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Condition Assessment for Optimal Planning and Operation of Power Systems with the Aid of Ageing Models

Leyla Asgarieh, Gerd Balzer, Armin J. Gaul

***Abstract*—In times where the reduction of the yearly expenditures of utilities and therefore the optimal assignment of assets have a very high priority, the knowledge about future expenditures of the following 40 or 45 years is very useful. This paper shows a method to calculate the yearly capital and operational expenditures CAPEX and OPEX, respectively with the aid of ageing models consisting of different condition states. Furthermore, a procedure in order to calculate the required transition rates between successive condition states will be described, and the calculated values will be verified. The ageing model is useful for planning and operation of power systems under market conditions. The main advantage results from considering both the condition as well as the age of the assets in a power system. Therefore the asset manager receives lifelike results over a certain time horizon. The simulations will be performed by means of an appropriate system dynamics software.**

***Index Terms*—Ageing model, asset management, CAPEX, OPEX, planning and operation of power systems.**

I. Introduction

IN a liberalized market cost reductions in all areas have a very high significance, which has to be taken into account for planning and operation of power systems under market conditions. The annually arising expenses have to be divided into two parts: On the one hand the capital expenditures (CAPEX) and on the other hand the operational expenditures (OPEX). CAPEX are due to new installations caused by replacement and grid enlargement. OPEX result from the summation of following costs:

- Maintenance costs (overhaul and inspection),
- repair costs (caused by minor and major failures),
- costs due to expected energy not supplied,
- costs due to power losses.

In order to calculate all these values the age distribution as well as the condition of the assets in a grid are required. Since it is too complex and expensive to measure the condition of each piece of equipment every year, an ageing model has to be developed. Therewith simulations can be performed to obtain the age distribution over a predetermined simulation horizon.

The ageing model is implemented within the simulation software Powersim Studio®. These simulations work on the base of system dynamics and were developed by Jay W. Forrester. The use of this computer based simulation modeling methodology allows the asset manager to see not just events, but also patterns of behavior over time, because it "is the study of information feedback characteristics of industrial activities to show how organizational structure amplification and time delays (in decisions and actions) interact to influence the success of the enterprise" [1]. It mirrors the reality in a model and displays the interactions between flows of:

- information,
- money,
- orders,
- materials,
- personnel and capital equipment in a company, an industry or a national economy [1].

"System dynamics is a powerful methodology and computer simulation modeling technique for framing, understanding, and discussing complex issues and problems. Originally developed in the 1950s to help corporate managers improve their understanding of industrial processes, system dynamics is currently being used throughout the public and private sector for policy analysis and design" [2].

In this paper an ageing model will be described using the example of high voltage circuit-breakers. The model consists of different condition states, which will be described in the following chapter, in order to replicate the real behavior and condition of circuit-breakers under consideration of their age.

Objective of the ageing model is to calculate the yearly expenditures under consideration of asset condition and service age.

The first chapter gives a brief overview of the ageing model, the second one describes the procedure of the condition assessment as well as the transfer of this information into the ageing model. Apart from this, a method to calculate appropriate transition rates between the condition states of the ageing model will be described. Finally, data (transition rates)

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used at the beginning of the simulation will be compared to those after a certain simulation horizon.

II. Ageing Model

The proposed ageing model mirrors the behavior of circuit-breakers over their lifetime under consideration of external events like overhaul and inspection as well as in dependence on the respective failure rate. In this special case the following three different circuit-breaker types were individually investigated:

- SF_6,
- air blast and
- minimum oil.

The model can also be used for other pieces of equipment, like

- instrument transformers,
- disconnectors,
- power transformers,
- cables or
- overhead transmission lines.

The combination of different equipment types enables a simulation of the whole grid.

The developed model has four condition states with different residence times which are dependent on the equipment type and can differ by determining other devices. The coherence between the number of condition states and the residence time for each respective condition state can be derived from the bathtub curve, which is a hazard function describing the expected failure of electrical equipment over service time. It starts with a high value at the beginning, drops to a constant value for the greatest part of equipment life time and rises again at the end of the equipment lifetime [3]. The curve represents the idea that the operation of a population of devices can be viewed as comprised of three main distinct periods:

- The “early failure” period, in which the hazard function decreases over time,
- the “random failure” period, where the function is constant over time and
- the “wear-out” period, in which the hazard function increases over time [3].

The name bathtub curve is due to its curve progression, which looks similar to a bathtub, as shown in Fig. 1.

