At last, the effect of 6-pulse SVC compensation is compared with 12-pulse SVC within the active filter in hybrid system.

Key-words: Static Var Compensator, Active Filter, Passive Filter, Harmonics.

1 Introduction

The purpose of reactive compensation is to change the natural electrical characteristics of the transmission lines to make it more compatible with the general load demand.
Var compensation is thus used for voltage regulation at the middle (or some intermediate) to segment the transmission line and at the end of the (radial) line to prevent voltage unsteadiness, as well as for dynamic voltage control to increase transient stability and damp power oscillations. According to the pollution of distribution systems as mentioned in [1], shunt and series active filters are used to improve the total power quality inside or instead of the FACTS devices. Active filters by frequently switching and injecting current to the point of common coupling perform the filtering job successfully and according to [2] are named as power converters. The reactive currents produced by unbalanced and balanced loads in a three-phase distribution feeder are often dynamic in nature. Disadvantage of negative sequence current produced by unbalanced loads, is additional generator, transmission line and transformer losses. The variation of the current is controllable by gate firing instant of the thyristors and thus of the conduction length in each half cycle.
The 6-pulse scheme produces not important third harmonics, but large amount of 5^{th} and 7^{th} harmonic currents are present (up to 5% of the rated TCR current) and harmonic filters are used to improve the distortion in power transmission. The 12-pulse design gives better harmonic compensation, the principal harmonics being 11^{th} and 13^{th}, which are of relatively low current magnitudes (around 1%), and harmonic filters can eliminate them. As mentioned in [4] closed-loop voltage for control of transmission and utility applications is recommended. By designing control systems for sudden changes of system voltage, the corresponding var change along the controlled slope line depend on the system short-circuit level can have a speed of response of one to three cycles.
Compensating the reactive power by using Active power inside the SVC is used in [5], [8]. Here the using of small rating of active filter to improve filtering characteristics of the passive filter inside the SVC and mitigate the possible resonance between the

Proceedings of the 5th WSEAS Int. Conf. on Power Systems and Electromagnetic Compatibility, Corfu, Greece, August 23-25, 2005 (pp347-352)

impedance of the system and the passive filters is discussed. This results show that the reactive power can be compensated perfectly with this method and the power factor would be improved, also this configuration is able to eliminate harmonic currents and can truly balance currents.

It is known that the SVCs with delta-connected thyristor controlled reactors (Δ-TCRs) and fixed capacitors (FCs) can be used to eliminate fundamental negative-phase sequence (NPS) currents and used to improve the power factor. This result is discussed in [6]. The SVC structure consist of a Δ-TCR and a Y-TCR, and a needed rating of passive filters used for compensating, where the Δ-TCR as mentioned in [7] is used to eliminate the NPS currents and compensate the imaginary part of the positive-phase sequence (PPS) currents while the Y-TCR eliminates the ZPS currents. In this paper a small rating of active filter inside the compensators such as SVC and shunt passive filter is tested in an unbalanced system. As in [7] the instantaneous analyzing of powers derives is used for control signals of TCRs and active filter.

2 Model and Characteristic of SVC

One of the best reactive shunt compensators is SVC. SVC by using a conventional PV (generator) bus with reactive power limits can be modeled as a slope representation. Its slope is typically 1-5%. SVC by producing and injecting the needed reactive power has the ability to overcome the limitation that imposed voltage stability in power systems. Voltage in the converted P-V busbars is fixed. In these busbars, Q is varied and voltage calculating is used in SVC to output reactive power analysis. If P-V busbars in distribution systems were well located, the tendency of the system against the voltage sags and voltage collapse is greatly reduce because the effective system strength at the P-Q busbars would be increased by the P-V busbars located nearby. According to [5] there is generally two kind of static var compensation equipment. The basic elements of a usual SVC are:

- Thyristor control rector (TCR)
- Thyristor switched capacitor (TSC)
- Fixed or mechanically switched capacitor/filter.

