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Probabilistic Evaluation of Voltage Stability in MV Networks

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Abstract: In today's planning of MV networks voltage stability is evaluated using deterministic extreme-value estimations the results of which are very improbable and cause very expensive network extensions. Therefore a simulation tool using probabilistic methods has been developed considering the essential parameters for voltage stability in MV networks: The HV/MV transformer and its stochastically operating voltage regulator, consumers, suppliers and the switching state of the network during normal operation, maintenance activities or after faults. For the period of evaluation the operation values of all parameters and their durations are determined continuously. The simulation results are finally used to show the voltage state distributions at every network node.

Keywords: Power quality, voltage stability, probabilistic simulation, MV networks, voltage state distibutions.

I. INTRODUCTON

Power quality – especially in distribution networks – is divided into reliability of supply and voltage quality; sometimes the system frequency is mentioned as well. The voltage quality is evaluated by its short-term effects (e.g. dips, flicker etc.) and its long-term or quasi-stationary voltage stability. If a supply outage is interpreted as a voltage failure and the frequency as a voltage attribute it may be defined: Power quality is voltage quality [1].

Short-term effects of the voltage quality are caused by switching operations or short circuits in the grid (e. g. dips) and by connected network users like consumers or suppliers (e. g. flicker, harmonics). These disturbances can be reduced, but they cannot be avoided by a topological network planning. For topological planning and dimensioning of MV networks it is essential to keep the quasi-stationary voltage in specific bands at the network nodes. Fig. 1 shows the cut-set between power quality and network planning on the MV level.

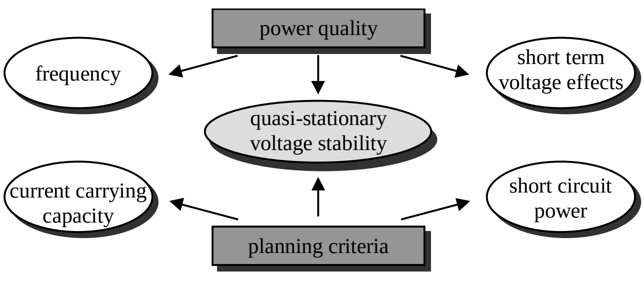

Fig.1. Voltage stability as the cut set of power quality and network planning criteria

Whereas the reliability of supply can be determined by means of probabilistic tools that take into account the practical network operation, the voltage stability has been evaluated so far using deterministic extreme-value estimations the results of which are very improbable and therefore may cause very expensive network extensions. Furthermore, cost-saving potentials revealed by probabilistic methods often cannot be verified by means of deterministic evaluation of the voltage stability. Additionally, normative regulations demand that during normal operation 95 per cent of the node voltages are located in a specific voltage band [2]. Although this requirement is planning-relevant, today it can only be tested during operation.

In order to better utilize the capacities of existing networks and to avoid expensive extension measures that seem to be necessary according to present planning principles, an appropriate simulation tool, integrating all relevant influencing parameters of voltage stability, to be used in network operating and planning for MV networks has been developed.

II. INFLUENCING PARAMETERS

The base voltage at the MV busbar of the HV/MV transformer, the consumers with their electrical load, suppliers and their generation and the network operation itself are the four most essential influencing parameters for the voltage stability in MV networks.

Base voltage

The base voltage at the MV busbar is the input value for the calculation. The time-behaviour at the high voltage (HV) connection point of the HV/MV transformer can be described by a uniform distribution between certain values; typical values are 115 kV ± 5 kV. The transformer is modelled by its – if available load-dependent (compounding coefficient R_C) – voltage regulator that adjusts the setpoint value $U_{setp.}$ at the MV busbar. The voltage regulator does not operate continously but in discrete steps that lead to a hysteresis characteristic. A typical hysteresis range is about ± 1 per cent of the nominal voltage at the MV busbar.

Fig. 2 shows on principle the working method and the resulting output voltage of the transformer with a constant voltage at the HV connection point. A not load-dependent voltage regulator and two regulators with a direction sensitiv load-dependency (~ current I) are shown.

