POWER QUALITY FACTORS IN EFFICIENCY BENCHMARKING

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Abstract - In this paper methods to take power quality factors (e.g. number and duration of planned and unplanned interruptions, number of auto-reclosing operations) account into efficiency benchmarking as outage costs is presented. The effects of outage costs in efficiency benchmarking are evaluated by means of sensitivity analyses. Effects of power quality factors in different kind of regulation models in actual network planning task are estimated.

INTRODUCTION

The importance of power quality (PQ) – including both voltage quality and interruptions – is growing in regulation process and distribution business. In many countries, e.g. in Norway [1] and in Finland [2], PQ is already part of efficiency benchmarking. Although PQ has been monitored rather detailed (e.g. number and duration of planned and unplanned interruptions, number of auto-reclosing operations, voltage levels etc.) many years, PQ is taken into account quite simplified way in efficiency benchmarking. Usually only duration of interruptions is notified in efficiency benchmarking. The main reason is that quality of data of PQ statistics is not good enough to use them in benchmarking. Other reason is that use of more than one PQ factor in benchmarking requires sophisticated efficiency benchmarking methods.

In Data Envelopment Analysis (DEA) it is possible to use factors, which are not commensurate with each other’s. This means that the factors with various units (time, number, currency etc.) can be used in benchmarking at the same time. DEA weights benchmarking factors so that efficiency score is as high as possible for every company. E.g. if company is best as a sense of one factor (e.g. PQ), DEA weights this property of company more than the factors which are not beneficial for the company in efficiency benchmarking. In practice this may cause problem in sense of insignificant factors. If PQ is included in DEA as four separated factors (e.g. number and duration of planned and unplanned interruptions), DEA may weight one or more of these factors so that the factor does not actually affect to the efficiency score at all. In this situation company may improve or worse these properties without affecting its efficiency score.

One way to avoid this problem of insignificant factors is to combine PQ factors to one outage cost and add this cost to operational costs. The basic idea of outage cost is to determine unit costs for different kinds of outages for different kinds of customer types. In Finland interruption time of customers is one and only PQ factor in efficiency benchmarking at the moment. Discussions that how the other power quality components such as number of interruptions, auto-reclosing operations and voltage levels can be included to efficiency benchmarking are active. Some of this data is already collected from network companies annually. Regulator can calculate outage costs for each company by using this data. This is possible when unit prices of each power quality factors are defined. In Finland e.g. price of unplanned (unexpected) interruption for residential customer is 0,068 €/kW and 0,61 €/kWh [3]. Unit prices are defined for five customer types and four interruption types. PQ factor can be formed as a sum of separated PQ cost components. In efficiency benchmarking it is possible to add outage costs to company’s operational costs as presented in Fig. 1.

Fig. 1. Outage cost method and DEA-model.

BACKGROUND OF POWER QUALITY REGULATION IN FINLAND

The Finnish Energy Market Authority presented efficiency benchmarking in 1999. Efficiency scores were calculated by using Data Envelopment Analysis (DEA) with five factors [4]. Power quality was one of those factors. It was measured as a total interruption time of customers. The reason why only interruption time was included in to efficiency benchmarking was insufficient PQ statistics. There was no reliable statistics of other kind of interruption types like number of short interruptions (e.g. auto-reclosing operations). The basic form of efficiency benchmarking with DEA is presented in (1).

\[
\text{Max } b_1 = \frac{u_1 \cdot \text{Energy} + u_2 \cdot \text{Network} + u_3 \cdot \text{Customers} - c \cdot \text{Interruption time}}{v_1 \cdot \text{Operational costs} + \text{Outage costs}}
\]

In (1) PQ is measured as a total interruption time of customers. Theory and features of DEA is presented e.g. in [5]. The problems considering insignificance of certain factors when DEA was used as a regulation tool was presented in [2]. Actual outage cost for company (€/customer,h) could be calculated because of link between efficiency benchmarking and allowed rate of return [6] in distribution business as presented in (2).