3 Implementing Filters beside SVCs

The SVC can give different quantity of reactive power to each phase to decrease the negative sequence currents and regulate the power factor to unity so that the power source provides only in phase-balanced currents. As mentioned in [5] this structure is twelve-pulse arrangement by Y-Y, and Y-Δ connected transformers and the revised structure of a TCR. Under unbalanced operation usually by loads, the fifth and seventh harmonics could not be eliminated by the twelve-pulse arrangement of TCRs. To overcome this problem, a combined system of a shunt passive filter in series with the small rating active filter to reduce the possible resonance in balanced systems is used. The small rating of active filter is also used to improve filtering characteristics of the passive filter and suppress possible resonance between the system impedance and the passive filter. This arrangement of active filter and passive filter inside the SVC is named hybrid compensation. In Fig.1, the studied system with the proposed hybrid compensator that is located between the load and the secondary side of the substation transformer is shown. The goal of using SVC in this system as a classic reactive power compensator is to compensate the imaginary part of positive sequence currents and fundamental frequency negative sequence currents.

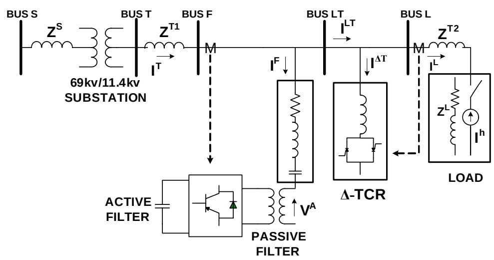


Fig.1 Distribution feeder with the proposed compensator [5]

3.1 Instantaneous power quantities

Control signals are derived from bus L by instantaneous calculating of power quantities for the thyristors of TCR in control system. This analysis is used for matching the TCR controlling and active filter. First the relationship between three-phase current at fundamental frequency in symmetrical mode with instantaneous power analysis must be described. To find this relationship, three-phase voltage and current are transformed into the α-β orthogonal coordinates as follow:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = [K] \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad , \quad \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = [K] \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{1}$$

where $[K]$ is the Clarke transformation matrix.

$$[K] = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \tag{2}$$

Only in the three phase three wire systems, the three phase currents can be declared in terms of positive and negative harmonic currents as follow:

$$i_a = \sum_h \sqrt{2}\,\mathrm{Re}[\bar{I}_{+,h} e^{jh\omega t} + \bar{I}_{\ ,h} e^{jjh\omega t}],$$

$$i_b = \sum_h \sqrt{2}\,\mathrm{Re}[\ \bar{I}_{+,h} e^{j(h\omega t\ \ \frac{2}{3}\pi)} + \bar{I}_{\ ,h} e^{j\ \ h\omega t\ \ \frac{2}{3}\pi}\ ],$$

$$i_c = \sum_h \sqrt{2}\,\mathrm{Re}[\ \bar{I}_{+,h} e^{j(h\omega t + \frac{2}{3}\pi)} + \bar{I}_{\ ,h} e^{j\ \ h\omega t + \frac{2}{3}\pi}\ ]. \tag{3}$$

where h is the harmonic order.

To describe the frame of α-β currents and voltages, it requires defining the instantaneous current and voltage vectors. These relations are defined as follows:

$$\bar{i} = i_\alpha + j i_\beta \quad , \quad \bar{v} = v_\alpha + j v_\beta \tag{4}$$

In addition, the vectors of instantaneous current and voltage can be written in terms of harmonic symmetrical currents as follow:

$$\bar{i} = \sum_h \sqrt{3}\left(\bar{I}_{+,h}\, e^{jh\omega t} + \bar{I}^{*}_{-,h}\, e^{-jh\omega t}\right),$$

$$\bar{v} = \sum_h \sqrt{3}\left(\bar{V}_{+,h}\, e^{jh\omega t} + \bar{V}^{*}_{-,h}\, e^{-jh\omega t}\right). \tag{5}$$

According to these equations, it is obvious that the positive sequence component of h^{th} harmonics rotates at an angular velocity of $h\omega$, while the negative sequence component rotates at an angular velocity of $-h\omega$.

To calculate the fundamental frequency symmetrical components from instantaneous powers, it is exigency to define the two complex quantities, ΔS and Δn as follows:

$$\bar{S} = \bar{v}.\bar{i}^{*} = (v_\alpha i_\alpha + v_\beta i_\beta) + j(v_\beta i_\alpha - v_\alpha i_\beta),$$

$$\bar{n} = \bar{p}^{n} + j\bar{q}^{n} = (v_\alpha i_\alpha \quad v_\beta i_\beta) + j(v_\beta i_\alpha + v_\alpha i_\beta) \tag{6}$$

Harmonic voltage distortion in comparing with harmonic current distortion has a smaller value. First, consider that the three-phase voltage has only fundamental frequency positive components that can be written as $\Delta v = \sqrt{3} V_{+,1}\, e^{i\omega t}$.

