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Evaluation of the Condition of Medium Voltage Urban Cable Networks using Fuzzy Logic

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Abstract-- **This paper describes a methodology to evaluate the condition of a given medium voltage urban cable network using fuzzy logic. Furthermore, it allows an asset-manager to estimate future network conditions on the basis of the actual network state. The goal of this work is to facilitate the decision-making for upcoming investments to be made in the grid, by determining not only the actual (or future) state of the whole network but also the weak points of the considered system.**

Index Terms-- **Actual network condition, asset group, deterioration model, estimated network condition, fuzzy logic system, reference medium voltage cable network.**

I. Introduction

THE reliability of the whole electrical network within Germany strongly depends on the condition of the medium voltage system. Eighty per cent of the lack of energy supply for low voltage customers is caused by failures in the medium voltage networks [1]. Therefore, it is highly important to develop a methodology which not only specifies and supervises the actual state of any given medium voltage network but also predicts the consequences of interferences into the grid. This way the investment and operating cost can be minimized by simultaneously maintaining high network reliability.

II. Methodology

Fig. 1 shows the general configuration of the methodology presented in this paper. The steps for determining the actual or future state of a given network are:

- First, the net is divided in asset groups comprising similar types of components (e.g. circuit breakers). The input values of the system are the condition evaluations of each asset group. One option to do this is to summarize the condition of each asset belonging to the group weighted with its importance. But an expert evaluation like the statement “the condition of the asset group circuit breaker is very good” is also sufficient.
- From the actual state of the network it is also possible to estimate future network conditions, through the use of an upstream deterioration model.

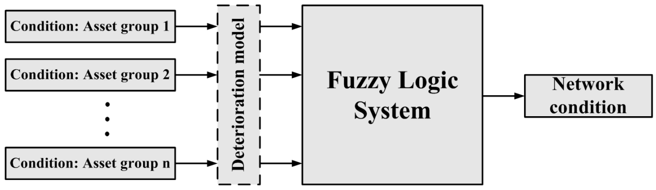

Fig. 1. General configuration of the developed methodology.

III. Development of a Reference Medium Voltage Urban Cable Network

The influence of each asset (and hence of each asset group) on the state of the whole network can be determined by its share on the total non-delivered energy of a network. The problem is that the share on the total non-delivered energy of a single asset does not only depend on its failure rate and its downtime, but is also significantly influenced by the network topology (Fig. 2).

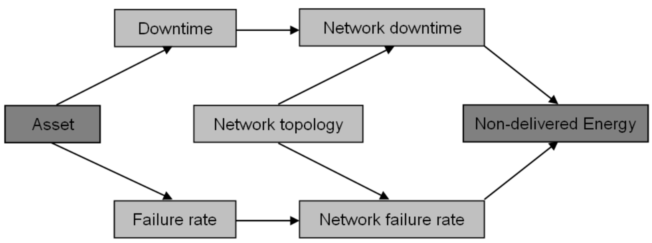

Fig. 2. Influence of the network topology.

If a paper insulated cable fails, for example, it takes an average time of 19 hours for it to be repaired [2]. In a radial distribution system, this means that the interruption time of a load fed by this cable corresponds to the cable downtime. In a loop network, however, the network downtime is only determined by the operating time of the circuit breakers and the disconnectors. The network failure rate is also influenced by the network topology. In a ring network, foreseeable interruptions (i.e. those necessary in case of reparations) can be prepared in advance so as to minimize their effect on the network.

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Due to the fact that both network failure rate and downtime are strongly influenced by the topology, a network which is representative of a German medium voltage cable network was determined. This was done based on data from the association of German network operators (VDN) statistics, which comprise 1040 medium voltage cable networks. By analysing the database, the average number of installed disconnectors, circuit breakers, etc. was determined. The general network information can be found in TABLE I.

TABLE I
GENERAL NETWORK INFORMATION

Network data	Number
Cable length [km]	70
Share of paper insulated cables [%]	41
Share of XLPE cables [%]	42
Share of other cable types [%]	17
Number of MV/LV transforming stations	66
Number of MV/LV transf. station fields	216
Number of circuit breakers	26
Number of disconnectors	183
Number of power transformers	71

Additionally, some boundary conditions had to be considered in order to develop the reference network. Usually, German medium voltage urban cable networks are operated with an open ring structure, are fed by two feed-in transformers, have one circuit breaker per outgoing line, the main busbar is divided by a coupler and every load is connected by three switch-disconnectors to the medium voltage ring network [3][4]. This is why this network topology was chosen for the reference network. Fig. 3 shows a section (two ring networks plus the feeder) of the constructed network.

