InnoSys 2030 – Innovations in System Operation up to 2030

Short Report on the Joint Project

Funded by:

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Overall Consortium InnoSys 2030

as associated partner

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1 Project overview – What are the core findings?

The InnoSys 2030 research project – Innovations in System Operation to 2030 – showed how innovative system operation can enable the grid in 2030 will be able to transport even more power while maintaining system security. InnoSys 2030 was carried out with the participation of a total of 17 research partners from Germany under the funding of the Federal Ministry for Economic Affairs and Climate Action (BMWK, formerly BMWi) with EUR 9.375 million under the overall project management of TenneT. The 17 partners were the four German transmission system operators (50Hertz, Amprion, TenneT and TransnetBW), five distribution system operators (Avacon, EWE Netz, Mitnetz, Netze BW and Westnetz), six research institutes (TU Dortmund University, FAU Erlangen-Nuremberg, Fraunhofer IEE, Fraunhofer FKIE, TU Ilmenau and RWTH Aachen University) and two SCADA system manufacturers (PSI Software AG and Siemens AG). After an extensive project application and approval phase, the processing period began in October 2018 and the project was completed in December 2021. The core findings of the project results are presented below. Furthermore, a long German version of the final report and additional supporting documents are available[1].

1.1 What are the results of InnoSys 2030 needed for?

The energy policy goals of the EU and the German government require a significant expansion of electrical power plants based on renewable energy by 2030. In order to enable the integration of these plants into the electricity supply system and at the same time ensure secure and economic operation, new and innovative system operation concepts are required that enable a higher utilisation of the existing grid infrastructure. The framework conditions that existed at the start of the project due to the federal government's target of increasing the share of renewable energy to 65% by 2030 have changed significantly due to the adjusted targets of the current federal government with the increase to 80% share of renewable energies, which reinforces the necessity.

This changes the structure of electricity production and distribution and leads to increased transport requirements. This includes the increase in decentral electricity production due in particular to wind feed-in in the north and the decommissioning of conventional power stations as well as the displacement of gas power plants near load centres. The integration of the European electricity market and the intensified trading activity reinforce the trend towards a significantly increased utilisation of the electrical transmission system.

Due to complex approval procedures and long project durations, the urgently needed grid expansion cannot keep pace with the increasing demand for transport. To ensure grid and system security, grid

[1] Long German version of the final report and further documents at www.InnoSys2030.de - Project Results

operators take measures such as redispatch as well as the use of reserve power plants, which are associated with additional costs in the billions.

With the further planned expansion of renewable energy plants and the considerable delays in grid expansion, these costs are expected to rise even further in the future. In order to counteract this increase in costs, new approaches to solutions in the area of system operation are increasingly being discussed, which should enable a more efficient utilisation of the grid. A much-discussed solution approach involves so-called curative system operation. This is seen as having high potential for increasing capacity utilisation and reducing redispatch measures. Existing studies on curative system operation, however, often neglect operational and technical constraints.

The InnoSys 2030 project closes this gap by developing new innovative system operation concepts and evaluating them holistically – especially by taking into account the practical application. These concepts should contribute to higher utilisation of the existing grid infrastructure with high grid and system security. This should enable a significant contribution to increasing the renewable energy share and providing expanded options for action in system operation in the short term until 2030. In the long term, after 2030, these innovative system operation concepts could help to reduce the grid expansion that is actually necessary.

Already today, grid operators are using innovative approaches to enable higher utilisation. This includes power flow control measures such as phase-shifting transformers in Germany, dynamic line rating and the use of high-temperature conductors. It can be assumed that these measures will be implemented in the short term, i.e. by a target horizon of 2023 to 2025. There is further potential in the area of improved, coordinated identification of measures to eliminate congestions. With the results from InnoSys 2030, new concepts are presented that build on this and expand on these approaches.

Another important aspect of InnoSys 2030 is the coordination between the actors in system operations in order to be able to use all potentials of higher utilisation. The cooperation between the relevant players of the transmission and distribution system operators as well as other market participants is thus moving further into the foreground and must be expanded. Likewise, the legally binding framework must be taken into account which is set up in particular by European directives. For example, with regard to the exchange of data between the actors, InnoSys 2030 shows a need for adaptation here in order to enable the new developments. The need for further action in the corresponding fields of action is shown in the InnoSys roadmap.

