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An advanced method for steady-state security assessment considering dynamic thermal capacities of grid assets

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SUMMARY

The (n-1)-criterion is a commonly used criterion for secure grid operation. Violations of this criterion lead to remedial actions in short-term and the construction of additional transmission capacities in the long-term to reduce congestions in the grid. An alternative strategy in reducing necessary interventions is to consider the natural dependency of the transmission capacity of an installed grid component from its environmental conditions. The application of dynamic component rating is offering additional transmission capacities for system operation. For the consideration of these capabilities in the day-ahead operation planning, forecasting the trend of the component ratings is needed. The implementation of such methods, especially for overhead lines, is tested by different system operators around the world.

A further strategy in enhancing transmission capacity for the operation is to utilize the thermal inertia of a component for small and short exceedances of the ratings without violating the component's thermal limits. Currently available static emergency ratings of components respect this capability. Such as component ratings, emergency ratings are also dependent on environmental conditions. Furthermore, the available emergency operation duration is dependent on the development of the loading current in the recent past. By equipping assets with real-time monitoring systems, utilization of the components current transmission capacity is possible for the different operation states.

This paper presents a method to consider the thermal transmission capacity of power system components, enabled by real-time monitoring systems, in the contingency analysis. The approach is an assessment at system level combined with a time-domain simulation for the evaluation of the impact of an examined contingency on a component's relevant thermal parameters. The result of the method is compatible with the current binary statement but extended with an availability duration if a contingency occurs in the examined grid.

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Introducing this duration can assist the planning of curative remedial actions for the operation. Further, three specific durations were proposed for benchmarking a contingency in the different levels of analysis. These durations are the result of the time-domain simulation. The presented method is capable of analysing a network consisting of assets equipped with a monitoring system and assets without such a system.

The second part of this paper presents the operation simulation of an exemplary grid for one operational year to illustrate the effect of the approach on the results of the contingency analysis in day-ahead planning.

KEYWORDS

Contingency analysis – Monitoring system – Dynamic component limits

1. Introduction

For a secure grid operation, the (n-1) criterion is a commonly used operational criterion today. In case of violation of operational security limits of any component in an examined contingency, the system is identified as not steady-state (n-1)-secure. Operation planners and dispatchers have to eliminate those violations by using remedial actions such as re-dispatching power plant operation to recover compliance with the (n-1)-criterion.

The most common way to reduce the need for interventions is to increase transmission capacity by building new lines, installing new transformers, etc., or installing load flow influencing devices, such as phase-shifting transformers. These strategies lead to high investment costs for TSOs and DSOs. In some cases, the construction of new transmission capacities satisfying regulative, legislative, and environmental issues takes decades.

One alternative strategy is considering environmental condition based steady-state thermal current limits for grid components in control room applications. Adding this capability allows utilizing the natural dependency of the component's transmission capacity on ambient temperature, wind, etc. for power transmission. For the contingency analysis, those models are extending the existing method by transforming the continuous (or seasonal) permissible static limit to a dynamically changing limit. Introducing dynamic component rating in system operation needs applicable thermal component models, as well as monitoring systems for environmental and component parameters. In the recent past, some TSOs and DSOs implemented dynamic line rating (DLR) in their control room applications to reduce apparent congestions on transmission lines. The use of dynamically calculated steady-state loading limits in control room applications may be considered as an evolutionary step of these applications.

In cases of small and short exceedances of stationary state limits, the load profile of an examined contingency may be tolerable for the installed equipment without violating its thermal limits due to thermal inertia. Currently available static emergency ratings of assets try to consider this capability. Real-time monitoring systems for components can enable the safe utilization of the thermal inertia under such overloading conditions. Enabling a controlled temporary grid operation above steady-state limits of the component but below its dynamic thermal limits can support the grid operation in challenging situations and may allow a different choice of remedial actions to restore compliance with the (n-1)-criterion.