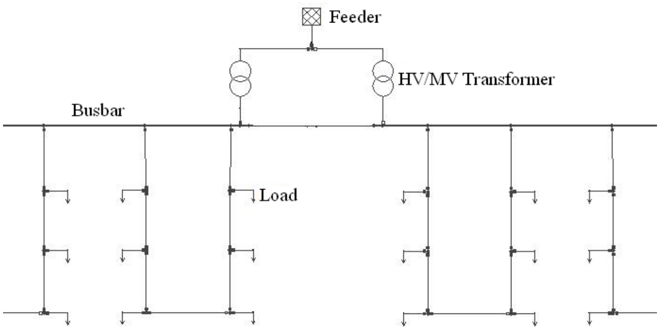

Fig. 3. Section of the reference network.

The network parameters for the reference network were deduced combining the information gained by the research (TABLE I) and the assumptions mentioned above. To find out the number of ring networks *RN* for the reference network, for example, the following equation was used (1).

$$RN = \frac{CB_{Total} - TRA}{CB_{Ring}} = \frac{26-2}{2} = 12 \qquad (1)$$

where CB_{Total} is the total number circuit breakers (TABLE I), TRA is the number of feed in transformers and CB_{Ring} is the number of circuit breakers per ring.

Two circuit breakers were subtracted from the total number listed of circuit breakers in TABLE I, and the resulting number was then divided by a factor of two. This is due to the fact that every HV/MV transformer is connected to the busbar on the medium voltage side by a circuit breaker and every ring network is connected to the busbar by two circuit breakers. For a better comparability, the resulting parameters are presented next to the data of an existing German network (TABLE II).

TABLE II
NETWORK DATA

Network data	Ref. net	Exis. net
Number of feed-in transformers	2	2
Number of ring networks	12	9
Average ring network length [km]	5.7	3.5
Average cable length per ring [km]	0.8	0.5
Average number of loads per ring	6	10

IV. CONSIDERED ASSET GROUPS

The network was divided in the following five asset groups: switch-disconnector (SWD), HV/MV transformer (TRA), busbar (BB), circuit breaker (CB), XLPE cable (XLPE) and paper insulated cable (PAP). To determine which asset groups have a considerable influence on the state of the whole network, the share of each asset group on the total non-delivered energy was determined for the reference network through a simulation with NEPLAN®. For this simulation, the mean failure rate a network component has throughout its useful life was assigned to every asset, because the failure rate of an asset depends on his age [2]. The following useful lifetimes (TABLE III) were used:

TABLE III
USEFUL LIFE FOR DIFFERENT ASSETS

Asset	Useful lifetime [a]
Switch-disconnector	40
HV/MV transformer	50
Busbar	50
Circuit breaker	35
XLPE cable	60
Paper insulated cable	70

The two cable types most frequently used in German medium voltage networks are XLPE cables in newer networks and paper insulated cables in older networks. To achieve a wider applicability for the developed approach, the influence of the cable type on the share of the non-delivered energy was also analysed, because the mean electrical failure rate of paper insulated cables is higher than the failure rate of XLPE cables [2]. Fig. 4 shows the results of the simulation for the reference network, which is composed of 12 open-ring networks.

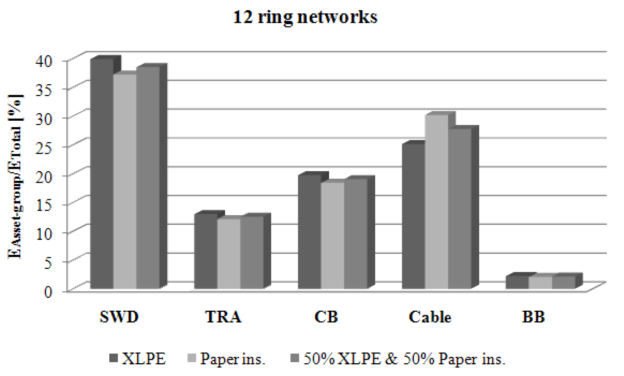

Fig. 4. Share of non-delivered energy.

