Fuzzy Risk Assessment of MV/LV Substations for Maintenance and Renewal Purposes

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Abstract—**Medium-voltage network operators in today's liberalized electricity market are forced to rethink their current maintenance strategies in order to improve their companies' efficiency. Consequently, preventive strategies such as reliability-centered or risk-based maintenance are increasingly gaining in importance, besides the traditionally implemented time-based maintenance [1]. One principal characteristic of preventive maintenance strategies is that the condition of the network components is inspected on a regular basis [2][3]. The presented methodology shows how MV/LV substation maintenance and renewal can be optimized on the basis of inspections. A fuzzy logic model processes the information gained during inspection and determines a risk index for any substation, as well as for all basic assets within the station. The model, therefore, makes the risks presented by different substations comparable. It also provides information on weak points within the substation. Thus, the model not only facilitates but also helps to objectify the decision-making for upcoming investments.**

Total risk; reversible risk; irreversible risk; substation; failure rate; outage costs; maintenance renewable; fuzzy logic

I. INTRODUCTION

Most electrical components within distribution networks in Germany were installed at the end of the sixties and the beginning of the seventies [4]. Generally, the useful lifetime of medium voltage assets is estimated at approximately 40-50 years. Consequently, a great number of assets are reaching the end of their useful lifetime. Those assets require increased maintenance and will have to be replaced in the next years (about 75% of all assets according to [5]). This is why it is highly important to develop a methodology which makes it possible to evaluate different maintenance and renewal activities in advance through a cost-benefit analysis.

In this paper an approach is presented which allows optimization for maintenance and renewal for MV/LV substations. For this purpose the risk carried by each asset within a given substation is analyzed first, in order to determine the entire risk the substation poses. The operating mode of the presented model is demonstrated with an example at the end.

II. ASSET RISK ANALYSIS

MV/LV substations are classified according to their construction type into indoor (in a building), pylon and compact substations. Indoor substations are mostly in urban networks, but also the share of compact stations in cities is increasingly growing because of their low space requirements. Pylon stations are usually installed in rural areas with low load density. Fig. 1 shows an equivalent circuit of a MV/LV substation. The low voltage load is supplied via three switch-disconnectors (SWD), a MV/LV transformer (TR), a fuse and a busbar to a ringed network. Additionally to the presented assets, many more network components like current and voltage transformers may be installed in MV/LV substations.

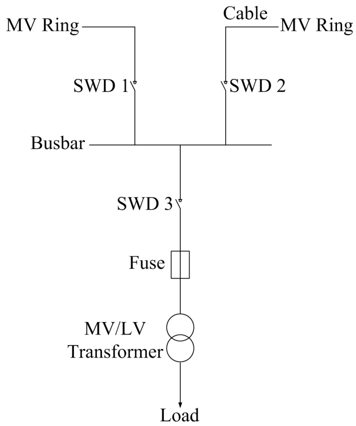

Fig. 1. Block diagram of a MV/LV substation [6].

According to [7], the MV/LV transformer, the switch-disconnectors and the building (BUI) or respectively the enclosure, are responsible for 77% of all damages within substations. Of the remaining assets none exceeds a share of 5%. This is why only the following five input values are considered in the presented approach: “MV/LV transformer”, “Switch-disconnector 1”, “Switch-disconnector 2”, “Switch-disconnector 3” and “Building/enclosure”.

In order to determine the risk values of these five assets within a substation, “risk” in general must be defined. A general definition of risk is given in (1) according to [8].

$$\text{Risk} = \text{Failure probability} \cdot \text{Failure consequence} \qquad (1)$$

In order to apply (1) on network components it is necessary to determine the failure probability and the failure consequences of the network component.

a) Failure probability

The failure probability of a network component primarily depends on the asset type and hence on the general proneness to failure [7]. A further significant influence factor on failure probability is the actual condition of the asset, which can vary between very good to very poor. It is therefore essential to evaluate the asset condition at first, in order to assess its failure probability.