1.2 The core findings of InnoSys 2030

The InnoSys 2030 research project showed how innovative system operation can enable the grid in 2030 to transport even more power while maintaining system security. To make this possible, among other things, comprehensive technological and procedural enhancements are required in today's system operation. The core finding is that a coordinated application of curative measures and power flow control resources enables higher utilisation of our grid. To achieve this, four core statements were formulated+ which summarise the results of the project in the following chapters.

> The system operation concepts developed in InnoSys 2030 complement
> **curative and preventive congestion management**,
> so that curative and preventive measures must consider a
> **joint system operation process**.

Ensuring system security is a top priority for transmission system operators. Therefore, in the event of potential grid bottlenecks, they use preventive measures such as redispatch or transformer steps to operate the grid securely. Due to the high coordination effort as well as technical and operational constraints, operational congestion management includes operational planning and real-time system operation. Multifaceted interactions make it necessary for curative and preventive measures to always be planned together. Therefore, curative measures must be taken into account in the entire process chain. How this can be done is described in chapter 2 with the answer to the question "What are the concepts for implementing curative system operation?“.

> The **system operation concepts** developed
> in InnoSys 2030 to increase the utilisation of the transmission system grid can help to
> **fulfil the transmission task**.
> However, they will not replace grid expansion.

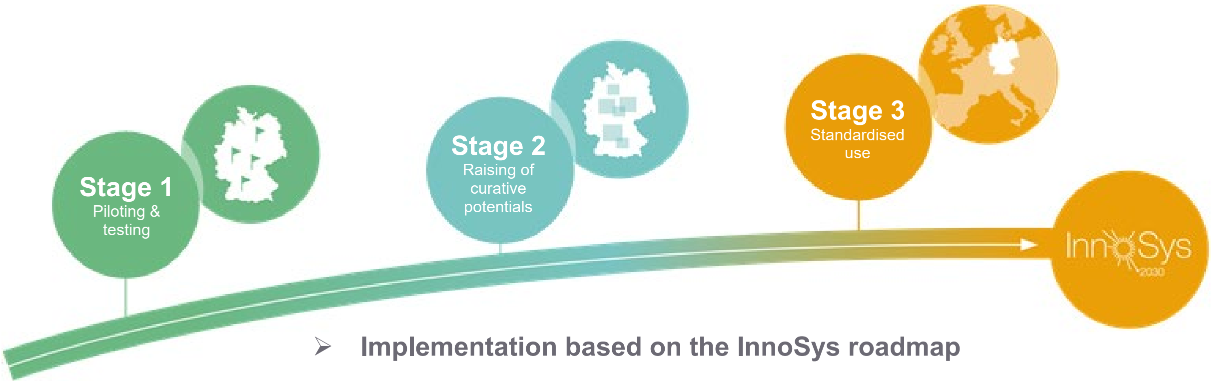
The research in InnoSys 2030 demonstrates the benefits and added value of curative system operation to address the transport task. In order to evaluate these, the concepts described in section 2.3 (“Six technology concepts for implementation“) were first examined in terms of their individual effects and finally in terms of their overall effect as an innovative package of measures in steady-state simulations. In addition, InnoSys 2030 focused on the practical development of results. For this purpose, three demonstrators and two field tests were carried out. The results of the investigations can be found in chapter 3 with the answer to the question “What are the potentials?”.

A higher utilisation of the grid reduces the inherent security of the system, regardless of the system operation concept. The desired **system security** of innovative system operation concepts can be achieved by the **degree of utilisation** and by a **secure and redundant design of the concepts**.

Maintaining system security is an important premise for all adjustments and changes in grid operations. The contribution that power-influencing resources and curative system operation can make to this was analysed on the basis of stability investigations using steady-state and dynamic simulations, and necessary collateralisation concepts were described. The results of this and the answer to the question "What are the challenges and risks?" are elaborated in chapter 4.

Transmission and distribution system grid only work together.
The distribution grid is where most electrical loads and renewable energy plants are connected and can make a supporting contribution to curative congestion management in the transmission system grid by providing flexibility while avoiding congestion shifting to the distribution system grid.