The consideration of this ability enabled by the monitoring systems in the day-ahead and intraday operational planning can support the reduction of preventive applied remedial actions or the utilization of new congestion prevention methods

This paper presents an adoption of the commonly used method for contingency analysis to consider the dynamic loading limits of components based on their dynamic thermal transmission capacity.

2. System analysis in the method

The developed contingency analysis method with consideration of the dynamic thermal transmission capacities has two levels of analysis. The top level of the system examination uses the well-known current methods for congestion detection in contingency scenarios. Those methods use load-flow analysis of the load and generation state of the expected grid configuration for those contingencies assumed to be relevant for a single point in time. The future development of the load flow in the examined grid is not considered in this step.

Violations of the stationary operating limits of one or more components in the load flow analysis of a contingency scenario are marked for a detailed analysis on component level. In the conventional contingency assessment method, these limit violations lead directly to preventive remedial actions to reduce loading and recover compliance with the (n-1)-criterion. However, in the presented advanced analysis method, the system analysis level is requesting a detailed analysis at component-level.

The analysis on component level is a time-domain simulation of the thermal behaviour of the examined component. For the simulation, it is reasonable to use the same models as implemented in the monitoring system. This constraint avoids discrepancies between simulation and operation.

The loading scenarios are generated based on the results for the expected loading of the element in the different contingency scenarios for the examined points in time in the system-level analysis. This additional step allows taking the available thermal inertia of the installed assets into account in the examination. The simulation results are returned to the system level of the analysis. On the system level, the component level results are merged and enhance the results of the prior load flow analysis of the contingency scenarios. Instead of a binary statement (permissible / not permissible), a minimum duration of permissibility for a contingency is generated, which is compatible with but extends the binary statement.

3. Definitions used in the method

3.1. Operation limits

The following four different kinds of component operation limits are distinguished for the developed contingency analysis method:

- static operation limit
- stationary operation limit
- dynamic operation limit
- absolute operation limit

The static operation limit is defined for a worst-case scenario of ambient conditions and operation history expected for the component's site of installation [1]. Continuous operation below this limit is allowed irrespective of current environmental conditions.

The stationary limit (also known as dynamic rating) is a time-variable limit for continuous operation, depending on the changing ambient conditions at the installation site. An unlimited continuous operation below this time-varying limit is permissible. If stationary limits are not available (e.g., the monitoring system is not providing stationary limits), the presented analysis method instead uses the static operation limits.

Dynamic operation limits are mostly temperature-based limits. For example, for a power transformer, the maximum hot spot temperature in the windings and the maximum top oil temperature define such limits. Those limits can have additional criteria for permissibility, e.g., the short-term emergency operation of power transformers, according to [2] is permissible for a maximum duration of 30 minutes.

Absolute limits cap the possible operating range even if no violation of dynamic operation limits occurs. Other effects (e.g., high magnetic forces in transformer through high load currents) cause a limiting of the operation. Operation above the absolute operation limits is allowed only for very short durations in case of transient processes, such as short circuits in the grid. The possible operation duration of a few seconds at maximum above this limit is ignored in this analysis. For a violation of the absolute limits, triggering an installed overcurrent protection relay is assumed, which leads to an unplanned outage of the component and probably further negative effects on the grid operation.

3.2. switching states

A switching state (SS) is describing the topology of the grid. It contains the information about opened and closed breakers in the grid. Different operational situations (e.g., outages of elements because of maintenance or faults) lead to different switching states. The occurrence of a contingency is changing the SS of the grid.

3.3. Loading scenario, switching state transition category

A loading scenario (LS) describes the development of the loading current of a component in the grid.

The contingency analysis examines the following kinds of LSs:

- Operation in a particular SS (Fig. 1)
- Operation with one or more changes of the SS to another SS (Fig. 2)

The first type of LS is furthermore called base LS. Every LS of the second type is a combination of two or more base LS. As an example, loading scenario 2 in Fig. 2 is a combination of the base LSs of SS 1 and SS 2. The values of the loading scenario are shifting at the 6th hour from the values of the base LS of SS 1 to the values of the base LS of SS 2.