The condition of a network component is always a function of time, since it changes permanently due to electrical and mechanical stress. This process can be divided in two categories, degradation and deterioration, according to [3]. Some examples are presented in TABLE I. It can be seen that degradation describes reversible processes and deterioration irreversible aging processes. Accordingly, degradation can be reversed through maintenance whereas irreversible aging can only be reversed through a renewal of the asset [9]. As different maintenance and renewal activities can be deduced from one and the same “total condition” value, it is always reasonable to split up the “total condition” into a “reversible” and an “irreversible condition”, to provide clearer information.

TABLE I. EXAMPLES FOR DEGRADATION AND DETERIORATION [3]

	Degradation	**Deterioration**
Oil-insulated transformer	• External corrosion • Pollution of bushing insulators	• Decomposition of insulationg oil • Embrittlement of the winding insulation
MV switching devise	• Pollution • Loss of SF6 gas or extinguishing medium	• Corrosion • Fatigue of material and massiv mechanical/electrical wear

Generally, there are two ways of assessing the condition of equipment. The first option is to derive a condition value through the evaluation of all available information sources (operational history of the asset and statistical data of type-like equipment). A more accurate way, however, is to assess the equipment condition through on-site inspections. From the gained information, the condition of all assets can be determined by evaluating their r./i. electrical and mechanical condition. Through weighting and addition of these values than the r./i. condition of each asset can be determined (Fig. 2).

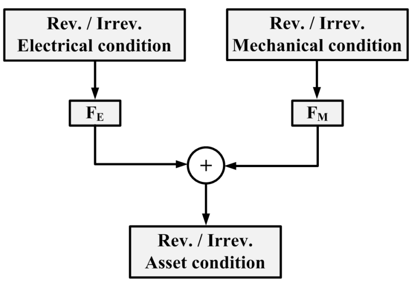

Fig. 2: Evaluation of reversible and irreversible asset condition.

The weighting factors F_E and F_M are calculated with (2). They depend on the share of failures caused through the decrease of electrical properties f_E and mechanical properties f_M.

$$F_{E/M} = \frac{f_{E/M}}{f_E + f_M} \tag{2}$$

TABLE II. shows the percentage share for MV/LV substation assets of failures caused through the decrease of electrical and mechanical properties. The remaining damages are mainly caused by external influences, mounting errors, manufacturing defects, etc. They are therefore not relevant for the presented approach.

TABLE II. CAUSE OF DAMAGE [7]

	Decrease of electrical properties	**Decrease of mechanical properties**
Switch-disc.	19 %	59 %
Building/Enclosure	1 %	85 %
MV/LV transformer	24 %	43 %

In a next step, the relationship between failure probability and condition must be analyzed. In [7] the relationship between asset age and failure rate (which is defined as the event rate at time t conditional on survival until time t or later) of MV equipment was analyzed. As a result, a hazard curves have been given as a function of time for every asset type. It was detected that the failure rate generally increases with the asset age. This is caused, as mentioned before, through a worsening of the asset condition by degradation and deterioration. It could be therefore assumed that the condition of a network component strongly correlates with its failure rate. A failure rate is assigned to every condition value. The highest failure rate within the useful lifetime of an asset is assigned to a very poor condition and the lowest failure rate to a very good condition. The mean failure rate an asset has throughout is useful lifetime is assigned to a moderate condition. All other values are linearly interpolated with the usage of fuzzy logic as described in chapter III.A.2).

b) Failure consequence

The consequence of a failure caused by a network component also reflects its importance within the station. One way of quantifying the failure consequence is through the evaluation of the mean outage costs. This, however, depends on whether the failure causes a load interruption or not as can be seen in TABLE III. Failures which cause a load interruption are usually more severe and cause greater follow-up costs (usually caused by an arc). Cost listed in TABLE III. include repair or renewal costs, but exclude any “dispense fees income costs”. The latter largely depend on network topology and will be explained in the following.