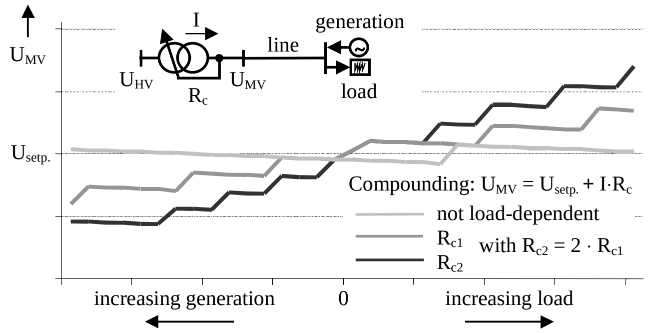

Fig. 2. Output voltage of a HV/MV transformer with a load-dependent voltage regulator

Consumers

Consumers are the most relevant group of network users. The purchase of electrical energy and the resulting load flow cause a voltage drop on the network lines that must not remain under a certain limiting value. Each consumer can be described by an individual or typical load curve. These curves have a special day- and week-cycle for every season in the year; the load curves of spring and autumn are nearly the same. The supporting points of these load curves have a standard deviation showing a normal distribution.

Typical load curves have been identified for domestic consumers with and without electrical heating, agricultural and industrial consumers with a 1-, 2- or 3-shift working day and craft consumers like bakeries.

To determine typical load curves measured curves have been analysed. Therefore a normalized correlation coefficient $c_{corr.}$ of two similar curves s(n) and g(n) with time-discrete steps n has been calculated as described in (1) and (2). Because of the time-discrete steps of the measured data (e. g. 15 minutes) the equations for time-discrete energy signals could be used for power values [3].

$$c_{corr.} = \frac{\sum_{n=-\infty}^{+\infty} s(n) \cdot g(n)}{\sqrt{E_s \cdot E_g}} \tag{1}$$

with the requirement

$$E_s = \sum_{n=-\infty}^{+\infty} s(n)^2 < \infty \quad \text{and} \quad E_g = \sum_{n=-\infty}^{+\infty} g(n)^2 < \infty . \tag{2}$$

In this examination only measured load curves with a correlation coefficient of 0.9 or higher have been used to build a typical load curve for the simulation tool.

Such a typical load curve for a winter workday of an industrial 2-shift consumer is shown in Fig. 3. The curve is described by the average points for active power P related to the maximum power P_{max} and their standard deviations.

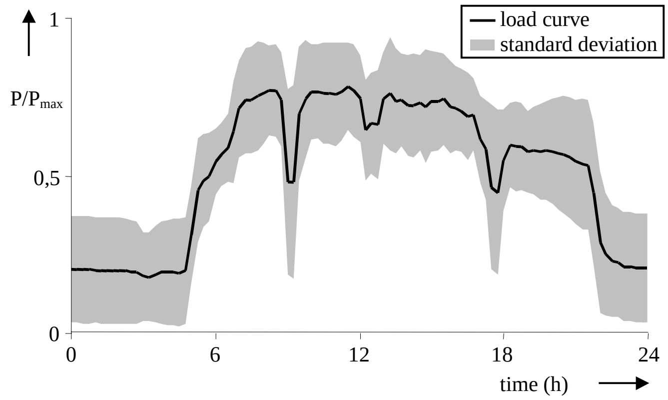

Fig. 3. A typical winter workday load curve of an industrial 2-shift consumer

Normally reactive power of consumers is proportional to the active power. A typical (inductive) power factor is between 0.95 and 1.0.

Suppliers

Similar to the consumers, suppliers inside the network cause a line voltage drop. The reference point of this voltage drop, however, is the MV busbar of the HV/MV transformer. Therefore a voltage increase can occur at the connection point that must not exceed a certain limiting value.

Suppliers as well as consumers can be discribed by individual or typical generation curves with stochastic distributions of the supporting values. Typical suppliers integrated in European MV networks are block-unit power stations or wind energy converters.

Fig. 4 shows a normalized generation curve of a 2-block power station for a winter day.