The time horizon of the ageing model relates to the time period of the bathtub curve and consequential to the sum of the residence times in the condition states.

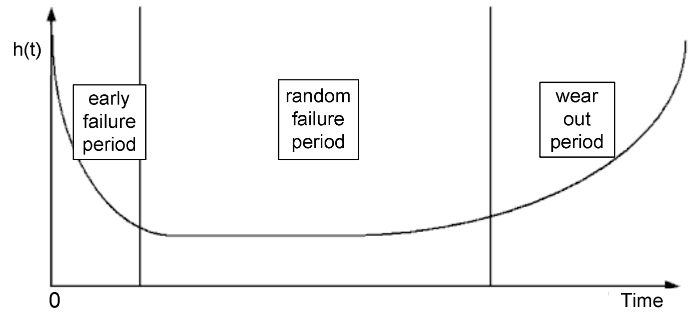

Fig. 1. Bathtub curve [4].

Fig. 2 shows an exemplary ageing model with four condition states. The three main parts of the bathtub curve from Fig. 1 are extended to four states in this case and have to be adjusted to the basic conditions of every issue and therefore can also be extended to more condition states if necessary. The number of required condition states is dependent on the behavior of the asset over time. If the condition of the assets is strongly correlated with the age and changes after short intervals more condition states are necessary, compared to assts which have long intervals without changing the condition.

The outer rectangles in Fig. 2 represent the whole condition state whereas the inner rectangles describe the different age groups of the condition states. In this special ageing model the first condition state has a residence time of five years, the second one of 20 years, the third one of 10 years and the last condition state has a residence time of five years. The main assumption is that circuit-breakers have to leave the ageing model and therefore have to be replaced at the latest after the assumed life cycle.

To consider different basic conditions for every circuit-breaker type an ageing model for each circuit-breaker type is required and the results can be summed up to obtain information about a whole grid. Determination of the transition rates between two condition states, which are denoted with μ1 to μ4 in Fig. 2, will be described in the next chapter. The value of “in” in Fig. 2 describes the yearly new installations, because of grid enlargement and replacement of circuit-breakers, which leave the ageing model (“out”).

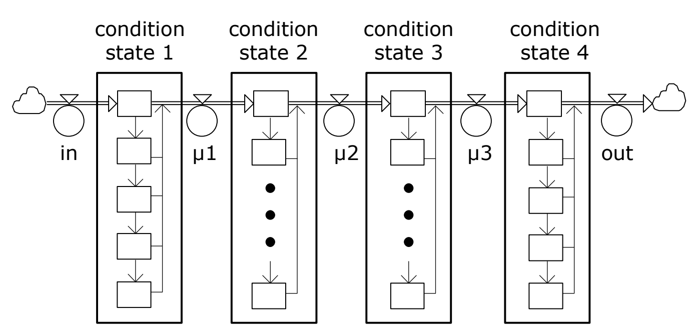

Fig. 2. Exemplary ageing model with four condition states.

It is further assumed that all newly installed circuit-breakers are of SF_6-technology, no matter which type of circuit-breaker has to be replaced.

After the first year all elements which had been in state one are transmitted into the second state. Every year a percentage of pieces of equipment have to transit from one condition state towards the next one. This transition can have two reasons: The first one is that a circuit-breaker has reached the maximal residence time of its condition state; this assures that an element leaves the system after its lifetime. The second one is a transition without reaching the maximal residence time. This occurs, when a circuit-breaker behaves older than its real age. In this case, the circuit-breaker ages artificially. It is ensured, that pieces of equipment, which have reached the maximal residence time, have to leave the condition states [5]. Additional information and detailed data can be taken from [5].

III. Condition Assessment of Assets

In a first step the technical condition of the circuit-breakers is required, which can be evaluated on the basis of different criteria (items of interest), some of which are:

- Age,
- experience with this type of circuit-breaker,
- maximum short-circuit capability,
- number of switching operations,
- number of short-circuit interruptions,
- type of circuit-breaker and
- measurement results [6].

It can be seen from the above list that not only nameplate data but also experience of the equipment user and results of typical measurements carried out on the assets are taken into account. Examples for the last mentioned point are the operating time, gas and oil analysis, tightness and synchronism of the contact switching [6].

Apart from this, rating and weighting factors are necessary to consider the influence of each criterion on the overall value of the technical condition of the asset. The condition values range from zero to 100. Zero represents circuit-breakers in good condition and 100 mirrors a bad condition [7]. In this case, it is possible that circuit-breakers with the same condition value have different ages or vice versa.