\[
\text{Price}\text{\_outage} = \frac{\Delta\text{DEA}}{\Delta\text{Interruption time}} \cdot \text{Operational costs}
\]

Where
As separated factor, interruption time was insignificant factor for many companies and actual cost of outages varied from 0 to 500 €/customer.h from company to another. Problem is solved in [7] where efficiency benchmarking with outage costs was presented. Basic idea was handle power quality as outage costs and adds outage costs to operational costs as presented in (3).

\[ \text{Max } h_u = a_u \cdot \text{Energy} + b_u \cdot \text{Network} + c_u \cdot \text{Customers} + c \cdot \text{Operational costs} + \text{Interruption costs} \]  

In Fig. 2 the numbers of companies that have insignificant factors are presented before and after development work. It can be seen that power quality is insignificant factor for over 20 companies if power quality is measured as separated factor (present DEA-model) compared to situation, where power quality is measured as outage costs and it is added to operation cost (developed DEA-model).

Fig. 2. The number of companies that have insignificant factors. [7]

During first three-year long regulation period (2005-2007) power quality has no specifically defined role in Finnish distribution regulation. During this time, regulator collects PQ reference data from distribution companies. This data will be used as a reference during second regulation period. Regulator has decided to collect following eight power quality factors now on [3], [8].

1. Customer’s average annual interruption time that is caused by unexpected interruptions.
2. Customer’s average annual number of interruptions that are caused by unexpected interruptions.
3. Customer’s average annual interruption time that is caused by planned interruptions.
4. Customer’s average annual number of interruptions that are caused by planned interruptions.
5. Customer’s average annual number of interruptions that are caused by delayed auto-reclosings.
6. Customer’s average annual number of interruptions that are caused by high speed auto-reclosings.
7. Annual number of unexpected interruptions in low voltage network.
8. Annual number of unexpected interruptions in medium voltage network.

PQ factors 1-6 are weighted with annual energy of the secondary (distribution) substation. PQ factors 7 and 8 have been collected earlier and they are on the list for PQ trend monitoring reasons.

OUTAGE COST MODELLING

The target of regulator is to define one outage cost for every company. This outage cost is combination of costs caused by factors 1-6 presented previously. Outage cost modelling requires that unit costs for power quality factors are available. Power quality unit costs in Finland are presented in Table I.

Unit costs are based mainly on a Nordic research work done by 90’s. More detailed definition of these unit costs is presented in [9] and [3]. There is going a new research work to update these unit costs. This is done co-operation with Finnish Energy Market Authority, technical universities and distribution companies.

To reach for as accurate interruption data as possible in economically, companies are obligated to collect interruptions on secondary (distribution) substation-specific. In Fig. 4 example of distribution substation-specific outage cost modelling is presented.

Table I. Unit costs for power quality factors for customer groups in Finland. (AR = auto-reclosing) [3]

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>0.068</td>
<td>0.61</td>
<td>0.034</td>
<td>0.30</td>
</tr>
<tr>
<td>Agriculture</td>
<td>0.54</td>
<td>4.9</td>
<td>0.18</td>
<td>1.6</td>
</tr>
<tr>
<td>Industry</td>
<td>2.6</td>
<td>8.7</td>
<td>0.80</td>
<td>3.8</td>
</tr>
<tr>
<td>Public</td>
<td>0.65</td>
<td>3.4</td>
<td>0.23</td>
<td>1.5</td>
</tr>
<tr>
<td>Service</td>
<td>1.9</td>
<td>11</td>
<td>0.80</td>
<td>7.2</td>
</tr>
</tbody>
</table>

DS = distribution substation (20/0,4 kV)

Fig. 4. Medium voltage line and example distribution substation (DS 4).

Distribution substation-specific outage cost modelling requires information of customer types and energy consumptions. In table II this kind of statistics for distribution substation 4 (DS 4) is presented.

Table II. Statistics of distribution substation 4 (DS 4).

