URBAN DISTRIBUTION NETWORK RELIABILITY SIMULATION AND STRATEGIES OF SUCCESSIVE REFURBISHMENT OF DISTRIBUTION TRANSFORMER STATIONS

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ABSTRACT

The refurbishment of distribution network assets is usually based on long-term strategies which the distribution system operator formulates for particular asset groups. One of the important asset groups (particularly in urban networks) consists of MV/LV distribution transformer stations (DTSs). The strategy of their refurbishment could rely on a simple refurbishment (i.e. on replacement of equipment with a functionally identical unit), but with regard to the smart grid trend, the refurbishment tends to be extended by installing the telecontrol as well as measuring and signalling devices. However, for the complete formulation and evaluation of the strategy, even in the case of the extended refurbishment, there are a number of questions to be answered.

The paper shows possible refurbishment strategies of DTSs in case of a large urban distribution network, picks up some details of carrying out the strategies by an algorithm and presents our specific approach to related reliability simulation.

INTRODUCTION

Distribution networks assets undergo gradual refurbishment, which is derived from long-term strategies of distribution companies. These highest level long-term strategies set the guidelines for the allocation of total resources for the refurbishment and development of the network to individual groups of equipment. On this level the statements of strategies tend to be rather general and vague - they don't focus on individual equipment. However, the refurbishment strategy on the level of a certain group of equipment is different - its form is more specific, with a number of related details.

The group of equipment that this paper mainly focuses on are MV/LV distribution transformer stations (DTSs). In their case the refurbishment strategy can rely on a simple refurbishment (replacement with a functionally identical unit), or on a refurbishment extended by implementation of present-day telemetry and telemechanization elements, or on a combination of both. The spectrum of options is really wide.

What we have in mind by a refurbishment strategy are answers to questions that can be expressed in the briefest possible way like this: "Which? - When? - How?". These questions will be elaborated in the following sections and the issues will be consequently demonstrated by specific examples of DTSs refurbishment of a PREdistribuce, a.s. extensive cable network.

DTS REFURBISHMENT STRATEGY

The question "How?" focuses on the equipment of a specific DTS. We can assume that the refurbishment of a station will be accompanied by the installation of short-circuit current indicators with remote signalling of the status to the control centre, as well as telecontrol of switches (with a partial installation - in outgoing feeder bays and feeder bays with normally open switch-disconnectors - or with a full installation - in all feeder bays).

The questions "Which?" and "When?" are closely linked. Answers to these questions are referred to as scenarios.

One of the scenarios can be represented by a refurbishment that is based purely on age and is therefore close to the current practice. In the case of DTSs it is mainly based on age, and its range represents a simple refurbishment. Practical implementation, however, takes into account a number of other factors.

A close alternative is represented by a refurbishment based on increasing age, but a DTS is passed over if the neighbouring DTS has already undergone refurbishment and has been newly equipped.

In contrast to the quoted cases are scenarios that proceed with refurbishment primarily along feeders, and in each feeder a uniform rule is applied: first all designated DTSs are equipped at a given feeder, and only then the next feeder is equipped. Distribution feeders are sorted in descending order in accordance with the number of customers. Thus preference is given to the parts of network that have a greater impact on the distribution continuity indices. Scenarios based on the above-described procedure are referred to in this paper as the "selective" scenarios.

The first rule applied in all the following selective scenarios (functioning also as a separate "SS" scenario) is the refurbishment and the installation of equipment to all DTSs with more than two cables connected, as well as to DTSs with normally open points.

Other rules specify that DTSs in distribution feeder "branches" should be refurbished and equipped. What is meant by a "branch" is a sequence of consecutive DTSs with two cables connected and with both feeder switch-disconnectors closed (DTSs with three or more cables connected and DTSs with at least one switch-disconnector opened are not included) - see Fig. 1.

The rules applied to branches can designate each *x*-th DTS to be refurbished and equipped (e.g. each second, each third, etc.; such scenarios are marked as "SS e.2", "SS e.3", etc.). The selected rule can be applied to each branch (uniformly within the framework of the scenario), or the selection can take into account the number of sections making up the branch (scenario "SS Tab").

It is appropriate to add a condition in the above-stated selective scenarios that the last DTS in the branch would be excluded in order to avoid equipping two adjacent DTSs.

It is also possible to simply request a refurbishment and equipment of a DTS in the middle of a branch ("SS 1/2").