The above described assessment has been done, in this example, for 100 circuit-breakers of the three different types. These data has to be evaluated by regarding the condition value as well as the age of the asset.

Fig. 3 shows the distribution of condition values (plotted on the ordinate) and service age (plotted on the axis of abscissa) for the three circuit-breaker types. The black line in Fig. 3 is a frequency polygon through the circuit-breakers with the best condition values. These elements are not artificially aged, but all circuit-breakers above this line behave older, than they really are. The artificial age of the circuit-breakers can be seen from the chart by using a horizontal line through the coordinate of the circuit-breaker and the interception point with the frequency polygon.

An example can be seen in Fig. 3. The chosen minimum oil circuit-breaker has the condition value 37 and a real age of 25 years, but an artificial age of 27 years. For the transmission of these values into the ageing model, the real and artificial age must be considered [5].

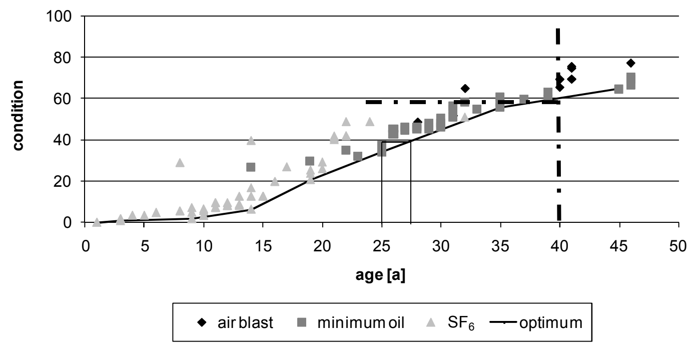

Fig. 3. Technical condition of circuit-breakers [4].

These values can be transferred into the ageing model by keeping the information of real and artificial age; therefore the condition of each circuit-breaker is retained even when the information is transferred into the model. In this case it has to be considered that all circuit-breakers which are older than the maximal life cycle, concerning the real and artificial age, have to be replaced in the first simulation year.

For example if the maximal residence time of the model is set to 40 years all circuit-breakers in Fig. 3 which are above the black dashed horizontal line and on the right hand of the dashed vertical line have to be replaced in the first year, because the 40-year value of the polygon frequency determines the boundary of the ageing model. Hence it can be seen that most of the air blast and some of the minimum oil circuit-breakers have to be replaced in the first year.

A. Examples with maximal life cycles of 40 and 45 years

In the following subchapter ageing models with different life cycles will be regarded and compared to each other. The first ageing model incorporates a maximal life cycle of 40 years (as shown in Fig. 2) and the second has an additional condition state and considers a maximal life cycle of 45 years for each circuit-breaker.

Besides, two different scenarios for the yearly new installations will be investigated: In the first one new installations will be calculated by adding the number of circuit-breakers which leave the model and the number of new installations caused by grid enlargement, in the other case by implementing a limit for the yearly maximum budget and thus for the amount of yearly new installations. Accordingly, if the first mentioned value exceeds the limit of the yearly maximum budget the delays of capital assess must be distributed to the following years. This mirrors the optimal use of personnel as well as of financial resources due to unification of the yearly capital expenditures.

The maximal investment value is determined to two times of the average investment costs (CAPEX) for the whole simulation period, which is 1,93 million €. More detailed information about the composition of the yearly investment costs can be taken from [5].

Apart from this the assumption is made that all circuit-breakers which have to be replaced will be replaced by new SF_6 circuit-breakers, independent from the type which have to be replaced.

Regarding Fig. 3 two investment peaks can be recognized. One in the first year, this occurs because of many old minimum oil and air blast circuit-breakers, which must be replaced, in the initial point because exceeding the maximal life cycle. The second peak of investment arises eleven years later. According to Fig. 3 the most minimum oil circuit-breakers are between 25 and 30 years old, therefore they have to be replaced approximately eleven years later.

After filling the ageing model with the above mentioned data of real and artificial age (Fig. 3), the transition rates between the condition states have to be determined. Therefore the artificial age, which can be calculated with the aid of the condition assessment as shown before with the example of a minimum oil circuit-breaker (Fig. 3), has to be plotted against the real age. This is shown in Fig. 4 for the SF_6 circuit-breakers which are the most important ones, because circuit-breakers of SF_6 technology will be the predominant one after the simulation time.