TABLE III. MEAN OUTAGE COSTS [7]

	With load interruption [€][a]	Without load interruption [€][a]
Switch-disc.	1,897	1,360
Building/Enclosure	4,309	1,549
MV/LV transformer	4,459	1,457

a. Includes repair / renewal costs as well as follow-up costs

In Germany, medium voltage networks are usually operated with an open ring structure with each ring connected to the MV busbar over two circuit breakers. Fig. 3 shows an example of an open ring network with seven MV/LV substations. In this case the effect of a failure in substation 2 on the connected customers is analyzed. It can be seen that the failure will also affect the loads connected to substations 1 and 3, since the whole radial system from the busbar to the open coupling point has to be disconnected until the failure location is isolated. Because switching operations are usually done manually in the medium voltage level, it lasts about one hour until the fault-free substations are reconnected to the grid. Therefore, the non delivered energy and consequently the dispense fees income cost are always case specific.

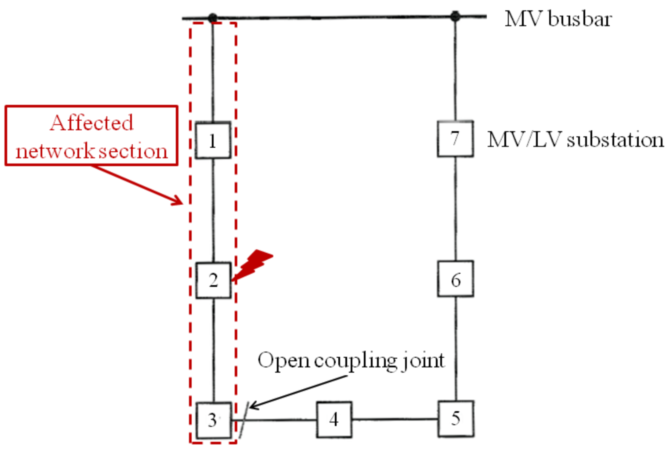

Fig. 3: Affected network section by failure in MV/LV substation 2.

Nevertheless, the mean outage costs are taken as constant in this approach, since the dispense fees income costs are negligible when compared to the total outage costs for outages with load interruption within MV/LV substations. This is demonstrated bellow.

Within Germany, a total of about 70,000 circuit breakers are operated in the medium voltage level with a total installed power of 165,537MVA [3]. In the medium voltage level the cos(φ)-value usually lies in a range between 0.9 and 1. (The outage costs, however, reach a maximum for cos(φ)=1). Therefore the mean load connected to a circuit breaker panel or respectively to an outgoing line is 2.36MVA. This corresponds to a worst case value of 2.36MW. This is also the active power that is interrupted for about one hour in case of a failure in a substation as explained above. Additionally, it usually takes one additional hour to re-supply the load connected to the substation in which the failure occurred [10]. The mean load connected to a substation can be calculated to 394kW with the data given in [3] (in Germany there are 419,731 MV/LV transformers installed which more or less corresponds to the same number of substations). Hence the mean dispense fees income costs ($C_{Disp.}$) can be calculated with (3) for a medium voltage network fee of 0.027€/kWh [11].

$$C_{Disp.}=(2{,}360\text{kW}\cdot 1\text{h}+394\text{kW}\cdot 1\text{h})\cdot 0.027\text{€/kWh}=74.4\text{€} \tag{3}$$

If this value is now compared to the mean outage cost values (with load interruption) presented in TABLE III. it can be clearly seen that the dispense fees income costs are negligible. Even if the minimum value of 1,897€ is considered, the dispense fees income costs only amount 3.9%. This result was additionally verified with a worst case analysis. For this worst case scenario, an existing network of a German city was analyzed. In this scenario the highest installed power of an outgoing line (4MW) and the highest load connected to a substation (2MW) were considered. Still, the share of the dispense fees income cost were negligible with 8.5%.

c) Calculation of the total, the reversible and the irreversible risk index-valuest for network components

With the information given in chapters II a) and II b) the reversible (R_R) and irreversible (R_I) risk-index values of all assets can be calculated according to (1). The resulting equations are given in (4) and (5).

$$R_R=0.4\cdot\lambda_{WLI}\cdot k_{WLI}+0.4\cdot\lambda_{WOLI}\cdot k_{WOLI} \tag{4}$$

$$R_I=0.2\cdot\lambda_{WLI}\cdot k_{WLI}+0.2\cdot\lambda_{WOLI}\cdot k_{WOLI} \tag{5}$$

where λ is the assigned failure rate and k the outage costs for failures which cause a load interruption (WLI) respectively do not cause a load interruption (WOLI).