<table>
<thead>
<tr>
<th>Customer group</th>
<th>Number of customers</th>
<th>Energy consumption [MWh/a]</th>
<th>Average power [kW/customer]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>3</td>
<td>42</td>
<td>1.6</td>
</tr>
<tr>
<td>Agriculture</td>
<td>2</td>
<td>50</td>
<td>2.9</td>
</tr>
<tr>
<td>Public</td>
<td>1</td>
<td>10</td>
<td>1.1</td>
</tr>
</tbody>
</table>

In table III interruption statistics for DS 4 is presented.
POWER QUALITY IN REGULATION AND EFFICIENCY BENCHMARKING

Next properties of different kind of regulation and efficiency benchmarking methods in sense of power quality and investments are described. 

Allowed rate of return and DEA efficiency benchmarking with interruption time

This is model, which has been used in Finland few years. Allowed rate of return is based on present value of the distribution network. The model encourages investing because every investment increases value of the network and by that way increases rate of return of company. Financing costs of investment can be gathered from customers. In efficiency benchmarking (1) power quality affects to efficiency score varying in companies as presented in Fig. 3.

Allowed rate of return and DEA efficiency benchmarking with outage costs

This is developed model [7] where power quality is measured as outage costs and they are added to operational costs in DEA-model (3). The model still encourages investing to network because every investment increases value of the network. Even investments are not part of efficiency benchmarking, efficiency score can be affected by investing to targets, which improve power quality (outage costs) and by that way improve efficiency score. If investment is beneficial as sense of better power quality, efficiency score grow up and this brings additional benefit for company. In Fig. 7 percentage values of outage costs for all companies are presented.

The bottom row shows total costs of each interruption type and rightmost column shows interruption costs of each customer type. Total interruption costs for this particular distribution substation are 200 €/a.

In Fig. 6 percentage values of outage cost components in every Finnish distribution companies are presented. At the moment reliable and extensive enough distribution substation-specific interruption statistics are not available. Outage costs are based on average values of companies and nationwide outage costs with common shares of customer groups. This is presented more detailed in [10].

Fig. 6. Percentage values of outage cost components in Finland.

Fig. 7. Average percentage values of a) total cost (outage cost and OPEX) and b) outage costs in Finland.

It can be seen from Fig. 7 a. that outage costs are on the average 17 % of total costs (outage costs and OPEX). Half of outage costs are caused by interruption time as it can be seen from Fig. 7 b.

Allowed rate of return and DEA efficiency benchmarking with outage costs and investments

This is developed model [11] where investments are taken account in efficiency benchmarking and they have as importance role as outage costs and operational costs in benchmarking. This model directs investments to those targets where minimum of total costs (operational costs,

### Table III. Interruption Statistics of DS 4.

<table>
<thead>
<tr>
<th>Interruption type</th>
<th>Number of interruptions per year</th>
<th>Total interruption time per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unplanned</td>
<td>6</td>
<td>3.5 h</td>
</tr>
<tr>
<td>Planned</td>
<td>1</td>
<td>1.0 h</td>
</tr>
<tr>
<td>High speed AR</td>
<td>12</td>
<td>-</td>
</tr>
<tr>
<td>Delayed AR</td>
<td>4</td>
<td>-</td>
</tr>
</tbody>
</table>

It can be seen that number of unplanned interruptions is 6 and they have last 3.5 h together. Outage cost e.g. for duration of unplanned interruptions can be calculated as presented in (4).

\[ C_{\text{Unplan-time}} = C_{\text{Unplan-time}} \cdot n_{\text{customer}} \cdot P_{\text{customer}} \cdot t_{\text{Unplanned}} \]  

(4)

Where

- \( C_{\text{Unplan-time}} \) = unit cost for duration of unplanned interruption [€/kWh]
- \( n_{\text{customer}} \) = number of customers in customer group
- \( P_{\text{customer}} \) = average power of customer in group [kW/customer]
- \( t_{\text{Unplanned}} \) = duration of unplanned interruptions in DS 4 [h]

From table I, II and III outage costs for residential customers caused by unplanned interruptions \( (C_{\text{Unpl-an-time-res}}) \) are (5)

\[ C_{\text{Unplan-time-res}} = 0.61/\text{kWh} \cdot 3 - 1.6 \text{kWh} \cdot 3.5/\text{h} = 10/\text{h} \]  

(5)

In table IV outage cost for all customer types and interruption types is calculated for distribution substation 4.

