

**FACULTY OF ELECTRONICS,  
COMMUNICATIONS AND  
AUTOMATION**

**Power Systems and High Voltage  
Engineering**

**REPORT**

Theme:

Monitoring, Controlling and Automation  
of Secondary Substations

presented by: Jens Werner, TU DRESDEN, Faculty Electrical Engineering, Germany

handed in on: January 26th, 2011

## Contents

<b>1. Introduction .....</b>	<b>3</b>
<b>2. Current Implementation of Secondary Substations in Power System.....</b>	<b>3</b>
<b>3. General View.....</b>	<b>5</b>
<b>4. Specific View .....</b>	<b>6</b>
<b>4.1. Voltage and current monitoring.....</b>	<b>6</b>
<b>4.1.1. Possibilities due to voltage and current measurement .....</b>	<b>6</b>
<b>4.1.2. Influence of Distributed Generation on the LV level and the power flow direction .....</b>	<b>6</b>
<b>4.1.3. Influence of Distributed Generation in case of fault .....</b>	<b>7</b>
<b>4.2. Concept of automatic earth fault protection.....</b>	<b>10</b>
<b>4.3. Flexible maximum load current .....</b>	<b>10</b>
<b>4.4. State estimation.....</b>	<b>18</b>
<b>4.4.1. Transformer .....</b>	<b>18</b>
<b>4.4.2. Connection.....</b>	<b>19</b>
<b>4.5. Fire prevention and fire protection.....</b>	<b>20</b>
<b>4.5.1. Fire detectors .....</b>	<b>21</b>
<b>4.5.2. Fire extinguishing systems .....</b>	<b>22</b>
<b>4.5.3. Fire protection systems .....</b>	<b>23</b>
<b>4.6. Others .....</b>	<b>23</b>
<b>5. Economic aspect and analysis.....</b>	<b>24</b>
<b>5.1. reliability worth – customer interruption costs .....</b>	<b>25</b>
<b>5.2. asset capital costs.....</b>	<b>29</b>
<b>5.3. asset operation and maintenance costs .....</b>	<b>31</b>
<b>6. Conclusion.....</b>	<b>33</b>
<b>7. References .....</b>	<b>33</b>

**ABSTRACT - In the year 2013 digital power measurement instruments will be required by law in the households. Additionally the Primary Substation has been integrating in the remote-control system of the power system since a lot of years. On the other side the states of Secondary Substations were not and are not well known. The installation of devices for Automation, Monitoring and Controlling is principle motivated by the connection of controllable consumers and Distributed Energy Sources (DES) in the Low Voltage (LV). The report deals with the main possibilities for Automation, Monitoring and Controlling of the Secondary Substations and should explain the current and coming development of the power system and the arising influence on the substations. The main requirements and solution approaches should be considered, even under economic aspects.**

## **1. Introduction**

The Distribution Power System is changing from a static to a dynamic system. Regarding this, different demands are made to the power system by Distributed Generation, Demand Side Management/ Demand Response or the requirement for a higher reliability of supply in future. Additionally the security aspects in view of the population and the environment should be considered. Due to the further development the communication and connection between the different levels of the power system and to the civil constitutions like the fire department will be more important.

Furthermore it has to consider, that a balance between the costs for equipment and the necessary infrastructure and the importance of the specific Secondary Substation has to exist. Therefore, influencing variables can be defined:

- relevance of the specific Secondary Substation
- accessibility of the Secondary Substation
- consumer power / load flow in LV
- reliability of supply in the part of power system
- costs of outages - depend on consumer structure (industrial, commercial, residential)

The Distribution System Operator (DSO) has the target to minimize the costs and simultaneously increase the reliability and decrease time for outages. To reach these targets, different possibilities exist. These are summarized under the topic "Automation, Monitoring and Controlling of Secondary Substations". In the following explanations the use of the substation, possibilities, essential problems, which exist and the application of the collected information should be described in regard to electrical and non-electrical aspects. In the last part investigations concerning the economic aspects especially the potential of savings will be described.

## **2. Current Implementation of Secondary Substations in Power System**

The power system was designed for a unidirectional power flow from the power plants to the end-consumer over different voltage levels. The Secondary Substation is the interface between the Medium Voltage (MV) and Low Voltage (LV) power system, shown in Figure 1. In the MV the ring network is used as the common grid structure, the mode of operation could be closed or opened controlled by the Nodal Opening Point (NOP). In the LV radial networks are often used or in some case meshed networks. Regarding Figure 1, the Secondary Substation consists normally of the disconnectors in the MV-network, the Highvoltage-Highpower-fuse (HH-fuse) for protection of the transformer, the MV/LV-transformer and the Lowvoltage-Highpower-fuse (LH-fuse) for protection of the outgoing in the LV.

Different requirements and deductive different implementations arise to the Secondary Substation depend on

the operating places. These could be:

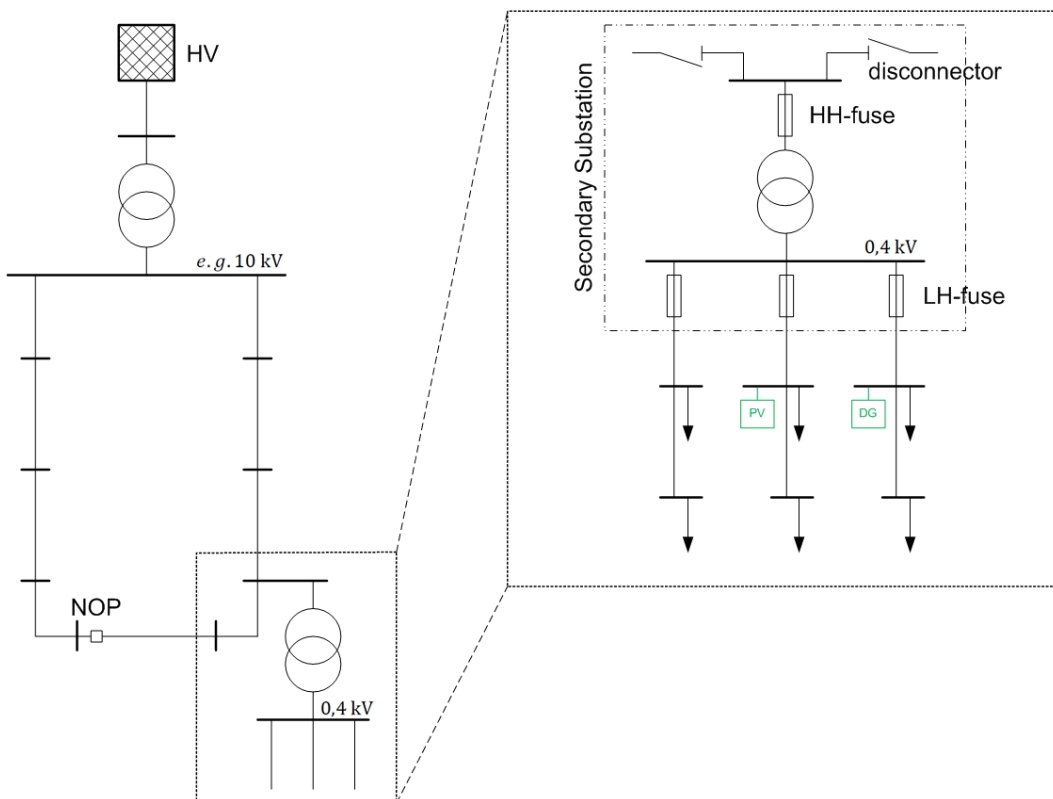
- urban, suburban or rural areas
- inside of buildings, outside in compact stations or free standing transformers

Based on the stochastic operation of consumers, this means that not all devices works at the same time, the dimensioning of the equipment ensues with the coincidence factor (CF):

$$g = \frac{S_{\text{dimensioning}}}{S_{\text{installing}}} \quad (1)$$

The CF results basically from the consumer structure and the amount of connected consumers. In presence and future it exists and will exist reinforced connection of Distributed Generation, for example combined heat and power plant (CHP) or Photovoltaic (PV). Concerning the network planning it should be mentioned, that a CF of one has to adopt, because it is possible that all works at the same time and an active power control is not provided.

A feed-in of a reactive current by the DG in the LV is not planned or foreseeable to fulfil the requirements of voltage support during a fault now. In Germany, the feed-in in MV networks have been required by law for wind power plants since 2010 ([3]). Some further information are seen in section 4.1.3..



**Figure 1:** implementation of Secondary Substation in the power system

### 3. General View

In the following topic an overview of the possibilities concerning Automation, Controlling and Monitoring of Secondary Substations should be given. Up to now in the Secondary Substations is no state estimation implemented and they are not connected to the communication network. Outages are reported by the consumers and a service team search the fault location and repair the faulted section.

In case of a fault in the MV, the protection relays in the Primary Substation, normally overcurrent-time protection is used, clear the fault. After this, the ring network and all consumers are disconnected from the remaining power system. For searching of fault location, the service team checks all short-circuit indicators (in case of earth fault the earth passage indicators) along the path to find the fault location and to separate it by open the disconnectors. They are normally hand-operated and no remote-controlling or remote-monitoring is provided.

These are only some facts, in which Automation, Controlling and Monitoring can help to reach the targets, decrease the cost or increase the reliability.

In Table 1 should be given an overview of the possibilities, which should be explained after this in some cases. They can be distinguished in belonging to electrical and nonelectrical equipment.

**Table 1:** possibilities for Automation, Controlling and Monitoring

electrical possibilities	nonelectrical possibilities
<ul style="list-style-type: none"> <li>• voltage and current               <ul style="list-style-type: none"> <li>– power flow</li> <li>– power quality</li> <li>– fault protection</li> </ul> </li> <li>• transformer               <ul style="list-style-type: none"> <li>– oil-temperature</li> <li>– oil-wetness</li> <li>– gas-content in oil</li> <li>– wetness of paper insulation</li> <li>– pressure in boiler</li> <li>– tap-changer (if-possible)</li> <li>– winding temperature – hottest spot temp.</li> </ul> </li> <li>• switch-gears</li> <li>• automatic earth fault protection in MV</li> <li>• temperature of connections</li> <li>• resistance of connections</li> <li>• line thermal monitoring</li> <li>• partial discharge monitoring</li> <li>• SF6-pressure (if SF6 is used)</li> </ul>	<ul style="list-style-type: none"> <li>• signal of door status (open, close)</li> <li>• temperature (inside, outside)</li> <li>• external cooling or ventilation (controlling)</li> <li>• SF6-content in air (if SF6 is used)</li> <li>• fire detection               <ul style="list-style-type: none"> <li>– heat detector</li> <li>– smoke detector</li> <li>– photoelectric detector</li> <li>– flame detector</li> <li>– air sampling detector</li> </ul> </li> <li>• motion sensor</li> <li>• water level sensor</li> <li>• emergency power supply (battery capacity)</li> </ul>

To transmit the data, e.g. voltage, current or switch gear status, to the Control Room, possibilities for communication are required. For the right choice of the technology for communication you have to decide, which function should be fulfilled by the communication, depending on the costs and the important values. You can distinguish generally between remote-monitored and remote-controlled.

Possible ways are shown following:

- SMS
- GRPS
- TETRA
- SCADA
- GPS (time-synchronisation)
- carrier frequency transmission

It should be mentioned, that it is not necessary to transmit all information from the Secondary Substation to the Control Room. One motto could be: "Communication only on request". For this the SMS-Technology could be a good choice.

## 4. Specific View

### 4.1. Voltage and current monitoring

In the following subsection possibilities by voltage and current monitoring should be shown and results of the development of the power system should be explained. Voltage and current can be monitored on the LV side of the transformer, because this reduces the costs for the equipment. For example, for the current measurement can be used the cheap variants Shunts and Rogowski-Coil or the more expensive variant of Current Transformers.