According to the statistics 40% of all failures in MV/LV substations are caused through degradation and only half as much are caused through deterioration (The remaining failures are not recognizable or caused by external influences) [3]. Therefore λ_{WD} and λ_{WOD} are weighted with a factor of 0.4 and 0.2. With R_R and R_I the total risk-index (R_T) can now be calculated:

$$R_T=R_R+R_I \tag{6}$$

The total risk-index values for switch-disconnectors, building / enclosure and the transformer are shown in TABLE IV. The risk-index values "very low" and "very high" are determined through the assignment of the lowest and the highest failure rate values (cf. chapter II a)). The "low", the "average" and the "high" risk-index values were deduced from the other three risk-index values through averaging. It can be clearly seen that the most sensitive component of a MV/LV substations is the "Building / Enclosure". Furthermore it can be stated that the risk level presented by an asset only depends on its condition, since the expected outage costs of every asset type are taken as constant. Finally all input values are standardized to values between zero and one. The risk-index values were assigned as follows: very low = 1, low = 0.75, average = 0.5, high = 0.25 and very high = 0.

TABLE IV. TOTAL RISK-INDEX VALUES

	Switch-disc. [€/a]	Build. / Encl. [€/a]	Transformer [€/a]
Very high	6,20	81,18	13,20
High	4,81	61,25	11,17
Average	3,43	41,31	9,14
Low	2,06	21,39	7,12
Very low	0,68	1,46	5,09

III. MV/LV SUBSTATION RISK ANALYSIS

In order to determine the optimal maintenance and renewal activity for a given substation after an inspection, three risk terms are introduced. Using the "irreversible risk index", the necessity of renewal can be determined; while the "reversible risk index" provides information with respect to the need for maintenance activities. The "total risk index" is composed by the irreversible and the reversible values (Fig. 4) and reflects the urgency for maintenance of a MV/LV substation.

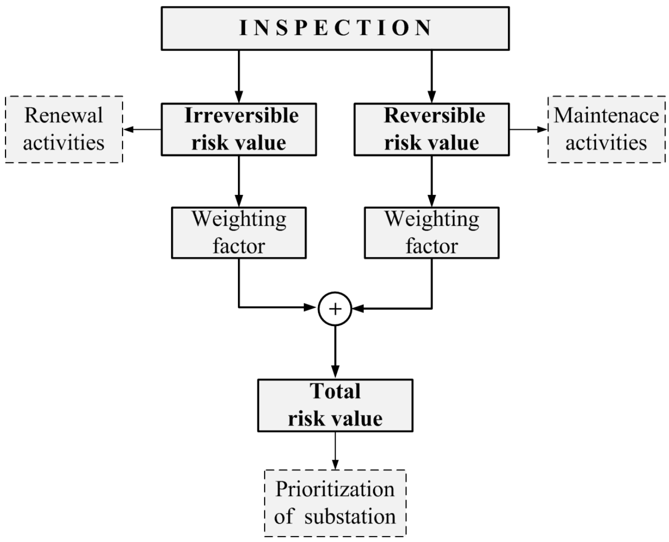

Fig. 4. General configuration of the developed methodology.

A. Determination of reversible and irreversible MV/LV substation risk-index values

The two models for the determination of the reversible and the irreversible risk-index values are designed similarly with a fuzzy logic system and were implemented in MATLAB®. The fuzzy logic system is shown in Fig. 5 and can be divided in five sections: input data, fuzzification, fuzzy output, fuzzy knowledge processing and defuzzification. In the following each of these sections is analyzed.