### Table IV. Total Interruption Costs for DS 4. \( (N = \text{number}, T = \text{duration}, HS AR = \text{high speed auto-reclosing}) \)

<table>
<thead>
<tr>
<th>Unplanned interruption</th>
<th>Planned interruption</th>
<th>HS AR</th>
<th>Delayed AR</th>
<th>Total costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>2.0 10</td>
<td>0.2 1.4</td>
<td>1.0 9.1</td>
<td>2.0 1.7 17</td>
</tr>
<tr>
<td>Agriculture</td>
<td>18 98</td>
<td>1.0 9.1</td>
<td>3.0 9.1</td>
<td>17 16 159</td>
</tr>
<tr>
<td>Public</td>
<td>4.3 13</td>
<td>0.3 1.7</td>
<td>0.3 1.7</td>
<td>3.2 26</td>
</tr>
<tr>
<td>Total costs</td>
<td>24 120</td>
<td>1.4 12</td>
<td>12 22 21</td>
<td>100 %</td>
</tr>
</tbody>
</table>

The bottom row shows total costs of each interruption type and rightmost column shows interruption costs of each customer type. Total interruption costs for this particular distribution substation are 200 €/a.
outage costs and investments) can be achieved in the long run. The investments, which does not affect to operational costs or power quality, decrease efficiency score of the company. In Fig. 8 percentage values of outage costs, investments and operational costs in Finnish distribution companies are presented.

**Revenue regulation and power quality**

One example of network revenue regulation model with outage costs is presented in [1]. In this Norwegian model outage costs are part of network revenue evaluating process. If outage costs are more than expected outage costs for certain time period, company are forced to diminish its revenue by corresponding sum. If company can improve its power quality so that outage costs are less than expected outage costs, company may increase its profit as presented in Fig. 9.

![Fig. 9. Cost structure of network revenue regulation with outage costs.](image)

**Fig. 9.** The relative parts of operational costs, investments and interruption costs in Finnish distribution companies.

In Norway power quality is also taken account in efficiency benchmarking done by DEA-model. Demand for improving power quality is delivered for a time period.

**EFFECTS OF REGULATION TO THE POWER QUALITY INVESTMENTS**

Profitability of power quality investment depends greatly on chosen regulation model. In next example effects of regulation model and efficiency benchmarking method to power quality investment is presented. In Fig. 10 typical medium voltage feeder is presented. In this case it is studied, is it profitable to invest to remote-controlled disconnector as a sense of smaller outage costs.

![Fig. 10. Medium voltage feeder and potential place for remote controlled disconnector.](image)

**Fig. 10.** The relative parts of operational costs, investments and interruption costs in Finnish distribution companies.

Investment of remote-controlled disconnector is 20 000 € and annual cost of investment is 1 420 € (p is 5 %). This investment affects mostly on interruption time. Unit price for unplanned interruption time is 4,3 €/kWh. This figure based on unit costs (table I) and nationwide energy consumption weighting in customer groups [10]. In table V changes in interruption times and savings in outage costs in different areas after investment is presented.

**Table V. Savings in interruption times and outage costs after remote-controlled disconnector investment.**

<table>
<thead>
<tr>
<th>Fault, effect</th>
<th>Saving [h] before-after</th>
<th>Saving [€/a]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 1 – 0,6 = 0,4 (0,05 · 4 km)</td>
<td>200 kW · 0,8 h · 4,3 €/kWh = 86 €/a</td>
<td></td>
</tr>
<tr>
<td>B 1 – 0,2 = 0,8 (0,05 · 8 km)</td>
<td>100 kW · 0,8 h · 4,3 €/kWh = 138 €/a</td>
<td></td>
</tr>
<tr>
<td>C 1 – 0,2 = 0,8 (0,05 · 8 km)</td>
<td>200 kW · 0,8 h · 4,3 €/kWh = 344 €/a</td>
<td></td>
</tr>
<tr>
<td>A 1 – 0,2 = 0,8 (0,05 · 9 km)</td>
<td>100 kW · 0,8 h · 4,3 €/kWh = 155 €/a</td>
<td></td>
</tr>
<tr>
<td>B 1 – 0,2 = 0,8 (0,05 · 9 km)</td>
<td>200 kW · 0,8 h · 4,3 €/kWh = 310 €/a</td>
<td></td>
</tr>
</tbody>
</table>

