**Mahammad A HANNAN**

Universiti Kebangsaan Malaysia

# Effect of DC Capacitor Size on D-STATCOM Voltage Regulation Performance Evaluation

***Abstract**. This paper describes the modelling and simulation of distribution static compensator (D-STATCOM) focused with effect of DC capacitor size and voltage regulation. Different capacitor values have been investigated to reduce the load ripple voltage during the charging and discharging of the capacitor. The optimum capacitor valuse has been determined to obtained the lowest ripple voltage within the rage of 8%. Capacitive and inductive mode of D-STATCOM operation have been also investigated and obtained results proved that the capability of the D-STATCOM in regulating the system voltage is near to the rated value of 1.0 p.u.*

***Streszczenie.** W artykule przedstawiono sposób budowy modelu i symulacje kompensatora pasywnego D-STATCOM, ze naciskiem na analizę wpływu pojemności kondensatorów oraz regulacji napięcia na jego działanie. Badania wykonano dla różnych pojemności i wyznaczono optymalną, zapewniającą najmniejsze wahania napięcia (w zakresie 8%). Analizie poddano działanie kompensatora przy charakterze pojemnościowym i indukcyjnym. (**Badanie wpływu pojemności kondensatora DC na skuteczność regulacji napięcia kompensatora pasywnego D-STATCOM**)*

**Keywords:** D-STATCOM, DC capacitor, power quality, voltage ripple, voltage regulation.
**Słowa kluczowe:** D-STATCOM, kondensator DC, jakość energii, wahania napięcia, regulacji napięcia.

## Introduction

D-STATCOM is a kind of custom power device which is used to regulate the system voltage and thereby protect the distribution system from power quality disturbances such as voltage sags, swells, voltage flicker and voltage unbalance [1, 2]. The main components of the D-STATCOM are the inverter using either GTO or IGBT, dc capacitor, coupling transformer and control system. It can be regarded as an active energy-exchanging device because it utilizes the passive energy storage component to realize the energy storing and exchanging and the switches to control the reactive power flow between different phases of a distribution system [3, 4]. The reactive power provided by the D-STATCOM is either capacitive or inductive depending on whether the magnitude of the D-STATCOM output voltage is larger or smaller than the magnitude of the system voltage [5, 6].

In recent years, D-STATCOM has been extensively studied in which many papers in the literature have discussed its theory, modelling, control and applications [3-9]. Design and performance evaluation of a D-STATCOM requires extensive analysis of the interaction between the D-STATCOM and the associated distribution system. Such an analysis is usually done by using time-domain simulation tools.

In the operation of D-STATCOM, the problem of power quality problems like voltage regulation, ripple voltage, harmonics generated by the device have been addressed in [3, 10]. Methods for reducing ripple voltage, harmonics produced by D-STATCOM are by means of capacitance effects and the PWM switching technique and filters. Studies on the use of D-STATCOM in improving voltage regulations have been investigated by many researchers [11-14]. The D-STATCOM is simulated on a test distribution system for improving voltage regulation to critical loads by either absorbing or injecting reactive power on an ac system at the distribution voltage. Sensarma et al. (2001) and Dong et al. (2000) addressed the application of D-STATCOM for voltage sag compensation and solving the problem of voltage unbalance [15, 16].

The D-STATCOM is a shunt reactive power compensating device functions as a controlled shunt reactive admittance and generates ac voltage, which in turn causes a current injection into the system through a shunt transformer [17]. The injected current is kept in quadrature with the load voltage to achieve the desired voltage correction by injecting only reactive power into the system [18]. However, for higher voltage sags, injection of active power in addition to reactive power is essential to correct the voltage magnitude. Shunt reactive power compensator is capable of generating or absorbing reactive power but the active power injection of the device must be provided by an external energy source. So as to reduce the ripple voltage and improve voltage regulation, an optimum size of capacitance is to be needed.

This paper deals with the development of a D-STATCOM model with focus on the effect of capacitance towards ripple voltage and regulation in a test distribution system. The concept of shunt reactive power compensation and the theory behind the D-STATCOM mode of operation has also been explained.

## Determination of Capacitor Size

The capacitor plays an important role in the D-STATCOM operation by acting as a dc source to provide reactive power to the load. An optimum size of dc capacitor can be determined by considering its physical size, cost and the possibility of resonance for a given coupling reactance. If the frequency of the resulting harmonic component coincides with the resonance frequency of the dc capacitor and the coupling reactance then the resulting harmonic distortion at the ac side can be very high. The dc capacitor resonance may lead to excessive magnifications of some harmonic components and increasing harmonic distortion of the D-STATCOM current. In the simulation, the coupling reactance is not considered so the possibility of harmonic resonance to occur will be reduced. But consideration of harmonic resonance is given because loads are inductive and this may have some effect on the dc capacitance.