The influence of the grid size (number of ring networks) on the share of the non-delivered energy was also analysed and can be seen in Fig. 5 (at this point it should be mentioned that the qualitative run of the curves does not change with the usage of paper insulated or XLPE cable only).

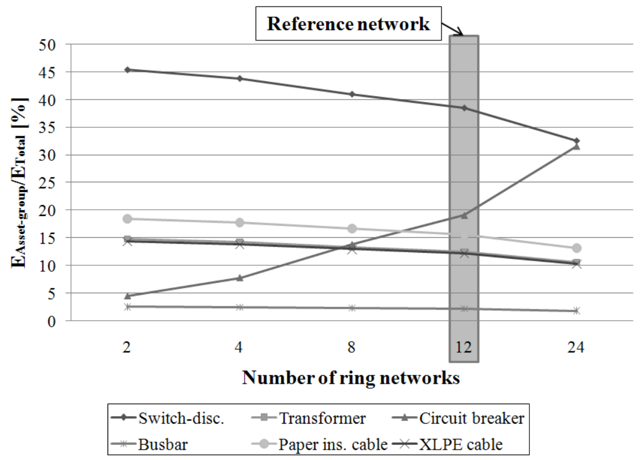

Fig. 5. Influence of the grid size on the share of the non-delivered energy.

From Fig. 4 and Fig. 5 it can clearly be seen that the influence of the asset group “busbar” is negligible for the total condition of the network. In addition, the failure rate of a busbar can be seen as constant throughout its useful lifetime [2] (which means that its influence does not increase with time). Therefore, this asset group was not considered for the determination of the network condition.

V. Design of the Fuzzy Logic System

The configuration of the designed fuzzy logic system can be seen in Fig. 7 (next page). The presented fuzzy logic system was built based on a standard approach that has proven successful in a number of practical applications [5]. For the input values triangular membership functions were chosen, while singletons were used for the output value. Five linguistic variables were defined for the condition evaluation of input and output data: very good (VG), good (G), moderate (M), poor (P) and very poor (VP).

To determine the influence of the state of each asset group on the condition of the whole network, it is necessary to define general rules for the fuzzy knowledge processing. Those rules were ascertained on the basis of the non-delivered energy for the entire network. Using the developed approach the network condition can be calculated for every possible input combination. The total number of rules depends on the number of input values and of linguistic variables. Three fuzzy systems were developed: one for newer networks (four inputs: SWD, TRA, CB & XLPE), one for older networks (also four inputs: SWD, TRA, CB & PAP) and one for the standard application (five inputs: SWD, TRA, CB, XLPE & PAP).

In the first two mentioned cases there are 625 ($=5^4$) possible input combinations which lead to 625 rules for the fuzzy logic system. In the last case 3125 ($=5^5$) rules had to be defined. The rule generation happened according to the four steps described in the following.

A. Determination of the non-delivered energy of each asset in dependence of its condition.

In this work the condition of an asset is seen as a function of time, since the failure rate of each network component increases with time as described in [2] (whereas the run of the curves were adjusted to the useful lifetimes shown in TABLE III). The following fixed conditions states (linguistic variables) were determined for every asset and can be seen in Fig. 6 for a HV/MV-transformer.

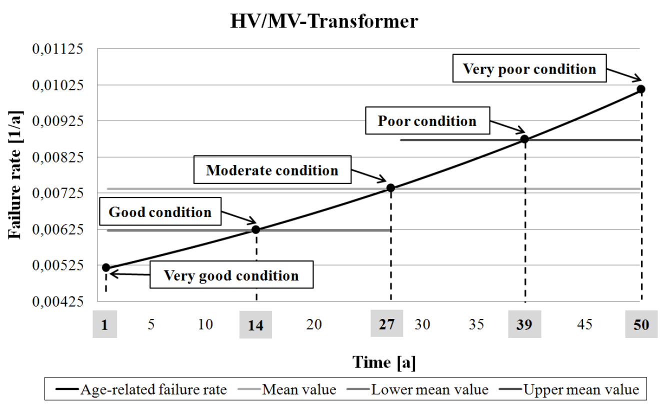

Fig. 6. Assignment of condition states to failure rates.