LSs which are describing the same change of SSs on different points in time are related LS and are considered members of the same SS transition category (SSTC). The second type of LS leads to several SSTCs in the analysis.

An event as considered in the contingency analysis is equal to an SSTC describing the change of SS from the actual SS to the SS considering the element outage in the examined event.

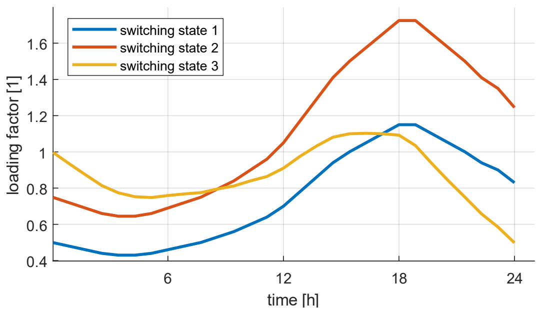

Fig. 1 Example of base LS in different SS

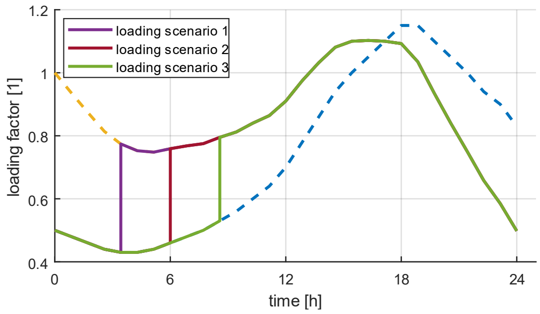

Fig. 2 Example of different LS of an SSTC describing one SS-transition from SS 1 to SS 3

3.4. Permissible scenario duration and permissible switching state operation duration

The time from the beginning of a components loading scenario (LS) to the instant of violation of at least one dynamic operational limit of the component is defined as the permissible scenario duration (PSD) of the examined scenario. If no violation of any dynamic operational limit occurs, the PSD is at least equal to the duration T_{ds} of the loading data sample for the scenario examination and therefore considered to be T_{ds} . Based on this definition, the value of the PSD is in the range $0 \leq PSSOD \leq T_{ds}$.

If a monitoring system is not available for an asset (e.g., no monitoring system installed or the connection to the system is lost) or the operation under overloading conditions for the component is not allowed, the determination of the PSD is also possible. In this case, the relevant operation limit is the static operation limit, or if calculated otherwise, the stationary operation limit of the component. The result of the PSD for such components is zero if the loading is momentarily higher than the applicable limit. If no violation occurs, the PSD is equal to T_{ds}. In this case, the PSD can only take one of the two values.

The permissible switching state operation duration (PSSOD) of a SS is the minimum available operation duration in this SS. An SSTC is pooling all n LSs, which are describing the change from the current SS A to another SS B but on different points in time. For a grid with an amount of m SSTCs defined as relevant for the contingency analysis, the PSSOD of an SSTC is given as:

$$PSSOD_k = \min\left\{PSD\left(LS_{k,i}\right)\Big|_{i=1}^{m}\right\};\ k = 1 \dots m; i = 1 \dots n;\ n, m \in \mathbb{N} \qquad [1]$$

The PSSOD is the minimum duration for the operation of a component in a specific SS without violating the dynamic operation limits of that component.

The definition of the PSD and the PSSOD is valid for a single component. For a dispatcher, the minimum available operation duration of all installed assets in a particular SS is even more relevant. The available SS operation duration (ASSOD) of the grid in a SS is the minimum of the PSSOD of the components in those SS. This duration is the available operation time of the examined grid after a contingency without required interventions by the dispatcher. The remedial actions must become effective within the ASSOD.