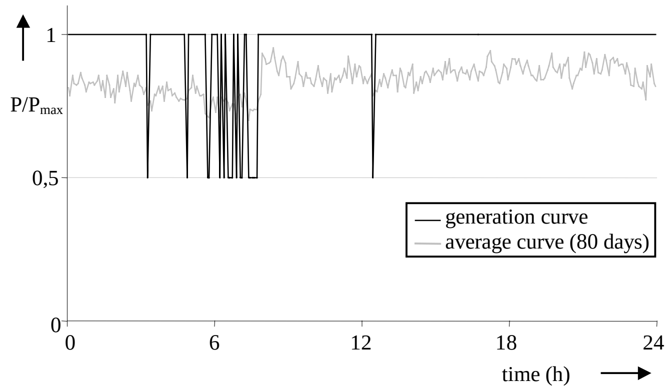

Fig. 4. A typical winter day generation curve of a 2-block power station

From the average values of many time periods the typical discrete curve is got by quantization. The quantization error is a measure for the probability that one gerneration block more or one less is operating. This probability is used in the probabilistic simulation.

To describe the generation of wind energy converters it is necessary to analyse the stochastical behaviour of the wind velocity v_{wind}. The power spectral density of the wind velocity shows two separated parts for the wind velocity changing frequency f_{wind} [4]: One range for frequencies of less than one cycle per hour, where the expected value of the average wind velocity $\overline{v}_{wind}$ is Weibull distributed; the other one for sub-hour frequencies, where the wind velocity has a normal distribution.

The local coherence $coh(f_{wind})$ of the wind velocity corresponding to the changing frequency f_{wind} can be approximated by the exponential function (3) and is shown in Fig. 5 for typical ranges of MV networks in central Europe (diameter from 10 to 50 km) [5]. The parameter a(d) can be determined empirically and depends on the distance d between two analysed locations.

$$coh(f_{wind}) = e^{-a(d)\cdot f_{wind}} \quad \text{with} \quad a(d) = a_0 + a_1 \cdot d \qquad (3)$$

The power spectral density and the diagram in Fig. 5 show that the average value of the wind velocity $\overline{v}_{wind}$ can be determined for the entire MV network area out of existing curves for the hourly expected value of $\overline{v}_{wind}$ and its Weibull distribution. Then the wind velocity v_{wind} at the location of the wind energy converter can be determined by $\overline{v}_{wind}$ and its normal distribution.

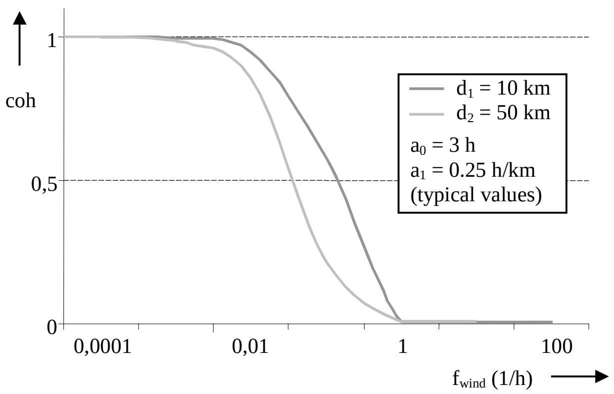

Fig. 5. Coherence $coh(f_{wind})$ of the wind velocity changing frequency f_{wind} for two distances d_1 and d_2

The normal distribution of v_{wind} is described in [6] by the area-wide mean value $\overline{v}_{wind}$ and its standard deviation s_{wind} following (4):

$$s_{wind} = \overline{v}_{wind} \cdot \frac{1.0}{\log \frac{z}{z_o}} \quad \text{with} \quad \begin{array}{l} z \hat{=} \text{pylon height} \\ z_0 \hat{=} \text{ground index} \end{array} \qquad (4)$$

The electrical power P_{wind} of the generator is normally proportional to the cube of v_{wind} and follows generator specific curves like Fig. 6.