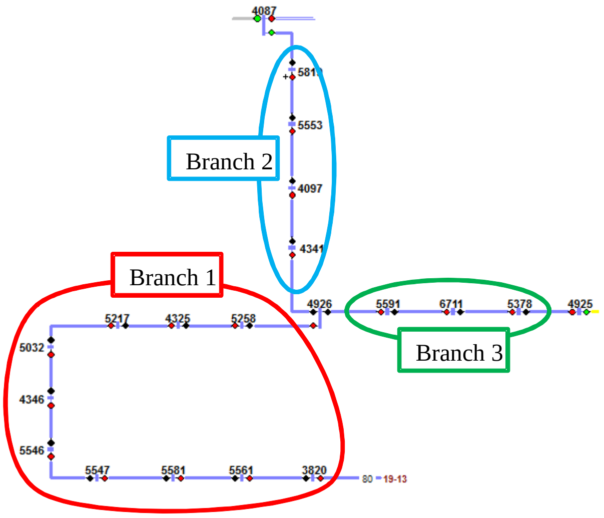


Fig.1 Illustration for the definition of branches in a distribution feeder

The listed options define the sequence of DTS refurbishment without specifying the year of refurbishment. It is therefore necessary to also add the time point of view and the overall time frame, for which scenarios should be considered. In our case, the constant annual rate of refurbishment is based on the numbers of DTSs refurbished in recent years and the rounded normal value (100 DTSs). The total time frame of the evaluation period comprises 15 years.

SPECIFIC FEATURES OF THE IMPLEMENTATION OF REFURBISHMENT STRATEGIES FOR AN EXTENSIVE CABLE NETWORK

The actual refurbishment scenarios for the considered distribution network hide a number of interesting points, which may not be obvious at first sight. Their detailed analysis, however, provides a solid foundation for a number of related considerations.

Input data

Should the DTS refurbishment strategy outlined in the previous section be implemented in a real cable network, the fundamental input data are those related to the topology of the MV network, which includes sections of MV lines (lines between stations, or as the case may be, between switches), DTSs, switching stations, MV substations in 110/22 kV transformer stations and switches in the MV network (including links to incidental elements and information on the type and state in normal connection). In the case of MV network of PREdistribuce, a.s. there are more than 4,000 DTSs and nearly 13,000 switches.

It is also necessary to know the number of customers supplied, the age and the ownership for each DTS.

Suitable arrangement of these data allows blanket algorithmic processing of the refurbishment strategies.

Exhausting the selective scenarios

Although the network under analysis is the largest (urban) cable network in the Czech Republic, some of the selective scenarios only cover a limited number of DTSs, and by the end of the fifteen-year period they will be "used up" (if solely the specified rules are applied).

In our case the "SS" scenario will all be used up in the 7th year, the "SS e.3" scenario will be used up in the 11th year, the "SS e.4" scenario in the 10th year, the "SS e.5" scenario in the 9th year and the "SS Tab" scenario in the 11th year. The only scenario that fills up the entire fifteen-year period is the "SS e.2", which represents refurbishment of DTSs with three or more cables connected, refurbishment of DTSs with open points, and refurbishment of every second DTS in the branches.

In practice it would certainly be inappropriate to stop the refurbishment of DTSs after the rules of the selective scenario have been exhausted. They can be followed up either by adding more interventions within branches (i.e. if every 4th DTS has been refurbished, now every 2nd can be done, except for those already completed), or then the refurbishment can solely follow the principle of age. In this situation the second option is more advantageous, as it eliminates older DTSs, whose number has grown during the selective process (these scenarios are marked with suffix "x/a").

The transition from a selective scenario to a refurbishment based on age can also be done before the selective scenario has been exhausted. In our case, we considered scenarios in which this transition takes place at the beginning of the 6th year ("5/a").

The development of age

An important criterion for the assessment of DTS refurbishment scenarios is the development of their age.

The development of the average age of all DTSs in the network does not give a clear picture. The courses of individual scenarios in group "5/a" almost overlap, and the courses of scenarios in group "x/a" are also very close. All the selective scenarios mature in their 15th year to an average age, which is only slightly higher than the average age in that year in the refurbishment scenario based solely on age.

A better picture is provided by the numbers of DTSs of higher age. Figure 2 shows the numbers of DTSs older than 40 years, and older than 45 years during the evaluated period.

If refurbishment had been based solely on age, then by the end of the first year there would have been only 21 DTSs in the network older than 40 years, and none older than 45 years. If the refurbishment had been based solely on age with the limitation stated above, then the numbers of DTSs older than these limits would have grown and by the end of year 15 there would have been more such DTSs than in other scenarios, which results from neglecting refurbishment of DTSs neighbouring with the ones where refurbishment has already been completed.

In scenarios switching from 6th year to refurbishment by age ("5/a"), the numbers of such DTSs first rise, and then after switching they fall. From 9th year there is not a single DTS in the network that would be older than 40 years. Scenarios switching to refurbishment by age only after the selective scenario has been exhausted ("x/a") do not behave in this way. The number of DTSs first grows and then, with one exception, it decreases, but the end value is more than double of the initial value.