#### 4.1.1. Possibilities due to voltage and current measurement

Under consideration of the measurement, different possibilities for use the data exist:

- power flow:
  - direction of load flow, important in case of distributed generation
  - calculation of active and reactive power, e.g. for billing
  - use data for power system planning
  - determine maintenance cycle for transformers
  - state estimation of the equipment
- power quality:
 

The PV or CHP is connected to the power system by DC/AC or AC/AC-converters. These converters cause system perturbation like harmonics in the current. Additionally to that, flicker is also important in the LV. The system perturbation influences the consumer devices and is deductive a question of quality of supply. By monitoring voltage and current it is possible to detect abnormalities to the norm of the power quality and the perpetrators. In the case of compensation claims, a simply way to reconstruct the situation exist.
- fault protection:
  - detect outages (normally signaled by the consumer)
  - clarify reasons for outages
  - detect faulted section by calculation the fault impedance with algorithm like the Phadke/Ibahim used in Distance protection relays

#### 4.1.2. Influence of Distributed Generation on the LV level and the power flow direction

With increasing of the Distributed Energy Resources, which are connected to the LV, the voltage control will be more and more important. Two important facts should be mentioned. The first fact is the increase of the voltage due to the feed-in. The tap changer of the MV/LV transformer is normally fixed, this means that no direct voltage control in LV is possible. The basically influence is shown in Figure 2. The figures are constructed under the following terms:

$$P_{\Sigma \text{consumption}} = P_{\Sigma \text{production}} = 6 \text{ kW} ; P_{\text{DG1}} = P_{\text{DG2}} ; P_{\text{H1}} = P_{\text{H2}} = P_{\text{H3}} \quad (2)$$

It is obvious, that the feed-in of the DG increase the voltage, a breach of the voltage threshold values is possible. The critical situation is characterized thereby, that no consumption and the maximum of feed-in exist in the power system. Deductive it might be necessary to control the voltage, for example by influencing the position of the tap changer, which is normally fixed.

In case of higher feed-in as consumption the power flow change the direction. Contrary to the historical development of the power system the unidirectional power flow will change to a bidirectional power flow. This has no direct influence on the equipment in the LV. The dimensioning of the equipment was basically explained in section 2. After the basic principles, the consumption or the feed-in should not exceed the rated values of the equipment in the LV. The fuses are laid out after the minimum rated current of the following equipment. For example, the HH-fuse are laid out by the rated current of either the transformer or the sum of rated current of outgoings and the LH-fuse are laid out by the rated current of the following line-section.

Because of the rules to determine the maximum feed-in, which is lower than the corresponding rated current, no tripping of the fuse is possible.

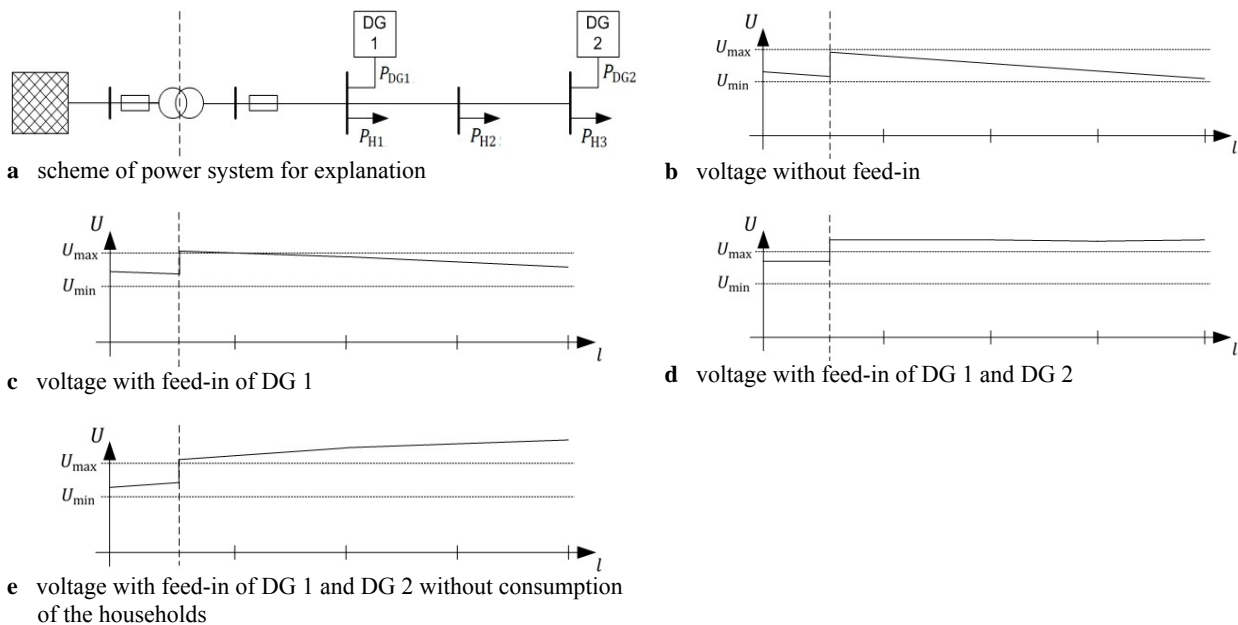


Figure 2: influence of feed-in on the voltage level

#### 4.1.3. Influence of Distributed Generation in case of fault

In the previous paragraph two different influences in stationary operation was explained. In case of a fault in the power system the reaction of the DG and of the protection system are important. At the moment, the DG will be disconnected in case of fault because of voltage drop or abnormalities of frequency. In future, it could be possible, that the DG should be connected to the power system during the fault and feed-in a reactive current, the so called "Fault-Ride-Through (FRT)" property. The reason for this underlie in the decrease of conventional power caused of the increase of regenerative power, thereby it is necessary, that the DG feed-in active power immediately after fault is cleared.

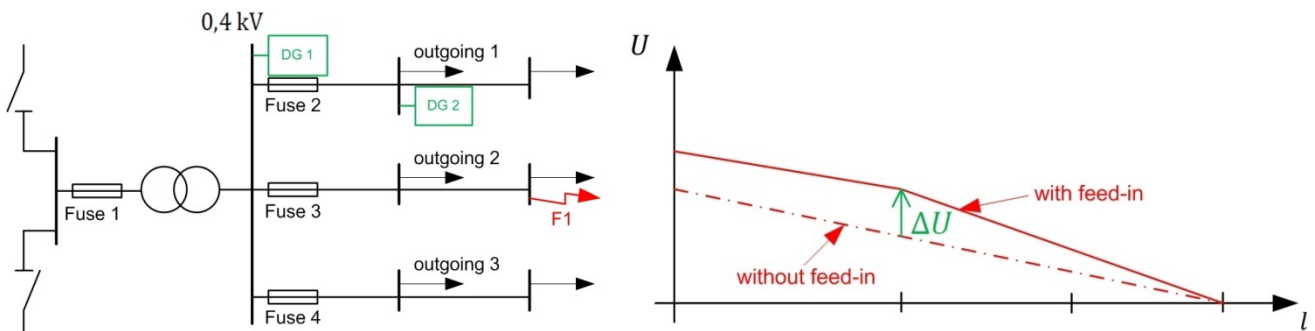
For wind power plants a law exists in Germany, which regulates the requirements to operation of the wind power in static and dynamic situations. In case of a fault, this means the dynamic situation, the main operation function is evaluated by the highest phase-to-phase voltage and the reactive feed-in is evaluated by the voltage of the positive sequence system. So this could be a possibility to characterize the feed-in current.

Due to the connection of the DG with converters to the power system, it is possible to control the power feed-in (active, reactive), but it is limited to the rated values. The feed-in of reactive power in case of a fault cause a following voltage support. The voltage will increase, which can lead to a decrease of the fault current from the higher voltage level, depend on the fault location. In the next steps, this should be explained further.

Without feed-in the whole fault-current flows from the MV to LV and further to the fault location. In case of the same lines the referred voltage drop is equal over the current-path (compare Figure 3). Due to the feed-in of DG, the short-circuit power will increase, so the fault-current from the feed-in location to the fault location will increase too. The result is, that the voltage will be higher and the voltage difference from the fixed voltage point (phase voltage of generators) to feed-in location will decrease, so that the fault current from the MV network will decrease too.

For the further development of the Secondary Substation, this circumstances should be mentioned. In some cases, there is the possibility, that the fault could not be clarified by the fuse. This depends on the feed-in, the short-circuit power without feed-in, the rated current and the type of fuse, partial-range fuse or full-range fuse. A replacement with controllable switch-gear of the fuse might be necessary. Different feasibilities exist:

- power contactors in combination with fuses
- on-load disconnectors in combination with fuses
- compact circuit breakers
- in future: Smart Fuses (compare further paragraph)



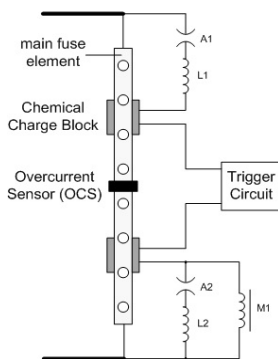
**Figure 3:** influence of reactive power feed- in during fault

The power contactor and also the on-load disconnector can only be used additionally to a fuse, because they are not able to switch high fault currents. Therefore, fault currents, which are in the range of the rated current can be clarified by the switches, faults with higher currents will be clarified by the fuse.

The switches and also the Smart Fuse could be controlled by a protection algorithm based on the monitored voltage and current. With implementing of switches, the DSO gets the possibility to remote-control the LV-outgoing. This function can be needed in the case of islanding power system operation in the future.



## Smart Fuses



**Figure 4:** construction of Smart Fuses

Smart Fuses (SF) are a further development of the normal fuses. The last publication about this topic dated to the year of 1994. During a web-search only one available product of "Glück Engineering GmbH" [20] was found, a request for further information about this product was not replied.

The idea of the SF is to combine the conventional time-current-characteristic (TCC) with a trigger circuit, which should allow to control the fuses by an external source. The trigger circuit operates on demand of for example the oil-temperature or the pressure of the boiler.

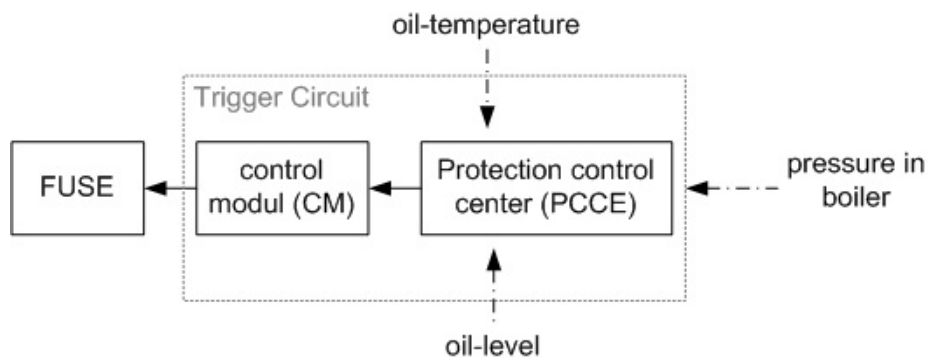
The SF should be an alternative to the installing of the circuit breaker under consideration, that they do not have the same operation functions. In the following explanation the function and the principle construction will be explained.

In Figure 4 is the principle of the construction of the SF obvious. The over-current-sensor (OCS) in the center is responsible for the TCC. During a high current, the main fuse element melt and arcs will develop. If the needed arc-voltage is high enough, the arc will be cleared and the current will be interrupted.

To interrupt low currents a minimum of arcs are required, which depends on the fuse rated voltage and the design. In conventional fuses, the TCC is fixed. Therefore chemical charges are placed on different points of the main fuse element during designing of the SF to allow a changeable characteristic. This enables, that low current can be interrupted with a high reliability. The control of the SF is reached by the Trigger-Circuit. Under normal operating conditions the trigger circuit is disconnected by the Air Gap A1. If the OCS opens for any reason, the arc-voltage causes, that the Air Gap A1 is bridged, the current flows through the trigger circuit and the chemical charges will be fired. The chemical charges are therefore responsible for the required number of arcs.