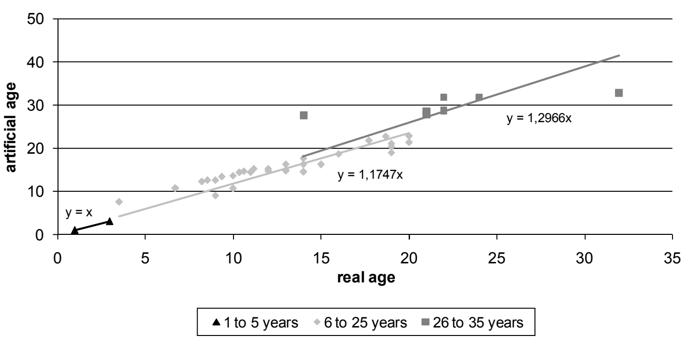

Fig. 4. Determination of the transition rates at the initial point.

In order to calculate the appropriate transition rates, mean straight lines through zero are required for each condition state. In Fig. 4 the linear equations for the first three condition states can be seen. The transition rate values of the last two condition states must be estimated, because there is no information available about SF_6 circuit-breakers which are older than 35 years.

Regarding Fig. 4 it becomes reasonable that if real and artificial age of the circuit-breakers had corresponding values the gradient of the mean straight lines would be one. But regarding the condition of the circuit-breakers, it can be seen that normally the real and artificial age are not congruent, hence the gradients are greater than one and this must be taken into account in the ageing model in order to receive reliable results. Only condition state one has corresponding values of real and artificial age, because a deviation can primary occur after the first transition from one condition state into the next one and thus from the second condition state.

Aside from the goal to simulate the shape of the bathtub curve in this ageing model another expedient reason to choose a quite small residence time for the first condition state is the request to determine the real and artificial age.

Moreover the gradients and therefore the transition rates for the last two condition states have to be estimated. The difference of the first two gradients is 17,47% and from the second and third gradient 10,04%, therefore the assumption is made, that the last two gradients are 7,75% higher than the third alternatively the fourth one.

With the information that uniformly distributed transition rates corresponds to a gradient of one, because of identical real and artificial age, the proper transition rate values for these circuit-breakers can be calculated for each condition state.

The next important point is to evaluate the same data after the simulation time and to compare these values. The calculation of the deviations between transition rates at the initial state and transition rates after the simulation time shows, how the circuit-breakers behave during simulation.

Small deviations would prove that the adjusted transition rates are appropriate.

The values of the real and artificial age after a simulation horizon of 40 years without and with a limit of capital assess are displayed in Fig. 5 and Fig. 7. Respectively, the values for a simulation horizon of 45 years without and with an investment limit are displayed in Fig. 6 and Fig. 8.

The calculation of the new transition rates after the simulation time is done in an analogous manner as in Fig. 4 with mean straight lines through zero for each condition state. In the Fig. 5 to Fig. 8 the linear equations for all condition states can be seen.

Besides the deviation between real and artificial age of the circuit-breakers are shown in the figures and corroborates the importance of keeping the information about real and artificial age.

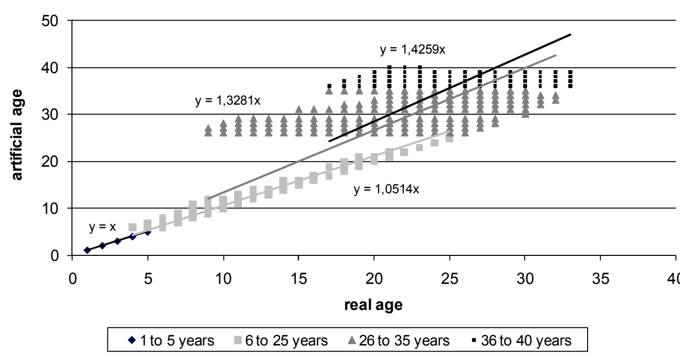

Fig. 5. Determination of the transition rates after the simulation time of 40 years without a limit of investment.

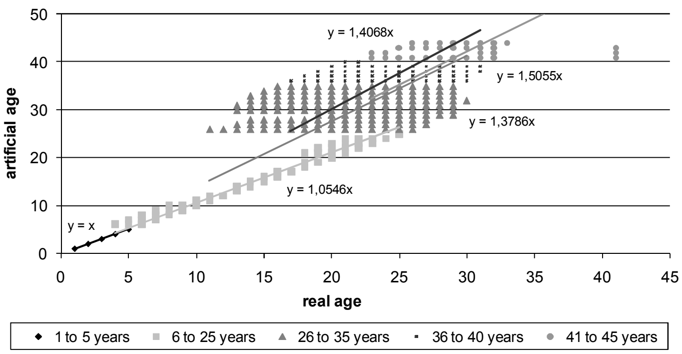

Fig. 6. Determination of the transition rates after the simulation time of 45 years without a limit of investment.