To determine the dc capacitor size, $C_{dc,}$ firstly consider the energy loss of the capacitor in one period as [19],

(1) $$\Delta E_c(t) = \frac{C_{dc}}{2}\left\{V_{c,\ max}^2 - V_{dc}^2\right\}$$

where, $V_{c,max}$ is the pre-set upper limit of the voltage across the capacitor, $V_{dc}$ is voltage across the capacitor and $C_{dc}$ is dc capacitor.

But the energy loss is also supplied by the utility voltage source, $V_S$ and the peak value of the charging current, $I_{SC}$, in which the energy loss can be written as,

(2) $$\Delta E_c(t) = \int_0^T V_S\, sin\omega t\ \ I_{SC}\ sin\omega t\, dt$$

Simplifying equation (2),

(3) $\Delta E_c(t) = V_{SC} I_{SC} \int_0^T \sin^2 \omega t\, dt = \frac{1}{2} V_{SC} I_{SC}\, T$

where, $V_S$ is peak phase voltage of the D-STATCOM and $T$ is the period of one cycle

Equating equations (1) and (3), gives,

(4) $$\frac{C_{dc}}{2}\left\{V_{c,\ max}^2 - V_{dc}^2\right\} = \frac{1}{2} V_{SC} I_{SC}\, T$$

While the load current is reduced, the charging current $I_{SC}$ will be equal to the change in load current $\Delta I_L$ . Hence, an extra utility source current $\Delta I_L$ will charge the energy storage capacitor. Substituting $\Delta I_L$ for $I_{SC}$, equation (4) becomes,

(5) $$\frac{C_{dc}}{2}\left\{V_{c,\ max}^2 - V_{dc}^2\right\} = \frac{1}{2} V_{SC} \Delta I_L\, T$$

where, $\Delta I_L$ is the step drop of load current which can be determined by the difference between the load current before and during faults. .

Therefore, using equation (5) the dc capacitance value for a three phase system can derived as,

(6) $$C_{dc} = 3\, \frac{V_S\, \Delta I_L T}{V_{c,\ max}^2 - V_{dc}^2}$$

where, $V_{dc}$ is the $\frac{3\sqrt{3}}{\pi} V_S$ and the derivations of $V_{dc}$ and equation (6) can be found in [20, 21], respectively.

Thus, to calculate the dc capacitance value, the load currents profile at the distribution system without the D-STATCOM connected is obtained 102 A. This current is dropped to 78 A during a voltage sag which is due to a three-phase fault as shown in Fig. 1. From Fig. 1, $\Delta I_L$ is 24×22/4.16 = 126.92 A. The value of $V_{dc}$ is also calculated and found to be 5.45 kV. So, for $V_S$ = 3.3 kV, $\Delta I_L$ = 126.92 A, T = 20 ms, $V_{Cmax}$ = 6.33 kV and $V_{dc}$ = 5.45 kV, the dc capacitance value is calculated using equation (6) and found to be 2430 μF.

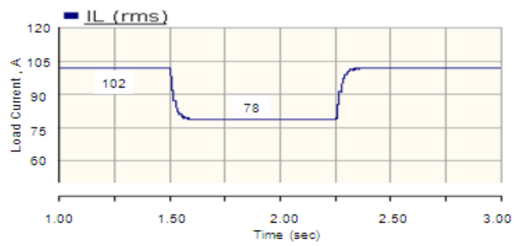


Fig. 1. Load current at the distribution system without the D-STATCOM

**Mode of D-STATCOM Operation**

The operation of the D-STATCOM, the active and reactive power flows ($P_S$, $Q_S$) between the system voltage and the D-STATCOM voltage are considered and written as [19],

(7) $$P_S = \frac{V_S\, V_M}{X_L} \sin\delta$$

(8) $$Q_S = \frac{V_S}{X_L}(V_S - V_M)\cos\delta$$

where $V_S$ is the system voltage, $V_M$ is the D-STATCOM voltage, $X_L$ is the line reactance and $\delta$ is the phase angle displacement between $V_S$ and $V_M$.