Due to add a special block (trigger circuit), which can be used to fire the OCS, the TCC can be taken out of service. By firing the fuse, a break can be reached, so that a normal opening point will originate. Following more breaks occur because of the chemical charges. The special, external block consist of a control modul (CM) and the protection control center (PCCE), the whole model is shown in Figure 5. The CM is the interface between the PCC and the fuse and works on the same voltage level like the fuse. The PCCE combines the signals, which can result in opening of the circuit by the fuse and send a electrical impulse to fire the fuse.

The coils are provided for lightning surge immunity.



**Figure 5:** concept of Smart Fuse

## 4.2. Concept of automatic earth fault protection

In MV power systems are very often used Earth Passage Indicators to detect the faulted section in case of an earth fault for example in a cable network. Anyway a considerable loss of revenue occurs because of time taken to locate the fault location during the MV network is separate from the feed-in. Normally circuit breakers only exist in the Primary Substations, which clear the fault. When the MV network is separated an engineer check the path of the earth fault along the grid by checking the earth passage indicators in every Secondary Substation. If the place is located the part of the grid will be isolated.

The financial loss can be decreased because of the use of Faulted Section Indicators. These one transmit the faulted section to a receiver in the Primary Substation, which is connected to the Control Room, with high frequency, time slotted and main borne signals. The correct faulted section is consequently available in the Control Room, so the time taken to separate the faulted section decrease. A further development in the direction to automate the grid-switching is possible, but remote-controlled switch-gears in the Secondary Substations are necessary. More information is shown in [1].

## 4.3. Flexible maximum load current

Generally the maximum load is secured to the rated values of the equipment and it is limited by the mechanical and electrical stability. The following section should describe the fact, that the rated values are fixed and do not present the current maximum value depending on the ambient conditions. A big influence concerning this has the ambient temperature and it should be taken into account that a correlation between the load peaks and ambient temperature exist. Hence, this can be used to exploit the equipment in the best possible way. It will be done for lines, especially for cable, and the transformers in the Secondary Substation.

With the implementation for calculation the maximum load current, we can easily specify the peak-load limits and thus a good adjustment of the maximum load to the current generation is possible in future, when the Low Voltage power system is characterized by more DG-units. Additionally the data can be used for protection against overload and for power system planning. This result in a higher reliability and a flexible power system

Concerning to the Automation, Monitoring and Controlling of Secondary Substations exist the possibilities to monitor the current, the voltage and different temperature, e.g. ambient temperature, winding temperature or oil-temperature. Basically the possibilities would exist to evaluate a maximal adapted load current for the equipment by using the temperature, which deductive result in:

- installation of transformers and cables with a lower rated current during planning of new distribution systems
- longer operation of transformers and cables, even when the capability line is reached after previous designing and under consideration of the estimated load growth

The basics for the planning process of a secondary substation were shown in section 2. For this the connection power is used. Not considered will be the correlation between the ambient temperature and the peak load, which exist normally in Winter days with the lowest temperature because of the use of electric heatings. This should be shown next to prepare the investigations regarding to the maximum load current depending on the ambient temperature.

For evaluation of the energy consumption respectively the maximum power, load profiles can be used. Ordinarily no load profile electric meter exists for small consumer. Thus standard load profiles are used, for example released by the BDEW<sup>1</sup>. These exist for different consumer categories:

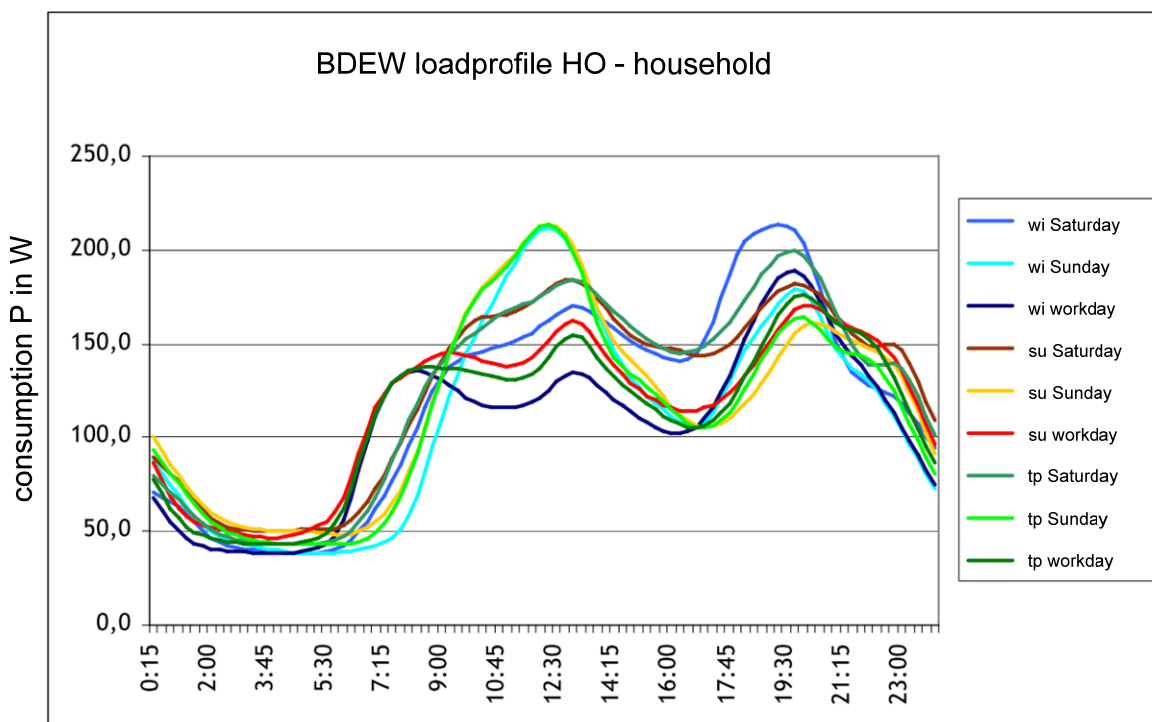
- households
- public services and commercial
- agriculture

For every category are given a overview about the typical load profiles for:

weekdays (workday, Saturday, Sunday)

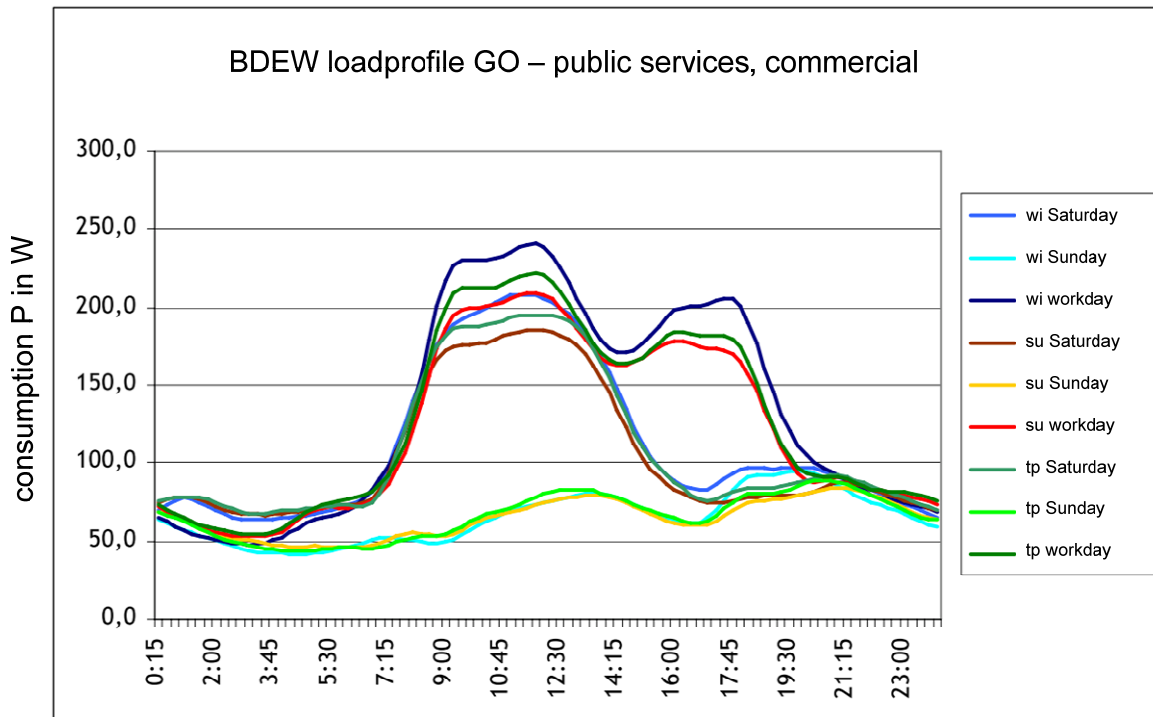
season (Winter, Summer, transition period)

The load profiles for households and public services are shown next.



**Figure 6:** standard load profile for households (Winter (wi), Summer (su), transition period (tp))

<sup>1</sup> Bundesverband der Energie- und Wasserwirtschaft – Organization for Energy- and Watereconomy



**Figure 7:** standard load profile for public services and commercial (Winter (wi), Summer (su), transition period (tp))

Principally the consideration of load peak is important for the next investigations. If you consider the load profiles of the households, it is obvious, that no essential difference regarding to the season exist. The maximum occur Sunday at 12 o'clock independent of the season. Furthermore a load peak exists in the winter on Saturday at approximately 19 o'clock.

For load profiles of commercial and public services clear differences between winter and summer exist in the maximum power according to the consideration period. The maximum occur in this case at 12 o'clock at workdays. An estimation of the proportions reveals:

$$\text{su} : \text{tp} : \text{wi} = 0,896 : 0,92 : 1 \quad (3)$$

Basically this is determining by the heating and the lightning.

Regarding to the following investigations it should be mentioned, that only in case of commercial and public services differences according to the load peak exist, on the other side for households no differences for the seasons are obvious. This is only valid for the German area. In other regions with another temperature profile, this could be different.

Attention should be given to the fact, that the load profiles are not used for network planning. During the planning of distribution networks the connection power of every consumer is decisive. Under consideration of the coincidence factors the dimensioning of the equipment ensued. The load profiles should explain that the load peak and following the dimensioning can be realized after the "winter values", which is characterized by lowest temperature and so a higher maximum load current is possible. This should be explained and more exact investigated in the next step. But this should be only some approaches.

Urban core areas are normally characterized by strong commercial using and also with a high percentage of public services. It will be taken into account a network, with 50 % households and 50 % commercial use and public services. In the following investigations it should be considered, how the differences in the peak load

for the different seasons can be used. For this the investigations are divided to investigations for cables and for transformers.

#### 4.3.1. correlation maximum load of cable to ambient temperature

The following explanations can be used for cables and basically also for overhead lines, but for this some additional aspects have to be considered. For the further investigations for cables, a variety of cables with different rated currents exist. The conditions, which have to pay attention, are defined for example in the German DIN-VDE standard. Deductive the rated currents describe the possible load for a definite operation condition. These are:

- level of loading:  $m = 0,7$
- ground temperature:  $\vartheta_{Gr} = 20\text{ }^{\circ}\text{C}$
- specific ground thermal resistance:  $\lambda_{Gr} = 1 \frac{\text{K}\cdot\text{m}}{\text{W}}$
- installation depth:  $d_{inst} = 0,7 \dots 1,2\text{m}$

If the conditions vary from the definite rated conditions, correction factors are given, which have to consider for planning of distribution networks. This ensued after the principle of the worst case, what means, that the worst operation conditions for the cables have to be observed. The acceptable load results according to that in:

$$I_{acc} = f_1 \cdot f_2 \cdot F_3 \cdot I_r \quad (4)$$

- $f_1$ : correction factor for various ground temperatures depending on the specific ground thermal resistance and the level of loading
- $f_2$ : correction factor for various installation conditions like the cable alignment depending on the specific ground thermal resistance and the level of load
- $f_3$ : correction factor installation in a pipe or under cover cap

For the investigation should be assumed, that the level of loading and the specific ground thermal resistance are constant / same like the definite operation conditions. Only the dependence to the ground temperature should be considered. For a special cable, the correction factor for different ground temperatures is shown in Table 2.