4. Execution of the contingency analysis

4.1. Creation of loading scenarios

The base of all LS in one SSTC are the basic LSs of all involved SSs created from the results of the contingency analysis on system-level. A load-flow calculation for every point in time in the forecast data set and every contingency provide the loading data for the LS generation. For the creation of the basic LS of a particular SS for a specific component, the loading results of the individual analysis calculations in this SS are chronologically assembled.

An LS with a SS change at another point in time is a combination of the two basic LS of the corresponding SS.

4.2. Analysis of SSTC

To reduce the amount of executed time-domain simulations, the examination of an SSTC is an iterative process. If the values of the base LS of the SS after the transition are in all points in time higher than the values of the base LS before, the examination is executed as follows: The first LS in the simulation has a change of the SS at the beginning of the inspected interval. If the PSD of the LS is equal to T_{ds}, further analysis of other points in time of change of the SS is not necessary. LS with a change of the SS at a later time, have the same PSD because the operation time with element outage in the scenario is lower than in the LS analyzed before. This step is not influencing the result of the PSSOD of the SSTC. If the PSD is below T_{ds}, the analysis creates a further LS with a later change of the SS and continues the examination.

In the case, the values of the base LS of the SS after the transition are in all points in time lower than the values of the base LS before; the iteration is executed backwards and starting with LS transitions at the end of the examined timeframe.

If both preconditions not pertain, the examination is generating a set of LSs containing SS transitions at different points in time, computing the PSD of every generated LS and determining the PSSOD according to Eq. 1.

An additional pre-analysis step before the execution of the time-domain simulation allows skipping simulation runs if an assumption of the result of the simulation from the LS is possible. The PSD of an LS is definitively equal to T_{ds}, if the components loading at every point in time in the scenario is below or equal to the stationary limit for the same point in time. Similarly, the PSD of an LS is zero if the loading is at least once above an existing absolute loading limit.

Before the execution of the time-domain simulation, an interpolation of the LS data is necessary for the calculation. The minimum resolution of the input data depends on the used thermal model for the component and has to be respected.

5. Simulation of one operational year

For the demonstration of the results of the presented method, the analysis of a fictive grid shown in Fig. 3 is computed for one operational year. The design of the grid is not optimized to face the (n-1)-criterion for every loading state. It is assumed that a new forecast data set for a 24 hours period with a 15 minutes resolution twice a day exists. The timeframes for the analysis are beginning at 00:00 and 12:00. The contingency analysis executes the presented method for the computation of every forecasted data set. Applicating preventive remedial actions to the grid and a further contingency analysis for the evaluation of the effectiveness of those are not part of this simulation.

The simulation is using scaling of the nominal load values (Table VI) of active and reactive power to represent the loading development during an examined period. The generation of the load profiles is using a blend of load profiles from [3] from the year 2018. The applied shares for the load profiles are in Table VII.

For the generators in the grid, a simplified dispatch model, using the generation curves in Fig. 4, is representing the applied dependency of the power generation from the load demand.

