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DOI: 10.22032/dbt.50143

URN: urn:nbn:de:gbv:ilm1-2021200163

Original published in:	*Power and Energy Student Summit 2019 / Wolter, Martin. - Magdeburg : Universitätsbibliothek, 2019. - (2019), p. 31-36.* *ISBN 978-3-944722-84-9* *(Res electricae Magdeburgenses; 77)*
Original published:	2019-07-08
ISSN:	2628-1716
DOI:	10.24352/UB.OVGU-2019-086
[*Visited:*	2021-10-14]

Development of an Automated Tool to Generate Test Cases for Preventive and Curative HVDC Methods

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Abstract— **The expansion of renewable energies and the growing decentralized infeed into the AC grid are causing an increased utilization of the transmission grid and require the transport of electrical energy over long distances. The expansion of the grid is an important issue to further ensure secure grid operation. The high voltage direct current (HVDC) solution based on voltage-sourced converter (VSC) technology is suitable to support the AC network to guarantee system stability. Equipment outages within the AC grid can cause line overloads that can be compensated by an overlay HVDC system. To demonstrate this, test cases for a given grid must be generated which contain critical outage scenarios. The developed algorithm is able to automatically generate cases to demonstrate the supporting function of an HVDC overlay system. The procedure is based on sensitivity factors, which are required for the developed variable selection methodology. The algorithm can thus generate scenarios with the desired properties, taking resource limits into account.**

Keywords—AC-HVDC-systems, Operational security, n-1 security, test cases

I. Introduction

The energy transition pushed by politics and the innovations demanded by the Renewable Energy Sources Act (EEG) pose major challenges for the energy sector in Germany. The resolution [1] resulted in an increasing shift from fossil fuels such as coal, oil, natural gas and nuclear energy to environmentally friendly renewable energies such as wind power and photovoltaics. Due to the uncertainties in energy production resulting from the nature of weather-related renewable energy sources and the spatial distance between energy production and energy consumers, the existing grid structure must be both expanded and used more efficiently [2]. In order to ensure the security of supply and avoid transmission bottlenecks, transmission system operators rely on redispatch measures. In recent years, an increasing frequency of such interventions in the active power operating points has been observed. Network operators in Germany such as TenneT, for example, reported costs of over one billion euro for redispatch measures in 2017 [3]. In order to keep the redispatch measures and network expansion requirements to a minimum, network expansion in Germany is based on the so-called NOVA principle (network optimization before expansion [4]).

One of the most promising technologies for grid expansion is high-voltage direct current transmission (HVDC) based on the Voltage Source Converter technology (VSC). DC transmission causes lower losses than equivalent AC transmission over the same distance and thus offers a practicable solution especially for large transmission distances [5], [6]. The technology allows the construction of multi-terminal HVDC systems or even meshed HVDC grids. These can contribute to the necessary grid expansion and enable the connection of large offshore wind farms [7]. Such an HVDC grid can be operated in parallel to the existing AC system. Self-guided converters (VSC) can connect the two grids at different nodes. Such a superimposed DC grid can not only improve the quality of the current energy transmission, but also improve the overall system security. Parallel operation of both networks only makes sense if network security is also considered in combination. There are already existing studies for this, e.g. [8], [9].

In the course of this approach to relieve the AC grid, a benchmark system was developed [9] as a testbed for algorithms to improve the overall system security such as SCOPF methods.. The benchmark system composes two kinds of information: the grid topology and the load and generation scenario.

The subject of this paper is the development of an automatic algorithm that can create different cases for a network with a given topology to prove the aforementioned improvement of the overall system safety. The generation of these cases should be automatic and applicable to any system. The test cases from [9], [10] are used as a basis for the scenarios to be generated. Congestions are implemented to create cases that can validate the operational planning methods of the system as well as possible. A distinction is made between congestions caused by generator, line or VSC outages.

The approaches chosen to develop the scenarios are presented in section II. Building on this, section III deals with the development of the method used for this purpose. Subsequently, the numerical results and conclusions are presented in sections IV and V.

