A NOVEL APPROACH TO DISTRIBUTION GRID AUTOMATION AT NESA A/S

Peter VINTER, Henrik VIKE&GAARD
Nesa A/S - Denmark
pvi@nesa.dk, hvi@nesa.dk

INTRODUCTION

Showing a positive cost-benefit relation in Distribution Grid Automation has always been a challenge. The Electric Utility NESA A/S and Kasmatic Innovation A/S has developed a cheap and reliable, decentralised supervision and control system for the distribution grid – thus named 'DISCOS'.

After two years of development and testing, test installations began July 2004. During 2005, 330 substations – or 5 % of all substations – will be equipped with DISCOS.

The expected benefits of the investment are:
− Immediate improvement in overall power supply quality
− On-line information on disturbances in distribution grid
− On-line access to information on voltage quality
− Better data for daily operation and long-term planning

This paper focuses on the technical solution, implementation issues and the strategic background for the project.

THE STRATEGIC BACKGROUND

Needs for reinvestment in the infrastructure

The major part of the Danish electric power infrastructure was built throughout the 1960’s and 1970’s. For benchmarking purposes, the Danish Energy Board has defined standard lifetimes for different types of components. E.g. MV transformers and MV switchgear is assumed to have an average lifetime of 45 years; MV cables 40 years, etc.

From a technical point of view, these lifetimes are on the 'safe side'. Applying these values on NESAs distribution grid, the future reinvestments would follow this profile:

Following this conservative approach, NESA – and other utilities – would face an awesome task in the years to come.

Asset Management study

To improve the company’s basis for reinvestment decisions, NESA carried out a comprehensive Asset Management study of the distribution grid in 2002. One important aspect was the economically optimal lifetimes of different types of equipment (cables, power transformers, etc.).

In brief, these lifetimes were estimated by comparing the lifetime costs of two scenarios:
− Replacing the old component with a new one
− Keeping the old component in operation

The lifetime costs include the following elements:
1. Replacement costs (only replacement scenario)
2. Accumulated maintenance costs
3. Accumulated repair costs due to component failure
4. Accumulated costs for NDE¹ due to component failure

Failure rates of new and older equipment have been estimated, based on fault statistics. Consequently, cost elements 2., 3. and 4. increase with the age of the component.

The economically optimal lifetime of a certain type of equipment is the number of years that minimise lifetime costs. In the study, the following lifetimes were found:

TABLE 1 – Economically optimal lifetimes of different equipment types

<table>
<thead>
<tr>
<th>Equipment type</th>
<th>Econ. lifetime, yrs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 kV cable, city</td>
<td>96</td>
</tr>
<tr>
<td>10 kV cable, open land</td>
<td>56</td>
</tr>
<tr>
<td>10 kV cable, 1. generation XLPE</td>
<td>33</td>
</tr>
<tr>
<td>10 kV cable terminations</td>
<td>63</td>
</tr>
<tr>
<td>Air-insulated switches</td>
<td>50</td>
</tr>
<tr>
<td>Epoxy-insulated switches</td>
<td>27</td>
</tr>
<tr>
<td>SF6-insulated switches</td>
<td>50</td>
</tr>
<tr>
<td>Oil-insulated switches</td>
<td>51</td>
</tr>
<tr>
<td>10/0.4 kV power transformer</td>
<td>100</td>
</tr>
</tbody>
</table>

The point is that it is economically wise to exchange some equipment types sooner than other. With this insight, reinvestments can be directed to high-benefit areas.

In some cases, the economically optimal lifetime exceeds a reasonable technical lifetime, e.g. 10 kV cables in built up areas. However, factors such as insufficient capacity, lack of spare parts, tools, etc. were not included in the study.

Applying the economically optimal lifetimes, the future reinvestments follow this profile:

Notes:
¹ NDE: Non-delivered energy. For this study, NDE was priced at 100 DEK/kWh or 13 €/kWh.
The pace is significantly slower than before, but still increasing with respect to today’s level.

As in most other countries, deregulation has led to strict limitations on the utilities’ spendings. In Denmark, cost reductions of 3 to 10% per year are common. This of course has a negative effect on maintenance, refurbishment, etc.

**Power supply quality**

The study also focused on supply quality, expressed in terms of NDE. NDE in NESAs distribution grid is currently in the range of 200,000 – 250,000 kWh per year. This corresponds to approx. 420 kWh per 1,000 points of delivery per year.

Using the ‘low’ reinvestment profile in Figure 7 as base case, NDE is simulated over a 20-year period (red / upper line). Using the economically optimal lifetime as reinvestment guide, the NDE nearly doubles in 20 years. How can this be?