From equation (8), it can be implied that reactive power exchange between the D-STATCOM and the ac system is controlled by varying the amplitude of the D-STATCOM output voltage. If the ac system voltage is lower than the D-STATCOM output voltage, that is, $V_S < V_M$, current will flow through the transformer from the inverter into the ac system, and the device acts as a capacitor which generates reactive power. However, if the ac system voltage is greater than the D-STATCOM output voltage, that is, $V_S > V_M$, current will flow from the ac system into the inverter, resulting in the device acting as an inductor which absorbs reactive power. By controlling the D-STATCOM output voltage, the capacitor voltage can be decreased or increased so as to control the reactive power output of the device. The operating modes of the D-STATCOM showing leading and lagging conditions are illustrated in Fig. 2.

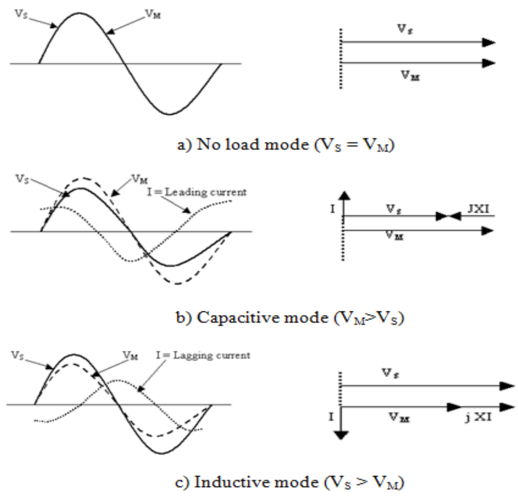


Fig. 2. Operation modes of D-STATCOM

The real power exchange between the D-STATCOM and the ac system can be controlled by adjusting the phase shift between the D-STATCOM output voltage and ac system voltage. The D-STATCOM can supply real power into the ac system if the D-STATCOM output voltage is leading the system voltage, that is, δ>0. On the other hand it absorbs real power from the ac system if its voltage lags behind the system voltage, that is, δ <0.

The capacitor in the D-STATCOM is used to maintain dc voltage to the inverter. The amplitude of the inverter voltage $V_M$ is proportional to the dc voltage of the capacitor, which is proportional to the amount of energy stored in capacitor. If there is a small lagging or leading phase shift, active power flows through the inverter, charging or discharging the capacitor. The charging or discharging of the capacitor affects the dc voltage level and consequently, alters the amplitude of the inverter ac voltage.

**D-STATCOM in a Distribution *System***

A simplified distribution system model has been chosen as a test system for investigating the performance of the D-STATCOM. The system considers several static and induction motor (IM) loads, which are connected to a common load bus. The D-STATCOM is connected in shunt between the loads and the 22 kV substation. The detailed load characteristics of various ratings are given in Table 1. The D-STATCOM in the test distribution system has been implemented in PSCAD/EMTDC.

Table 1 Loads in the test distribution system

| Load | Type | Rating | Parameters | |
|---|---|---|---|---|
| | | | R (Ω) | L (H) |
| Load 1 | RL | 1.2 MVA, 0.90 P.F. | 363.33 | 0.46 |
| Load 2 | RL | 0.5 MVA, 0.95 P.F. | 871.21 | 1.119 |
| Load 3 | IM | 1600 H P, 50 Hz | --- | --- |
| Load 4 | IM | 1600 H P, 50 Hz | --- | --- |
| Load 5 | RL | 1.2 MVA, 0.90 P.F. | 363.33 | 0.46 |

**Results and Discussion**

To evaluate the performance of the D-STATCOM, it is simulated using the PSCAD/EMTDC transient simulation program. There are twelve single-phase transformers with each rated at 5 MVA, 22/4.16 kV and a leakage reactance of 0.01 p.u. Simulations were carried out to illustrate the effect of dc capacitor size, D-STATCOM as voltage regulator. Prior to simulations, sizing of dc capacitance value, D-STATCOM mode of operation were investigated.

**Effect of DC Capacitor Sizing:** As mentioned earlier, the size of DC capacitor is chosen by considering its physical size, cost and performance of the D-STATCOM. To investigate the effect of the capacitance on the performance of the D-STATCOM, the capacitance values are varied using the values of 1500 μF, 1800 μF, 2000 μF. However, an optimum capacitance value of 2430 μF is calculated using equation (6). To illustrate the effect of the capacitance, simulations were carried on the D-STATCOM by creating a three phase fault at time t=1.5 s for a duration of 0.75 s. During the fault condition, a voltage sag condition is created and the D-STATCOM performs its voltage sag mitigation capability. In this simulation, the load voltage responses are recorded for different capacitance values as shown in Fig. 3.