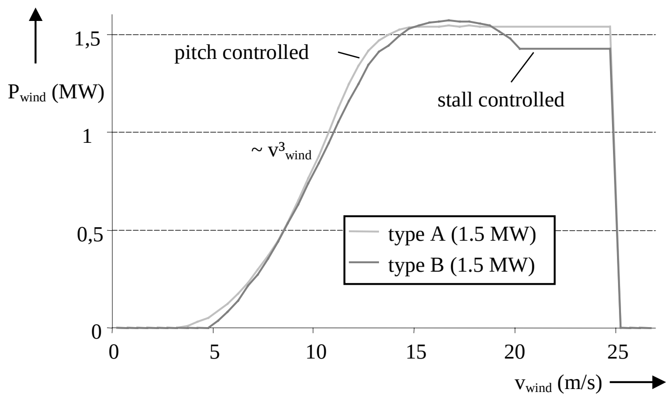

Fig. 6. Electrical power generation of two wind energy converters dependent on the wind velocity.

Normally the reactive power generation in MV networks is used for voltage control but with completely individual values.

Network operating

The switching state of the network itself is essential to evaluate the voltage states at every connetion point. During normal network operation only determined switching activities e. g. caused by maintenance have to be considered. Therefore a definite date of the beginning and the end of this activity during the simulation period (normally one year because of the annual periodicity of consumption and generation) is given.

Another time range longer than one year has to be simulated if the operation under fault condition has to be evaluted, because one year would not be representative of the failures of the network components. Due to this fact the operation under fault condition has to be simulated seperately. To describe, which components have the most important effects on network operation as a result of failures, table 1 shows the annual failure frequency of overhead lines, cables and substations [7].

Table 1.

annual failure frequency (20 kV-level)	
overhead line	3,2 failures/100 km·a
cable	4,8 failures/100 km·a
substation	0,4 failures/100 substations·a

Consequently it is sufficient to simulate overhead line and cable failures for an evaluation of voltage stability during operation under fault condition.

III. METHODOLOGY

As an analytical solution of the problem is not possible, a sequential Monte-Carlo-Simulation is used in this evaluation method. Fig. 7 shows the working mode of the simulation tool on principle.

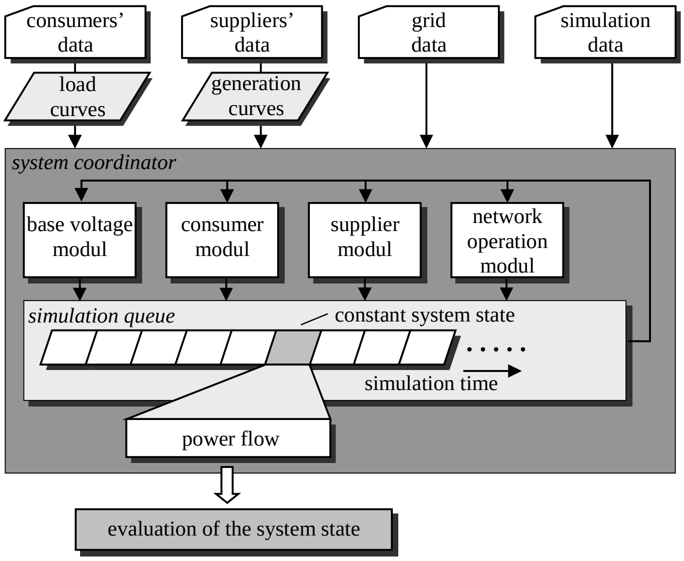

Fig.7. The simulation tool for voltage stability evaluation

For the period of evaluation the operation values of all influencing parameters and their durations are determined continuously by the modules. The minimum duration of a constant state of one parameter fixes the minimum constant system state before the next step is calculated. If the voltage states and state durations are known for the whole simulation period, the respective distributions at the individual network nodes can be determined.

Base voltage module

The base voltage module operates as described above. The incoming HV value is determined accidentally if requested by the coordinator. The mean time for a constant state of this component can be approximated by the reciprocal frequency of the transformer's voltage regulator switching during a day. These data are counted at the transformer and available for the simulation tool.

Consumer module

For every consumer connected to the evaluated MV network an individual or typical load curve – described above – is deposited in the simulation tool. The load values inserted into the simulating calculation (power flow) can be taken accidentally from the normal distributed supporting points as Fig. 8 shows. The simulation coordinator determines the time step T and the values P(T) are valid for next minimum duration of a constant system state. Thus the temporal interaction of all consumers can be simulated according to their real behaviour.

