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# Cost estimation for reactive power compensation in distribution power system by using D-STATCOM

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## ABSTRACT

The D-STATCOM is most widely used for power factor correction, load balancing, and load voltage regulation in distribution system. Although significant improvements in the overall power quality can be achieved, the high cost of the D-STATCOM can limit the benefits resulting from its application. This paper presents cost estimation of the D-STATCOM for reactive power compensation. The voltage regulation, power factor correction and energy loss reduction are chosen as the main target for the investigation. The process of costs estimation and comparing the different sizes for improving performance involves determining the net present values (NPV) for each size, including the sum of all benefits and costs of implementing the D-STATCOM. The 5 MW with power factor = 0.80 industrial plant supplied by the Nakhonrachasima electricity authority, Thailand is used in this paper.

## 1. INTRODUCTION

The flexible AC transmission technology (FACT) allows a greater control of power flow. Since these devices provide very fast power swing damping, the power transmission lines can be securely loaded up to their thermal limits. In a similar way power electronic devices can be applied to the power distribution systems to increase the reliability and the quality of power supplied to the customers. The technology of the application of power electronics to power distribution system for the benefit of customers is called custom power devices (CPDs). The concept of CPDs was introduced by Hingorani and Gyugyi (1995). The CPD provides an integrated solution to the present problems that are faced by the utilities and power distributions. Through this technology the reliability of the power delivered can be improved in terms of reduced interruptions and reduced voltage variations. The proper use of this technology will benefit all the industrial, commercial and domestic customers.

The CPDs are basically of two types as network reconfiguring type and compensating type. The network reconfiguring equipment can be GTO based or thyristor based. They

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are usually used for fast current limiting and current breaking during faults. They can also prompt a fast load transfer to an alternate feeder to protect a load from voltage sag / swell or fault in the supplying feeder. The compensating devices are used for active filtering, load balancing, power factor correction and voltage regulation. The active filters, which eliminate the harmonic currents, can be connected in both shunt and series. However, the shunt filters are more popular than the series filters because of greater ease of protection. A D-STATCOM is basically a shunt connected bidirectional converter based device which can act as a generalized impedance converter to realize either inductive or capacitive reactance by changing its output voltage levels (Bhattacharya et al., 1997). By proper tracking of the load current, the converter can generate such voltages and currents so that the harmonics and oscillations generated by the load current do not get transmitted to the supply side. A state of art D-STATCOM is capable of cancelling or suppressing; the effect of poor load power factor, the effect of poor voltage regulation, the harmonics introduced by the load, the DC offset in loads such that the current drawn from the source has no offset, the effect of unbalanced loads such that the current drawn from the source is balanced, and if provided with an energy storage system, it can perform load leveling when the source fails. Therefore, the D-STATCOM can solve most of the customer's load related to power quality problems. Furthermore, the major attributes of D-STATCOM are quick response time, less space requirement, optimum voltage platform higher operational flexibility and excellent dynamic characteristics under various operating conditions.

Although significant improvements in the overall power quality can be achieved, the high cost of the D-STATCOM can limit the benefits resulting from its application. This paper presents cost estimation of the D-STATCOM for reactive power compensation. The voltage regulation, power factor correction and energy loss reduction are chosen as the main target for the investigation. The process of costs estimation and comparing the different sizes for improving performance involves determining the net present values (NPV) for each size, including the sum of all benefits and costs of implementing the D-STATCOM. The 5 *MW* with power factor = 0.80 industrial plant supplied by the Nakhonrachasima electricity authority, Thailand is used in this paper.

## 2. BENEFITS AND COSTS OF REACTIVE POWER COMPENSATION

Power quality problems can lead to a number of costs to industrial and commercial facilities. These costs can include the value of lost production, increased labor costs, damage to work-in-process with resulting reduced value or costs of reworking, value of lost materials, equipment damage, revenue (opportunity) loss due to failure to perform contracts, transaction processing losses and the need to ration services to customers. Table 1 shows average costs of a single power interruption for industrial plants.