The answer lies in the price of NDE, which in this study is set at 13 €/kWh. At this price, most optimal lifetimes exceed the actual average age of the equipment today. Following this line of thinking, most equipment types should be allowed to grow older, leading to higher failure rates. Under this assumption, the present quality of supply actually is too high!

In the next scenario reinvestments were increased to a level where the quality of service could be maintained at the present level, see Figure 7 (green / vertical line).

The impact on NDE from reinvestments vary from component type to component type. Depending on the technical solution, we have to accept a NDE price in the range of 250 – 900 DEK/kWh or 33 – 120 €/kWh to maintain status quo.

Three important conclusions from the study:

- Maintaining power supply quality through heavy reinvestment schemes in grid infrastructure is theoretically possible
- In practice such schemes are not feasible, due to the limitations on utilities’ costs
- There is a need for more ‘clever’ solutions that will reduce the number and/or duration of interruptions at a lower price, i.e. with a lower cost-benefit ratio

NESA therefore decided to develop a simple automation solution for the distribution grid as a cost-effective supplement to reinvestments.

**SYSTEM APPLICATION AND REQUIREMENTS**

**NESAs distribution grid**

The MV grid is a traditionally designed 10 kV grid with a mainly meshed structure, operated radially. All lines are underground cables. The grid is reactance-coil grounded, allowing temporary operation with single earth faults.

Field staff locates short circuits, reading off mechanical or electro-mechanical short circuit indicators. Indicators are present in nearly all substations, but have no directional sensitivity. Older types have to be reset manually; newer types reset automatically 2 – 4 hours after re-energisation.

Switching operations in 10 kV substations are also carried out manually on order from the control centre.

Local production units such as CHP and wind turbines are found in most parts of the grid; in some cases leading to false short circuit indications, since the indicators have no directional sensitivity.

**DISCOS system requirements**

The system should provide the operator with reliable information from the MV/LV grid, both under normal conditions and during unplanned outages.

- General design criteria
  - For use in MV distribution grids with reactance-coil grounded neutrals
  - For use in all types of stations and virtually all types of switchgear, regardless type and age
  - Simple and fast installation and calibration – ½-1 day per station depending on complexity
  - Integrated battery condition monitor and charger control
  - Modularity – easy to adapt to the specific application and with a minimum of external wiring
  - Cordless communication (GSM)
  - Lifetime, sensors: 40 years; control modules: 15 years

- Operational measurements
  - Voltage (LV; MV values calculated from LV voltage, transformer load, ratio and vector group). Measuring accuracy, current: 2% in the range 180 – 260 V
  - Current (LV and MV). Measuring accuracy, current: 5% in the range 20 – 20,000 A
  - Active and reactive power
  - 1 – 2 additional analogue inputs per system

- Commands
  - MV circuit breaker open / close command
  - 1 – 2 additional command relays per system

---

2 The amount of energy delivered at NESA was 5,911 GWh in 2003.

3 DNM: Digital Network Mapping
Indications and alarms
- MV short circuit indication, directional
- Calculation of electrical distance to fault
- MV earth-fault indication
- MV open-phase fault / fuse blown
- Voltage out-of-range on LV side of transformer
- Schedule service (system battery, sensors, etc.)
- System faulty
- 1 – 2 additional alarm inputs per system

DISCOS system application

The system may be applied in three different schemes, depending on the MV/LV station’s topological importance in the grid and the installation costs for the specific station:

FIGURE 3 – Simplified MV feeder showing different installation types

The three installation types and their use are explained below.

**Type A installation.** Type A installations are typically used in strategic branch points stations, located on the first sections of the feeder. In case of a short circuit on e.g. section 2, the entire feeder will be de-energised at the 132/10 kV or 50/10 kV main station by an overcurrent relay. Immediately after, the type A station will report information on fault type and direction back to the control centre.

On basis of this information, the operator decides to trip the circuit breaker in the type A station towards the faulted section 2. When the operator receives the feedback (‘Circuit breaker open’), the healthy sections 1 and 3 may be re-energised from the main station.

In type A stations the circuit breaker equipment has to support remote control. NESA has decided to use simple spring-mechanism breakers that can be actuated via a trip coil – similar to the type normally used in MV fuse-protected transformer bays. Energy for one Close-Open cycle is stored before closing the breaker, thus leaving the it ready to trip.

Most modern types of switchgear support this feature, e.g. the ABB Safering and ABB Safeplus RMU ⁴. The equipment and maintenance costs are lower than for a motor-drive solution; so is the demand for back-up battery capacity. The breaker has to be re-closed manually however; the field staff does this after the fault has been located and isolated.