**Table 2:** correction factor for different ground temperatures

conductor temperature: $\vartheta_{con}$ in $^{\circ}\text{C}$	ground temperature: $\vartheta_{gr}$ in $^{\circ}\text{C}$	$f_1$
90	5	<b>1,07</b>
	10	<b>1,05</b>
	15	<b>1,02</b>
	20	<b>1</b>
60	5	<b>1,09</b>
	10	<b>1,06</b>
	15	<b>1,03</b>
	20	<b>1</b>

This means, that in case of a cable with rated current of  $I_r = 330\text{A}$  and a maximum conductor temperature of  $60^{\circ}\text{C}$  a acceptable maximum load of  $I_{acc} = 1,07 \cdot 330\text{A} = 359,7\text{A}$  is allowed for a ground temperature of  $5^{\circ}\text{C}$ .

The method to evaluate correction factors to implement them in the planning process are the result of consideration of the thermal network, which allow the calculation of thermal flows under given circumstances.

For adaption of the maximum load to the ambient temperature can be used the correction factors with more detailed scaling as a simple way or the more exact possibility called “Dynamic Rating Cable System (DRCS)”. This allows an up to date calculation of the acceptable load, based on the thermal network and the measured or given data. The target should be to maximize the asset utilization without jeopardizing the system facilities and/ or compromising the reliability of the cables. A further operation range is, if bottlenecks, mostly during winter, exist in the distribution network, then the transfer capability can be increased, the damaging of the equipment can be avoided and so the cable reliability increase. Following some facts concerning to the DRCS should be mentioned.

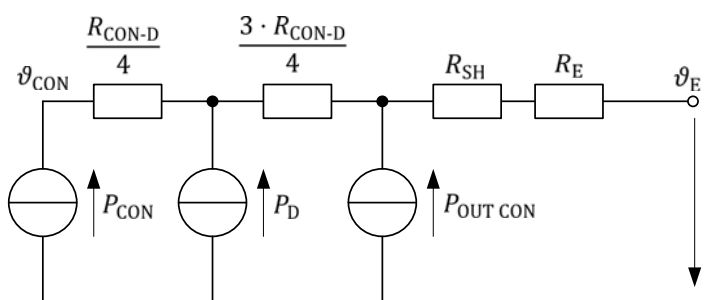
#### DRCS function description

The DRCS is explained in [25]. It is able to evaluate or determine the steady state and dynamic estimation of cable rating based on the:

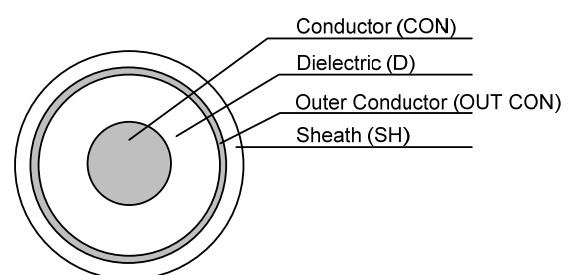
- real time cable loading – measured value in Secondary Substation or result of the calculation with the data of the meters of the end-consumer
- cable’s surface temperature
- ambient temperature – measured value in the Secondary Substation
- forecasting temperature – data from weather forecast over communication possibilities provided

Therefore, two different calculation methods can be provided, offline and online operation. For the offline operation, the DCRS is a useful planning tool for the system engineer to understand the steady state and dynamic characteristics. In case of online operation, the DRCS provide real time system information, for example cable loading, cable temperature etc., which are accessible in the Control Centre by implementation of communication.

The cable’s surface temperature can be measured or estimated by the ambient temperature in the past under consideration of the history out of a database, potential variations should be considered. The cable’s surface temperature is the basic for the calculation of the thermal network, shown in Figure 8 referring to Figure 9



**Figure 8:** simple thermal network of a cable



**Figure 9:** simple structure of a cable

With the thermal network, which is a simple one and do not contain the connection to other cables in the near, the acceptable current in dependence to the surface temperature is calculable. The basic for the following formulas is the superposition principle.

$$\begin{aligned} \Delta\vartheta &= \vartheta_{\text{CON}} - \vartheta_{\text{E}} \\ &= P_{\text{OUT CON}} \cdot (R_{\text{SH}} + R_{\text{E}}) + P_{\text{D}} \cdot \left( R_{\text{SH}} + R_{\text{E}} + 3 \cdot \frac{R_{\text{CON-D}}}{4} \right) + P_{\text{CON}} \cdot (R_{\text{SH}} + R_{\text{E}} + R_{\text{CON-D}}) \end{aligned} \quad (5)$$

with

$$P_{\text{OUT CON}} = \alpha_1 \cdot P_{\text{CON}} \quad (6)$$

$$P_{\text{D}} = \alpha_2 \cdot P_{\text{CON}} \quad (7)$$

$\vartheta_{\text{CON}}$  can be assumed to be known and is constant. Not known is the thermal energy, which results from the losses in the conductor. The next steps for calculation of the acceptable current are shown following.

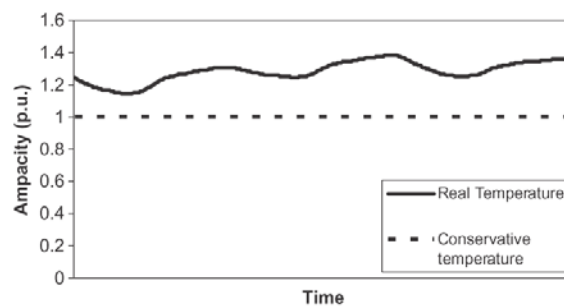
$$P_{\text{CON}} = \frac{(\vartheta_{\text{CON}} - \vartheta_{\text{E}}) - \alpha_1 \cdot (R_{\text{SH}} + R_{\text{E}}) - \alpha_2 \cdot \left( R_{\text{SH}} + R_{\text{E}} + 3 \cdot \frac{R_{\text{CON-D}}}{4} \right)}{R_{\text{SH}} + R_{\text{E}} + R_{\text{CON-D}}} \quad (8)$$

$$P_{\text{CON}} = I^2 \cdot R_{\text{el CON}} \quad (9)$$

$$I_{\text{acc}} = \frac{\left( (\vartheta_{\text{CON}} - \vartheta_{\text{E}}) - \alpha_1 \cdot (R_{\text{SH}} + R_{\text{E}}) - \alpha_2 \cdot \left( R_{\text{SH}} + R_{\text{E}} + 3 \cdot \frac{R_{\text{CON-D}}}{4} \right) \right)^{0,5}}{(R_{\text{el CON}} \cdot (R_{\text{SH}} + R_{\text{E}} + R_{\text{CON-D}}))^{0,5}} \quad (10)$$

The calculation was done with the steady state thermal network. For implementation in a real system with online monitoring of the acceptable current is the dynamic system necessary. This should be considered. Furthermore it has to be mentioned, that the losses in the outer conductor are not constant because they are load dependent due to arising through magnetic induction. The losses in the dielectric are approximately constant, because they are voltage-dependent and thus load independent. The other fact is, that the thermal earth resistance is not constant due to desiccation by the thermal output.

For the system availability and a good reliability, the surface temperature should be measured, if possible on three different locations (front, middle, end) of the cable. In [25] the ampacity of a cable, which was investigated, is shown in Figure 10.



**Figure 10:** acceptable current / ampacity over time for assumption of constant temperature and for use of the DCRS [25]

In Figure 10 is obvious, that the ampacity is between 10% and 40% higher for use of the DCRS. This can be used to maximize the cost-effectiveness considerations. The ampacity is as well higher compared to the correction factors, which were only in the range up to 9%. Therefore, the better possibility is the DCRS, the simplest one is the method with the correction factors. Principally it is possible, to increase the operation range of the used cable, necessary for this is the computer technic, the software and dependent on the method the measurement of the surface temperature.

#### 4.3.2. correlation maximum load of transformer to ambient temperature

Analog to the cable, following should be done the investigations regarding to the dependence of the maximum load of the transformer to the ambient temperature. Therefore two different publications are used ([26] and [27]). The target should be to describe how the ambient temperature can be used to calculate the maximum load, the correlation between these two aspects will be determined.

Written in the beginning of section was the fact that the annual peak load agrees approximately with the lowest ambient temperature in the year. Similar to the cables, the loadability of a transformer is limited by the insulation level. Responsible for the decrease of the insulation level are hot spot and thus the hottest-spot temperature (HST) limit the maximum load of the transformer. The hottest-spot temperature is depending on the ambient temperature and the current load, shown following.

$$\theta_{\text{HST}} = \theta_{\text{A}} + \Delta\theta_{\text{TO,R}} \cdot \left( \frac{K^2 \cdot R + 1}{R + 1} \right)^n + \Delta\theta_{\text{H,R}} \cdot K^{2m} \quad (11)$$

$\Delta\theta_{\text{TO,R}}$  ... top-oil rise above  $\theta_{\text{A}}$  at rated load

$\Delta\theta_{\text{H,R}}$  ... is the hot-spot conductor rise above top oil temperature at rated load

$K = \frac{S}{S_r}$  ... ration between current load to rated load

$R = \frac{P_{\text{L dep r}}}{P_{\text{L ind r}}}$  ... ratio between the load dependent losses at rated load to load independent losses

$m, n$  ...  $m, n$  are constant

The publication [26] deals the transformer loading analysis for HV/MV-transformers, but a comparison to MV/LV-transformers in the Secondary Substations is in a sense possible. Following the results, how far a correlation between ambient temperature and maximum load exist, should be reflected.

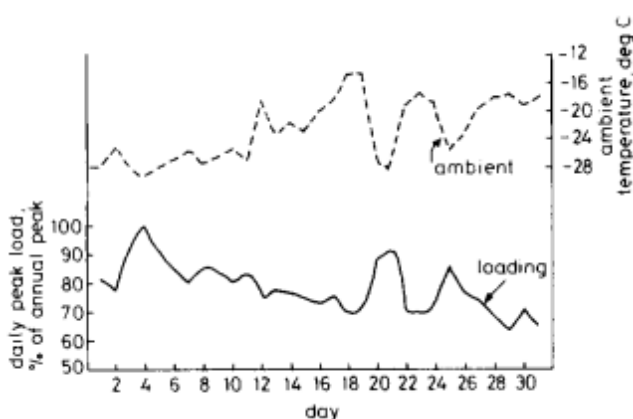


Figure 11: typical substation winter daily peak-load and ambient-temperature [26]

❖ on a typical day, substation loads vary from 60% to 100% of the daily peak load and a correlation to the change of the ambient temperature is obvious – the peak exist at the lowest temperature in winter days and highest temperature in summer days

❖ during the month, the daily peak loads vary from 60% to 100% of the monthly/ annual peak and correlate well with the ambient temperature change (compare

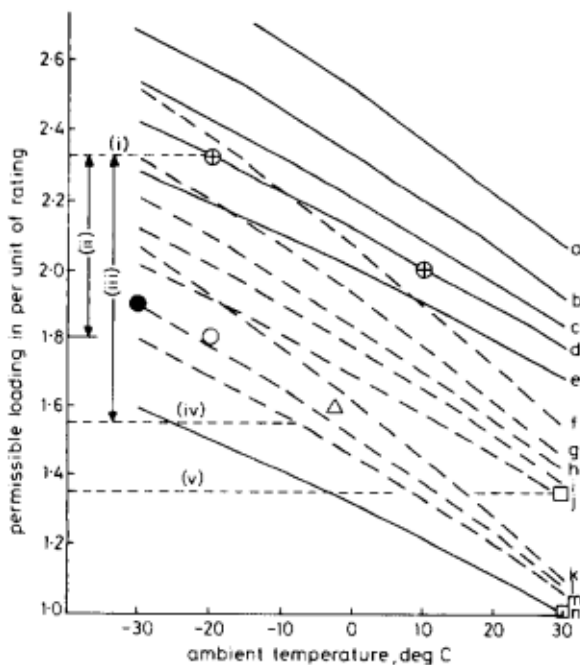


- ❖ during the year, the monthly peak loads vary from 20% to 100% of the annual peak, which always occur on the coldest day at the ambient temperature

In Table 3 is a summary for the operating conditions for the different seasons.