**Table 1** Average costs of a single power interruption for industrial plants

| Plants | Costs |
|---|---|
| All plants | 214.21(*Baht*) / *kW* + 303.48(*Baht*) / *kWh* |
| Plants > 1,000 *kW* max. demand | 118.93(*Baht*) / *kW* + 106.60(*Baht*) / *kWh* |
| Plants < 1,000 *kW* max. demand | 519.69(*Baht*) / *kW* + 918.45(*Baht*) / *kWh* |

Costs will typically vary with the severity (both magnitude and duration) of the power quality disturbance. This relationship can often be defined by a matrix of weighting factors. The weighting factors are developed using the cost of a momentary interruption as base. The weighted events can then be summed, and the total is the total cost of all the events expressed in the number of equivalent momentary interruptions. Table 2 provides an example of weighting factors that were used for one investigation. The weighting factors can be further expanded to differentiate between sags that affect all three phases and sags that only affect one or two phases. Furthermore, Table 3 provides a hypothetical example of the power quality disturbances seen by a large commercial or industrial customer on a distribution system (Darrow and Hedman, 2005). As can be seen in this table, the sags trip sensitive equipment off-line resulting in a 50 minutes loss of productivity for the facility for each occurrence whereas the momentary interruptions disrupt the facility for 1.4 hours each time. Recovery from such a long duration outage requires 4 hours.

**Table 2** Example of weighting factors for different voltage sag magnitudes

| Event Category | Weighting for Economic Analysis ($W_{int}$) |
|---|---|
| Interruption | 1.0 |
| Sag with min. voltage below 50% | 0.8 |
| Sag with min. voltage between 50 and 70% | 0.4 |
| Sag with min. voltage between 70 and 90% | 0.1 |

**Table 3** Power quality disruption and facility disruption per occurrence

| Power quality disruption | Duration per occurrence | Facility disruption per occurrence (*F*) |
|---|---|---|
| Voltage sags | 0 - 2 seconds | 50 minutes |
| Momentary interruptions | 0 - 2 seconds | 1.4 hours |
| Long duration interruptions | 2 - 60 minutes | 4.0 hours |

Note that the D-STATCOM cannot completely mitigate for all of sags and interruptions. For example, the D-STATCOM designed for 100% mitigation of sags with minimum voltage over 65% can mitigate about 20 – 30% for sag with minimum voltage below 50%. Thus, benefit due to voltage sag mitigation can be calculated as follows.

$$\Phi_{sag} = k_{sag} \times F_{int} \times \left(W_{bef} - W_{aft}\right) \times Cap \qquad (1)$$

where

$\Phi_{sag}$ is benefit due to voltage sag mitigation (*Baht*)

$k_{sag}$ is the cost of per unit losses (*Baht / kWh*)

$F_{int}$ is the facility of momentary interruption (*h*)

$W_{bef}$ , $W_{aft}$ are weighting factors before and after mitigation for different voltage sag magnitudes

$Cap$ is the capacity of customer (*kW*)

In general, installing a reactive power source such as the D-STATCOM can correct the load power factor as well as reducing the electricity charge when the loads have low power factor. The corrected power factor may be interpreted as a reduction of the electricity charge from the utility. Thus, the reduction of the low power factor charge can be expressed as follows.

$$\Phi_{PF} = k_{PF} \times Q_{com} \tag{2}$$

where

$$Q_{com} = P_L \left( \sqrt{\frac{1-PF_{old}^2}{PF_{old}^2}} - \sqrt{\frac{1-PF_{\min}^2}{PF_{\min}^2}} \right) (kVar)$$

$PF_{\min}$ is the acceptable minimum power factor

$PF_{old}$ is the power factor before installation

$\Phi_{PF}$ is benefit due to power factor correction (*Baht*)

$k_{PF}$ is the cost of low power factor charge (*Baht* / *kVar*)

The power losses of the power distribution system can be reduced by the installing of the reactive power source such as the D-STATCOM. The saved power losses may be interpreted as a reduction of the cost of the electric power supplying. Thus, the reduction of the electric energy charge can be expressed (Zhu and MOmoh, 1998) as follows.

$$\Phi_E = k_E \times \Delta E_{loss} \tag{3}$$

where

$$\Delta E_{loss} = \Delta E_{loss}^{old} - \Delta E_{loss}^{new} \ (kWh)$$

$\Delta E_{loss}^{old}$, $\Delta E_{loss}^{new}$ are the energy losses before and after installation, $E_{loss} = \int P_{loss} dt$

$\Phi_E$ is benefit due to energy loss reduction (*Baht*)

$k_E$ is the cost of per unit energy charge (*Baht / kWh*)

The costs of the reactive power source such as D-STATCOM can be divided into two parts: 1) fixed cost, and 2) operating costs. The fixed costs mainly consist of the D-STATCOM device cost and the cost to install it including labor hours, footprint of the device, time and so forth. The operating or variable costs are those which allow the D-STATCOM device to work. These operating costs consist of heating losses and maintenance costs etc. In principle, however, the operating costs may differ from year to year. The investment cost for the used D-STATCOM is given in Table 4 (Purewave, 2008).