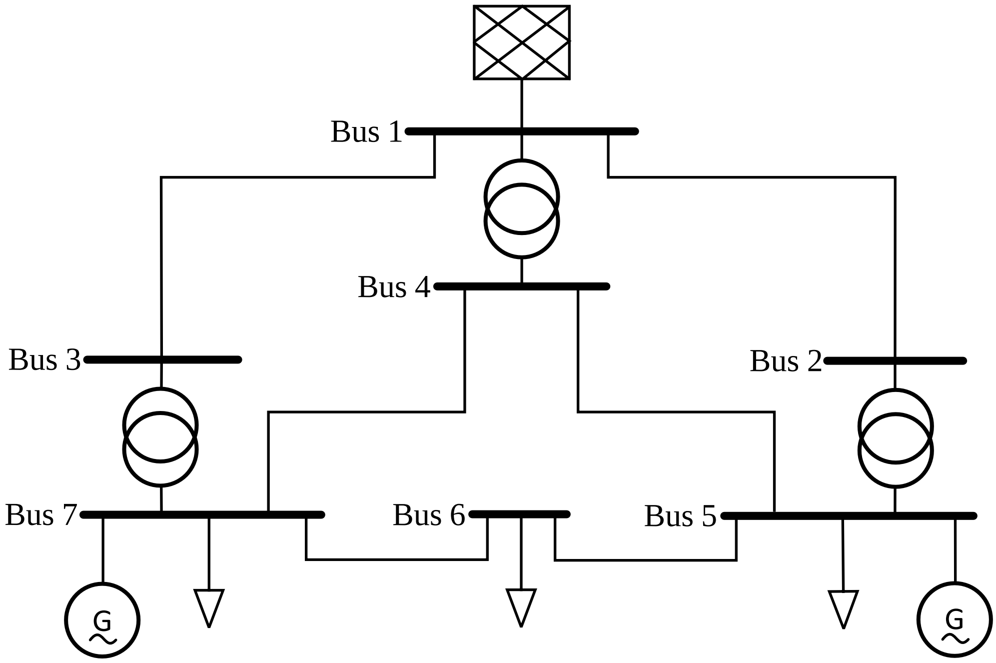

Fig. 3 Single line diagram of the exemplary grid used for demonstration of the method

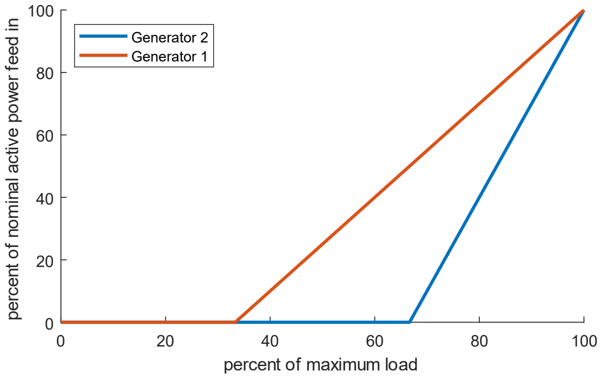

Fig. 4 Dependency of generation from load demand in the examined grid

It is assumed that every power transformer in the grid has a monitoring system installed. The monitoring systems are using the thermal model from [2]. For the monitoring system, it is further assumed that temporary operation above stationary limits is supported by continuous delivery of the calculated current hot-spot temperature to the SCADA. For the transformer, the thermal model parameters are chosen according to the recommendation from the IEC standard. The applied electrical and thermal model parameters are given in Table IX and Table X in the appendix. The specified operation limits of the transformers are the maximum permissible temperature limits from [2]. A temporal limitation of the short-term emergency operation is set to 25 minutes. The absolute operation limit is equal to the current limitation in the standard for the short-term operation.

The absolute limit for the transformers is set to a loading factor of 1,5. For the lines, the absolute limit loading factor is one because their absolute limit is through the missing monitoring system equal to the static limit.

Since the dynamic thermal behaviour of a transformer is dependent on the ambient temperature at the site of installation, the simulation is using hourly measured ambient temperature profiles of three Austrian cities from the year 2016.

For the contingency analysis, all nine (n-1) scenarios containing outages of lines and transformers are in the selection of the relevant cases. It is assumed that an outage of a component is only deactivating the affected component itself.

The static loading limit applied to all components is at 100 % of the rated current. The allowed voltage band for all buses is between 0,9 p.u. and 1,05 p.u.

The implementation of the contingency analysis and the thermal models is done in the programming language Python 3.6. For the load flow calculations, the simulation uses the pandapower package [4]. The implementation of the thermal model for the power transformers in the grid uses the difference equations from [2].

For the operational year, no violation of the voltage limits was detected. Thus, the permissibility of a contingency situation is in this grid only dependent on the loading and the loading limits of the components.