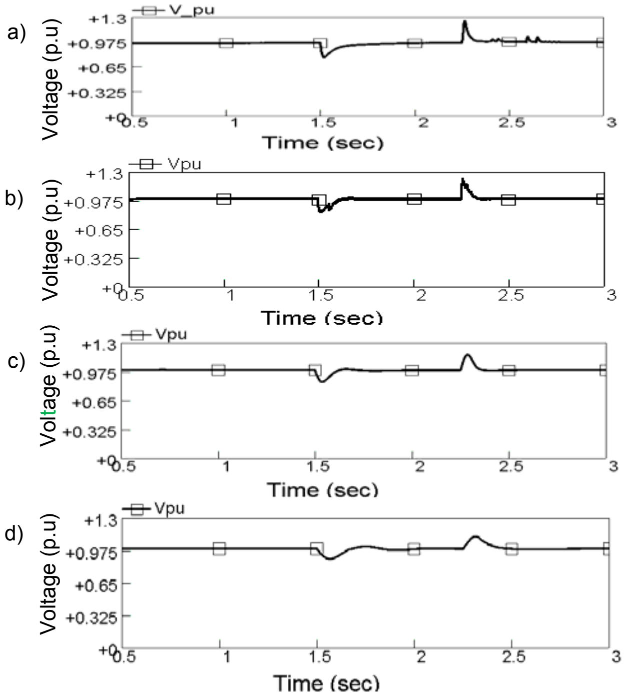


Fig. 3. Load voltage response for capacitance values of a) 1500 b) 1800 c) 2000 d) 2430 μF.

Table 2 Effect of DC capacitance on ripple voltage

| DC Capacitance value in μF | Max Ripple Voltage in p.u | Min Ripple Voltage in p.u |
|---|---|---|
| 1500 | 1.29 | 0.82 |
| 1800 | 1.23 | 0.86 |
| 2000 | 1.17 | 0.89 |
| 2430 | 1.08 | 0.94 |

The load ripple voltages which are due to the charging and discharging of the capacitor can be seen in the figure and are recorded as shown in Table 2. Results shown in Table 2 indicate that by increasing the capacitance values, the range between the per unit maximum and minimum ripple voltages decreases. Using the optimum capacitance value of 2430 μF, the lowest ripple voltage can be obtained to within the range of 8% considering an ideal voltage of 1.0 per unit.

**D-STATCOM as a Voltage Regulator:** To show the effectiveness of the D-STATCOM in providing continuous voltage regulation, simulations were carried under two load conditions, that is, considering either a capacitive load or an inductive load in which both are rated at 1.2 MVA. Simulations were first carried out by considering a purely capacitive load and the results are shown in Fig. 4 (a) in which it indicates that without the D-STATCOM connected in the distribution system, the effect of the capacitive load results in a high load voltage of 1.10 p.u. With the D-STATCOM connected and switched at time t = 0.45 s, the load voltage returns to near its rated voltage of 0.996 per unit as shown in Fig. 4 (b). Figure 5.8 shows the D-STATCOM current lagging behind the load voltage by 90 degrees so as to illustrate the operation of the D-STATCOM as an inductive compensator.

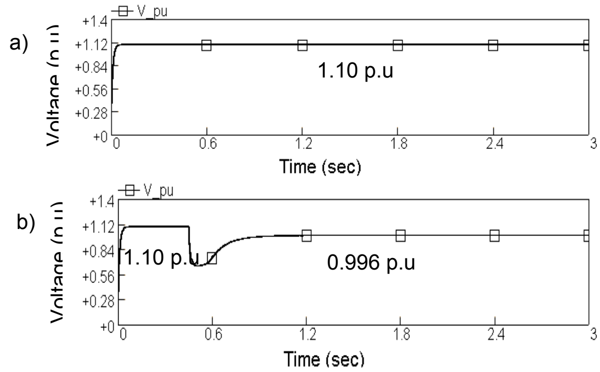


Fig. 4. Capacitve load voltage a) without b) with D-STATCOM

To illustrate further the operation of the D-STATCOM as an inductive compensator, the dc voltage and the reactive power responses are measured and shown as in Fig. 5. It can be seen that the excess MVAr generated by the capacitive load is absorbed by the D-STATCOM and the dc capacitor voltage is reduced, thus reducing the overall system voltage from 1.1 p.u to 0.996 p.u.