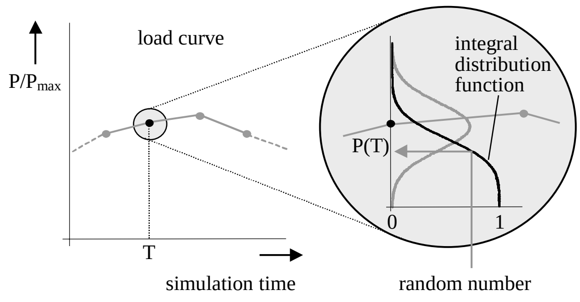

Fig. 8. Accidental determination of a load value

Supplier module

The generated power of suppliers is determined in a similar way. Generation curves or wind velocity curves and their specific distributions are used to determine the operation values accidentally for every time step of the simulation.

A special aspect in the supplier module is the voltage controller. If a certain voltage level at the connetion point is exceeded the voltage controller of the supplier can increase the reactive power (like inductive consumption) up to its limit or reduce the active power until the authorized voltage level is met.

Network operating module

Evaluating the non-disturbed network operation only the normal operation switching state of the network and maintenance instants and activities are defined. If a maintenance instant is reached during the simulation the coordinator requests a changed network topology for the next steps.

For evaluating network operation under fault condition only the disturbed time ranges are simulated. Therefore the simulation period (SP) is analysed n times because of the seldom faults of network components. Fig. 9 describes the module.

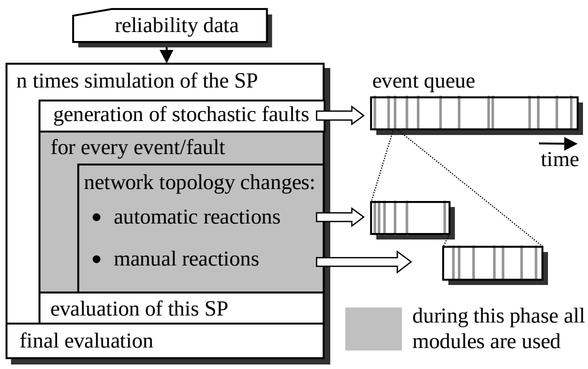

Fig. 9. Network operation considering faults

IV. CASE STUDY

In the following results are presented from a simulation of a typical rural MV network. In this network voltage limits corresponding to [2] and considering the demands of the low voltage network below are exceeded using extreme-value estimations. Additional to this plannig question a wind energy converter (P_{wind} = 0.5 MW) is to be integrated as shown in Fig. 10. An available compounding element is not used so far.

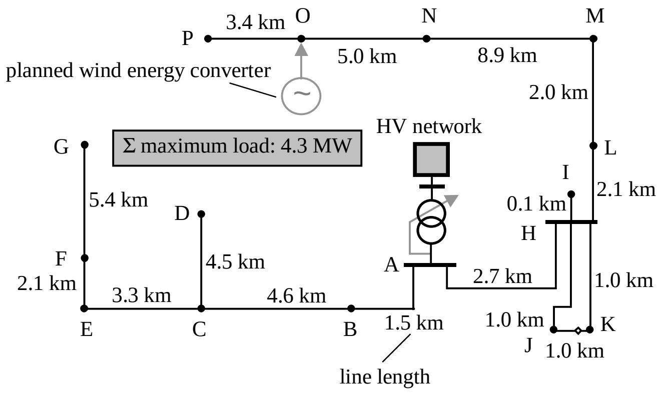

Fig. 10. The simulated rural 20 kV network

The results of two one-year-simulations for network operation under normal condition (without the wind energy converter) illustrate the improvement by using the compounding element of the transformer as shown in Fig. 11. The voltage bands are lifted up and become thinner at the end of the long lines. The opposite effect can be noticed at the nodes closed to the transformer.