1) Input data

In total, six input values are defined for the fuzzy logic system. Five of these input values are reversible / irreversible (r./i.) asset risk-index values, since normally the substation risk-index values are evaluated by the risk of the assets comprised by it. The sixth input value "MV/LV substation", however, is an exception and describes whether the risk carried by the substation is acceptable or not. For example, a damaged substation which poses a threat to humans or environment represents an unacceptable risk. In this case a knock-out rule is activated (cf. chapter III 4)) in order to give the substation the highest priority for maintenance. If the substation risk is acceptable, however, the maintenance and renewal optimization process has to be primarily focused on those assets which can cause the greatest damage from a network operator's perspective.

2) Fuzzification

Five linguistic variables were defined in accordance with TABLE IV. for every asset input value. Therefore, a membership value can be assigned to every input value, between zero and one from these predefined values through linear interpolation. The linear interpolation is realized through the usage of triangular membership functions. Fuzzification of input data with triangular membership functions is a standard approach that has been proven successful in a number of practical applications [12].

For the input value "MV/LV substation" singletons were used, since the condition of a substation can only be acceptable or inacceptable with a degree of membership of one.

3) Fuzzy output

Seven singletons and hence were seven linguistic variables were defined in total for the fuzzy output in order to achieve a high accuracy of the model. In practice singletons are used as a standard for the output of fuzzy logic systems [12].

4) Fuzzy knowledge processing

In order to determine the influence of the r./i. risk of each asset on the r./i. risk of the whole MV/LV substation, it is necessary to define general rules for the fuzzy knowledge processing. The rule-bases of both fuzzy systems, designed to determine the reversible and the irreversible station risk-index values, are generated on the basis of risk outage costs. One exemplary fuzzy rule is presented below. As can be seen one output value has to be assigned to every possible input combination:

"If the risk-index of the MV/LV transformer is average, the risk-index of the building / enclosure is high, the risk-index of switch-disconnector 1 is very high, the risk-index of switch-disconnector 2 is average, the risk-index of switch-disconnector 3 is very high and the risk-index of the MV/LV substation is acceptable then the risk-index of the MV/LV substation is high"