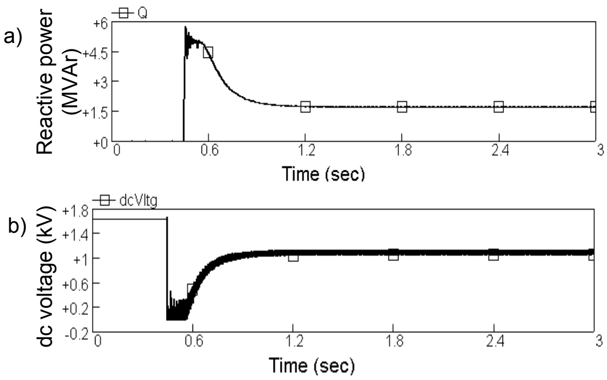


Fig. 5. Reactive power of the system and dc capacitor voltage

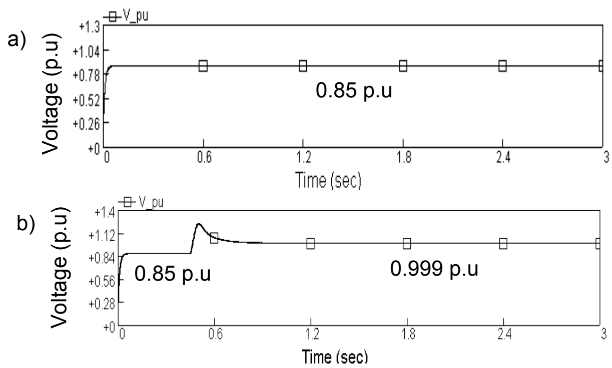


Fig. 6. Inductive load voltage a) without and b) with D-STATCOM

To simulate a relatively low voltage condition, the system is connected to a purely inductive load. Fig. 6 (a) shows the system voltage response under an inductive load condition in which the voltage reaches a low steady-state value of 0.85 p.u. without the D-STATCOM connected in the distribution system. By connecting the D-STATCOM to the system, the system returns to its rated voltage of 0.999 p.u within a very short time as shown in Fig. 6 (b).

Fig. 7 shows that the reactive power is generated and the dc voltage is increased, so as to increase the load voltage from 0.85 p.u. to 0.999 p.u as shown in Fig. 7 (b). These results thus prove the capability of the D-STATCOM in regulating the system voltage to near its rated value of 1.0 p.u.

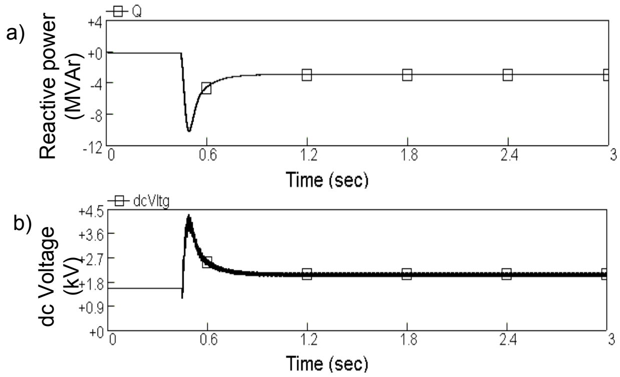


Fig. 7. Reactive power of the system and dc capacitor voltage

**Conclusion**

The simulation of D-STATCOM model focused on effect of capacitance towards ripple voltage and regulation in a test distribution system were developed using the PSCAD/EMTDC electromagnetic transient program. In this studies, the effect of the capacitance values of 1500 μF, 1800 μF, 2000 μF and 2430 μF have been investigated on the performance of the D-STATCOM. However, an optimum capacitance value of 2430 μF provides the lowest ripple voltage within the range of 8% considering an ideal voltage of 1.0 per unit. Capacitive and inductive load have been considered to to show the effectiveness of the D-STATCOM in providing continuous voltage regulation. In both cases, the D-STATCOM provides near its rated voltgae to the distribution system. This study has been made the suitable capacitance value on the effectiveness of the D-STATCOM in reducing ripple in a test distribution system. The improved simulation models, analyses on the capacitance values have been addressed and provided a better understanding of the compatibility between the D-STATCOM, the distribution system and loads. Thus, this model can be used as a basis for the development of prototype D-STATCOM.