II. Basics

A. Sensitivity factors

The Power Transfer Distribution Factor (PTDF) shows how the power flow on a branch l changes when the power is supplied to a node i and taken from a reference node (II.1) [11]. The PTDF is determined using a transaction as described above. The exchange does not take place directly between two nodes, as from an economic point of view, but the actual power flow is distributed throughout the entire network according to the physical topology of the network. This is expressed by equation (II.2).

$$PTDF_l^i = \frac{\Delta P_i}{\Delta P_l} \tag{II.1}$$

$$\Delta p_{ij} = \begin{bmatrix} b_{ij,1} z_{ij,1} \\ \vdots \\ b_{ij,n_z} Z_{ij,n_z} \end{bmatrix} \Delta\delta = \underbrace{\begin{bmatrix} b_{ij,1} z_{ij,1} \\ \vdots \\ b_{ij,n_z} Z_{ij,n_z} \end{bmatrix} B^{-1}}_{PTDF} \Delta p = PTDF \Delta p \tag{II.2}$$

A part of the power from the infeed point does not flow directly to the reference point, but also takes the path via other nodes and thus via the corresponding lines. The PTDF now expresses how the power flow is distributed in the network. This is repeated until the PTDFs of all lines are determined in relation to a transaction. The PTDFs together describe how a current transaction between two nodes affects all network branches.

If the calculation is performed for all lines and transactions, the result is a PTDF matrix that shows the distribution of the energy fed into the individual lines. It is important that a start and end node are defined for each line.

Like the PTDF, the Load Outage Distribution Factor (LODF) is a sensitivity factor and indicates changes of the power flow on a line *k* in the event of an outage of a line *l* [11], [12]. As previously mentioned, this means that in the event of a line outage, the power flow is distributed according to the new conditions in the network. If power previously flowed through a line, which is now considered as an outage, the power flow in the other lines increases accordingly.

III. Automated Generation of Contingency Scenarios

As described in the introduction, the goal of this paper is to create an algorithm that automatically generates contingency scenarios for any power system with defined topology. The cases enable, through their different contingency types, the testing of different HVDC operation methods by incorporating critical contingencies (criCo) into the system. Regarding the N-1 criterion, critical contingencies are outages that result in the violation of any defined security criterion. The following violations are considered overloads:

- Violation of the AC voltage range from 1.1pu - 0.95pu
- Utilization of a single line over 100%

In order to identify criCos, power flow calculations must be performed in the course of a contingency analysis

If there are critical contingencies in a network, it should be checked whether these can be solved with curative measures. A distinction is made between curative HVDC OPF and curative generator OPF. This distinction is made between the two curative measures, since generator OPF (redispatch measures) cause economic costs, whereas HVDC OPF (adjustments of the VSC operating points) cause no costs except the investment costs. An OPF algorithm is used for these calculations. As basis for the new test cases, the initial scenarios described in [9], [10] are used.

A. Definition of Critical Contingencies Types

To ensure that the generated cases cover as many different types of critical contingencies as possible, critical contingencies are defined in advance, as shown in Tab. 1.

A classification is made between different cases of outages and effects. The outages are divided into generator outages (gen_out), line outages (line_out/intcon_out) and VSC outages (VSC_out), whereas the effects generated by the outages include voltage band violations (volt_vio) and line overloads (line_vio/intcon_vio). Furthermore, the lines of the system are divided into lines and interconnectors (intcon) connecting two control zones.

The table serves as a defined framework in which the functionality of the algorithm can be checked. The algorithm to be designed is universally applicable to every system. Therefore, several control zones (CZ) were assumed in the table. Voltage range violations (volt_vio) are considered and generated in the work, but are not checked for their feasibility, since reactive power optimization lies outside the scope of the paper.

Tab. 1: List of critical contingencies being implemented

Outage		**Effect**	
Location	**Type**	**Location**	**Type**
CZ a	gen_out	CZ b / CZ c	line_vio
CZ a	gen_out	CZ a	line_vio
CZ a	gen_out	CZ a	volt_vio
CZ a	gen_out	CZ a – CZ b	intcon_vio
CZ a	gen_out	CZ a – CZ c	intcon_vio
CZ a	line_out	CZ b / CZ c	line_vio
CZ a	line_out	CZ a	line_vio
CZ a	line_out	CZ a – CZ b	intcon_vio
CZ a	line_out	CZ a – CZ c	intcon_vio
CZ a- CZ b	intcon_out	CZ a – CZ c	intcon_vio
CZ a- CZ c	intcon_out	CZ a – CZ b	intcon_vio
CZ a	line_out	CZ a	volt_vio
CZ a	VSC_out	CZ b / CZ c	line_vio
CZ a	VSC_out	CZ a	line_vio
CZ a	VSC_out	CZ a	volt_vio
CZ a	VSC_out	CZ a – CZ b	intcon_vio
CZ a	VSC_out	CZ a – CZ c	intcon_vio

B. Selecting the control parameters

To design cases with the defined properties from the previous section, a control parameter must be selected. On the one hand, the active power components of the loads would be a conceivable degree of freedom, on the other hand, the active power operating points of the VSC converters and the generators would also be possible as degree of freedom. The control parameter P_{gen} was selected, since the loads in the system are assumed to be constant. Another reason for selecting the active power of generators as the degree of freedom of the algorithm is that the adjustment of the active power reflects redispatch measures. The approach of sensitivity factors could also be further pursued, since the degree of freedom P_{gen} is directly related to the transactional consideration of PTDF and LODF. As described at the beginning of this paper, the expansion of renewable energies leads to a decentralized infeed in the AC-system. As a result, the generator nodes are distributed more evenly in the topology of the grid and can thus influence large parts of the electrical grid with their active power operating points. P_{gen} thus forms the general control parameter which must be distinguished from the control variable, which is the generator whose effective power operating point is going to be adapted.