With the type A station, the extent of the outage can be reduced significantly. In NESAs grid, the outage duration for the majority of customers will be reduced from $\frac{1}{2} – 1\frac{1}{2}$ hours to the range of 3 – 5 minutes.

The outage duration on the faulted section is more or less the same. However, type A stations can also estimate the electrical distance to a short circuit, using algorithms similar to those in numerical distance protection relays. This information will speed up the detailed fault location process, since the operator can direct the field staff to the right part of the feeder section from the start.

In addition to the MV supervision and control, LV loads, voltages and other parameters are monitored.

A cost-benefit analysis shows that type A installations are relevant for 5 % of NESAs MV/LV stations.

**Type B installation.** From an operational point of view, all stations ought to be of type A. In most cases however, upgrading switchgear to remote control is either expensive or impossible. A type B station may be used instead.

FIGURE 4 – Reducing outage extent & duration, using A and B installations

Type B installations are also typically used in branch points stations; see Figure 3. Type B stations can generate the same information for the control centre as type A. In case of a short circuit on the outer part of section 2, the fault location is now down to 2 potentially faulted lines / stations. Using the distance to fault, the location can be narrowed further down, allowing the ground staff to concentrate on fault isolation and power restoration when arriving at the place.

Using type B installations, the outage duration for customers on the faulted section can now be reduced. This is illustrated graphically in Figure 4.

In addition to MV supervision, LV loads, voltages, feeder fuses and other parameters are monitored. A cost-benefit analysis shows that the type B installation is relevant for about 20 % of NESAs MV/LV stations.

**Type C installation.** Types A and B combined give an optimal ‘coverage’ of the MV grid. For the remainder of

---

⁴ RMU: Ring Main Unit
stations, a more simple type C installation may be used, giving rapid information on LV outages on feeder level, transformer load, voltage quality, etc.

An analysis of the costs and benefits of type C installations has not been carried out, however.

SYSTEM STRUCTURE, SENSOR TECHNOLOGY AND SCOPE OF FUNCTIONS

System structure and modules. The system features modules for MV and LV current measurement, LV voltage measurement, battery charger control, battery condition monitor and GSM-communication with the control centre.

Current and voltage sensors. The current sensors are optical Faraday sensors. The sensor is approx. 50 mm long and consists entirely of plastic (95 %) and glass (5 %):

![FIGURE 5 – MV and LV current sensor](image)

The Faraday principle states that the plane of a polarised incident light undergoes a rotation relative to the magnetic field applied. Since any electric current generates a magnetic field, the current may be measured by determining the angle of rotation of the polarisation plane.

The sensor is used by the DISCOS-system for MV current measurement. The same sensor type may be used in all types of stations and equipment; e.g. existing open-air stations as well as modern compact switchgear.

The sensors are clamped directly onto a cable surface or a bare conductor and connected to the measuring module, ‘DISCOS Opti’, using optical fibres that guide the polarised light. This eliminates problems with electrical interference and ensuring galvanic separation between high-voltage and control circuits.

The sensor housing is manufactured from temperature resistant materials, giving it a working temperature from -40 °C to +120 °C and a capability of withstanding peak temperatures up to 250 °C in case of a short circuit current passing through the cable / conductor.

The sensor is capable of measuring currents up to 350 kA, but has been optimised for a maximum short circuit current of 20 kA for this application. The electrical properties of the sensor housing and the optical fibres have been tested according to IEC 60168 as an indoor isolator without mechanical demands.

Voltage measurement is done on the LV side of the transformer only by the module ‘DISCOS Master’. Power transformer ratio and vector group is selected during set-up. The module then continuously calculates the corresponding voltages on the MV side of the transformer. In this way costs and risks using direct MV voltage measurement are avoided.

Scope of functions. The scope of functions is seen below:

| TABLE 2 – Measurements, indications, alarms and commands |
|-------------|---------------|---------------|
| Operational measurements | MV line bay | Transf. bay | Station |
| Voltage | + | + |
| Current | + | + |
| Active power | + | + |
| Reactive power | + | + |
| Daily peak load | + | + |
| Additional measurements | + | + | + |
| Pressure, oil filled cables | + | + | + |
| Transformer temperature | + | + | + |
| SF6-pressure, switchgear | + | + | + |
| Air temperature, humidity, etc. | + | + | + |
| Commands and indications | + | + | + |
| Circuit Breaker open/close | + | + | + |
| Breaker position | + | + | + |
| Indications and alarms | + | + | + |
| Short circuit indic., directional | + | + | + |
| Short circuit indic., non-dir. ° | + | + | + |
| Distance-to-fault, Ω | + | + | + |
| Earth-fault indication | + | + | + |
| Open-phase fault / fuse blown | + | + | + |
| Voltage out-of-range | + | + | + |
| High temperature | + | + | + |
| System faulty/schedule service | + | + | + |
| Extra indications (examples) | + | + | + |
| Station door open | + | + | + |
| SF6-pressure low, switchgear | + | + | + |

During normal operation the system calculates voltages, currents, active and reactive power in all bays and transmits them to the operator on request.