The interaction of electrical loads and power plants across all voltage levels is a key element in implementing the energy transition. The necessary coordination for extended interaction between transmission and distribution system operators for a joint system operation process is described in chapter 5 under the question "What is the interaction with the distribution system grid like?".



➢ **Implementation based on the InnoSys roadmap**

The research results of InnoSys 2030 show new options for action for grid operations from the perspective of system operation. Thanks to the involvement of the various partners with their respective expertise and the implementation of demonstrators and field tests, the results are very practical. For the subsequent implementation of the developed concepts, technical and organisational prerequisites have to be created which in some cases involves very extensive developments in the relevant areas. Various other stakeholders must be involved to create the necessary conditions and make the development steps possible. To this end, the InnoSys 2030 roadmap was formulated which shows the most important fields of action associated with it. How things will continue after InnoSys 2030 is therefore described in the concluding chapter 6.

2 What are the concepts for implementing curative system operation?

Curative system operation is a promising approach to utilise the existing grid infrastructure to an even higher degree and thus reduce necessary measures to eliminate congestion as much as possible. The underlying idea of activating measures only after an actual incident has occurred and using the thermal reserve of operating resources can be clearly illustrated using simple examples. The concrete implementation, however, represents a paradigm shift in system operation and is associated with numerous practical and technological challenges due to its complexity and multi-layered nature. The concepts developed in InnoSys 2030 therefore focus on practical integration into system operation, while placing emphasis on innovation. Central aspects here are the reduction of complexity in order to ensure operational manageability, as well as the guarantee of system security, which must not be reduced by the increased utilisation of the existing grid.

How an innovative and practical integration of curative measures into system operation can succeed is described in the following sections on the basis of the concepts which were developed.

2.1 Mechanisms of action of Mechanism of Curative Remedial Actions – What is it?

According to German[2] and European[3] legislation, grid operators are obliged to secure a reliable system operation. A central aspect is the guarantee of grid security. Uniform operational rules, such as the (n-1) criterion, minimise the risk of supply interruptions in case of any disturbances, e.g. as a result of cascading fault extensions. A disturbance is a failure of grid operations equipment that would cause a limit value violation.

The application of the (n-1) criterion is done by adhering to limit values in undisturbed operation as well as in failure situations. Limiting factors are current limit values of grid operations equipment and voltage limit values. Exceeding the limit values can result in irreversible damage to grid operations equipment or in the triggering of equipment or system protection. To avoid this, grid security calculations are carried out from week-ahead to day-ahead to real-time and potential violations of the (n-1) criterion are forecast or determined. If necessary, optimisation algorithms are used to determine suitable measures for relieving the grid in accordance with §13 EnWG. These typically include the redispatch of conventional power stations or the staging of transformers. Such remedial actions can in

[2] Federal Republic of Germany: EnWG - Energy Industry Act of 7 July 2005 (Federal Law Gazette I p. 1970, 3621)
[3] European Commission: Commission Regulation (EU) 2017/1485 of 2 August 2017 establishing a guideline for transmission system grid operation, Brussels, 2017

principle be used both preventively and curatively. The difference in the effect of preventive and curative measures is shown in Figure 2-1.

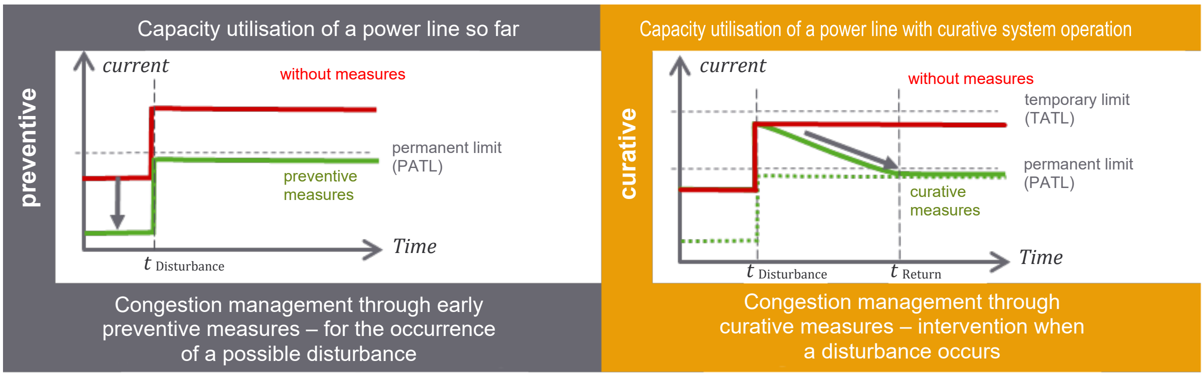


Figure 2-1: Comparison of the mechanisms of action of preventive and curative system operation