C. *Algorithm design*

In order for the algorithm to edit the cases automatically and independently, it must find the control variables with whose changes it can generate the desired congestion. The algorithm should be able to independently find generation operating points that lead to critical contingencies during a contingency analysis. The selection of these control variables represents the greatest challenge of this approach. To find the correct control variables, the dependencies of the components are examined. This is done by means of sensitivity factors.

With regard to this approach, the algorithm described later on using the flow chart in Fig. 1 is developed. The program is divided into five modules. The five modules contain the following points and are described in more detail in the next sections.

- Initialization: Import of system data and grid properties

- Contingency analysis: determination of outages that result in a violation of security constraints (critical contingencies)

- Selection of control variables: Selection of the control variables on the basis of the load factor, load change and sensitivity factors of the corresponding network element.

- Adaptation of control variables: Adjustment of the selected control variables by an iterative process

- Solvability check: Checking the solvability of critical contingencies by a CSCOPF

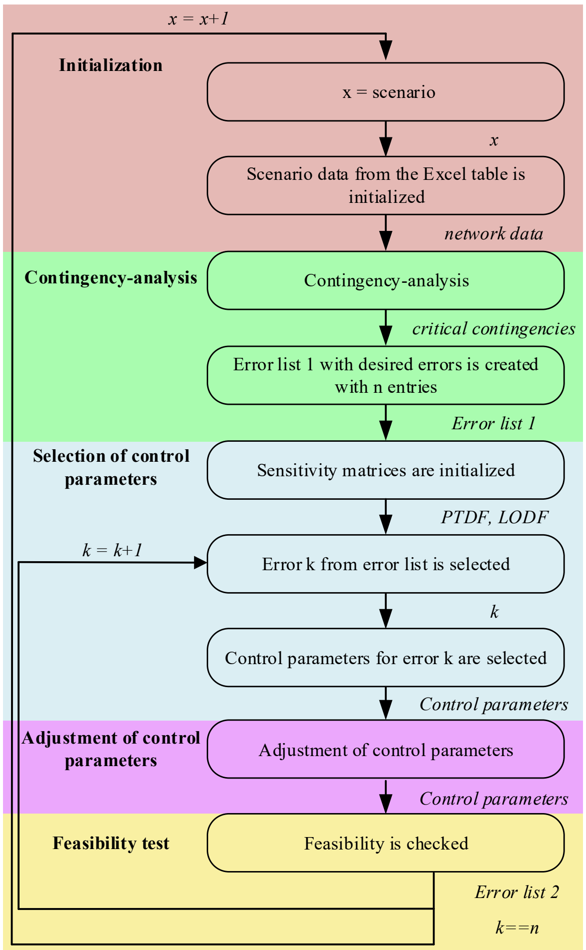

Fig. 1: Structogram of the developed algorithm

The algorithm starts by initializing the network data. Consecutive a contingency analysis is then performed to determine the existing critical contingencies ($criCo_{ist}$). The results of the power flow calculations are checked for violations of the defined limits, such as voltage range and line loading. If a limit violation occurs, the contingency is marked as critical. The advantage of the reduced consideration of only critical contingencies instead of all possible occurring contingencies is that the computing power can be drastically reduced in the following modules.

The critical contingencies are passed on to the next module, which categorizes the critical contingencies and classifies them. In this way it can be determined which critical contingencies are already contained in the initial scenario and no longer need to be generated. The module uses the critical contingencies that have already occurred to create a list that contains information about which critical contingencies still need to be generated (error list 1).

After the list of critical contingencies still to be generated ($criCo_{soll}$) has been created, the PTDF and LODF sensitivity matrices are initialized. They contain the PTDF and LODF of all lines for all transaction options. Once the sensitivity matrices have been created, the first case is selected from error list 1 and the function for determining the control variable being adjusted is started.