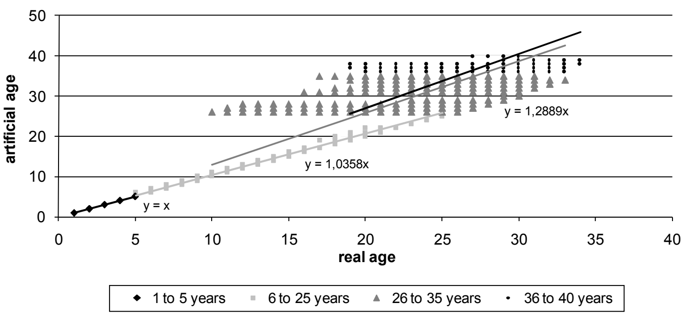

Fig. 7. Determination of the transition rates after the simulation time of 40 years with a limit of investment.

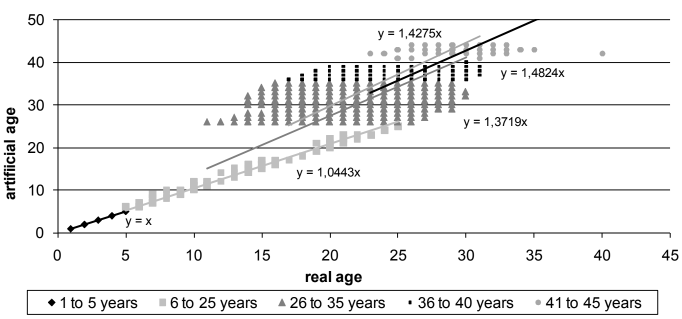

Fig. 8. Determination of the transition rates after the simulation time of 45 years with a limit of investment.

Table I and Table II show the deviations of the transition rates µ1 to µ4 for a simulation horizon of 40 years as well as the deviations of µ1 to µ5 for the simulation time of 45 years without a limit of capital assess (Table I) and with an investment limit (Table II).

A comparison of the deviations, in both tables, regarding the two different simulation horizons shows that an extension of the useful life time and therefore the insertion of an additional condition state leads to increasing deviations. This is due to the fact that a longer life time and thus an extended model enlarge the yearly ageing options of the assets. In summary it can be said the smaller the simulation time the more reliable the results.

Nevertheless, the calculated deviations for both cases are quite low, and represent therefore a reliable ageing model, which can be used to calculate the required information for planning and operation of power systems.

Comparing the deviations with and without a budget limitation it is noticeable that transition rate values of µ3 to µ5 will be emended. This is due to the fact that the new installations are allocated more evenly, because the delay of new installations leads more or less to consistent investments and thus to consistent new installations.

The value of the second transition rate (µ2) increases about 1% to 1,5%, because the number of new installations at the same time will be reduced and this reduces the number of prematurely aged circuit-breakers and enlarges the deviation. Due to the fact that the circuit-breakers cannot age artificially in the first condition state, the deviation of the first transition rate is 0% independent whether an investment limit is considered or not.

TABLE I

Deviation of the Transition Rates before and after the Simulation Time in a Model without a Limit of Investment

transition rate	deviation (cycle 40 years)	deviation (cycle 45 years)
µ1	0,00%	0,00%
µ2	11,73%	11,39%
µ3	2,37%	5,95%
µ4	2,02%	7,20%
µ5	-	7,01%

TABLE II

Deviation of the Transition Rates before and after the Simulation Time in a Model with a Limit of Investment

transition rate	deviation (cycle 40 years)	deviation (cycle 45 years)
µ1	0,00%	0,00%
µ2	13,41%	12,49%
µ3	0,60%	5,49%
µ4	3,31%	5,75%
µ5	-	5,46%

The described procedures of chapter three can be combined into a flowchart in order to show once again the coherence between the steps (Fig. 9).