A moderate condition (condition value of 0.5) was defined at the mean failure rate an asset has throughout his useful life. A new component (condition value of 1) always has the lowest failure rate, independently of the considered network component type and can be considered as an asset in a very good condition [2]. The worst condition is always reached when the asset age equals the useful lifetime (condition value of 0). Moreover, the poor and the good conditions were defined at the mean failure rate of the two resulting sections (condition values of 0.25 and 0.75 respectively).

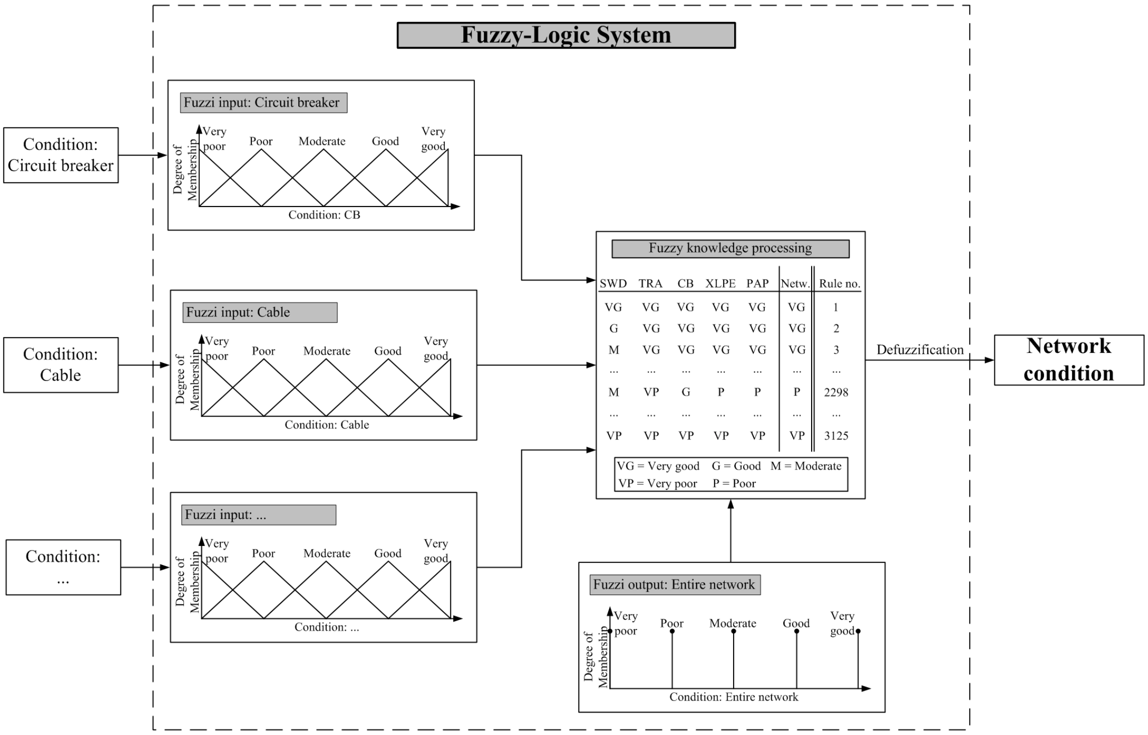

Fig. 7. Configuration of the designed fuzzy logic system

How the failure rate of each asset increases with time can be seen in TABLE IV (The presented XLPE values are only valid for XLPE cables of the new generation, which are usually in a good or very good condition because they are not older than 20 years [2]). The failure rates are given in per unit (p.u.), whereas the mean failure rate was defined as 1 p.u.

TABLE IV
ASSET FAILURE RATES (IN P.U.)

Condition	Very poor	Poor	Moderate	Good	Very good
SWD	1.11	1.05	1	0.95	0.90
TRA	1.37	1.18	1	0.84	0.70
CB	1.83	1.40	1	0.70	0.46
XLPE	2.58	1.69	1	0.54	0.25
PAP	1.53	1.27	1	0.74	0.47

Through the assignment of a failure rate to each of the mentioned conditions, the non-delivered energy of every asset could be calculated with NEPLAN® on the basis of the created reference network.