To select a control variable, information on the location, type and trigger of the violation is first retrieved from the list of $criCo_{soll}$. A distinction is made between whether the cause of the violation is a line, generator or VSC outage. Furthermore, a distinction is made between the two types of violations to be generated: voltage range violation and line overload. In the further course of the control variable selection, the lines or network elements interesting for the contingency generation are examined for three selected criteria:

1. largest change of the value being considered, voltage or power, in comparison to the base case scenario.
2. minimum difference between the value taken into account and the limit to be exceeded.
3. maximum absolute value of the sensitivity factors.

The first characteristic can be used to determine which network element will be reacting the most to changes. The second characteristic serves to find the grid element which is closest to its limits. In the third and last selection criterion, the network element which can be influenced by changes the most is found.

The three attributes are determined for each network element being investigated and stored in a three-dimensional matrix. In order to select the network element that is to be overloaded, the stored matrix is sorted according to the three properties and thus three different sequences are defined. The scores of the network elements in the generated sequences are summed up. This results in a numerical evaluation of the network elements, in which the network element with the lowest evaluation value is selected, since it comes closest to fulfilling the three criteria. The criteria are all weighted with the same priority.

Once the network element of interest has been selected , the sensitivity factors define the control parameters that has the biggest impact on the respective equipment. The control parameters are stored in priority order in a control parameter matrix.

Once the control variables have been selected, they are transferred to the next function in order to adapt them. A start value for the change being made is calculated. Starting with the calculated start value, the selected control variable is changed. The network data with the changed control variable are examined with a contingency analysis. The resulting critical contingencies are compared with the critical contingency to be implemented. If the desired critical contingency has not yet been reached, but the control variable is still within its operating limits, the initial value calculated before is increased iteratively until the desired critical contingency occurs. If the critical contingency occurs without any limit violation, the new values of the grid data are stored in a table.

An list with the existing contingencies is generated from the new grid data. The new contingency list (error list 2) is compared with the old contingency list (error list 1). The algorithm checks whether no previously existing contingencies have been lost due to the creation of the newly introduced critical contingencies. If all entries in error list 2 are correct, it is checked whether the built-in contingencies can be solved. For this, a CSCOPF with different optimization variants is carried out. The CSCOPF algorithm introduced in [13] is used for these optimizations. With regard to the developments, a distinction is made between two optimization variants. In the first variant, the effective generator power P_{gen} is chosen as degree of freedom, because it represents the currently common redispatch measures. In the second optimization, the CSCOPF is performed with the active power of the VSCs (P_{VSC}) and the DC-sided voltage (U_{DC}) as optimization parameters in order to show the solvability of the critical contingency cases with the future method of adjusting the VSC operation points. This has the advantage that, in contrast to redispatch measures, it is cost neutral.

The CSCOPF algorithm only makes a statement as to whether a critical contingency can be solved or not. Since the CSCOPF does not perform reactive power optimization, critical contingencies with a voltage band violation are not investigated.

The now modified Excel table functions as a further starting point for the implementation of the next critical contingency from error list 1 and the algorithm starts over at the selection of the control variable.

IV. Numerical Case Study

This section reviews the derived methodology. The algorithm developed is checked for functionality by means of a numerical simulation with the reference network presented before. The functionality of the developed algorithm is determined by the implemented critical contingencies, which were predefined before (Tab. 1).

The 67-node network presented in [9] serves as the AC-DC hybrid network at which the investigations take place. It consists of an AC network, which is superimposed by an HVDC network and connected to it at eight nodes via VSCs. The AC network consists of 67 nodes connected by 102 lines. Furthermore, the AC network is divided into three control zones (CZ), which are connected to each other via AC interconnectors. The maximum load of the system amounts to 11817 MW, which is divided between the control zones. The superimposed HVDC network consists of nine nodes and has two designs. The first design, the network is meshed, in the second the network is set up with point-to-point connections and one multi-terminal connection. The connection points between the AC and DC grids are the eight onshore VSCs, three in each CZ and one VSC for connecting the offshore wind farm. There is no (n-1) security in the reference grid. This applies to both superimposed grids, AC and DC. The critical outages that lead to overloads of network elements include the failures of AC and DC lines as well as converters and generators. For AC and DC lines, a load of more than 100 % is considered critical. The prerequisites for the generated scenarios are that all bottlenecks present in the grid can be eliminated by corrective measures. This means that there must be no structural bottlenecks.

The table Tab. 1 forms the basis for the evaluation of the results of the algorithm. The aim is to implement each critical contingency from Tab. 1 automatically using the methodology described and then to check its solvability using a CSCOPF with various optimization parameters (P_{Gen}, U_{DC}, P_{VSC}). The following table (Tab. 2) exemplary shows the results of the implementation through the algorithm, on the basis of line outages.