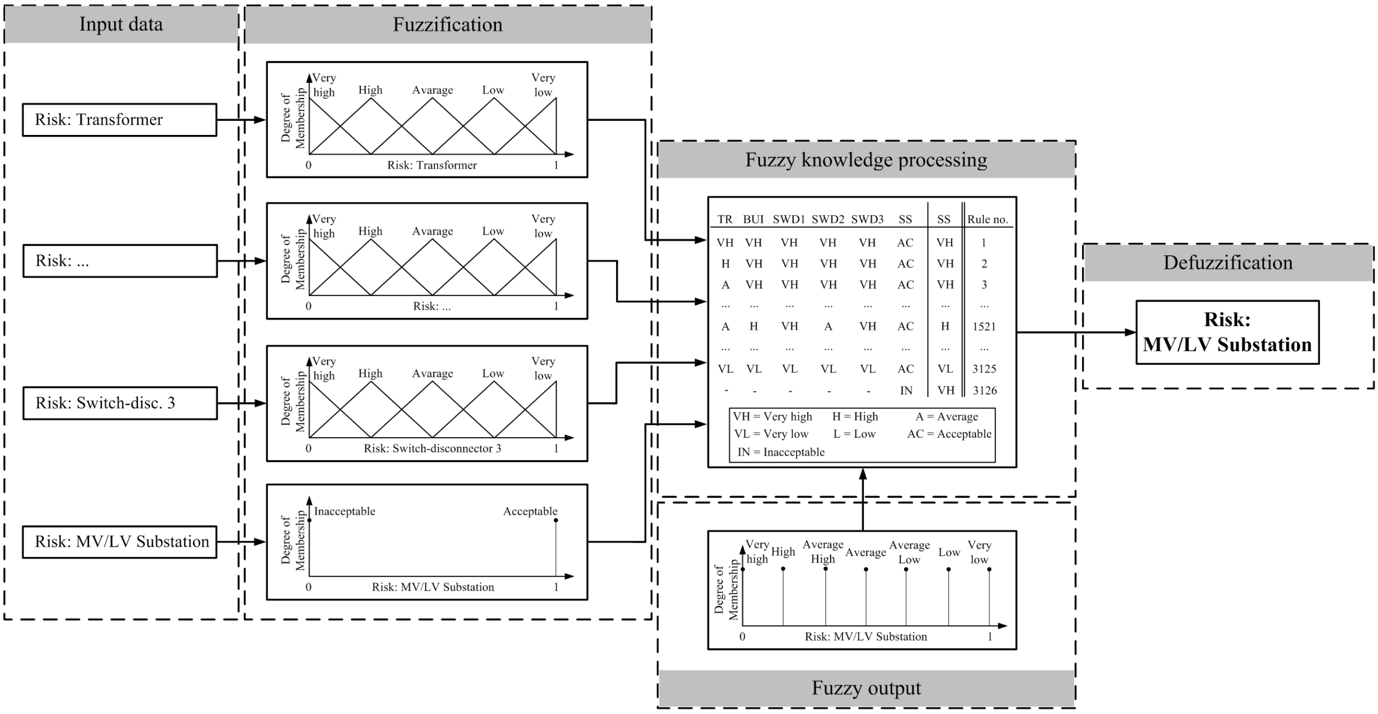

Fig. 5: Configuration of the fuzzy logic system to determine the reversible and irreversible risk carried by a MV/LV substation.

The risk of the entire MV/LV substation is judged in this approach by the expected value of the risk costs of the whole station. This value is calculated by adding the risk values of the single assets for every input combination. Since, however, the ratio of reversible, irreversible and total risk costs is constant for every asset (cf. chapter II c)) and the evaluation of the risk of the substation is a relative one, both rule bases for the reversible as well as the irreversible risk-index, are similar and were generated by the total risk-index values presented in TABLE IV. Depending on the resulting value, it is possible to assign an output value to every rule and to generate the fuzzy logic rules automatically. The total number of rules is composed by the number of input values and the number of fuzzy input linguistic variables. Hence, 3125 rules have been defined.

Additionally to those rules a "knock-out rule" was added in order to assign the highest priority for maintenance to substations whose risk was classified as "inacceptable". The usage of knock-out rules is one of the main advantages of fuzzy logic, since they make a nonlinear relation between input and output of the model possible.

5) Defuzzification

The last step in the determination process of a substation risk-index value after the input data was generated, fuzzified and the corresponding rules were activated is the defuzzification. Through the usage of the centre of area method a risk-index value between cero and one is generated.

B. Determination of total risk-index value

Through the determination of the reversible and the irreversible MV/LV substation risk-index values, it is now possible to calculate the total risk-index. The reversible and irreversible risk-index values are first weighted and then added (Fig. 4). As already mentioned above, 40% of all failures within MV/LV substations are caused through degradation and only 20% through deterioration. This is why the reversible risk-index value is weighted with a factor of 2/3 and irreversible risk-index value with a factor of 1/3. Herefrom results a total risk-index value which reflects the total risk carried by the substation. Therefore the total risk-index represents a ranking index, in case a group of substations are considered (denoted with an X in Fig. 6). At this point it should be pointed out that the ranking of a substation only depends on its condition, since the costs which arise through the non-delivered energy are negligible (cf. chapter II b)).