B. Determination of the non-delivered energy of each asset group in dependence of its condition.

The condition of an asset group is determined by the condition of all its network components. The total non-delivered energy for an asset group is the sum of the values calculated from each asset. This means that the condition of an asset group is "very poor" if the condition of every asset belonging to the group is also "very poor" and thus the contribution to the non-delivered energy is maximal. From this it follows that the amount of non-delivered energy of each asset group depends on the group's condition. This relation is shown in Fig. 8 for the asset group "HV/MV transformer".

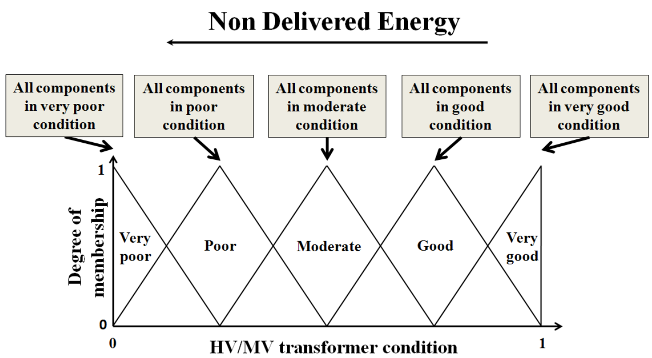

Fig. 8. Determination of the non-delivered energy for "HV/MV transformer".

C. Determination of the non-delivered energy for the entire network in dependence of its condition.

The condition of the entire network is judged by the expected value of the non-delivered energy of the whole grid. The non-delivered energy values are calculated in dependence from the condition of the entire network by adding the non-delivered energy values of the single asset groups (Fig. 9). For this reason, the maximum respectively the minimum non-delivered energy amount is reached if all asset groups are in a very poor respectively very good condition.

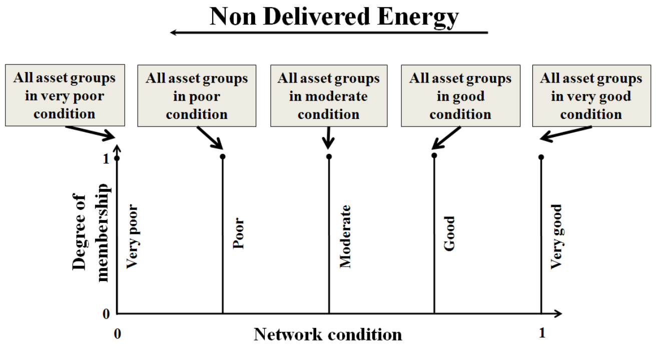

Fig. 9. Determination of the non-delivered energy for the entire network.

D. Rule Generation.

With the assignment of a non-delivered energy value to both each network and also each asset group condition it was possible to generate the fuzzy logic rules automatically. For every input combination a value is calculated by taking the sum of the non-delivered energy values for each asset group. Depending on the resulting value, an output value is assigned to every rule. The applied classification for the output value determination can be found in Fig. 10 for a standard network.

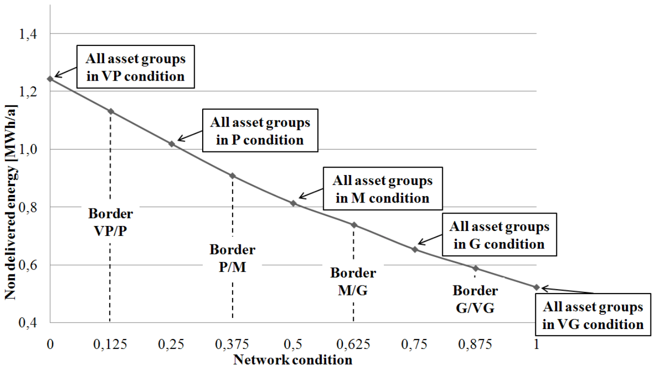

Fig. 10. Applied classification for the output value determination of a standard network.

In Fig. 10 it can clearly be seen that the dependence of the network condition to the non-delivered energy is non linear. This means that a worsening of the condition for low condition values has a bigger impact on the change of the non-delivered energy than for high condition values.

VI. Determination of Actual and Future Network Conditions

In order to determine the actual condition of a given network, the condition values of its single asset groups are simply inputted into the model. For the estimation of future network condition, however, a further processing of the input data with a deterioration model is necessary (Fig. 11).