The compliance with the (n-1)-criterion of the network, using static limits for all assets, is not given in any of the 730 executed day-ahead analyses. In all these cases, for at least one component, the loading in case of a contingency is above its static limit for at least one point in time. Interventions into the grid operation are always necessary for the whole year. If the utilization of the dynamic thermal transmission capacity is allowed, the percentage of day-ahead analyses resulting in a need to apply preventive remedial actions is reduced to 98,9 % of all analysed 24 h timeframes to restore compliance with the (n-1)-criterion. This means that for this example using the dynamic thermal capacity does not significantly reduce the need for operator intervention in advance, but only helps for a small number of situations. However, the example was not tweaked to show such an effect.

Table I is showing in detail which outages lead to a non-compliance in case of allowing the use of dynamic transmission capacities or not and how often this happens. The violation of at least one component limit in one of the analysed cases for the examined timeframe is causing the grid to be not compliant with the (n-1)-criterion. For example, an outage of Line 1 results in 100 % of all executed day-ahead analyses to violation of limits, if only static limits are considered. If allowing to respect dynamic operation limits in the examination, the same contingency is leading to a non-compliance of the grid in 98,9 % of all examined time frames.

Table II is presenting the reasons for inadmissibility of the analysed cases if a limit violation occurs in the examination. For components not equipped with a monitoring system, the static limit is the absolute limit. As a consequence, the results of violations of the static limits of a line is affecting the result for absolute limit violations. For the outage of Line 1, the adapted method returned that in 100 % of all inadmissible timeframes, an absolute operation limit is violated. The reason is in this case in all examined, as inadmissible marked, timeframes a violation of the absolute operation limit of transformer 3. In the acceptable timeframes, no violation of the dynamic operation limit occurs.

In case of an outage of Line 4, 30 % of all non-compliant results are due to a violation of a component's dynamic operation limit. The reduction of the results in this contingency case is an effect of the consideration of the dynamic thermal transmission capacity of transformer 3 which is most affected.

Table I detected violations of component limits per contingency. Per cent Values referred to the total amount (730) of timeframes in the contingency analysis

element out of service	current method [%]	presented method [%]
Line 1	100	98,9
Line 2	100	98,9
Line 3	98,2	0
Line 4	100	2,3
Line 5	52,6	0
Line 6	100	0
Transformer 1	100	7,8
Transformer 2	100	98,9
Transformer 3	100	98,9

Table II Share of reasons of inadmissibility of analysed case, when dynamic operation limits considered in the analysis. Per cent Values referred to the number of timeframes in the particular contingency violating static operation limits

element out of service	Violation of dynamic operation limits [%]	Violation of absolute operation limits [%]
Line 1	0	100
Line 2	0	100
Line 3	-	-
Line 4	30	70
Line 5	-	-
Line 6	-	-
Transformer 1	21	79
Transformer 2	0	100
Transformer 3	0	100

Table III Decisions of system for the execution of particular computation steps. Per cent Values referred to the total amount (730) of timeframes in the contingency analysis

element out of service	Examination on component level necessary [%]	Time-domain simulation execution after pre-analysis [%]	Elements responsible for an ASSOD < T_{ds}
Line 1	100	1,1	Transformer 3 (98,9 %)
Line 2	100	1,1	Line 4 (43,4 %), Transformer 3 (55,5 %)
Line 3	98,2	98,2	-
Line 4	100	98,4	Line 5 (1,6 %), Transformer 3 (0,7 %)
Line 5	52,6	52,6	-
Line 6	100	100	-
Transformer 1	100	93,8	Transformer 2 (6,2 %), Transformer 3 (1,6 %)
Transformer 2	100	1,1	Transformer 3 (98,9 %)
Transformer 3	100	1,1	Line 4 (43,4 %), Transformer 2(55,5 %)

In case of an outage of line 4, for 98,4 % (Table III)of all analysed timeframes, the examination started after the pre-analysis a time-domain simulations of the generated LSs for a detailed analysis. In 0,7 %

of all computations of this contingency case, the simulation is determining an ASSOD below T_{ds} for the transformer. The congestion in the grid moved in this contingency from transformer 3 to line 5. All violations of absolute operation limits, in this case, are at line 5.