**Table 3:** typical operating conditions

	winter	summer	fall and spring
ratio peak load to annual peak	80 – 100%	20 – 50%	50 – 70%
duration of peak load	0,5 – 2h	1 – 3h	1 – 2h
ambient temperature during peak	-35 – -15°C	25 – 35°C	-10 – 10°C
frequency of peak per month	1 – 3	1 – 3	1 – 3



**Fig. 5** DS-transformer loadability against ambient temperature

55°C rise in insulation temperature, self-cooled, 100% preloading	
a 0.5 h, loss 0.128%, 150°C	
b 1.0 h, loss 0.256%, 150°C	
c 1.5 h, loss 0.380%, 150°C	
d 2.0 h, loss 0.500%, 150°C	
e 3.0 h, loss 0.780%, 150°C	
f 0.5 h, loss 0.007%, 120°C	
g 1.0 h, loss 0.015%, 120°C	
h 1.5 h, loss 0.022%, 120°C	
i 2.0 h, loss 0.030%, 120°C	
j 3.0 h, loss 0.043%, 120°C	
k 1.0 h, loss 0.002%, 100°C	
l 2.0 h, loss 0.003%, 100°C	
m 3.0 h, loss 0.005%, 100°C	
n 24 h, loss 0.038%, 95°C	

**Figure 12:** substation transformer loadability against ambient temperature [26]

further, because they are laid out after the rated currents of the transformer and the cables. The rated currents are the highest possible currents without consideration of the correlation to the ambient temperature. But with the consideration of the correlation, the maximum current is flexible and can be higher than the rated current.

To get back in mind, the proportion after the German load profiles is  $s_u : t_p : w_i = 0,896 : 0,92 : 1$ . The reason for the high differences is the result of the difference in the temperatures. Thus it is obvious, that in areas with very low temperatures in winter, it could be more economic to implement algorithm for consideration of the ambient temperature in the maximum load.

In [26] were done investigations for different transformers, which result in curves of loadability against ambient temperature. One example is shown in Figure 12, in which is also presented the dependence the loss of life due to aging.

It is obvious, that the maximum load can be increased heavily in case of small ambient temperatures.

A simple possibility will be to investigate and measure the hottest spot temperature depending on the ambient temperature and maximum load to get the curves. After this, by measuring of the ambient temperature and following a comparison with curves allows the estimation of the maximum load. To control it, the winding temperature and the oil-temperature can be used.

A really important fact, which should be considered, is the protection system. In case of a flexible maximum load, the used fuses are not possible to use

## 4.4. State estimation

Aging is an important fact concerning the economic and the electrical use of the equipment in the Secondary Substation. The main electrical equipment, which should be monitored, are the transformer and connections. With different simple methods it is possible, to detect outages before they happen and decrease costs due to calculation of the remaining life time, which allows the operation of the equipment with the optimal life-time depend on the load-time-characteristic.

### 4.4.1. Transformer

Transformers in Secondary Substation are normally installed and work for a defined time under consideration of maintenance-periods. The aging results essentially from the load current and following with the hottest spot temperature, explained in section 4.3.2.. The aging could be estimated with the values:

- oil-temperature over time
- oil-wetness over time
- gas-content in oil over time
- water in paper insulation over time

Combined with the aging is the estimation of the remaining life-time, to which must be added the required calculation-technic and the software.

In some publications the aging of transformers was under investigation. One example is [26]. As mentioned, the aging is showing in a deterioration of the transformer insulation and is a function of the hottest spot temperature and the hours of load. For a special transformer could be given a equation, to estimate the loss of life for a specific duration of operation at a specific hottest spot temperature. One example is showing next:

percentage loss of life: 
$$LOL = 100 \cdot (\text{hours of load}) \cdot 10^{-\frac{6972.15}{\theta_{\text{HST}}+273} D} \quad (12)$$

with:  $D = 14.133$  for  $55^\circ\text{C}$  or  $D = 13.391$  for  $65^\circ\text{C}$  rise insulation

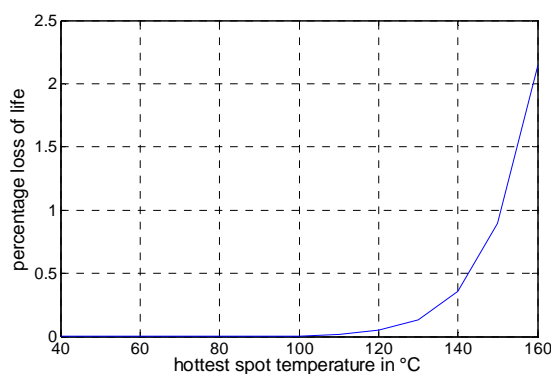


Figure 13: percentage loss of life depending on hottest spot temperature

Equation (13) is valid for a specific type of transformer. The principle trend is universally valid, only the numbers depend on the design of the transformer. For this the graph is shown in Figure 13, which presents the percentage loss of life about the hottest spot temperature. Up to a hottest spot temperature of  $100^\circ\text{C}$  the loss of life is very small, after this, it increases vigorous. Therefore hottest spot temperatures over  $120^\circ\text{C}$  should be prevented.

Some results of [26] should be summarized following:

- ❖ transformer aging is a cumulative process – an increase of the hottest spot temperature of 33.33% from 120°C to 160°C would result in an increase of loss of life from 0.049% to 2.15% for a duration of 2h, that means a 44-times increase
- ❖ hence if transformers operate with a HST not greater than 120% for the most of the time, the loss of life can be minimized to a tolerable value
- ❖ the HST is a function of ambient temperature, load shape and the transformer characteristic
- ❖ the ambient temperature has an important influence to the HST for determining of the loadability

Due to the dependence of the lifecycle to the operation and environmental conditions, a calculation of the life-cycle in respect to the conditions and the economic aspects should be aimed at. Obvious outages can be realized with sufficiency. At the end of the aging, there will be an outage of the transformer due to a loss of the insulation capability, which causes arcs. To use the transformer on an economic way, maintenance is necessary. This should be explained in the section regarding to the economic analysis.

#### 4.4.2. Connection

Analogous to the transformer, aging-processes exist also in the case of connections. These can be:

- Chemical Reactions
- Intermetallic Diffusion
- Creepage
- Electromigration
- Fretting

In the aging process the connection resistance  $R_C$  increase and so the temperature of the connection can rise, because the loss power  $P_L$  in the connection result from:

$$P_L = I^2 \cdot R_C \quad (13)$$

The rise of temperature cause a melting of the material, so the connection will be dropped. Relating to the aging, this can be rated by two values:

- connection resistance respectively quality factor
- temperature of connection

The quality factor is the result from the proportion of connection resistance  $R_C$  to the resistance  $R_L$  of a piece of the line with the same length  $l_L = l_C$  (compare Figure 14).

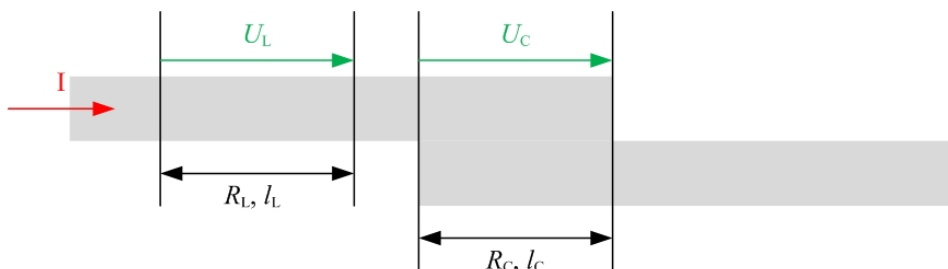


Figure 14: quality factor

So the equation for the quality factor is defined to:

$$k_U = \frac{R_C}{R_L} \quad (14)$$

The quality factor has normally the in Figure 15 shown characteristic during the lifecycle of the connection. After a phase of formation, the normal life cycle begin, signed by a quality factor of  $k_U \leq 1,5$ , and will end in abrupt rise of the quality factor in the range of  $k_U = 4 \dots 8$ . The high quality factor means a high resistance and follows in high loss power, which is also perceptible in the temperature.

The measurement of the connection resistance ensues by voltage and current measurement, the quality factor is the result of a calculation. To value the state of the connection, the temperature is another possibility, which can be measured for example with thermal imaging camera or a thermo element. Under consideration of the current, the connection resistance and the quality factor can be calculated.

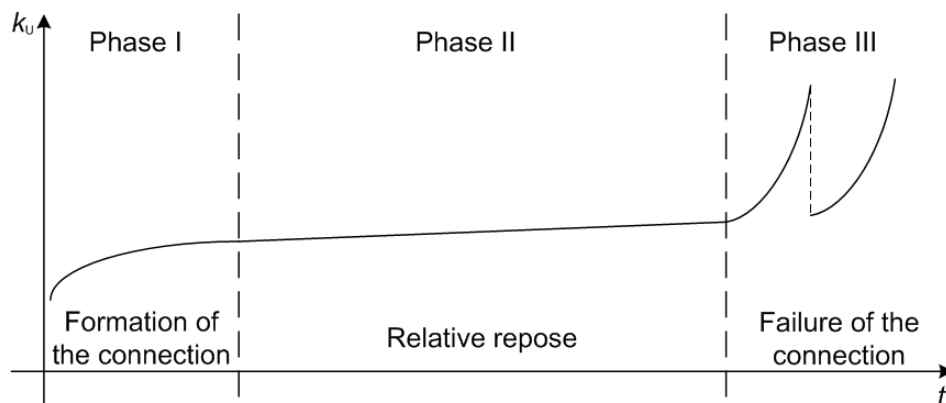


Figure 15: characteristic quality factor over time

#### 4.5. Fire prevention and fire protection

In the last paragraphs concepts for Automation, Controlling and Monitoring concerning the electrical equipment were explained. Following the fire protection of Secondary Substations should be dealt with. As already mentioned, Secondary Substations are implemented in different regional locations. Concerning these locations, the substations can be placed in buildings, compact stations or outside free standing. Due to the use of transformers, cables and other equipment a lot of combustible materials exist and these can cause a fire. Especially the risks within of buildings are very high. Deductive the fire protection and fire prevention is an important topic for the safety of humans and material.

The fire prevention and fire protection has four targets:

- to minimize the fire exposure to life
- to minimize spread of fire
- to minimize fire exposure to other close-by properties
- to minimize the loss of transmission capability

For fire three different components are needed. At first a source for heat for starting the fire, for example overload, gradual insulation failure, low oil-levels in transformer boiler, wetness or other acids ingredients in the oil or unmounted contacts, which can lead to an arc. In the transformer the arc involve high pressure and other gases arise. The high pressure can cause damage to the boiler.

The second is the fuel as the combustible material, for example oil, cable insulation or building materials. The third requirement is oxygen for reaction and growing the fire.

It is necessary to detect the arising fire as early as possible to prevent and to extinguish the fire without a big damage or a catastrophic failure. For fire prevention and detection different types of detectors can be used. An overview should be given following.

#### 4.5.1. Fire detectors

Regarding fire detectors you can distinguish between sensors, which are used direct and indirect for fire detection. It is for example possible to use the built-in sensors of the transformer, to detect the risk or the existence of a fire, although they are used to detect failures. Available are for example, but it should be mentioned, that they are only usable for transformer fire detection:

- hot spot temperature sensor
- high oil temperature sensor
- sudden pressure surge sensor
- combustible gas detection sensor

Sensors, which are used for direct fire protection, are mounted in the building or the compact station. The practical effect is only fire protection. Concerning this, different types exist, which are introduced next. To eliminate incorrect tripping and deductive faults in the Secondary Substation, the fire detection should be designed after the principle of redundancy and diversity, which means, that two different types for detection have to be installed and the signals have to be analyzed together.