After calculating the real and imaginary part of fundamental frequency of positive and negative sequence currents, $\Delta I_{+,1}$ and $\Delta I_{-,1}$. The related equations are as follow:

$$Re(\bar{I}_{+,1}) - j\,Im(\bar{I}_{+,1}) = \frac{\bar{n}_{av}}{3V_{+,1}} = \frac{\bar{p}^{n}_{av} + j\bar{q}^{n}_{av}}{3V_{+,1}},$$

$$Re(\bar{I}_{-,1}) - j\,Im(\bar{I}_{-,1}) = \frac{\bar{s}_{av}}{3V_{+,1}} = \frac{p_{av} + jq_{av}}{3V_{+,1}}. \tag{7}$$

where subscript (av) corresponds to the average value.

3.2 Thyristor Controlled Reactor

The theory of load balancing with the SVC are well known and used in many cases to compensate the fluctuating in voltages at PCCs. To suppress the fundamental frequency negative sequence currents and imaginary part of positive sequence currents, some equations are needed as follows:

$$\bar{I}^{L}_{-,1} + \bar{I}^{\Delta T}_{-,1} + \bar{I}^{F}_{-,1} = 0,$$

$$\mathrm{Im}[\bar{I}^{L}_{+,1} + \bar{I}^{\Delta T}_{+,1} + \bar{I}^{F}_{+,1}] = 0. \tag{8}$$

where L corresponds to the load, ΔT to the TCR, F to the positive filter, +, - respectively to the positive and negative sequence components of current, and 1 to the fundamental frequency of current.

The TCR can inject different amount of reactive current to each phase and the TCR by installing the passive filter inside it, can suppress the negative sequence currents, and correct the power factor close to unity by controlling the conduction angle of the thyristors at each phase of TCR.

3.3 Passive filter structure

The TCR also has the ability to set susceptance in each cycle. This information should be acquired at first before the design of the passive filter, such as the harmonic current spectrum of the load and the TCR, the system impedance boundary, and the harmonic distortion limitation. According to the unbalanced operation of the TCR while switching, a third order harmonic filter is needed to compensate the generated harmonics by TCRs. As recent recommendations, small rating of active filter is proposed to compensate the disadvantages of passive filtering.

3.4 Active filter

The main goal of active filtering is to compensate the filtering characteristics of the passive filter that generates harmonics. The instantaneous values of the three phase harmonic currents at bus F, i^T_{iref}; as a reference voltage for the active filter is multiplied by a gain D and sent to the active filter as reference voltages as follow:

$$v^A_{iref} = D.i^T_{iref} \tag{9}$$

where $i = a, b, c.$ and A corresponds to the active filter and T to the transmission line. It is important to note that i^T_{iref} only contains the harmonic components of i^T_i. By using the instantaneous power analysis, it is possible to get the three phase harmonic currents by subtracting the α-β frame currents $i^T_{\alpha ref}$ and $i^T_{\beta ref}$, which are calculated as follow:

$$i^T_{\alpha ref} - j i^T_{\beta ref} = \mathrm{Re}\left(\frac{p^T_{\beta ref} + jq^T_{\beta ref}}{v^F_\alpha + jv^F_\beta}\right) + j\,\mathrm{Im}\left(\frac{p^T_{\beta ref} + jq^T_{\beta ref}}{v^F_\alpha + jv^F_\beta}\right) \tag{10}$$

substituting Eq. (10) into Eq. (4), $p^T_{\alpha ref}$, $q^T_{\alpha ref}$, $p^T_{\beta ref}$ and $q^T_{\beta ref}$ can be obtained from the equations shown below:

$$p^A_{\alpha ref} = p^F - p^F_{av} + \bar{p}^{nF}_{av},$$
$$q^A_{\alpha ref} = q^F - q^F_{av} + \bar{q}^{nF}_{av},$$
$$p^A_{\beta ref} = p^F - p^F_{av} - \bar{p}^{nF}_{av},$$
$$q^A_{\beta ref} = q^F - q^F_{av} - \bar{q}^{nF}_{av}. \tag{11}$$

For a larger D that could result with smaller I^T_h, a larger active filter capacity is needed. As in [5], [8], the selection of D value is based on trial and error methods. To overcome this problem, sending both the fundamental frequency voltage and the dc-side capacitor voltage to the control circuit of the active filter as the feedback signals is proposed.