Impact on the supply quality

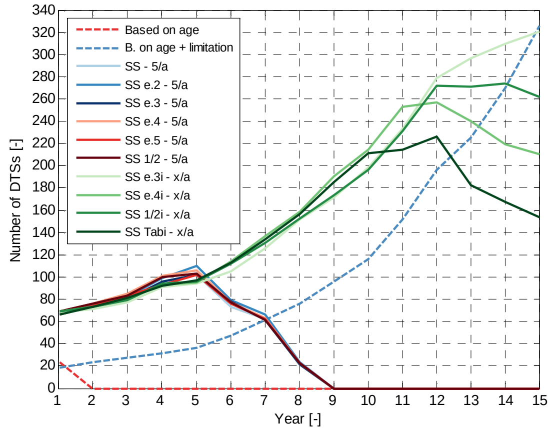
Another criterion that has been monitored in assessing scenarios is the impact on the quality of power supply, or the impact on changes of supply continuity indices *SAIDI* and *SAIFI*. The importance of the selective scenarios has been revealed here, because especially in the first five years they contribute to a significant reduction of indices compared to refurbishment scenarios relying solely on age. The improvement is more evident in *SAIDI* values, as this index depends on the time needed for locating a failure, and subsequently for restoring supply to customers.

Influence of deviations from the rules

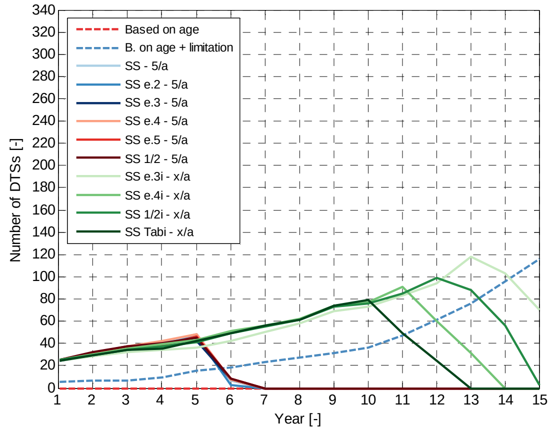
In some scenarios (in Fig. 2 these cases are marked with a letter "i") the so-called "±1 DTS" interval has been implemented, which defines a circle around the DTS on a branch that has been selected by means of the applied rule. This circle consists of 1 DTS on each side of the DTS selected by the rule. Then the DTS in the circle selected for refurbishment is the oldest one.

The "±1 DTS" interval has little impact on the average age. The interval usually affects less than half of DTSs refurbished in a given year. If it can be applied, then only minor differences in the age of refurbished DTSs prevail, as is documented in Fig. 3 for one of the scenarios and for individual years of evaluated period. A minimum difference in age is always zero, a maximum usually exceeds 24 years of age, and the average of the differences is between 4 and 10 years (except for the last year).

It was interesting to find out that the introduction of this interval does not have any significant impact on changes of *SAIDI* and *SAIFI* values.



a) Age higher than 40 years



b) Age higher than 45 years

Fig. 2 The number of DTSs of higher age - the selected scenarios

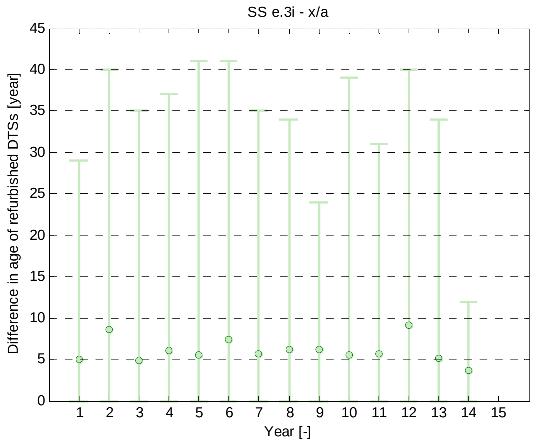


Fig. 3 Average, minimum and maximum difference in age of refurbished DTSs through implementation of the "±1 DTS" interval (the average is marked with a point) - the selective scenario proceeding along distribution feeders and refurbishing every third DTS until the rule has been exhausted, then proceeding according to age

RELIABILITY SIMULATION

Method

A simulation has been performed for a whole network supplying more than 770 thousand customers through more than 4,000 DTSs. The non-sequential Monte Carlo simulation was implemented in Matlab. Statistical distributions used for the simulation of annual numbers of failures have been derived from failure data recorded during 10 years. Regarding the MV cable sections (sections between stations) the simulation has distinguished between internal failures and external interventions. Negative-binomial distributions that best fit the data have not changed with the age, because the available data have not proved a clear relationship between the cable section failure rate and the age. On the other hand, with DTSs an influence of the age in the data has been observed. This fact is reflected by an exponentially increasing failure rate in the simulation (fig. 4).