#### Heat detectors

Heat detectors can work after different principles of operation. These are:

- fixed temperature detectors
- rated compensated detectors
- rate of rise detectors
- combination of fixed-temperature and rate of rise with thermally sensitive elements

The classic detector, which works with a fixed temperature, is the bimetallic strip thermostat. Other types are:

- snap action disc thermostat
- thermostatic cable
- thermistor line sensors
- fusible metal
- quartzoid bulb

In case of implementation of the fusible metal, quartzoid bulb and of the thermostatic cable it should be mentioned, that the function could be not guaranteed after high temperature rise, thereby a replacement is necessary. Concerning the other types neither the bimetallic thermostats nor the snap action thermostats are destroyed or permanently damaged by actuation. Rate compensate detectors are spot detectors that alarm at a predetermined air temperature under consideration of a thermal lag.

Rate of rise detectors works after the principle, detection of the temperature rise. So they operate rapidly and are effective in a wide range of temperatures. Furthermore they tolerate slow increases of the temperature without giving alarm.

The combination of fixed temperature and rate of rise detector responds without a lag to a rapid rise of temperature in case of fire and tolerates slow increases without giving alarm. The main types are the thermopneumatic, thermoelectric and the thermopneumatic tube detectors.

### **Smoke detectors**

Instead of temperature detection the invisible and visible products of the fire could be detected. For this smoke detectors are employed. In some case these detectors give alarm earlier than heat detectors, because the smoke concentration can increase faster than temperature.

### **Photoelectric detectors**

Photoelectric detectors use the characteristic of a visible gas, which is a product of combustion, that it reflects a part of the beam between a light source and the receiver. If the received light is under the limited value, a alarm will be actuated.

### **Flame detectors**

This detectors alert in case of flickering lights from the flames using the ultra-violet or infrared wave-length range. The detectors should operate with a time delay to eliminate false alarms from other flickering light sources.

### **Air sampling detectors**

Air sampling detectors draw a sample through the air to detect particles generated during the incipient stage of fire. For detection the light-scattering or cloud chamber method can be used. For both systems several levels for alarm thresholds can be previously programmed. Principal it is feasible to provide a staged, early-warning regime that responds to increasing of particles.

## **4.5.2. Fire extinguishing systems**

For fire protection are additionally the fire extinguishing systems necessary. For this, different solutions exist, which have their own advantages and disadvantages. Under consideration should be, that the extinguishing system works in an area, where electrical equipment is installed and faults caused by the operation of the extinguishing system should be prevented. For extinguishing the fire, external ventilation should be stopped automatically, if signals of the fire detection sensors exist. Due to this the supply of oxygen will be interrupted up to a minimum.

### **Fixed water extinguishing system**

The most common type of fire protection is the employment of water extinguishing systems. For this, distributed discharge nozzles are used to provide a specific water discharge and distribution over the equipment, but the system should be designed for prevention of flashovers through completely wetted insulators. As a solution to clarify this problem, it is possible to switch off the Secondary Substation in case of a alarm by the fire detection or by tripping of the fire extinguishing system, but switchgears are necessary for this.

### **carbon dioxide as extinguishing system**

Carbon dioxide is a noncombustible, but also a dangerous gas. For fire extinguishment the concentration should be at least 30%, for humans a concentration of 9% is dangerous and can cause death. However the big

advantage is, that it can be used without provisos in the field of energized electrical equipment. Compared with this exist the disadvantage, that it can only be used indoor.

For protection of humans it is necessary to implement some security algorithms. To prevent danger to personal the following equipment has to be installed and external control is available:

- motion detector
- door opening sensor
- switch for deactivation besides the main entrance
- automation system for deactivation in case of signal from motion detector or door opening sensor

Other types, for example dry chemicals or foam, should not be used where electrical equipment is located. They are electrically conductive or toxic and can damage the electrical equipment irreversible.

#### 4.5.3. Fire protection systems

A possible solution for a fire protection system is shown in Figure 16. For fire detection three different sensors are used for redundancy and diversity. If the smoke detector or the air sampling detector trips, a warning signal will be sent to the Control Room. First when the heat detector trips, a fire will be detected. If it is possible, the carbon dioxide extinguishment system can be used. In case for example of deactivation or the door is open, the carbon dioxide extinguishment should not be used due to the danger for humans. So the Secondary Substation should be switch-off, if a switch-gear is installed. After this as redundancy a water extinguishment system can extinguish the fire. If it is successfully, the ventilation, which was stopped before, can work again.

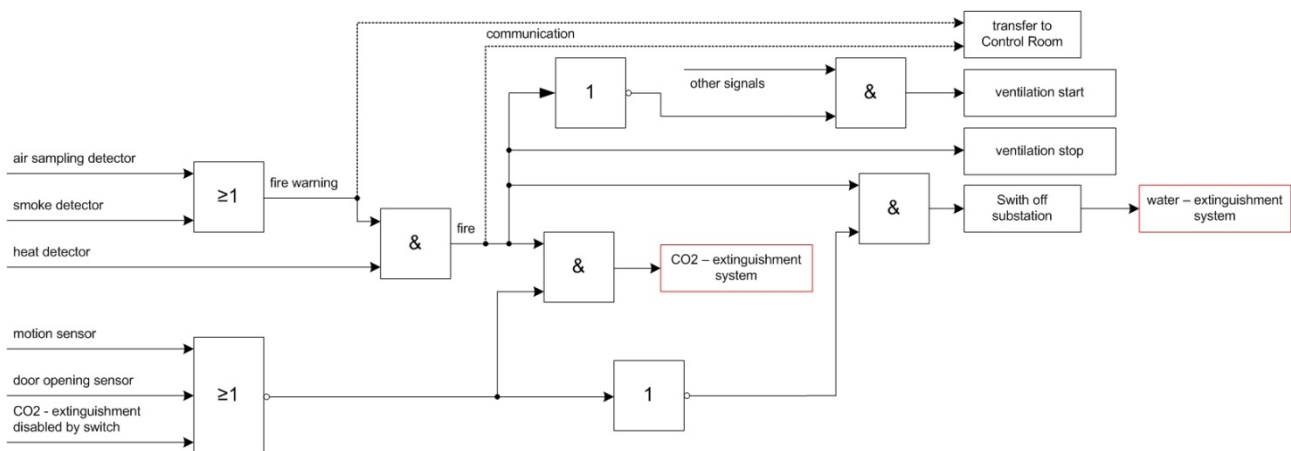


Figure 16: fire protection system

#### 4.6. Others

Different other possibilities were mentioned in section 3. These should be summarized in the following section and some approaches should be given.

The monitoring of the temperature inside and outside should be used for controlling of the external cooling or the ventilation and the signal of the door can be used to detect burglaries. In some switching stations or switch gears are used SF6 as a insulation medium. SF6 is a really dangerous and environmentally unfriendly gas. The loss of pressure in the devices should be detected, because it means on the one side a loss of

insulation capability and on the other side the inhalation of SF6 can cause apnea. Deductive the SF6 pressure and the SF6 content in the air should be detected.

In some areas, Secondary Substations are installed in the near of the coast or of the river. In case of risk of flooding it might be useful to install water level sensors.

The last fact is a new fact concerning the topic. If some possibilities for Automation, Controlling and Monitoring will be installed in the Secondary Substation, a emergency power supply could be necessary. Concerning this, the charge of the batteries can be detected.

## 5. Economic aspect and analysis

After explaining the main possibilities the basics for a cost-benefit-equation should be dealt with. This is essential for the DSO to decide, which devices he will install in next time under the requirement, that these are not technical necessary. At first, some generally aspects will be mentioned before at a later time the basic aspects concerning the topic will be examined. The fundament should be [23], a dissertation about economic aspects in the power system.

Concerning the electrical power system four different cost drivers can be defined:

- customer structure
- geographical area
- construction conditions
- climatic conditions

The first two points consider the basic supply task, the second the environmental conditions affecting network construction and operation. In the power system a classification of acting on parameters can be classified into endogenous and exogenous factors. The network operator has different possibilities to influence the cost drivers, the so called endogenous factors. These could be the construction planning, distribution system planning or reliability engineering, whereas exogenous factors describe the specific invariable parameters for the DNO.

Secondary Substations are used in different types of areas (rural, urban, suburban), which can be described by different factors:

- |               |  |
|---------------|--|
| • energy      | • number of customers                        |
| • peak demand | • connection proportional to geographic area |

The named cost drivers are abstract, so a split up in precise groups of the cost drivers could be helpful. These are shown following

- |                          |   |
|--------------------------|---|
| • transmission grid fees | • reliability worth – customer interruption costs |
| • overhead, taxes        | • asset capital costs                             |
| • return on investments  | • asset operation and maintenance costs           |

Ordinarily the cost factors in the right column are open to influence by the topic of Automation, Monitoring and Controlling possibilities. This will be reached by the endogenous factors, whereas the line between the two types is not strict. So far as it is possible, the network operator can influence the load profile by demand side management or can take part in the process of land use planning.



How far the costs can be decreased by Automation, Monitoring and Controlling should be considered qualitative in the first instance. The solutions are discussable and should be investigated for a real network with all necessary parameters in further investigations. Here should only be presented some basic approaches.

### 5.1. reliability worth – customer interruption costs

The part reliability worth contains mainly the interruption costs, which could be split into the customer interruption costs and the network repair costs. The latter are very small compared to the customer interruption costs, which can be quantified by the not supplied energy and is deductive dependent on the time.

To minimize the influence of the cost factors, the duration of the outage should be minimized, because the repair costs and other service costs could not be affected by the implemented devices. In the High Voltage this is reached by the autoreclosure, which is not achievable in the Low Voltage due to missing switches/circuit breakers.

The total unavailability time in case of outages due to equipment failures can be divided into three parts, the “locating time” to find a fault, the “sectionalizing time” to isolate the fault and restore the supply partially or totally and a “repairing time” to repair the damaged equipment.

Principally the “repairing time” is fixed due to the necessary work time. The “locating time” is at the moment basically determined by the time it requires for report of the outage by the consumer. By implementation of algorithms, which calculate the fault impedance and the fault distance similar to the Distance Protection Relay by the monitored voltage and current if necessary, in connection to the digital meters of the private households, the fault location can be determined with adequate accuracy.

The “sectionalizing time” can be reduced by using of remote controlled switch gears and disconnectors. In the Low Voltage the isolating distance is reached by taken fuses or isolation links. But there are no disconnectors provided, so it is not possible to reduce the time easily.

However, to undertake a detailed analysis the fault statistics for the Low Voltage has to be considered. It is applied for this the statistic of the VDN<sup>2</sup>. The statistic based on the data of German DSOs, which were evaluated respective and due to the participating number of DNOs, it can be supposed to be representative (compare Table 4). Shown statistics are valid for the year 2006

**Table 4:** rate of recording for the availability statistic

total CLL <sup>3</sup> in km	recorded CLL in km	total end-customer	recorded end-customer
1,067,100	779,717	44,500,000	32,171,971
rate of recording: 73,1 %		rate of recording: 72,3 %	

For evaluation of service reliability from a customer’s point of view was calculated different parameters, named as DISQUAL, based on the international UNIPED<sup>4</sup> experts group. They are shown following:

<sup>2</sup> VDN: Verband deutscher Netzbetreiber – Association of German network operators

<sup>3</sup> CLL: connection line length

<sup>4</sup> Union Internationale des Producteurs et Distributeurs d’Energie Electrique

- *Interruption Frequency  $F_1$  in  $1/a$ :*  
This index gives the average number of interruptions per customer in a year.
- *Supply Unavailability  $Q_1$  in  $min/a$ :*  
This index gives the average time without supply per customer in a year. It is a measure of the probability, which describes how often a customer is affected by an interruption of supply in a random moment respectively the average duration of an interruption for a customer in a year.
- *Interruption duration  $T_1$  in  $min$ :*  
This index gives the duration of a supply interruption.