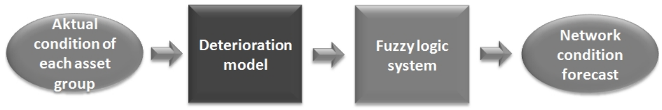

Fig. 11. Network condition forecast with deterioration model.

To give a prognosis for the non-delivered energy it was necessary to find out how the condition of every asset group changes over time.

As has already been mentioned, five condition state points were predefined for every asset group. This means that an asset group with these conditions has a hypothetical age and failure rate (Fig. 12).

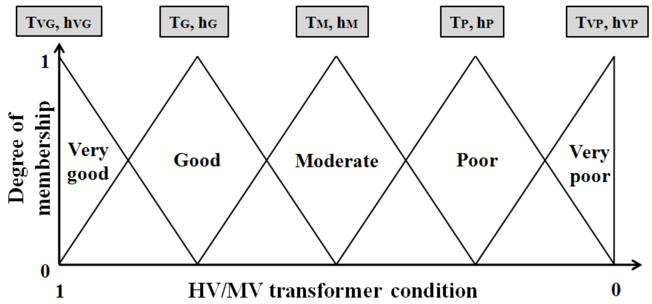

Fig. 12. Assignment of an age and a failure rate to every predefined condition state.

Of course, an asset group is composed of a high number of components which can all differ in age and importance. So the asset group age and failure rate fictitious values which are representative for all the assets comprised by the asset group. This is why the asset group age is called “relative age” (T) and the failure rate, “relative failure rate” (h). The relative ages for the asset group “HV/MV transformer” are e.g.: T_{VG}=1 a, T_G=14 a, T_M=27 a, T_P=39 a and T_{VP}=50 a. This means that the translation in time from one predefined condition state to another is not constant (compare Fig. 6). How fast the condition changes in a certain time period depends on the increment of the relative failure rate in the same time period. Because of this reason, the run of the curve from the asset group condition over time was adapted to the failure rate curve (as presented in Fig. 6 for a HV/MV transformer) through a non linear interpolation. Therefore the following condition was set:

$$h_m(c(t)) = h_r(t) \quad for \quad t = 1 \ldots T,\ c \in [0,1] \qquad (2)$$

where $h_m(c(t))$ is the failure rate as calculated by the fuzzy logic model (Fig. 12) for condition $c(t)$ and $h_r(t)$ is the failure rate as calculated by Fig. 6.

Equation (2) is de facto fulfilled at the centre points of the linguistic variables (degree of membership equals one, compare Fig. 12). The failure rate calculated by the fuzzy logic model is given by equation (3).

$$h_m(c(t)) = \sum_{i=1}^{n} \mu_{c_i}(c(t)) \cdot h_m(c_i) \quad (3)$$

where $\mu_{ci}(c(t))$ is the degree of membership to linguistic variable i, $h_m(c_i)=h_r(t_i)$ is the failure rate for linguistic variable i (see Fig. 6) and n *the* number of linguistic variables.

Equations (2) (3) can be solved for discrete time steps in order to determine the condition for each time step. The calculated curve of the condition over time is shown in Fig. 13 using the asset group “HV/MV transformer”.

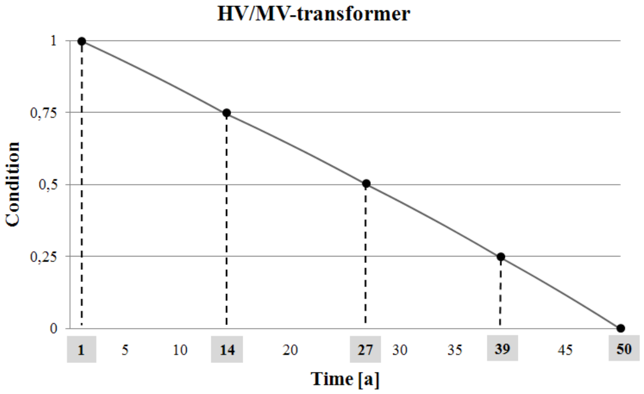

Fig. 13. Condition decrement over time for the asset group “HV/MV transformer”.