**Table 4** Example cost for the D-STATCOM device

| Device | Initial cost (*Baht / kVar*) | Annual cost (%) |
|---|---|---|
| D-STATCOM | 5330 – 6662 | 5 |

For simplification, the fixed costs can be considered as shown in (4).

$$C_{fixed} = k_q \times Q_c \tag{4}$$

where

$C_{fixed}$ is the fixed cost (*Baht*)

$Q_c$ is the size of the reactive power of D-STATCOM to be installed (*kVar*)

$k_q$ is the per unit cost of the reactive power (*Baht / kVar*)

In addition, the operating cost can be described as follows (Chung and Shaoyun, 1997).

$$C_{op} = \sum_{y=1}^{y_{life}} C_{ann} \times \left( \frac{100 + \lambda}{100} \right)^{y-1} \tag{5}$$

where

$C_{op}$ is the total operating cost (*Baht*)

$C_{ann}$ is the annual maintenance cost (*Baht*)

$\lambda$ is the annual percentage increment of the maintenance cost (%)

$y_{life}$ is the lifetime of the D-STATCOM to be installed (*years*)

Therefore, the cost function of the reactive power compensation for the customer, utility and both of customer and utility are summarized as (6), (7) and (8), respectively.

$$C_{func,CUS} = -C_{fixed} + \left( \Phi_{sag} + \Phi_{PF} - C_{op} \right) \tag{6}$$

$$C_{func,EA} = -C_{fixed} + \left( \Phi_{E} - C_{op} \right) \tag{7}$$

$$C_{func,CUS\&EA} = -C_{fixed} + \left( \Phi_{sag} + \Phi_{PF} + \Phi_{E} - C_{op} \right) \tag{8}$$

where

$C_{func,CUS}$ is cost function for the customer

$C_{func,EA}$ is cost function for the utility

$C_{func,CUS\&EA}$ is cost function for the both of customer and utility…

## 3. COST ANALYSIS AND METHODOLOGY

Several evaluation methods can be used to cost analysis. It is important to include account of the different economic values of investments made at different times during the analysis period. When money is invested, compound interest is paid on the capital sum. The interest rate comprises inflation, risk and real costs of postponing consumption. Thus, money used to invest in this situation could be invest elsewhere and earn a dividend. To consider this effect, all future costs and benefits are discounted to convert them to the net present values (NPV) of costs as shown in (9). NPV is a measure of the economic worth of an investment (Robinson et al., 1998). A positive NPV indicates that the investment is justified economically at a given discount rate.

$$NPV = -C_{fixed} + \sum_{i=1}^{n} \frac{B_i - C_i}{\left(1 + \frac{r}{100}\right)^i} \tag{9}$$

where

$n$ is the analysis period in years

$B_i$ is the sum of all benefits in year *i*

$C_i$ is the sum of all costs in year *i*

$r$ is the discount rate in percentage

The methodology for cost analysis can be described as follows:

1. Investigate and design the size of the D-STATCOM.
2. Estimate the number and severity of events the plant is subject to per year.
3. According to Table 3, convert the different events to a per unit interruption base value and determine the weighting factors before and after mitigation.
4. Calculate benefit due to voltage sag mitigation per year (for the customer side considerations) by using (1).
5. Calculate benefit due to power factor correction per year (for the customer side considerations) by using (2).
6. Calculate benefit due to energy loss reduction per year (for the utility side considerations) by using (3).
7. Determine the cost of installation such as the fixed costs and operation costs for the D-STATCOM by using (4) and (5).
8. Determine the cost function for the customer, utility and both of customer and utility side considerations by using (6), (7) and (8), respectively.
9. Estimate the future costs and benefits by converting them to the net present values (NPV) of costs as shown in (9).
10. Discuss and comment on the results.