4 Simulation Results

In appendix "A" case study is represented for simulation. The simulated system before any compensation is shown in Fig.2. Fig.3 shows the three-phase current. The active and reactive power in this condition is shown in Fig.4.

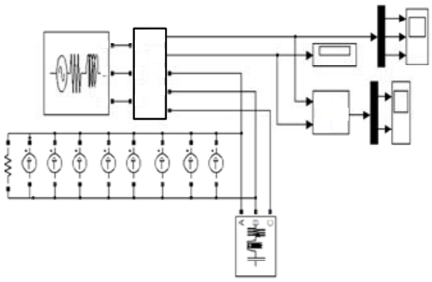


Fig.2 Simulated system before compensation

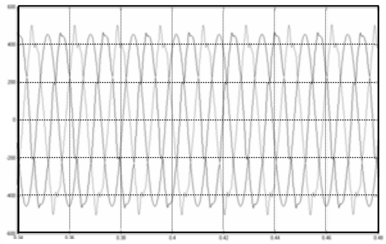


Fig.3 Three-phase currents before compensation

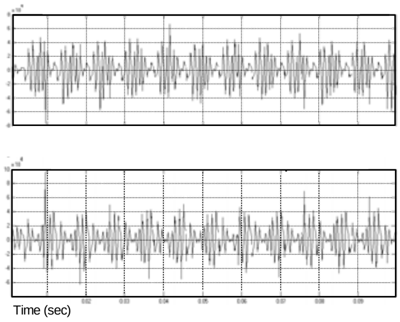


Fig.4 Active and Reactive powers before compensation

The system configuration of compensated system with passive filters is shown in Fig.5, also the improved three currents is shown in Fig.6. Active and reactive powers in this condition in the presence of passive filters are shown in Fig.7.

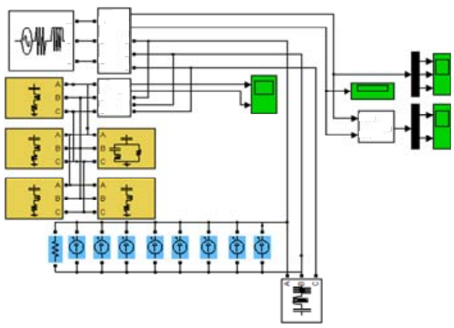


Fig.5 Simulated system in the presence of passive filters

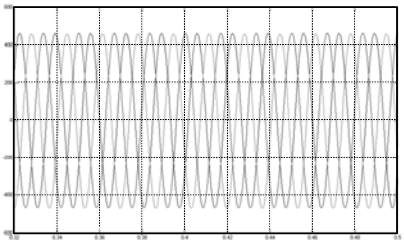


Fig.6 Improved Currents in the presence of passive filters

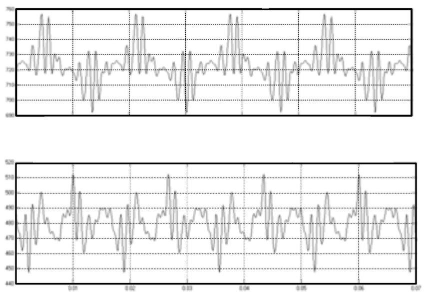


Fig.7 Active and Reactive powers in the presence of passive filters

The simulated system when adding SVC is shown in Fig.8. The references of dc-side capacitor C^A is 1000V. The gain D is set to 7.5, and the frequency of triangular carrier signal of PWM controller is 10 kHz. It is important to note that the capacity of the active filter is only 1.7% of the passive filter, so it is very used in very smaller rate rather than passive filters.