The individual outages are listed vertically. The lines are described by start and end nodes, as defined in [9]. The effects are listed horizontally. The classification takes place equivalent to the first column. The coloured cells make a statement about the solvability of the critical contingency. Again a distinction is made between the two optimization variants with the different optimization parameters. The first optimization variant is executed with P_{Gen} as the optimization parameter, whereas the second optimization variant is executed with the optimization parameters P_{VSC} and U_{DC}. If the critical contingency could be successfully solved by the CSCOPF, it is marked with a color. Green stands for solvability through optimization with P_{Gen}. If the cell is colored blue, the contingency can be solved by adjusting the VSC operating points (P_{VSC} and U_{DC}) and if the cell is yellow, the failure can be solved both ways.

The result table (Tab. 2) shows the critical contingencies that arise when a line outage in a control area triggers a line overload in the same control area. Tab. 4.1 shows that the critical contingencies could be implemented with the desired properties. As described in the legend, the solvability of the critical contingency is represented by the coloring. It is noticeable that there is not only one critical contingency with the desired properties, but that there can occur also several others. This is due to the fact that by adjusting the control variable to violate a security, the corresponding network element must be brought close to its overload limit in order to be susceptible to outages. Since the network element is then susceptible to outages, this can cause it to overload not only at the individual desired outage, but also at other outages.

Tab. 2: Solvability of line outages with line overloads in the same CZ

Outage \ Effect	4-19	10-22	26-40	39-43	41-42	43-44	56-58
4-14							
10-22							
19-23							
32-40			n.a.				
40-41							
43-44							
62-66							

P_{VSC} P_{Gen} P_{VSC} / P_{Gen}

This effect can be seen, for example, in the case of AC line 10-22, which overloads in several outage-cases.

Furthermore, it can be seen in one case that no statement (n.a.) can be made for its solvability. This is due to the fact that in the event of this outage, a voltage band violation also occurs in addition to the line overload. As the CSCOPF does not have reactive power optimization, the solvability of these cases is not considered in this paper.

The developed algorithm was able to implement the critical contingencies caused by line outages with the previously defined attributes in Tab. 1. Thus, the functionality of the control variable selection and the control variable adaptation could be confirmed. The algorithm was able to select the correct control variables using the selection criteria and it was able to adapt them successfully. All critical contingencies, which did not contain voltage band violations, could be solved. This was to be expected, since the control variable adaptation works with the operating points of the generators and thus normally does not generate any structural, unsolvable critical contingencies.

V. Conclusion

Due to the increasing decentralized infeed and the change from fossil to renewable energies, there will be a greater utilization of the electrical energy network. In addition to grid expansion, the focus is on more efficient usage of the grid. One promising concept is the use of AC-HVDC hybrid networks. It can also be used to relieve the increasing redispatch measures. A combined consideration of HVDC and AC system also requires an extended consideration of the (n-1) criterion. Suitable test scenarios are required in order to test the operational management methods of such electrical networks. The goal of this paper is the development of an algorithm, which is able to independently create cases for a given grid-topology. Therefore several approaches were considered, which allow a targeted creation of such scenarios. The methodology developed in the work is based on the approach of sensitivity factors and serves to select suitable control variables for the scenario generation. Once a suitable selection has been made, the scenario is adapted and tested for its solvability using curative measures. Exceptions to this are voltage band violations, as these require reactive power optimization. Due to the complexity of the topic, this was not done within the scope of this work. The special feature of the algorithm is that it is generally applicable for every system. With the generated cases, operational management methods of AC-HVDC hybrid networks can be tested, for example to reduce redispatch costs or avoid bottlenecks. To demonstrate the advantages of the AC-HVDC network, critical contingencies have been implemented by the algorithm. The grid, on which the developed algorithm was tested, is considered with two different designs of the superimposed HVDC grid. In the first variant, the AC reference network is superimposed with a meshed HVDC network. The second variant considers the superposition of the AC reference network with three point-to-point and one multi-terminal HVDC connections. The numerical results proved the functionality of the algorithm and gave a summarizing overview of the generated scenarios.

Further consideration of combined AC-HVDC networks and HVDC operational management methods is a promising area of development. With regard to the algorithm described here, further investigations could be undertaken with regard to an improved and more stable selection of the control parameters in the area of contingency screening and contingency filtering. So-called severity indices can contribute to a further optimization of the algorithm. As mentioned before in the summary, the solvability of voltage band violations was not considered. At this point, the methodology could be further expanded. A reactive power optimization with combined consideration would complete the curative SCOPF. In addition to a curative SCOPF, a preventive SCOPF of critical contingencies is another conceivable approach that can be pursued in the future.

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