The actual instruction and implementation of the identified relieving measures today is usually done preventively, i.e. before a possible disturbance. The preventive implementation of the measure reduces the load in undisturbed operation (n-0 state) of the affected equipment below the permanently tolerable current load (PATL[4]). For example, power circuits today are usually operated with certain safety margins that only come into play in the event of rare failure events.

When lines in the n-0 state are loaded with a current that is below the PATL, their thermal inertia allows the PATL to be exceeded for a short period of time without causing a thermal overload. This so-called thermal reserve can be used to take sufficiently fast measures immediately after equipment failure, i.e. curatively. The thermal reserve is described in operation by a temporarily tolerable current load (TATL[5]). To avoid thermal overloads, it must be ensured that the current does not exceed the TATL and is returned to the PATL after the measure has been fully implemented. The TATL depends on the type of conductor, the preload of a line, the time period $\Delta t = t_{\text{Return}} - t_{\text{Disturbance}}$ during which the temporary current may be applied, as well as on weather conditions. The higher the time span, the lower the TATL. The time span, in turn, is largely determined by the reaction time of the (curative) remedial action available to the system operator. This principle means that costly preventive measures can be avoided, as curative measures are only used when a failure of operating equipment actually occurs.

In practice, both the temporary and the permanently tolerable current limits are not only thermally determined, but also limited by numerous restrictions, e.g. protection and stability limits. In InnoSys 2030, the so-called InnoSys limit value concept has therefore been developed – based on the limit value concept of the German TSO[6] – in order to describe calculation rules for realistic simulations

[4] PATL: Permanent Admissible Transmission Loading
[5] TATL: Temporary Admissible Transmission Loading
[6] “German limit value concept”, https://www.netztransparenz.de/Weitere-Veroeffentlichungen/Planung-und-Betrieb

on the one hand and to obtain a basis for possible real implementations in grid operations on the other hand (Figure 2-2). The actual usable PATL and TATL values are determined by minimising the individual current limits.

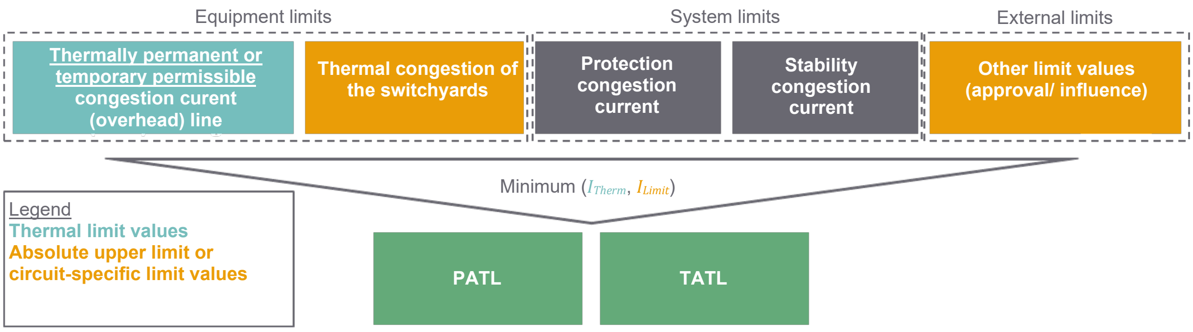


Figure 2-2: InnoSys limit value concept

The TATL depends on the time period during which the temporary current is applied. How long the temporary current is present that exceeds the PATL is again dependent on the reaction time of the curative measure itself. In order to map this interaction appropriately, reduce the complexity for calculating the TATLs, enable consideration in optimisation algorithms and ensure operational manageability, three fixed curative time windows were defined in InnoSys. Measures were assigned to these so-called reaction time windows depending on their reaction time. The classification was based on technical estimates and the type of trigger[7] of the measure itself for

- a decentralised triggering of very fast measures in several seconds,
- a central triggering from the control system for measures that react within several minutes, and
- slower measures, reacting within about a quarter of an hour.