## 4. CASE STUDY AND RESULTS

The process of costs estimation and comparing the different sizes for improving performance involves determining the net present values (NPV) for each size, including the sum of all benefits and costs of implementing the D-STATCOM. For example, the industrial plant supplied by the Nakhonrachasima electricity authority, Thailand is investigated. The facility has a total load of 5 *MW* with power factor = 0.80 must be protected to avoid production disruptions and corrected the power factor as more than 0.875. The cost of per unit low power factor charge is 15(*Baht*) / *kVar* / *month*. The voltage sag performance was given in Table 5. According to the average costs of a single power interruption for industrial plants in Table 1, the costs for an interruption are 118.93(*Baht*) / *kW* + 106.60(*Baht*) / *kWh*. The costs for voltage sags are based on the weighting factors in Table 2 whereas the momentary interruptions disrupt the facility for 1.4 hours each time. The three options given in Table 6 are analyzed. The net present values (NPV) for each size can be summarized as shown in Figure 1. The NPV are calculated based on a 30-year life and an interest rate of 10%.

**Table 5** Voltage sag performance

| Event Category | Weighting for Economic Analysis | No. Events per Year | Total Equivalent Interruptions |
|---|---|---|---|
| Interruption | 1.0 | 4 | 4 |
| Sag with min. voltage below 50% | 0.8 | 4 | 3.2 |
| Sag with min. voltage between 50 and 70% | 0.4 | 11 | 4.4 |
| Sag with min. voltage between 70 and 90% | 0.1 | 31 | 3.1 |
| **Total** | **-** | **50** | **14.7** |

**Table 6** Costs and effectiveness of the power quality improvement options

| Costs | | | Effectiveness for a particular example case | | | |
|---|---|---|---|---|---|---|
| **Sizes (*MVar*)** | **Fixed (*Baht*)** | **Operating (*% of fixed costs*)** | **Interruption (%)** | **Sag with min. voltage < 50% (%)** | **Sag with min. voltage 50-70% (%)** | **Sag with min. voltage 70-90% (%)** |
| 5 | 33,313,300 | 5 | 0 | 40 | 70 | 85 |
| 10 | 66,626,600 | 5 | 0 | 55 | 80 | 95 |
| 15 | 99,939,900 | 5 | 0 | 65 | 90 | 100 |

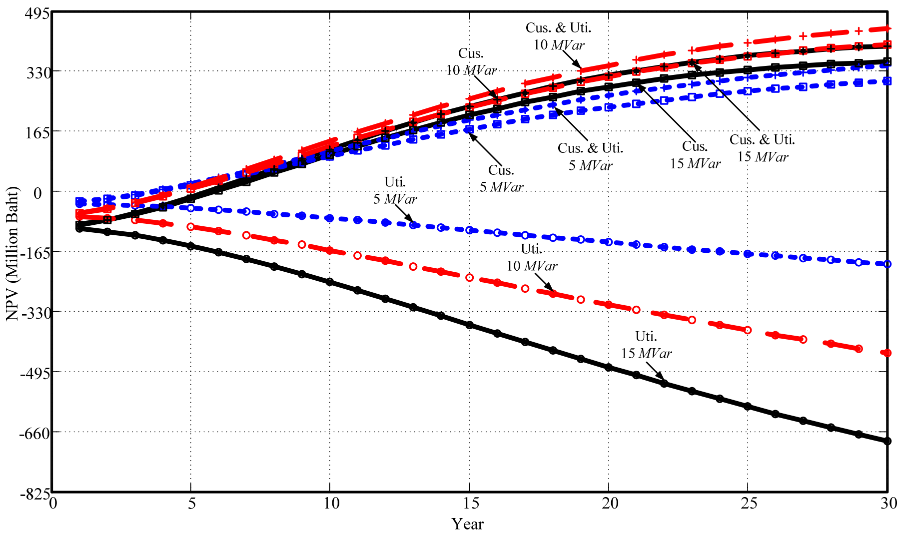


**Figure 1** Net present values (NPV) for 50 events per year

These calculations include the effect of discounting cash flow to convert all costs and benefits of each size to present values for comparison. As a result, it is interesting to note that all of the options would have a positive net benefit to the facility with the assumed interest rate and life-time for the customer and both of customer and utility side considerations whereas only the utility side consideration have a negative net benefit. It is also interesting that the 10-*MVar* D-STATCOM is the best option in this account.