The statistic gives a general overview about the interruptions and a special one regarding to the reasons and the affected equipment. The general one is shown in Table 5.

**Table 5:** general interruption statistic for Low Voltage

	$F_1/\frac{1}{a}$	$Q_1/\frac{min}{a}$	$T_1/min$
planned	0,025	3,5	139,4
unplanned	0,078	6,8	87,9

Following should be considered the special overview, which shows a differentiation concerning to the faulted equipment and the reason for the fault. For the following evaluation, this is important and should be therefore shown next.

**Table 6:** number of stochastic interruptions per failure location and occasion of interruption with percentage to the number of stochastic interruptions

occasion of outage occurrence	Failure location					
	overhead line (OHL)	cable	secondary substation (sec. sub.)	household connection (HC)	LV-Distributor (LD)	Others
	per 100 km OHL	per 100 km cable	per 100 sec. sub.	per 100 HC	per 100 LD	per 100 km CLL
no recognizable occasion	1.313	1.742	0.141	0.014	0.071	0.403
	3.3%	23.5%	0.9%	4.0%	1.3%	6.4%
atmospheric influence	3.779	0.182	0.07	0.005	0.024	0.091
	9.5%	2.5%	0.5%	1.3%	0.4%	1.4%
third part influence	2.33	1.49	0.035	0.013	0.123	0.074
	5.8%	20.1%	0.2%	3.8%	2.2%	1.2%
other influence	0.499	0.388	0.086	0.007	0.055	0.05
	1.3%	5.2%	0.6%	1.9%	1.0%	0.8%
secondary equipment	-	-	-	-	-	0.008
	-	-	-	-	-	0.1%
affected by failures in other system/ equipment	-	-	-	-	-	0.053
	-	-	-	-	-	0.9%

Table 6 gives an overview about the number stochastic interruptions. If you consider the numbers generally will be obvious, that cables, rather used in urban and suburban areas, and overhead lines, rather used in rural areas, are involved with a higher probability in the case of faults. Faults on overhead lines occur more frequently, even due to the susceptibility towards to atmospheric influence, e.g. thunder storm. Cables are influenced by this in a minor degree, faults occur with no recognizable reason. Due to the higher cable length preponderate with a higher percentage (compare Table 7). Also faults caused by third part, e.g. in case of

cables construction works, should be observed. The third biggest failure location is the secondary substation, whereby the rates are very small and mainly the faults occur without no recognizable reason.

**Table 7:** recorded datas of the area with following parameters

CCL overhead line / km	CCL cable / km	number of secondary substations	number of household connections
122,386	657,331	319,695	14,134,117

**Table 8:** interruption frequency  $F_1$  in 1/a per failure location and occasion of interruption with percentage to the interruption frequency due to stochastic interruptions

occasion of outage occurrence	Failure location					
	overhead line (OHL)	cable	secondary substation (sec. sub.)	household connection (HC)	LV-Distributor (LD)	Others
	per 100 km OHL	per 100 km cable	per 100 sec. sub.	per 100 HC	per 100 LD	per 100 km CLL
no recognizable occasion	0.001	0.007	0.000	0.001	0.000	0.003
	2.7%	29.8%	1.7%	2.1%	1.0%	12.0%
atmospheric influence	0.002	0.000	0.000	0.000	0.000	0.000
	7.5%	2.0%	0.4%	0.5%	0.3%	0.8%
third part influence	0.001	0.004	0.000	0.001	0.001	0.000
	5.3%	17.9%	0.3%	2.3%	2.3%	0.9%
other influence	0.000	0.001	0.000	0.000	0.000	0.000
	1.7%	4.2%	1.5%	0.5%	0.9%	0.9%
secondary equipment	-	-	-	-	-	0.000
	-	-	-	-	-	0.1%
effected by failures in other system/ equipment	-	-	-	-	-	0.000
	-	-	-	-	-	0.6%

The interruption frequency in the Low Voltage is shown in Table 8. During observation of this, it is obvious, that the biggest part exist in case of the failure location cable. The occasion is non-determinable (29,8%) of third part influenced (17,9%). However, if you consider the absolute interruption frequency, you can note that this is minor with 0,007 per year or 0,004 per year. In the first case this means, that you have 0,007 failure per year or every 142 years a failure on a cable with a length of 100 km.

**Table 9:** interruption duration  $T_1$  in min per failure location and occasion

occasion of outage occurrence	Failure location					
	overhead line (OHL)	cable	secondary substation (sec. sub.)	household connection (HC)	LV-Distributor (LD)	Others
	per 100 km OHL	per 100 km cable	per 100 sec. sub.	per 100 HC	per 100 LD	per 100 km CLL
no recognizable occasion	90.8	166.0	74.9	124.3	98.9	62.8
atmospheric influence	130.5	754.4	104.6	104.6	380.1	117.2
third part influence	107.8	116.7	162.1	162.1	106.0	134.4
other influence	66.7	186.2	60.1	60.1	100.7	67.8
secondary equipment	-	-	-	-	-	no data
effected by failures in other system/ equipment	-	-	-	-	-	no data

In connection to the interruption frequency stands the interruption duration (Table 9). This one is higher for

cable networks than for overhead line networks due to the higher effort for repair. For explanation you can use the repair-costs, showed in [23], are given for overhead lines with 1200 €/fault and for cables 3000€/fault. The interruption duration amount 166 min and 116,7 min for the both most occurring fault types. In the case of atmospheric influence, which only occur with a probability of 0,2 %, the interruption duration is in average 754,4 min.

**Table 10:** supply unavailability  $Q_1$  in min/a per failure location and occasion with percentage to the unavailability due to stochastic interruptions

occasion of outage occurrence	Failure location					
	overhead line (OHL)	cable	secondary substation (sec. sub.)	household connection (HC)	LV-Distributor (LD)	Others
	per 100 km OHL	per 100 km cable	per 100 sec. sub.	per 100 HC	per 100 LD	per 100 km CLL
no recognizable occasion	0.1	1.2	0.0	0.1	0.0	0.2
	1.8%	35.5%	0.9%	1.8%	0.7%	5.4%
atmospheric influence	0.2	0.4	0.0	0.0	0.0	0.0
	7.1%	10.7%	0.3%	1.3%	0.3%	0.8%
third part influence	0.1	0.5	0.0	0.1	0.1	0.0
	4.1%	14.9%	0.3%	1.7%	2.2%	0.8%
other influence	0.0	0.2	0.0	0.0	0.0	0.0
	0.8%	5.6%	0.6%	0.4%	0.4%	0.5%
secondary equipment	-	-	-	-	-	0.0
	-	-	-	-	-	0.0%
effected by failures in other system/ equipment	-	-	-	-	-	0.0
	-	-	-	-	-	1.0%

As a parameter, which conciliate the interruption frequency with the duration can be used the supply unavailability (Table 10). Thus faults through cables occur in total with 2,3 min/a per 100 km cable length. The supply unavailability is very small. How far this result in the customer interruption cost, this should be calculated following.

For evaluation of the occurring costs due to an interruption, the costs per kWh have to be considered. For this a statistic of [23] is used, which considers the cost per kWh for different areas. The results are shown in Table 11.

**Table 11:** composite customer damage function parameters for structural area types

type area	urban core	urban	suburban centre	suburban mixed	industrial	rural
costs $c_1$ in $\frac{\text{€}}{\text{kWh}}$	22,47	18,43	22,47	9,34	23,46	7,84

The target of the evaluation should be the interruption costs per secondary substation. Therefore the cable length per substation should be known. In [23] are shown some different statistics of the used networks, following should be used a network in a urban core area, which is characterized by high interruption cost per kWh. For this a cable length of 84,017 km in the case of 69 Secondary Substations is provided. Deductive this are 1,217 km cable per secondary substation.

The rated apparent power of the used transformers is in the range of 500 kVA up to 1250 kVA, in average  $S_{r,av} = 838$  kVA. The number of the MV-LV-customers is specified with 186. The next step is to calculate the active power.

The power factor is near to  $\cos \varphi = 0,95$  in the LV, the average utilization can be supposed to be 30 %, under consideration, that the maximum is much higher, normally 70 % or 80 % in winter. With the listed parameters, the interruption costs per Secondary Substation can be evaluated respectively estimated for one specific case. They could also be higher, if the average utilization is higher.

given:  $\eta = 0,3$  ,  $S_{r\text{av}} = 838 \text{ kVA}$  ,  $\cos \varphi = 0,9$  ,  $c_1 = \frac{22,47\text{€}}{\text{kWh}}$  ,  $Q_1 = \frac{2,3\text{min}}{\text{a}}$

$$P_{\text{av}} = \eta \cdot S_{r\text{av}} \cdot \cos \varphi = 238,83 \text{ kW} \quad (15)$$

interruption costs per  
secondary substation:

$$C_1 = Q_1 \cdot P_{\text{av}} \cdot c_1 = 205,72 \frac{\text{€}}{\text{a}} \quad (16)$$

The calculated or estimated costs per secondary interruption per year for an urban core area are quite small compared to the investment costs for example. But if you add the cost for every substation, it will be a high and noticeable sum. The estimation, how much can be saved due to implementation of Automation, Monitoring and Controlling possibilities, become to be difficult. As already mentioned, the interruption time can be divided in three parts, but only the “locating time” seems to be influenceable on a simple way. Because no specific values are ready in this way to split the interruption time in the three parts, a reducing of 20 % of the interruption cost should be supposed due to automatic fault location determination. So the yearly saving can be estimated to:

$$S_1 = 0,2 \cdot C_1 = 41,14 \frac{\text{€}}{\text{a}} \quad (17)$$

## 5.2. asset capital costs

In section 4.3 was shown, that a correlation between the ambient temperature and the maximum usable load exist, which can be used to design the networks with a lower rated current as it is necessary after the conservative design-rules, presented in section 2. Therefore cables can be used until a maximum load of 110% up to 130% of the rated current. For transformers the dependence to the ambient temperature is much higher than for cables, but a use up to 180% of the rated apparent power is possible under consideration of a low aging rate.

For evaluation of the influence to the asset capital costs, a general statement is not possible, on the contrary every case has to be considered. To estimate the influence, the investment costs for different cables and transformers are shown next. The facts are taken from [23].

Table 12: investment costs for cables and transformers

0,4 kV underground cables			20/0,4 kV transformers	
type	$I_r/A$	total unit price / €/kWh	$S_r/kVA$	transformers costs / €
Al 16	70	37945	30	2610
Al 25	100	37945	50	2610
Al 35	125	40575	100	2980
Al 50	150	40575	200	3780
Al 70	185	42255	315	4600
Al 95	220	43965	500	6070
Al 120	255	43965	630	8200
Al 150	290	52055	800	9760
Al 185	330	52055	1000	12180
Al 240	375	55305	1250	15920
Al 300	430	55305	1600	19570

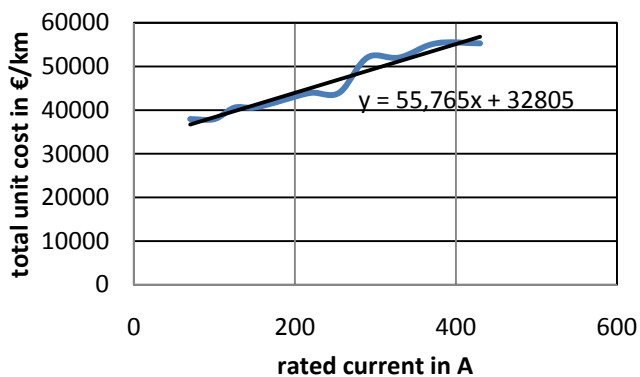


Figure 17: investment costs for cables

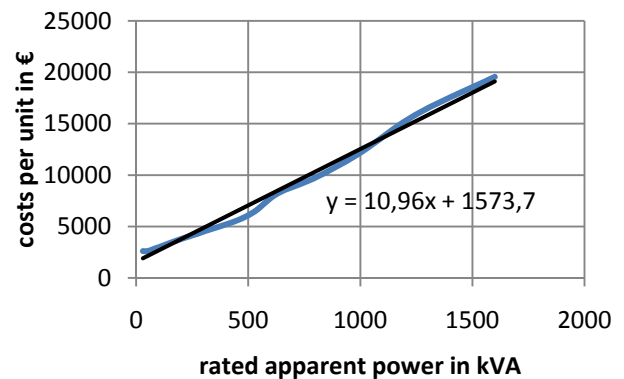


Figure 18: investment costs for transformers

From Figure 17 and Figure 18 the costs per A or kVA can be estimated. With the two factors, which are the result of the linear regression, the financial savings can be calculated approximately. For this one should be used a load of 600 kVA, under consideration of the coincidence factor, which has to be provided.