All curatively deployed measures are assigned to these reaction time windows (although certain types of measures can also be assigned to different time windows according to their reaction time windows, e.g. slow and fast distribution grid flexibilities). Although this classification means that the thermal reserves are not fully utilised, this is conducive to operational consideration in processes. The reaction time windows are taken into account in the entire process chain of system operation, as described in the InnoSys 2030 system operation process (section 2.2).

The integration of curative measures into system operation requires the consideration of individual TATL limits as well as curative measures per failure situation considered. Compared to the preventive elimination of congestion in which a single set of remedial actions is calculated and used for all possible failures, the solution space in curative system operation increases many times over. At the same time, short reaction times require the automated triggering of measures in the event of a disturbance. Due to these short lead times, there is hardly any room for manoeuvre for the system operators to actively

[7] Detailed descriptions of the releases are given in section 2.2

intervene in what is happening. Accordingly, high demands are placed on all procedures, processes and the remedial actions themselves in terms of availability, reliability and robustness. Higher grid utilisation associated with curative grid operations management must not lead to a reduction in system security. Ensuring system security must remain the top priority in the further development of operational congestion management – also taking curative measures into account. For example, assistance systems need to be further developed to support system operators in their system responsibilities. How this can be done and what the requirements are for the system operation infrastructure is outlined in the InnoSys system operation process.

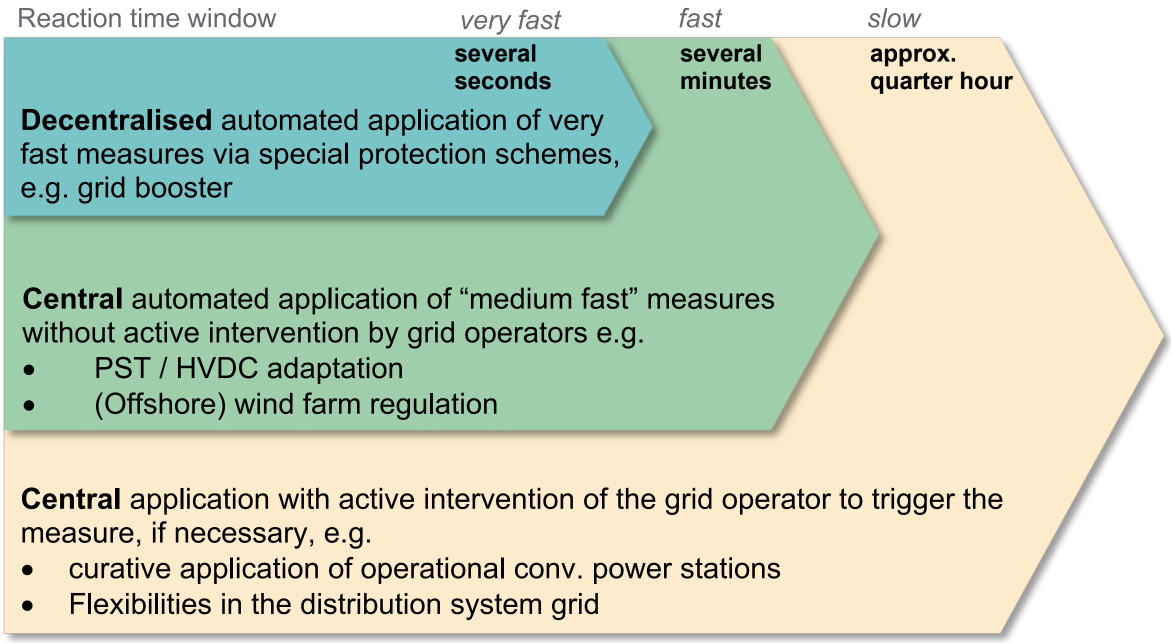


Figure 2-3: Reaction time window in InnoSys 2030

2.2 The InnoSys system operation process

The InnoSys system operation process describes how the integration of curative measures into operational congestion rectification can succeed. Today, congestion management distinguishes between operational planning and real-time system operation (Figure 2-4). The aim of operational planning is to prepare the actual real-time system operation, including the planning and partial implementation of remedial actions. The real-time system operation monitors and controls the grid on the basis of current measured values and implements remedial actions still available in the short-term time range should grid congestions occur.