In addition, the voltage sag performances in Table 7 are used to demonstrate the effect of amount of sag event on the benefits and costs of implementing the D-STATCOM. The magnitude of the voltage sag in each category can be obtained by random. Three different sizes e.g. 5, 10 and 15 *MVar* of the D-STATCOM for improving the performance are also presented. The net present values in each event range (10-20, 20-30 and 30-40 events per year) are calculated based on average of 10 iterations and can be plotted as shown in Figure 2 to Figure 4. As can be seen in these figures, all of the sizes have a negative net benefit for the amount of sag event between 10 and 20 events per year. For the amount of sag event between 20 and 30 events per year, the 10-*MVar* rating of the D-STATCOM has a positive net benefit for the customer and both of customer and utility side considerations. And the 10 and 15-*MVar* ratings give the positive net benefits for the customer and both of customer and utility side considerations when the sags occur between 30 and 40 events per year.

**Table 7** Number of the voltage sag event per year

| Event Category | 10-20 Events per Year | 20-30 Events per Year | 30-40 Events per Year |
|---|---|---|---|
| Interruption | 1-2 | 2-2 | 2-3 |
| Sag with min. voltage below 50% | 1-2 | 2-2 | 2-3 |
| Sag with min. voltage between 50 and 70% | 2-4 | 4-7 | 7-9 |
| Sag with min. voltage between 70 and 90% | 6-12 | 12-19 | 19-25 |
| **Total** | **10-20** | **20-30** | **30-40** |