The deterioration of each asset group condition over time can be described with these curves. They give the possibility to estimate the condition decrement for a certain forecasting horizon. For example, if the asset group “HV/MV transformer” as presented in Fig. 13 has a given condition of 0.64, then a relative age of 20 years is assigned to it. After seven years, the condition will have decreased to a value of 0.5, as can be read from Fig. 13. The prognosis is made similarly for all asset groups for the same time slope. With the knowledge of all estimated values, therefore, the network condition in seven years can be calculated. A more detailed example of the functionality of the deterioration model can be found in chapter VII.

It should be mentioned that this approach leads to a forecasting error, the exact composition of each asset group and the age of each asset being unknown, and the velocity of the deterioration process which each asset underlies depending on its age. It can be seen in Fig. 14 that the failure rate increases faster for an older circuit breaker CB2 than for a newer one CB1 in the same time slot of five years (ΔFR1 < ΔFR2). This is caused by the exponential run of the curve. The relative failure rate which is the outcome of the weighted failure rates of CB1 and CB2 in the year one will follow the run of the curve for the whole forecasting horizon.

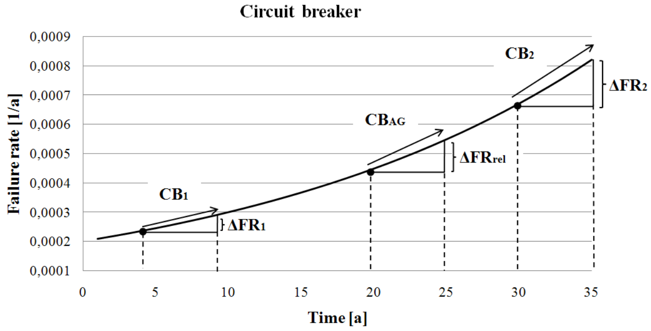

Fig. 14. Deterioration velocity of two different circuit breakers.

An exact prognosis of future network conditions can be made if the condition change and hence the increment of the failure rate is analysed for every asset. This kind of analysis, however, is usually very time and labour consuming for medium voltage networks, because of the high number of assets. With this approach a relatively accurate estimation of future condition values can be achieved by the sole knowledge of the actual state of the asset groups.

VII. Results

The operating mode of the developed approach is to be shown by means of an example. The demonstrated example was realized for the reference network which was described in chapter III. The following initial condition of the network and the asset groups was assumed as presented in TABLE V. Hereby the corresponding “relative age” values were deduced.

TABLE V
Initial Network Condition

Asset Group	Condition value	Relative Age
SWD	0.38	26
TRA	0.48	28
CB	0.35	25
XLPE	0.62	30
PAP	0.35	46
Network	0.375	-

It can clearly be seen that the network is in a critical state because of the low condition values of SWD, CB and PAP. The condition of the whole network shall be improved through an investment in the renewal of one of these three asset groups. The following costs were assumed:

TABLE VI
Asset Costs

Asset	Costs [k€]
Switch-disconnector	1
Circuit breaker	12
Paper ins. cable (per km)	100

Because the replacement of the cables would be too costly and the deterioration of paper insulated cables is very slow (expected lifetime left: 24 years) only the replacement of either all the switch-disconnectors or all the circuit breakers was analysed (this leads to a condition value of one).

In order to evaluate the yield network improvement over time for both hypothetical replacements, two simulations were realized. The results can be seen in Fig. 15.

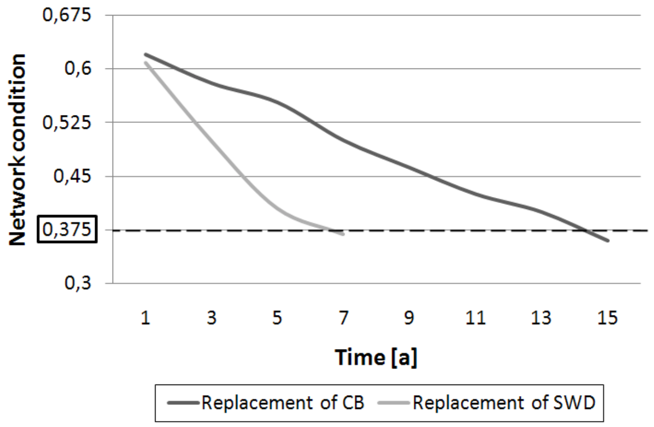

Fig. 15. Decrease of the network condition over time.

Through the replacement of all switch-disconnectors, which would cost 221,000 Euro, a network condition improvement of 0.234 could be achieved. However, the critical network condition would be reached again after only six years.