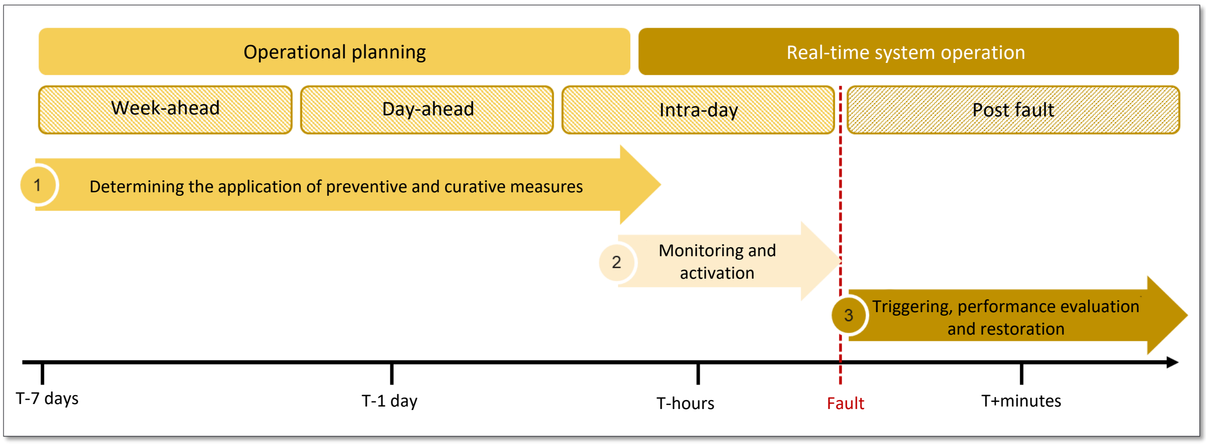


Figure 2-4: Overview of the InnoSys 2030 system operation process

Although curative measures are by definition very quickly applicable, a higher utilisation of the existing grid and the substitution of preventive redispatch quantities is only possible if preventive measures are dimensioned taking into account possible curative measures. Therefore, curative measures must be integrated along the entire process chain of operational bottleneck elimination. In concrete terms, this means that curative measures are precalculated and always updated up to real-time system operation.

As Figure 2-4 shows, the system operation process can be divided into the three sub-areas “application determination in operational planning”, “monitoring and activation” and “triggering and success evaluation” which are described in more detailed below.

2.2.1 Determination of application in operational planning

The aim of operational planning is to identify grid bottlenecks by forecasting power flows that occur and, if necessary, to determine measures to ensure grid security. Lead times of remedial actions (esp. redispatch) as well as coordination with neighbouring and subordinate grid operators make it necessary to carry out operational planning within various processes for a time range of seven days to a few minutes before the physical power flows are fulfilled.

Within the operational planning processes, optimisation algorithms are used to identify potential congestion based on forecasts of grid usage and to determine possible remedial actions. Measures are determined in a closed loop for all relevant control variables in grid operations.

The determination and application planning of curative measures is based on the calculated limit values (PATL and TATL), available potentials and the forecast grid situation. In this context, interactions of all possible potentials, regardless of their preventive or curative implementation, are to be mapped accordingly. These must be coordinated in such a way that PATL and TATL are not exceeded and curative measures develop their full effect within the defined period of time. Only a comprehensive consideration of all available measures leads to an overall optimised application of measures. Moreover, the closed view means that a possible curative measure implementation along the entire process chain from week-ahead to shortly before real time should be considered and updated on a rolling basis. Forecast errors and uncertainties must be addressed appropriately, e.g. by planning for safety margins. After the last optimisation run, a set of curative measures with a clear assignment to a failure situation ("reaction matrix") is then transferred to the real-time system operation where the precalculated measures are checked, monitored, activated and triggered if necessary.