Total saving: **1 100 €/a**

It can be seen that outage costs decrease 1 100 € per year if investment is done. Annual cost of investment is 1 420 €, so investment cost are more than savings in outage cost. This kind of investment affects also to operational costs but in this example, focus is on outage costs. Next it is presented, in which way decreased outage costs and disconnector investment affects to company’s allowed rate of return and efficiency benchmarking results.

**Allowed rate of return and DEA efficiency benchmarking with interruption time**

Investment is profitable in all cases because it increases present technical value of the network and by that way allowed rate of return. Because only interruption time is noticed in efficiency benchmarking, benefit of investment depends on savings in total interruption time and significance of PQ factor (interruption time) of company in DEA-model. If PQ factor is insignificant in DEA for the company (price of interruption is 0 €/customer,h) investment does not bring additional profit for the company. If price is >0, e.g. 50 €/customer,h, and annual change in interruption time is e.g. 100 customer,h/a, additional profit from DEA-model is 50 x 100 €/a = 5 000 €/a. The profit from DEA-model can be remarkable high compared to investment cost and savings in outage costs.

**Allowed rate of return and DEA efficiency benchmarking with outage costs**

Investment is profitable in all cases because it increases...
present technical value of the network and by that way allowed rate of return. If interruption time is one of the PQ factors in outage costs, efficiency score grows and investment is profitable. Additional profit from efficiency benchmarking is 1 100 €.

**Allowed rate of return and DEA efficiency benchmarking with outage costs and investments**

Investment is increases present technical value of the network and by that way allowed rate of return. Annual cost of investment is more than annual saving in outage costs and hence there is an additional 1 420 € – 1 100 € = 320 €/a payment from efficiency benchmarking. Investment affects also to operational costs but main effect is in PQ. Investment is profitable only if it reduces operational costs at least 320 €/a.

**Revenue regulation and power quality**

Cost structure of network revenue regulation with outage costs is presented in Fig. 9. Like in previous case annual cost of investment is more than savings in outage costs. Investment is profitable only if it reduces operational costs at least 320 €/a.

Four different ways to estimate overall profitability of remote-controlled disconnector investment in distribution business were presented. Two last regulation methods meet satisfactorily the requirements that are used in traditional network planning and development. In these options minimum of all cost components has to be founded before profitability of investment can be reached. In two first options (Allowed rate of return and efficiency benchmarking with interruption time/outage costs) there is possibility for local optimization in sense of short term cost minimization. Added to this, efficiency benchmarking contains a lot of uncertainty when PQ (interruption time) is handled as separated factor in DEA-model.

Similar case considering earth fault current compensation equipment is presented in [10].

**CONCLUSION**

Power quality factors affects in different ways in different kind of regulation and efficiency benchmarking methods. This has to be taken account when unit costs of outages are considered to be used in regulation process. In worst case some of PQ factors do not affect at all to company’s efficiency score and profit no matter how important and necessary investment is in sense of economic network developing. In DEA model power quality cannot be handled as a separated factor because of unfair behavior of power quality factor.

It is not enough to reach for as real outage unit costs for different customer types and for different interruption types as possible, but it is also necessary to understand in which way power quality factors (and outage costs) affects to companies net revenue e.g. after efficiency benchmarking with power quality in it. Because of new relation between power quality and net revenue or efficiency benchmarking exists, actual outage costs in companies’ perspective can be calculated. In this paper, effects of PQ investment to companies allowed rate of return in different kind of regulation models is estimated.

**REFERENCES**