Furthermore, with this ageing model the asset manager has the opportunity to obtain considerably more data and to compare the results of different assumptions to find the most appropriate for his utility. Some useful data which are delivered by the ageing model are for example:

- The value of the yearly capital expenditures (CAPEX) and its components
  - costs due to grid enlargement,
  - costs due to replacement,
- the value of the operational expenditures (OPEX) as well as the values of its components
  - maintenance costs (overhaul and inspection),
  - repair costs (caused by minor and major failures),
  - costs due to expected energy not supplied concerning losses in sales caused by not

delivered energy as well as economic disprofit,
- value of not delivered energy per breakdown and circuit-breaker,
- the number of pieces of equipment in general and for each type of circuit-breaker,
- the age distribution of the assets,
- deviation of overhaul cycle and the failure rate in order to reduce the operational costs,
- comparison of the behavior of the different circuit-breaker types during their life time.

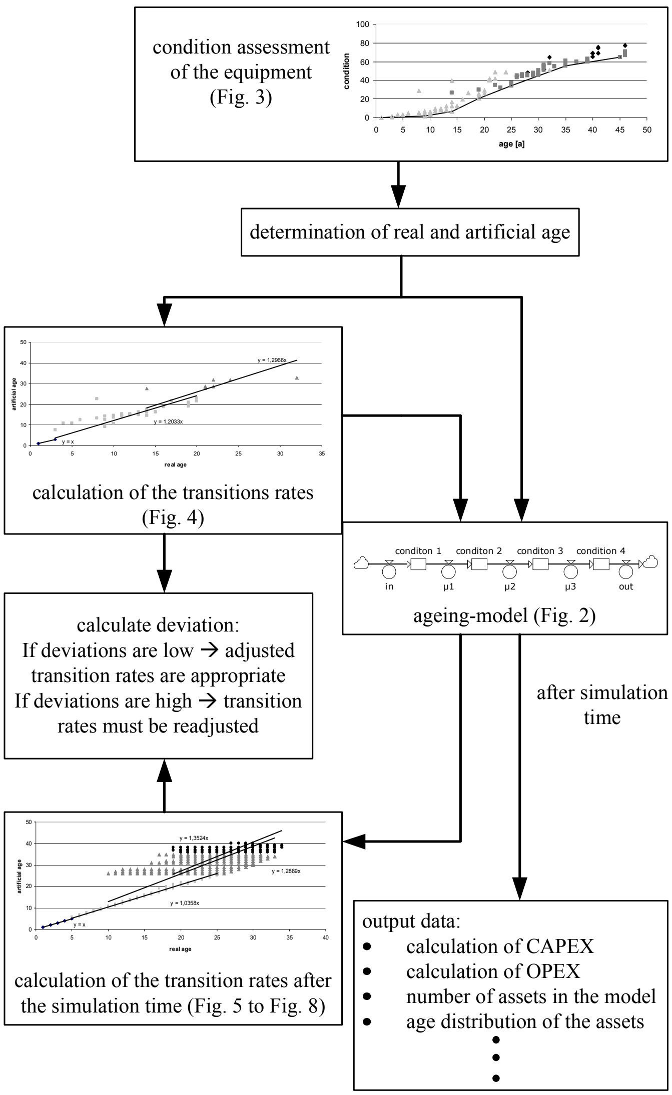

Fig. 9. Flowchart.

IV. Conclusions

Ageing models for circuit-breakers and other assets are of high importance for an asset manager and of course in general for the whole utility. With these calculations the asset manager has the possibility to make a forecast for the following 40 or 45 years for example concerning the yearly capital and operational expenditures, as well as the number of circuit-breakers in the grid or the number of the yearly failures.

It is moreover possible to extend simulation time in order to account for alternative maintenance or renewal strategies or in order to implement assets with a larger life time (for example cables).

Furthermore, the ageing model keeps the information of real and artificial age during the whole simulation time, so that the correlation between asset condition and age is retained.

This paper deals with the method of circuit-breaker assessment as well as with the calculation of the optimal transition rates between the condition states.

The extract of the items of interest used for the condition assessment showed that the combination of nameplate data, experience of the equipment user and results of typical measurements carried out on the assets is taken into account and therefore the assessment leads to a comprehensive approach and thus to a reliable result.

A comparison of the transition rates before and after simulation verified the proposed parameter determination procedure by demonstrating low deviations between the respective values. Due to this, it can be said that the calculated values of the model are reliable and can be used to estimate the demand of assets as well as of financial resources in the following years.

Apart from this the implementation of an investment limit is a reasonable method to achieve an optimal use of personal as well as of financial resources and it improves the informational value of the model which is shown by the reduction of the deviation of the transition rates before and after the simulation horizon.

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VI. BIOGRAPHIES

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