Since curative actions are only triggered when equipment failure has already occurred, and therefore there is very little time for active action by the system operator, any unplanned effect is potentially system-threatening and must be compensated immediately. Uncertainties such as unexpected unavailability, e.g. due to a faulty communication link, or insufficient effectiveness of the curative measure, must be secured by means of redundant measures. The necessary activation and triggering time for the redundancy measures must be taken into account accordingly. Collateralisation can be done, for example, by planning an additional curative measure that is triggered if another planned curative measure fails.

A tendency towards higher utilisation of grid operations equipment is also associated with higher reactive power requirements and higher angular differences and leads the system closer to its stability limits. Thus, the curative grid operations management increases the requirements for dynamic reactive power provision on the one hand and stability assessment on the other hand, which must be fulfilled both in terms of planning and operation.

The described requirements for integrating curative measures into the operational planning processes of operational congestion management thus place high demands on the existing systems, as well as the operational implementation. The extension of optimisation problems to include such requirements is already state of the art and poses comparatively few additional algorithmic challenges. The transfer to the state of the art is still pending. In addition to the algorithmic adjustments, the implementation within the operational planning tools requires a high level of robustness and result quality of the determined measures in a way that is comprehensible for the system operator. Besides the calculation routines, robustness also relates in particular to input data and the models used. It must always be ensured that the curative measures identified can actually be implemented under the given boundary conditions and that existing bottlenecks can actually be eliminated.

2.2.2 Monitoring and activation in real-time system operation

Within the system operation, the verification of availability, retrieval as well as the monitoring of the effectiveness of measures is carried out by the system operator. This is supported by functionalities in the control system, such as continuous security calculations, and always has the option of implementing further measures if necessary. A time-critical and automated implementation of measures immediately after an equipment failure thus represents a paradigm shift in system operation. This results in further high demands on the implementation of curative system operation in real-time system operation in order to be able to guarantee grid security at a high level. This concerns the extended monitoring of their availability and effectiveness which must therefore be integrated into the assistance systems of real-time system operation.

From a procedural point of view, measures identified in operational planning that are to be implemented curatively must have a clear allocation to equipment failure. This means that they can be taken into account within the grid security calculation in the control system by activating the assigned set of measures in the power flow calculation for each contingency considered. If, despite such consideration of curative measures, findings occur in the control system, i.e. operational limits (PATL or TATL) of secure system operation are violated in a contingency, the system operator must react and immediately implement redundantly planned measures. If there are no findings, i.e. no violation of limit values occurs in a contingency with an effective curative measure, a curative measure can be armed in the station control system or in the SCADA system.

2.2.3 Triggering and success evaluation

If an equipment failure occurs, a trip is triggered by an external signal. The automated triggering of curative measures with particularly short activation and reaction times can relieve system operators in real-time system operation. The information about the triggering and success of the curative measure must in turn be clearly and immediately recognisable in the assistance systems of the system operation. Other curative measures can be triggered by means of manual confirmation, thus allowing the system operator in real-time system operation the opportunity to take into account updated knowledge about the grid situation or to implement additional, e.g. stability-promoting, measures. For secure grid operations, it is also essential to return the system to the (n-1) secured state ("restoring") after the failure situation with the triggering of the curative measure and to replace curative measures that are only temporarily available.