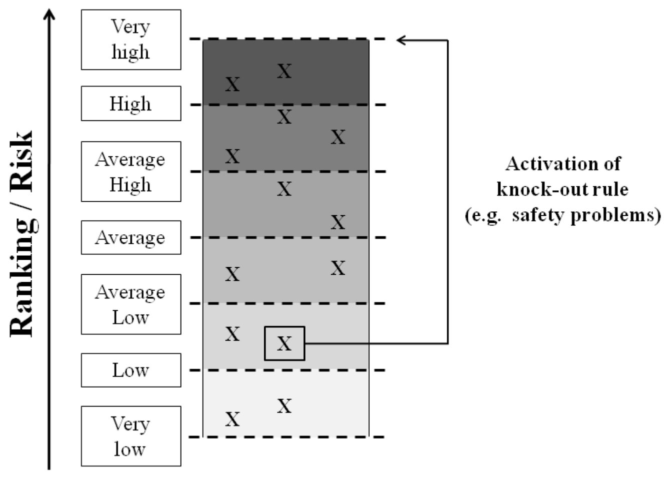

Fig. 6: Ranking of MV/LV substations.

IV. Cost Analysis of Maintenance and Renewal Activities

A cost-benefit analysis of maintenance and for renewals may be performed on the basis of findings during inspection of MV/LV substations. In the presented example, given in TABLE V. , the total risk-index of the substation is average and is composed by a reversible risk-index of 0.63 and an irreversible risk-index of 0.24.

TABLE V. Cost-Benefit Analysis for MV/LV Substation [7]

Total risk	**Action**	**Cost [€]**	**Improvement**	**Specific im.**
0.5	Maintenance	1,350	0.25	0.00019
	Renewal	20,000[a]	0.5	0.000025

a. Price of a new compact substation

For the given scenario two actions are analyzed. First maintenance of the substation is analyzed. This would decrease the reversible risk while the irreversible risk would remain unchanged. Hence, the investment of 1,350€ would cause a total risk-index improvement of 0.25. Therefore the total risk-value will decrease by 0.00019 per invested Euro. If this value is compared to the effect of a renewal, which would cause a specific improvement by 0.000025 per Euro, it becomes obvious that maintenance is clearly the better alternative. Furthermore it is also possible to evaluate the consequence of particular maintenance activities or the benefit of the renewal of single assets with this model. The latter case, however, is not realistic, since nowadays substations are only replaced as a whole by modern compact substations.

The maximal improvement of the total risk-index which can be achieved through maintenance, according to the presented model, is 0.66. This results from the weighting factors given in chapter III B. Respectively, the maximal improvement factor for a renewal is 1. However, the specific improvement will be usually lower due to high renewal costs. This leads to the conclusion that generally maintenance is the better option and MV/LV substations should be maintenance as long as possible. Nevertheless, criterions regarding the strategic asset management must also be taken into consideration, when thinking about renewal. Network operators, for example, are usually interested in replacing substations with outdated technologies long before the irreversible risk is very high.

V. Conclusions

In this paper a model is presented which supports asset managers at finding optimal maintenance and renewal activities for MV/LV substations after an inspection. It also allows for ranking single substations within a whole collective according to the "total risk" carried to the network operator by the station. In order to provide clearer information, and since different maintenance activities can be deduced from one and the same risk index, the "total risk index" is sub-divided into an "irreversible" and a "reversible" risk index. Using the irreversible risk index, the necessity of renewals can be determined, while the reversible risk index provides information with respect to the need for maintenance activities.

Two models for the determination of risk-index values are designed similarly and were implemented in MATLAB®. In both cases, a substation is evaluated with a fuzzy-logic system using the reversible and irreversible asset risk-index values. The rule-base of the fuzzy system is generated on the basis of risk outage costs. First, linguistic variables from "very high" to "very low" are predefined for input as well as output variables. Then, the share of each considered asset to the substation risk index is analyzed. This share depends on the assets importance within the substation and its proneness to failure, with the importance of an asset being the mean outage costs in case of its failure and the fault proneness depending on the asset's condition. The fault proneness of an asset is considered through the assignment of a failure rate in dependence of its condition. In this way an output value can be assigned to every input combination to generate fuzzy rules. It is also possible to assign the highest priority for maintenance to an inspected substation through the activation of knock-out rules, if for example a substation poses a threat to humans and / or environment.

Through a cost-benefit analysis the operating mode of the developed model was demonstrated. Furthermore, it was shown that maintenance activities usually produce better cost-benefit performance rates than renewal activities.

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