At first, the calculation/estimation after the conservative way should be ensued:

**transformer:** 630 kVA →

$$C_{Tr} = 8200€$$

**cable:**  $I_L = \frac{600 \text{ kVA}}{\sqrt{3} \cdot U_{LL}} = 866A$  → use 3 x Al 150 →

$$C_C = 3 \cdot 52055 \frac{€}{km} = 156165 \frac{€}{km}$$

For the following investigations the data from the publication are used, because the range is much higher and the data from the load profiles are only an estimation. For the transformer it should be assumed, that an overload of 50% is possible. For the cables, an overload of 10% is assumed. The next step is to calculate the necessary transmission capability. For this 2 ways exist. The first one is to use the price increase per unit and the other one is to use the price of the equipment with a lower transfer capability.

**transformer:**

$$S_{\text{nec}} = \frac{2}{3} \cdot 600 \text{ kVA} = 400 \text{ kVA}$$

financial saving: way I:  $C_{\text{sav I}} = (600 - 400) \text{ kVA} \cdot 10,96 \frac{\text{€}}{\text{kVA}} = \underline{2192 \text{ €}}$

way II: choose 500 kVA- transformer:

$$C_{\text{sav II}} = C_{\text{Tr 630kVA}} - C_{\text{Tr 500 kVA}} = \underline{2130 \text{ €}}$$

**cable:**

$$I_{\text{nec}} = \frac{10}{11} \cdot 866 \text{ A} = 787 \text{ A}$$

financial saving: way I:  $C_{\text{sav I}} = (866 - 787) \text{ A} \cdot 55,765 \frac{\text{€}}{\text{A}} = \underline{4405 \text{ €}}$

way II: choose 2x Al 120 and 1x Al 150:

$$C_{\text{sav II}} = C_{\text{C 866A}} - C_{\text{C 787 A}} = \underline{16200 \text{ €}}$$

Due to the calculation, you can see, that a lot of money per secondary substation can be saved due to implement a algorithm, which calculate the maximum power after the ambient temperature. More accurate is way II for calculation of the financial saving, because the rated values are standardized and not for every current exist the corresponding cable. For the sustainability and ratification investigations should be done for some examples, because this is only an estimation.

### 5.3. asset operation and maintenance costs

In addition to the outage and the asset capital costs exist the third part of the asset operation and maintenance costs, which can be influenced by the possibilities for Automation, Monitoring and Controlling of Secondary Substations. The part of the operation costs depend on the load-dependent and load-independent losses, which could not be modified well, because the voltage and the power consumption is provided from exogenous parameters. Basically the maintenance costs are influenceable in a certain manner.

For the maintenance the devices transformer and line are interesting for the next investigations. For the Low Voltage power system, the cables are mostly maintenance-free in my mind. Used are normally XLPE-cables, in the past also paper-insulated cables, which have a certain amount of oil in the insulation. The latter has to be checked concerning to the oil-amount and the oil-quality, e.g. water content, are not installed often nowadays. The most of the cables are of the type XLPE, which are maintenance-free.

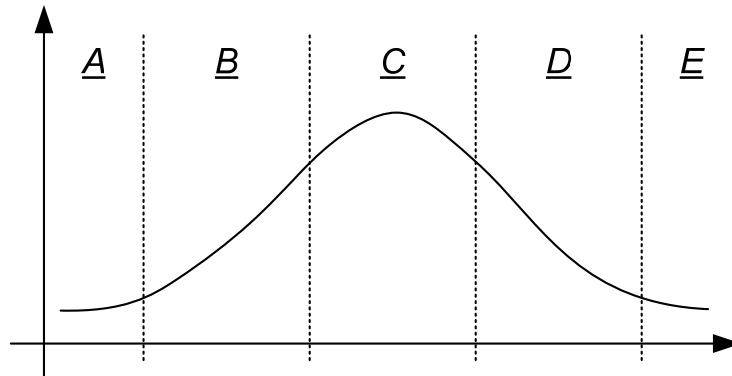
Overhead lines are used normally in rural areas. Contrary to the cables, they are not maintenance free, because the ropes of the overhead lines, the insulators or the path with regard to the growth have to be checked with a specific cycle. This belongs to the maintenance too. But this is not influenceable in this case, so that the overhead lines will not be considered following.

Higher maintenance effort exists concerning to the oil-insulated transformers, which succumb the load-dependent respectively temperature-dependent aging. The main idea is to take the dependence into consideration and determine a perfect maintenance cycle under economic and lifetime aspects.

For development of a scheme for determination of the maintenance effort, the evaluation of the used devices is basically necessary. Therefore, one way could be, to categorize them in 5 different state-levels:

- |                   |                  |            |
|-------------------|------------------|------------|
| a. unsatisfactory | b. below average | c. average |
| d. above average  | e. excellent     |            |

A distribution, which should be aimed for the equipment of one category, is shown in Figure 19.



**Figure 19:** normal distribution of expected equipment conditions

For the transformers with the state-level “below average” and “unsatisfactory” might be a higher maintenance effort useful to prevent outages and allow an economic operation of the transformer station. For the other state levels the maintenance can be decreased to a level depending on the state-estimation of the transformer. Following a general differentiation of the maintenance effort is possible, for example in “Operational Maintenance” and the “Full Maintenance”. In [28] with the topic “reducing outage maintenance costs by performance based maintenance” are given the ratio of the costs for “Operational Maintenance” to “Full Maintenance” with 1:3. So the potential for saving is approximately 70%.

For determination of the state and classification into the five groups should be used different parameters additional to the current test results. These are:

- history of test results
- environmental conditions
- loading conditions

All things can be facilitated by the shown possibilities. Based on [28], the results can be summarized as follows:

- the percentage of transformers, which need a higher maintenance level is 16,3% in average
- the percentage of transformers, which need a lower maintenance level is 46,9% in average due to a good state-estimation of the transformer

[23] deals with the topic of the maintenance, the costs for transformer stations are given. These are independent of the rated apparent power of transformer and can be seen for LV/MV-transformers following:

- 70 €/unit, a for pole-mounted transformer station
- 130 €/unit, a for transformer stations in buildings



The costs per year are very low, so that the saving per year is not really considerably. For economic aspects it should be mentioned, that for a life-cycle of a transformer the financial savings are higher and the necessary equipment can also be used for many other functions, so that the profitability increase.

## 6. Conclusion

...

## 7. References

- [1] Brewis, K.: Automatic earth fault protection and restoration of supply in cable distribution systems, IEEE, Apr 1989
- [2] Ranjan, R; Kalkstein, E. W.: Design, Development and Application of Smart Fuses – Part1, IEEE, January 1994
- [3] Verordnung zur Systemdienstleistungen durch Windenergieanlagen, Bundesgesetzblatt Jahrgang 2009 Teil I Nr. 39, Bonn , 10.07.2009
- [4] Nordmann, M; Lehtonen, M.: TETRA radio in Monitoring and Control of Secondary Substations, IEEE, 2001
- [5] Terese, J. R.; Thiagarajan, A.; Prasad, K. V.; Vaishnav, R.; Sarma, N. D. R.: City Distribution Automation Projects – Economic Justification Aspects, IEEE, 2007
- [6] Renforth, L.; Mackinlay, R.; Seltzer-Grant, M.: Deployment of distributed on-line partial discharge monitoring devices on medium voltage electricity networks, IEEE, 2009
- [7] Hyvärinen, M.; Pettissalo, S.; Trygg, P.; Malmberg, K.; Holmlund, J.; Kumpulainen, L.: A comprehensive secondary substation monitoring system, IEEE, 2009
- [8] Kindermann, J.: presentation – AMIS Infrastruktur als Basis für Smart Grids, 2010
- [9] Taylor, T.; Ohrn, M.: Netzmanagement für Verteilnetze – ABB Technik 3/2009, 2009
- [10] Brüggemann, G.: Ortsnetzstationen – Ein innovatives Konzept, April 2005
- [11] Shargal, M.: From Policy to Implementation: The Status of Europe’s Smart Metering Market, 2009
- [12] Mass, P.: Synergien zwischen Smart Metering and Smart Grid – ETZ 4/2010, 2010
- [13] Friedrich, W.; Seiler, A.: Presentation concerning FNN/ETG Tutorial Schutz- und Leittechnik 2010 – Betriebliche Anforderungen an ein zukünftiges Leitsystem für Ortsnetzstationen, 2010
- [14] Küchau, B.: Presentation concerning FNN/ETG Tutorial Schutz- und Leittechnik 2010 – Intelligente MS-/NS-Netze Automatisierung von Ortsnetzen mit neuen Kommunikationstechniken, 2010
- [15] Dr. Sengbusch, K.; Presentation concerning FNN/ETG Tutorial Schutz- und Leittechnik 2010 – Intelligente nachrüstbare Überwachung von Ortsnetzstationen als Teil von Smart Grids, 2010
- [16] Primus, I.F.; Buchenau, R.; Schlüter, B.: Sicherheit und Schutz beim Betreiben von Ortsnetzstationen – ETZ 20/2001, 2001
- [17] Dr. Zdrallekm, M.: CIRED 2009 – Verteilungsnetze mit Fokus auf Smart Grids, 04. Nov. 2009
- [18] Gwisdorf, B.; Stepanescu, S.; Rehtanz, C.: Effects of Demand Side Management on the Planning and Operation of Distribution Grids, IEEE, 2010
- [19] Bakari, K. El; Kling, W.L.: Virtual Power Plants: an Answer to Increasing Distributed Generation, IEEE, 2010
- [20] Glück Engineering GmbH: <http://www.glueck-engineering.de/entwicklung-produkte/entwicklung-produkte.php?id=35&seite=2> (24.11.2010)
- [21] The Institute of Electrical and Electronics Engineers, Inc.: IEEE Guide for Substation Fire Protection, 18 Apr. 1995
- [22] Kumpulainen, L.; Kauhaniemi, K.; Verho, P.; Vähämäki, O.: New requirements for system protection caused by distributed generation, IEEE, 6.-9. June 2005
- [23] Hyvärinen, M.: Electrical networks and economies of load density, TKK Dissertations 146, Espoo 2008
- [24] [http://www.virtual-powerplant.com/Sonstiges/Downloads/VPP\\_Kap.4-7\\_230s.pdf](http://www.virtual-powerplant.com/Sonstiges/Downloads/VPP_Kap.4-7_230s.pdf) (10.01.2011)
- [25] H, S.H.: An Online Dynamic Cable Rating System for an Industrial Power Plant in the Restructured Electric Market, IEEE, 2007

- [26] Wong, C.C.: Substation power-transformer-loading analysis and computer simulations of loadability under realistic operating conditions, IEEE, 1994
- [27] Li, X.; Mazur, R.W.; Allen, D.R.; Swatek D.R.: Specifying Transformer Winter and Summer Peak-Load Limits, IEEE, 2005
- [28] Paoletti, G. J.; Jordan, C.: Reducing outage maintenance costs by performance based maintenance, IEEE, 2005