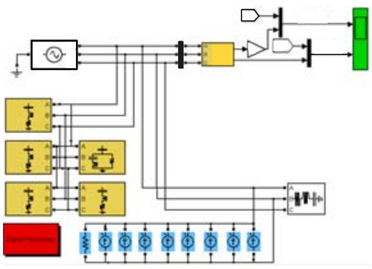
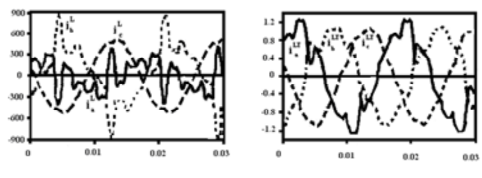


Fig.8 Simulated system when using SVC



a) Load currents b) Line currents of bus LT

Fig.9 Simulation results for the system with hybrid compensator

Fig.9 shows the simulation results when the system is compensated with the proposed hybrid compensator. As shown in Fig.9 (a) the load currents are unbalanced, and phases (a) and (b) are polluted with harmonic currents. Since the harmonic current distortion in phases (a) and (b) of bus LT is more severe than that of in phase (c), the magnitudes of $v^A{}_a$ and $v^A{}_b$ are larger than that of $v^A{}_c$. After compensating by the hybrid compensator, the currents at bus T are nearly balanced and sinusoidal. The numerical results of simulation without and with compensators are listed in Table 1.

According to the Table 1 the voltage and current harmonic distortions in the system with the hybrid compensator are very small. The classic SVC and the hybrid compensator improve the power factor from 0.52 to 0.979 and 0.993 respectively.

Table 1 rms values and harmonics of simulation results

	Without compensator	With 6-pulse classic SVC	With hybrid compensator
$I^T{}_a$, A	197.3	188.0	188.5
$I^T{}_b$, A	381.8	195.3	187.6
$I^T{}_c$, A	346.5	184.9	185.12
$I^T{}_{+1}$, A	137.5	184.8	186.9
$I^T{}_{-1}$, A	138	8.00	1.35
$V^F{}_{ab}$, V	11953	11900	11892
$V^F{}_{bc}$, V	11363	11876	11891
$V^F{}_{ca}$, V	11611	11894	11891
$V^F{}_{+1}$, V	11546	11886	11891
$V^F{}_{-1}$, V	250.9	15.28	1.09
P^F, MW	3.409	3.848	3.850
PF^F	0.52	0.979	0.993

After compensation with 6-pulse SVC, a new method can be used for better compensation. So the result of 6-pulse SVC compensation is compared with the 12-pulse SVC compensation which consist of a Δ-TCR, a Y-TCR and passive filters act as a classic SVC for load balancing, power factor correction and reactive power compensation in a three-phase, four-wire system. The configuration of this method for compensation is shown in Fig.10; this system is the same system configuration described in part 3. The results of this compensation method are listed in Table 2. According these results, it is found that in 12-pulse SVC compensation inside an active filter for hybrid compensation, the current total harmonic distortion (ITHD) decreases more than 6-pulse SVC compensation.

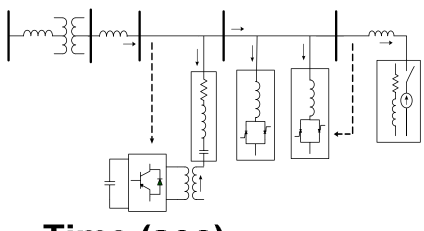


Fig.10 Distribution feeder with 12-pulse SVC and active filter [8]

Table 2 rms values and harmonics of simulation results

	Without compensator	With 12-pulse classic SVC	With hybrid compensator
I^T_a, A	278.6	147.9	143.6
I^T_b, A	101.7	147.9	149.5
I^T_c, A	240.6	144.0	142.9
I^T_0, A	38.36	2.00	1.80
I^T_+, A	196.54	141.9	142.8
I^T_-, A	57.55	1.32	2.22
V^F_a, V	6774	6890	6895
V^F_b, V	6895	6880	6889
V^F_c, V	6643	6899	6895
V^T_0, V	121.51	6.56	5.40
V^T_+, V	6725	6888	6892
V^T_-, V	61.8	1.36	2.49
P^T, MW	2.642	2.984	2.973
PF^T	0.569	0.986	0.999

5 Conclusion

In this paper, the effect of SVC on power quality and its practical uses is studied. In addition, a combined reactive power compensation method of an SVC and an active filter is proposed to balance load currents and correct power factor. The active filter can greatly improve the harmonics filtering ability of the passive filter in the SVC. First, the distribution feeder with the proposed hybrid compensator is studied, where a 6-pulse SVC is used to compensate the parameter of the system. The simulation results are shown in section 4. The result of using 12-pulse SVC as hybrid compensation to eliminate NPS, ZPS and the imaginary part of the PPS is also depicted in Table 2. The hybrid compensator shows better filtering in classic SVC. By comparing the compensation methods, it is found that by 12-pulse SVC using inside an active filter for hybrid compensation the current total harmonic distortion (ITHD) decreases more than 6-pulse compensation.