In case of a short circuit, the system calculates the current, fault direction and electrical distance to the fault. Values are relayed to the operator for faster fault location.

The operator may also use DISCOS for remote operation of controllable breakers / switches for fast fault isolation and power restoration. Breaker positions are continually monitored and relayed back to the operator.

Communication. Information from DISCOS is linked to a SCADA or DNM system through a separate communication module, ‘DISCOS GSM’. This is a separate module to make adaptation to the actual SCADA System easy.

The NESA version uses prioritised SMS messages for communication. This means relatively low implementation and operational costs due to existing GSM-infrastructure. These advantages fully compensate for the slight time delay using SMS (up to 2 minutes).

All messages are replied with either the requested data or an

5 Calculated from LV measurements, transformer load and ratio
6 Used in stations, where no transformer / LV measurement is present
acknowledge if no data is requested. Messages are retransmitted twice if no handshake is received.

Internally, the DISCOS modules are connected via a bus. The bus carries both analogue measurands, a CAN bus for communication and power supply for the different modules.

**Installation and calibration.** The system is designed to fit into almost all types of MV stations and switchgear.

System modules are normally mounted in the LV compartment. The low voltage inputs are connected to the busbar or a spare feeder over a Miniature Circuit Breaker. Sensors, optical fibres and circuit breaker control cables are led to the 10 kV compartment and mounted.

The current sensors are clamped directly onto the cables, cable end joints or bare conductors with two silicone strips and a sealing silicone compound; see Figure 6. Spacers are used to fix the optical fibres to the power cables and ensure a correct creepage distance and no humidity bridges.

**FIGURE 6 – Current sensors placed below a 10 kV cast-resin disconnector**

When a sensor is mounted onto a cable, it measures the resulting magnetic field at its location but not the current. To achieve this, a portable calibration system is used.

The Rogowski coils of the calibration system are mounted on all three phases of the cable system. Optical fibres from the coils to the calibration electronics ensure galvanic separation.

The installation and calibration process can be carried out in one line bay at a time. Installing and calibrating DISCOS in a RMU station can hence be carried out without interrupting the power supply to the customers.

**IMPLEMENTATION STRATEGY**

**General implementation strategy.** The implementation cost per type A installation mainly depends on the number of MV line bays and the MV switchgear type.

To make the most of the investment, the cost-benefit ratio was calculated for all 6,700 10/0.4 kV stations in NESA's distribution grid. In this respect, cost-benefit was defined as:

\[
\text{Cost - benefit} = \frac{\text{Installation and maintenance costs over lifetime [DEK]}}{\text{Reduction in NDE over lifetime [kWh]}}
\]

The potential reduction in NDE per station was found using network simulations. Stations showing a cost-benefit ratio below 100 DEK/kWh or 13 €/kWh were accepted as candidates for type A-installation.

The result was 330 substations (5% of all stations). Using these stations for fast fault isolation and power restoration, NDE per year is expected to decrease with approximately 45,000 kWh, or nearly 20% of the total NDE. During 2005, NESA will equip those 330 10/0.4 kV stations with DISCOS, and upgrade breaker equipment to remote tripping.

Depending on first operational experiences, NESA expects to continue with type B installations in about 1,500 10/0.4 kV stations. The expected development in NDE is shown below, based on implementation of type A and – later – type B.

**FIGURE 7 – Non-delivered Energy, forecasted; using DISCOS**

The planned type A and B installations will stabilise and even reduce the extent and duration of the outages significantly. In principle, the use of DISCOS postpones the need for general reinvestments with 8-10 years – at a significantly lower cost. An outage penalty scheme as known in other Nordic countries will make distribution grid automation even more beneficial.

**Number of installations per feeder.** The optimal number of installations per feeder depends on the overall grid structure, line lengths, loads, the frequency of fault, DISCOS installation costs, etc.

Using data for NESAs MV-grid, the optimal number of type A installations seems to be 0 – 2 per feeder:

- 0 installations on 55% of the feeders.
- 1 installation on 34% of the feeders and
- 2 installations on 11% of the feeders

Since type A-stations are selected with respect to both implementation costs and impact on NDE, some stations are not placed optimally regarding NDE only. For full benefit of the type A-stations, the feeder structure should always be reconsidered and optimised if necessary.