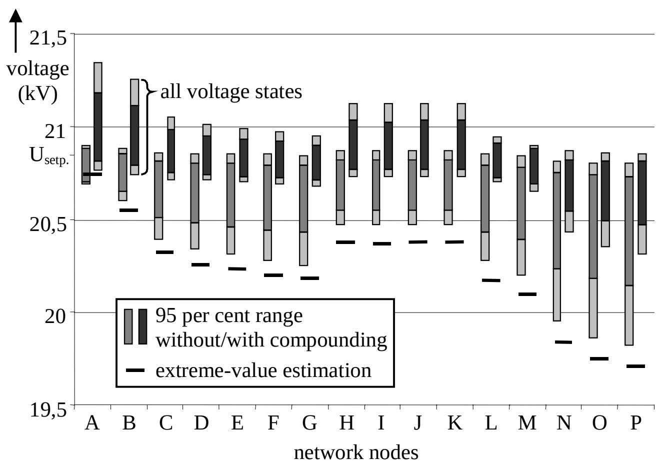

Fig. 11. Voltage stability evaluation

The comparison with the extreme-value estimation makes clear that this planning method leads to oversized networks, because the extreme voltage values are not reached during the whole simulation period, particularly regarding the 95 per cent ranges mentioned in [2].

Besides the consequences for the voltage stability caused by the integration of a wind energy converter has to be analysed. Therefore the voltage states have to be compared with and without the supplier. The results at the most affected node O are shown in Fig. 12. The compounding element of the transformer has not been used.

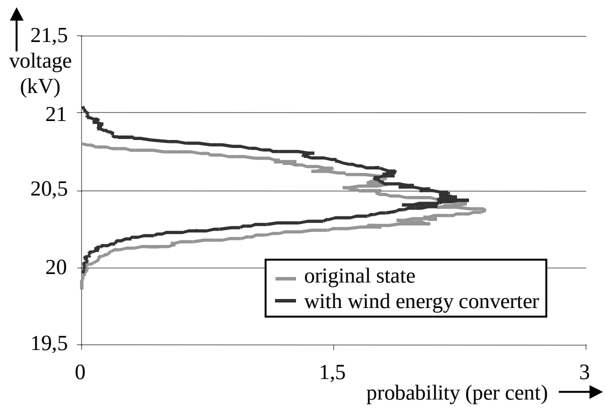

Fig. 12. Voltage states at node O

Due to this result the wind energy converter can be integrated without voltage stability problems. Using the compounding element at the transformer much more dispersed generation power could be integrated.

V. CONCLUSIONS

A simulation tool to evaluate the voltage stability in MV networks using probabilistic methods has been developed considering all influencing parameters. For the period of evaluation the voltage states and their distribution at all network nodes – including the operation under fault condition – can be determined. Besides the calculation gives an insight into the network losses, the distribution of current loads at the lines and the reliability parameters at the individual nodes.

Thus an efficient, comprehensive tool for the evaluation and planning of MV networks exists, which can also be used to set up normative regulations, e. g. a Grid Code for the distribution level.

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IV. BIOGRAPHIES

Klaus Engels was born in Aachen, Germany, on February 2, 1972. He studied Electrical Engineering at the University of Technology, Aachen, (RWTH Aachen) and graduated in 1997. Since the same year he worked as a research assistant at the Institute of Power Systems and Power Economics in the research group Structures of Power Systems at RWTH Aachen.

His research interests include the quality of power supply on the distribution level, technical and economic aspects of network planning and operating and the integration of dispersed generation in distribution networks. He is member of the CIGRE working group 37-28: Quality of supply – customers requirements.

Hans-Jürgen Haubrich was born in Montabaur, Germany, on March 1, 1941. He recieved the M. Sc. and Ph. D. degrees in Electrical Engineering from the Technical University of Darmstadt, Germany, in 1965 and 1971, respectively. In 1973 he joined the Vereinigte Elektrizitätswerke Westfalen AG, Dortmund, where he was head of the main departement network planning. At the same time he was teaching at the University of Bochum and the University of Dortmund as Honorary Professor.

Since 1990 Professor Haubrich is head of the Institute of Power Systems and Power Economics and the Forschungsgemeinschaft Energie (FGE) at the University of Technology, Aachen, (RWTH Aachen). His research is focussed on technical and economic fields of electrical power engineering. In 1999 he became the president of the Energietechnische Gesellschaft (ETG) in the VDE (Association of Electrical Engineering, Electrics and Information).