Appendix A: The Parameter of Studied System

The parameters of the studied system shown in Fig.3 are listed in Table 3 and 4.

Table 3 Parameters of distribution feeder

Distribution Line	Z^S	0.61+j2.61Ω	Z^{T1}	0.11+j0.45Ω
	Z^{T2}	0.6+j2.5Ω		
Transformer	69kV/11.4kV 25MVA Z=9%			
Load	Z^L_a	50+j50Ω	Z^L_b	10+j10Ω
	Z^L_c	10+j10Ω		
	I_{ab2}	10 < -90º	I_{ab9}	20 < -90º
	I_{ab3}	60 < 90º	I_{ab11}	40 < 90º
	I_{ab5}	100 < -90º	I_{ab13}	40 < -90º
	I_{ab7}	100 < 90º	I_{ab17}	20 < 90º

Table 4 Parameters of hybrid compensator

TCR	30MVAr			
Passive Filter	3^{rd}	4MVAr,Q=40	5^{th}	4MVAr,Q=40
	7^{th}	3MVAr,Q=40	9^{th}	1MVAr,Q=40
	11.5^{th}	3MVAr,m=0		
Active Filter	Matching transformer		0.25MVA	Z=10%
	jX^A	j0.3Ω	L^{R1}	84.43mH
	C^{R1}	0.3μF	R^{R2}	30Ω
	C^{R2}	3μF	C^A	5×10³μF

The definitions of passive filter parameters, Q and m, are given as follow:

$$Q = \omega_h \frac{L_h^F}{R_h^F} \;,\; m = \frac{L_h^F}{\left(R_h^D\right)^2 C_h^F} \tag{12}$$

where $R^D{}_h$ is damping resistor in parallel with the reactor.

To compare the performance of the classic SVC and the hybrid compensator, the parameters of the passive filter of the classic SVC are also listed in Table 5.

Table 5 Parameters of classic SVC

TCR	30MVAr	
Passive Filter	3^{rd}	6MVAr, m=0.02
	5^{th}	3MVAr, Q=40
	7^{th}	3MVAr, Q=40
	11.5^{th}	3MVAr, m=1

References:

[1] A. K. Jindal, A. Ghosh, A. Joshi, "The Protection of Sensitive Loads From Interharmonic Currents Using Shunt/Series Active Filter", Electric Power Systems Research, Elsevier Science, 2004

[2] R. El. Shatshat, M. Kazerani, M. M. A. Salama, "Power Quality Improvement in 3-phase Distribution Systems Using Modular Active Filter", Electric System Research, Elsevier Science, pp. 185-194, 2002

[3] K. T. G. Wong, "The Role of Static VAR Compensators In Staving Off Voltage Collapse", T&D Power Electronic Systems Limited, The Institution of Electrical Engineers, Printed and Published by the IEE, Savoy Place, London WC2R 0BL, UK, 1997

[4] A. T. Johns, A. Ter-Gazarian, D. F. Warne, "Flexible ac Transmission Systems (FACTS)", Published by the Institution of Electrical Engineers, London, The Institution of Electrical Engineers, 1999

[5] A. T. Johns, A. T. Gazarian, D. F. Warne, "Flexible ac Transmission Systems (FACTS)", Published by The Institution of Electrical Engineers, London, The Institution of Electrical Engineers, 1999

[6] S. Y. Lee and C. J. Wu, "Combined Compensation Structure of an SVC and an Active Filter for Unbalanced Three Phase Distribution Feeders with Harmonic Distortion", Fourth Conference on Advanced in Power System Control, Operation and Management, Vol. 2, No. 450, pp. 543-548, November 1997

[7] W. E. Kazibwe and M. H. Sendaula, "Electric Power Quality Control Techniques", Van Nostrand Reinhold, 1993

[8] H. Fujita and H. Akagi, "A Practical Approach to Harmonic Compensation in Power System Series Connection of Passive and Active Filters", IEEE Transaction, Vol. 6, pp. 1020-1025, 1991