REFERENCES


[1] Patil K. V., Dynamic Compensation of Electrical Power Systems using a new BVSI STATCOM, A thesis of Doctor of Philosophy, 1999, Department of Electrical & Computer Engineering, Faculty of Engineering Science, The University of Western Ontario, London, Ontario, Canada.

[2] Hannan M. A., Chan K. W., Modern Power Systems Transients Studies Using Dynamic Phasor Models, *The proceeding of the International Conference on Power System Technology,* Singapore, 21-24 November 2004, pp 1-5.

[3] Dong S., Wang Z., Chen, J. Y., Song Y. H., Harmonic Resonance Phenomena in STATCOM and Relationship to Parameters Selection of Passive Components. *IEEE Trans. on Power Delivery* 16 (2001), 46-52.

[4] Floricau D., Floricau E., Kisch D., Spataru L., The active-SNPC multilevel converter and its total loss balancing, *Electrical Review*, 9(2010), 284-288.

[5] Mohaddes M., Gole A. M., Sladjana M., Steady State Frequency Response of STATCOM. *IEEE Transactions on Power Delivery,* 16 (2001), 18-23.

[6] Ya ng H., Lin X., Muhammad K., Chen C., Power balancing control strategies for the cascaded H-bridge multilevel DSTATCOM, *Electrical Review*, 02(2011), 212-219.

[7] Sutanto D., Snider L. A., Mok K. L., EMTP simulation of a STATCOM using Hysteresis Current Control, *IEEE International Conference on Power Electronics and Drive Systems (*PEDS), July, Hong Kong, 1999.

[8] Carlos A. C., Watanabe E. H., Aredes, M., Multi-pulse STATCOM operation under unbalanced voltages, *IEEE Power Engineering Society Winter Meeting* 1 (2002), 567 –572.

[9] Peter W. L., A Benchmark System for Simulation of the D-STATCOM, *IEEE Transactions on Power Delivery* 12 (2002), 496-498.

[10]Mohaddes M., Gole A. M., claren P. G., A Neural Network Controlled Optimal Pulse-Width Modulated STATCOM, *IEEE Trans. On Power Delivery,* 14 (1999): 481-488.

[11] Peter W. L., A Benchmark System for Simulation of the D-STATCOM, *IEEE Transactions on Power Delivery,* 12(2002), 496-498.

[12]Garcia-Gonzalez P., Garcia-Cerrada A., Control System for a PWM Based STATCOM, *IEEE Transactions on Power Delivery,* 15 (2002): 1252-1257.

[13]Hannan M. A., Mohamed A., PSCAD/EMTDC Simulation of Unified Series-Shunt Compensator for Power Quality Improvement, *IEEE Transaction on Power Delivery*, 20(2005), 1650-1656.

[14]Hannan M. A., Mohamed A., Hussain A., Dabbay M., Power Quality Analysis of STATCOM using Dynamic Phasor Modeling, *International Journal of Electric Power System Research,* 79(2009), 993-999.

[15]Sensarma P. S., Padiyar K. R., Ramanarayanan, V., Analyses and Performance Evaluation of a Distribution STATCOM for Compensating Voltage Fluctuations, *IEEE Trans. on Power Delivery,* 16 (2001): 259-264.

[16]Dong S., Wenhua L., Wang Z., Study on the Operation Performance of STATCOM under Unbalance and Distorted System Voltage, *IEEE Power Engineering Society Winter Meeting,* 4 (2000), 2630 –2635.

[17]Gyugyi L., Application characteristics of converter-based FACTS controllers power system technology, *Proceedings of International Conference on PowerCon.*, 1 (2000), 391 –396.

[18]Haque M. H., Compensation of distribution system voltage sag by DVR and D-STATCOM, *Proceedings, IEEE Porto Power Tech Conference,* 1 (2001), 5-10.

[19]Hannan M. A., Modelling and Simulation of Custom Power Devices for Power quality Improvement, M. Sc. Thesis, Faculty Enegineering and Built Environment, Universiti Kebasaan malaysia, 2003.

[20]Rashid M. H., Spice for Power Electronics and Electric Power, Prentice Hall, Englewood Cliffs, New Jersey 07632, 1993.

[21]Chin-Yuan H., Horng-Yuan W., A new single-phase active power filter with reduced energy storage capacitor, *IEEE 26th Annual Power Electronics Specialists Conference,* 1 (1995), 202 –208.



***Authors**: Associate Prof. Dr M A Hannan. Dept. of Electrical, Electronic & Systems Engineering, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia; Corresponding author e-mail: hannan@eng.ukm.my*