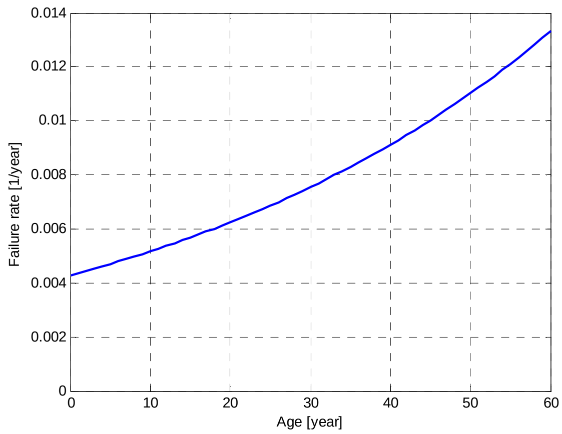


Fig. 4 Failure rate of DTS related to the age

Our own open implementation of simulation and evaluation algorithms brings a great advantage – flexibility. It allows utilization of 6 characteristic intervals for the simulation of durations. It also allows the number of subsequent manual operations for exact failure localization to be derived from the number of cable sections in the feeder segment localized in the previous step by means of telecontrolled switches. Log-normal distributions based on failure reports data have been assigned to particular simulated durations.

Due to the 15-year length of the evaluated period and in order to reduce the number of possible situations ("histories"), only every fifth year was evaluated (simulated).

The simulation itself contained 10,000 years and was organized into layers (distinguishing between cables and DTSs in different time intervals). Thanks to this simulation layout it was possible to evaluate (and correctly benchmark) all conceivable situations that could occur in the strategies on the basis of one unique simulation.

The main results

The results obtained for a given constant annual number of refurbished DTSs led to the following conclusions: If the "selective scenario" with a partial installation of equipment is only implemented during the first 5 years and the refurbishment based on age (also with a partial installation of additional equipment) follows during the next 10 years, the contribution of MV network to the average estimated *SAIDI* value at the end of the 15th year is by 56% to 62% lower than if age-based refurbishment is implemented during the whole period. If a full installation of equipment is selected, this contribution to *SAIDI* is only by 4% to 6% higher.

If refurbishment based on the selective scenario continues to the point of its exhaustion (i.e. up to the moment when no more DTSs comply with the given rule of the particular scenario) and age-based refurbishment follows afterwards (till the end of 15th year), the contribution to *SAIDI* increases by additional 9% to 13%.

Refurbishment of DTSs based on the above-described scenarios influences mainly *SAIDI*. Changes of *SAIFI* are considerably smaller (as only in some cases the fast remote localization of a failure results in a decrease of duration of supply interruption to less than 3 minutes).

All above mentioned results correspond to the level of failure rate observed in the network during the period prior to working on the study in selected group of failures that serves as a basis of this paper. The results do not reflect influences of other measures or factors.

CONCLUSION

The refurbishment strategy of MV/LV distribution transformer stations even for extensive real urban distribution networks can be formulated in an algorithmizable form. At the core of this formulation is a definition of the sequence in which the stations will be refurbished. This sequence can follow the usual criterion of the DTS age, or it can be designed in a way that favours refurbishment in those parts of the network where DTS telemetry and telemechanization components are prerequisite to effective gradual reduction of supply continuity indices. For a smooth and autonomous operation of the algorithm, it is necessary to introduce a series of rules for specific situations.

An important aspect of the selective refurbishment procedure is a possibility of its application for only a limited time period with subsequent transition back to "traditional" refurbishment based on age (precisely based mainly on age). Appropriate timing of this transition results in compensation of the negative features of the selective process - increasing the number of DTSs of higher age - within an acceptable time frame.

One possibility of mitigating the rise in the number of older DTSs already in the selective process is to ease the DTS refurbishment rule for distribution feeder branches by 1 DTS on each side from the DTS predetermined

strictly by the rule and select the oldest one of the three neighbouring DTSs for refurbishment. Although the introduction of the principle does not have much impact on aggregated parameters (e.g. on the average age), it has a significant effect on the local level.
From a practical point of view it is appropriate to evaluate the strategies in medium-length periods (e.g. every 5 years). Such a period absorbs the deviations between a refurbishment based solely on the strategy and its real course, as a number of factors arising from natural causes play a role, and these factors are difficult to assess beforehand.

On the basis of a reliability simulation it is possible to estimate the impact of individual strategies on the supply continuity indices, and to compare the strategies. The selective DTS refurbishment applied at least for some time significantly reduces mainly *SAIDI*, in comparison with refurbishment based on age.