A more costly investment would be the replacement of the circuit breakers. Through this investment the condition improvement in the first year is marginally better than for the SWD scenario. The next investment would have to be executed in 13 years (compare TABLE VII).

TABLE VII
EVALUATION DATA OF THE TWO SCENARIOS

Scenario	Investment costs	Condition improvement	Next investment
SWD	221 k€	0.234	ca. 6 a
CB	312 k€	0.245	ca. 13 a

The better scenario from a financial point of view was identified using the annuity method. The amount of annuity r was calculated for each option with equation (4):

$$r = K_0 \bullet \frac{i \bullet (1+i)^n}{(1+i)^n - 1} \quad (4)$$

where K_0 are the investment costs, i is the assumed interest rate (here 0.06) and n is the time until the next investment.

The resulting values from the calculation are presented in TABLE VIII.

TABLE VIII
ANNUITIES

Scenario	Annuity [k€]
SWD	44.943
CB	35.244

It can clearly be seen that an investment into the circuit breakers would be reasonable in this case.

VIII. CONCLUSION

In this paper a model which allows an asset manager to specify and supervise the actual state of a given medium voltage cable urban network is presented. The model can also be used to predict the consequences of interferences into the grid through the estimation of future network conditions. In this way, the investment and operating costs can be minimized by simultaneously keeping high network reliability.

The methodology is based on a standard fuzzy logic system well proven through practical experience (which is composed by triangular membership functions for the input values and singletons for the output value). This mathematical approach was chosen because it mimics the human way of thinking.

For the development of the model, a network which is representative of a German medium voltage cable network was determined, using data from the association of German network operators (VDN). The analyses of this network with NEPLAN® show that the condition of the entire network strongly depends on the state of the followings five asset groups (an asset group is a virtual aggregation of single assets of similar type): switch-disconnector, HV/MV transformer, circuit breaker, XLPE cable and paper insulated cable. Additionally, the condition of every asset group can be seen as a function of time, since the failure rate of each network component increases with time as described in [2]. Five linguistic variables were defined for the condition description of input and output values: very good, good, moderate, poor and very poor. How the condition of each asset group is exactly determined is not relevant for the model. An expert assessment like "The condition of the asset group switch-disconnector is good" would be fully sufficient, for example.

To determine the condition of the entire network, rules had to be generated for the fuzzy logic system. They were calculated automatically on the basis of the share of each asset group on the total non-delivered energy for the reference network. For this network, three fuzzy logic systems were created in dependence of the used cable types. For the data processing 625 (four inputs) respectively 3125 (five inputs) rules were generated.

Through the additional insertion of a deterioration model, it was possible to estimate future network conditions by the sole knowledge of the actual state of the asset groups. The forecast of the network condition was achieved through the characterization of the condition decrement over time for each asset group.

Finally, the functionality of the model was demonstrated with an example. It was analysed whether the investment into the circuit breakers or into the switch-disconnectors of a network in a critical condition is more efficient from a financial point of view. By the use of the annuity method it was ascertained that an investment in the circuit breakers would be more reasonable, although the initial investment is much higher.

Last of all it shall be mentioned that a big advantage of the usage of fuzzy logic is that the described methodology can easily be adapted to networks with a very unique topology by simply determining the share of the non-delivered energy for every asset group. Thus, a new rule base is established. Additionally, it is possible to incorporate the knowledge of experts into the system. This can be achieved through the consideration of their own fuzzy logic rules, e.g.: "If the circuit breakers are in a very poor condition the network is in a poor condition". Further network components can also be considered by simply adding new asset groups to the model.

IX. ACKNOWLEDGEMENT

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XI. BIOGRAPHIES

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Gerd Balzer received the Dr.-Ing. degree in 1977 from Technische Universität Darmstadt, Germany. He was employee of BBC/ABB and the Head of the Department of Electrical Consultancy for 17 years. He joined the Technische Universität Darmstadt in 1994 and got a full professorship in the Department of Electrical Engineering and Information Technology. His main research interests include asset management and network planning. Prof. Balzer is the Head of the Institute of Electric Power Systems, a senior consultant of ABB and the Chairman of the IEC Working Group "Short circuit calculations". He is member of the VDE and CIGRE.