As an example, in Table IV are the returned values for the ASSOD for day 190 of the examined year. For an outage of transformer 1, the analysis computed an ASSOD of 12,1 h. A dispatcher would have in case of this contingency at minimum 12,1 h after the occurrence of element outages to apply curative remedial actions to the grid before reaching the dynamic operation limit of an asset. However, the ASSOD of at least one other examined case in the analyses is at this day zero, which results in the need to apply preventive remedial actions to restore the compliance with the (n-1)-criteria.

Table IV detailed analysis results for day 190 in the examined year

element out of service	**ASSOD [h]**	**Reason of limitation of ASSOD**
Line 1	0	absolute operation limit of transformer 3 violated
Line 2	0	static operation limit of line 4 violated
Line 3	24	-
Line 4	24	-
Line 5	24	-
Line 6	24	-
Transformer 1	12,1	dynamic operation limit of transformer 3 violated
Transformer 2	0	absolute operation limit of transformer 3 violated
Transformer 3	0	static operation limit of line 4 violated

6. Conclusion

The presented extension of the current method to assess the steady-state security of a power grid allows considering the available dynamic thermal transmission capacity of an installed asset if it is equipped with a monitoring system. Mixing monitored, and non-monitored components is due to the time-based benchmark possible with the presented method. The presented ASSOD for an examined contingency case, respectively, the time of availability as a result of the contingency analysis can be benchmarks for applying remedial actions in grid operation and planning.

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Appendix

Component parameters applied to the simulation

Table V Line parameters used in the simulation

Line	Node from	Node to	Length [km]	R' [Ω/km]	X' [Ω/km]	C' [nF/km]	Voltage [kV]	I_{rated} [kA]
1	1	2	100	0,0328	0,312	11,5	380	1,32
2	1	3	100	0,0328	0,312	11,5	380	1,32
3	4	5	100	0,0653	0,398	9,08	220	1,14
4	5	6	25	0,0653	0,398	9,08	220	1,14
5	6	7	75	0,0653	0,398	9,08	220	1,14
6	4	7	100	0,0653	0,398	9,08	220	1,14

Table VI nominal load parameters used in the simulation

Load	Node	P [MW]	Q [MVar]
1	5	750	200
2	6	400	60
3	7	850	250

Table VII Shares of standard load profiles for loads in grid

Load	H0	G0	L0
1	70 %	30 %	0 %
2	60 %	10 %	30 %
3	30 %	60 %	10 %

Table VIII Parameters generators

Generator	Node	P [MW]	S_{rated} [MVA]	V [p.u.]
1	5	400	1000	1,03
2	7	400	1000	1,03
Slack	1	-	-	1,03

Table IX electrical transformer parameters used in the simulation

Transformer	Node from	Node to	Primary Voltage [kV]	Secondary Voltage [kV]	S_{rated} [MVA]	V_{SC} [%]
1	1	4	380	220	400	13
2	2	5	380	220	400	13
3	3	7	380	220	400	13

Table X parameters of the thermal model applied to the power transformers in the grid

cooling system	paper type	Moisture content in paper [%]	oil exponent x [1]	windings exponent y [1]	losses ratio R	hot-spot factor H
ONAF	Non-thermally upgraded	1,5	0,80	1,30	6,00	1,30
heat constant k_{11} [1]	**heat constant k_{21} [1]**	**heat constant k_{22} [1]**	**Time constant τ_o [min]**	**Time constant τ_w [min]**	**Excess temperature top oil [K]**	**temperature gradient between top-oil and hot-spot [K]**
0,50	2,00	2,00	150	7	52	26