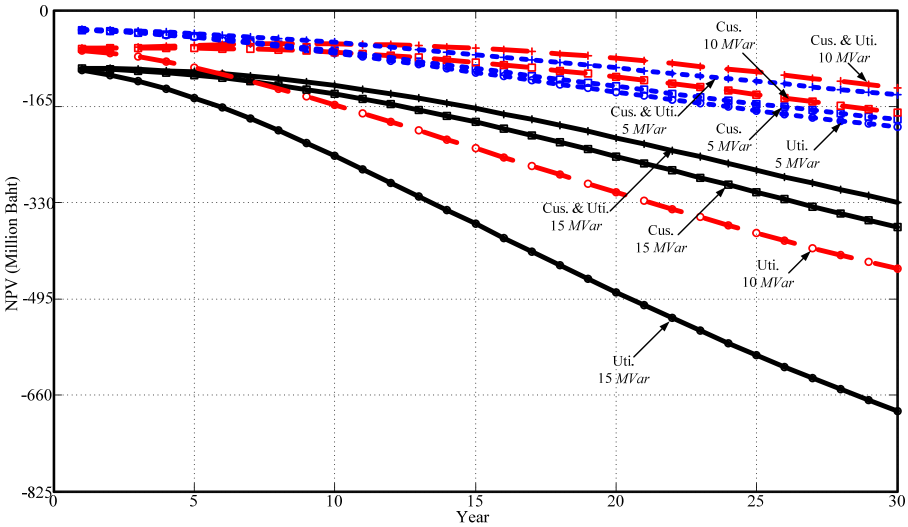


**Figure 2** Net present values (NPV) for 10-20 events per year

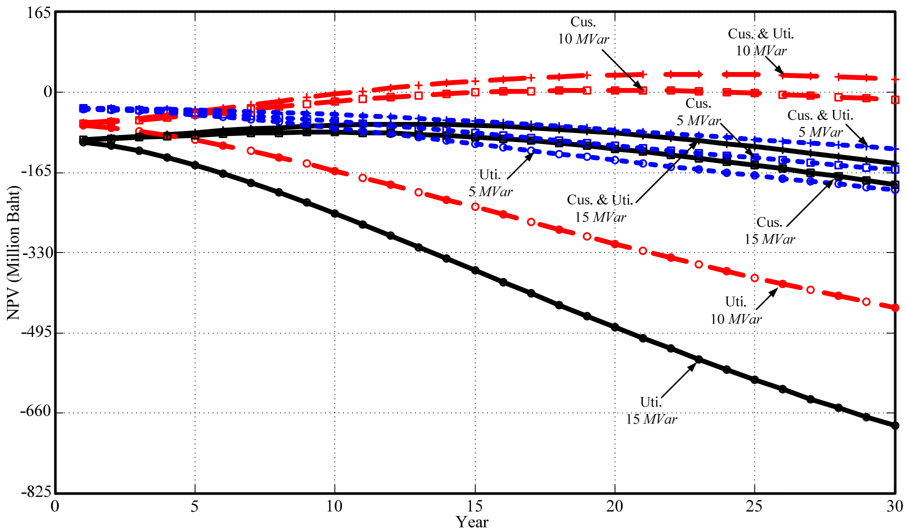


**Figure 3** Net present values (NPV) for 20-30 events per year

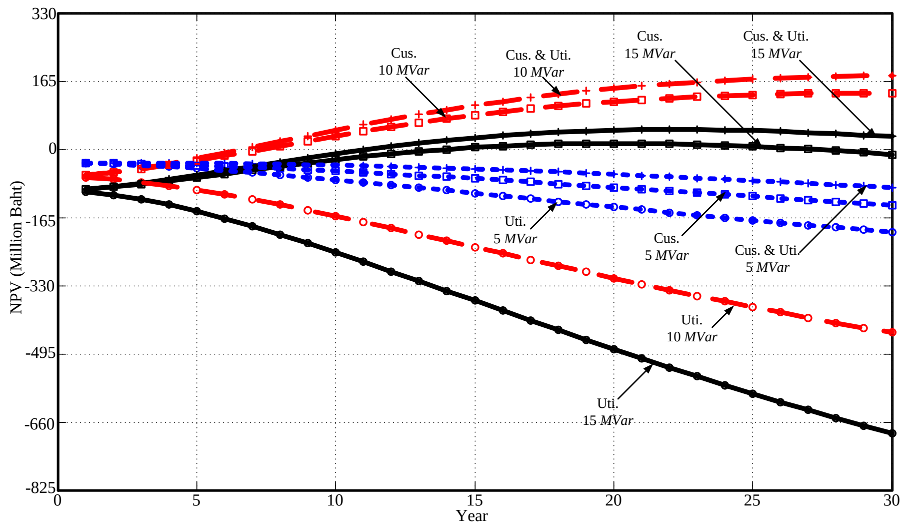


**Figure 4** Net present values (NPV) for 30-40 events per year

## 5. CONCLUDSION

This paper demonstrates the cost estimation of reactive power compensation by using the D-STATCOM in distribution power systems. The process of costs estimation and the comparison of three different sizes of the D-STATCOM (5, 10 and 15 *MVar*) for improving power quality are presented. The effects of the amount of sag event on the cost estimation are proposed. The voltage regulation, power factor correction and energy loss reduction has been chosen as the target for the cost estimation. The net present values (NPV) is applied to the cost estimation. The cost analysis procedure and the comparison among the results obtained from each option are proposed. With the assumed cost estimation parameters, the 10-*MVar* rating of the D-STATCOM gives the most benefit. In addition, the amount of sag event below 20 events per year gives the negative net benefit.

## REFERENCES


Hingorani, N.G. and Gyugyi, L. (1995). Introducing custom power. In **IEEE spectrum**. 32(6): 41-48.

Bhattacharya, S., Po-Tai Cheng and Divan, D. M., (1997). Hybrid Solution for Improving Passive filter performance in High Power Applications. In **IEEE Trans. on Indus. App**. 33(3): 1302- 1309.

Darrow. K. and Hedman, B. (2005). **The Role of Distributed Generation in Power Quality and Reliability**. New York: Energy and Environmental Analysis Inc.

Zhu, J. and MOmoh, J.A. (1998). Optimal Var pricing and Var placement using analytic hierarchical process. In **Electric Power Systems Research, Elsevier Science**. 48(1): (11– 17).

Purewave, (2008). dstatcom (On-line).

Avaliable: http://www.sandc.com/products/power-quality/purewave-dstatcom.asp

Chong, H., Zhanoning, Y., Bin, C., Huang, A. Q., Bin, Z., Ingram, M. R. and Edris, A. (2007). Evaluation of cascademultilevel converter based STATCOM for arc furnace flicker mitigation. In **IEEE Trans. Ind. Appl**. 43(2): 378-385.

Robinson, R., Danielson, U. and Snaith, M. (1998). **Road maintenance management: Concepts and systems**. London: Macmillan.