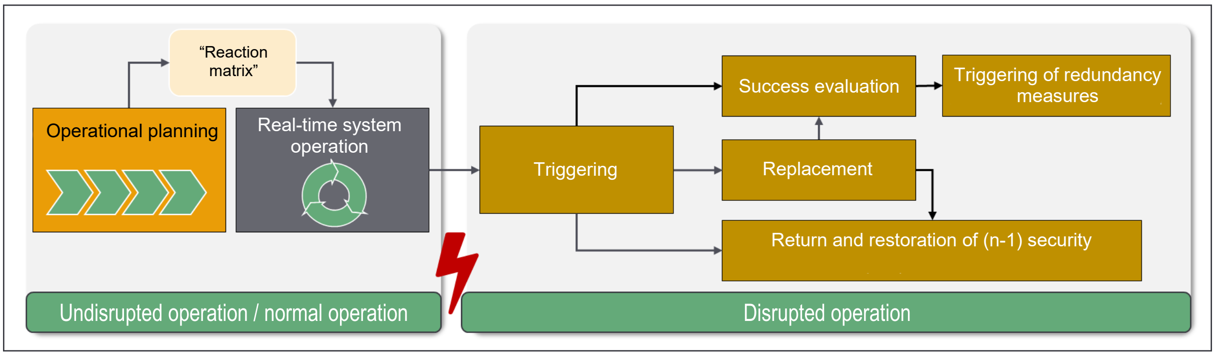


Figure 2-5: Course of curative measures in real-time system operation

2.3 Six technology concepts for implementation

Six technology concepts have been developed in InnoSys 2030. While the system operation process focuses on the framework conditions for integration into the system operation, the technology concepts focus on technology-specific aspects such as control or potential determination. It applies that the different technologies can also be used in combination and are integrated into the system operation according to the InnoSys system operation process. The technology concepts are the following:

- **Curative redispatch with conventional power plants.** Certain power plant technologies, such as gas turbines or pumped storage power plants, can be controlled quickly, so that they are basically suitable for curative application. This applies in particular to the replacement of measures that are only temporarily available (e.g. battery storage systems). However, it is also conceivable to use conventional power stations as collateral if other measures do not work according to the concept, or to act curatively within about 15 minutes. The great advantage of using conventional power stations as a curative measure is that they are existing assets that are already being used today for redispatch in established processes with a lot of operational experience (preventively).
- **Curative redispatch from the distribution grid.** Already today, remedial actions, such as the sinking of renewable energy plants, are frequently used in distribution grids to relieve grid elements in the transmission system grid. The introduction of Redispatch 2.0 systematises this procedure and creates coordination mechanisms and automatisms to call up flexibilities between different grid levels. These concepts have been further developed in InnoSys 2030, among other things in order to use high control potentials in the future (i.e. throttled plants that feed additional power into the grid when needed) and to take load control into account. This should enable curative remedial actions to be deployed in a coordinated manner between the distribution and transmission system grids.
- **Curative application of grid boosters.** Even before InnoSys 2030, grid boosters in the form of very fast battery storage systems were a much-discussed approach to enable curative system operation. In InnoSys 2030, a holistic grid booster concept has been developed in order to use grid boosters systemically. This applies, for example, to the combination of battery storage and offshore wind farms. One focus of this concept is the design of special protection schemes to enable decentralised triggering in the event of a fault. The approaches developed here flow directly into the implementation of the first pilot grid booster plants.
- **Curative application of high voltage direct current transmission lines (HVDC)**. With the entry into operation of the domestic HVDC transmission lines, the transmission system operators will have controllable operating equipment at their disposal very quickly. Due to their high congestion efficiency and speed, HVDC systems are particularly suitable for curative application, especially for central triggering from the control room within a few minutes. Building on the concepts already available for the preventive use of HVDC transmission lines, a concept has been developed in InnoSys 2030 on how these can additionally be used curatively. The focus here is particularly on coordination aspects and operational restrictions during use.

- **Curative application of phase-shifting transformers (PST).** The grid development plan provides for phase-shifting transformers (PST) at numerous locations within Germany. In contrast to PSTs close to the border which are used in particular for the control of power flows on interconnectors, the inner-German PSTs can be used directly for the elimination of congestion. This also includes the curative application of these elements. Although the concept developed here focuses on PST, it has been formulated in a way that is open to technology and can be applied to other flexible power flow control equipment.
- **Curative application of topology switching measures**. Adjusting the grid topology is an effective measure to control power flows and balance grid utilisation. Due to the partly high complexity in the determination and implementation of switching measures, a curative application is only conceivable for individual topological measures. How this can be achieved and which requirements have to be fulfilled for the implementation has been elaborated within this concept.

3 What are the potentials?

3.1 Estimation of redispatch reduction using curative concepts: Methodology and scenario for the potential assessment, results of different sensitivity studies

Using steady-state simulations of future grid operations, the IAEW at RWTH Aachen University investigated curative technology concepts within the framework of the project to determine their potential for reducing preventive redispatch demand. For this purpose, annual run simulations were carried out in hourly resolution.

The grid operation simulations were carried out for a grid model of the European transmission system grid, with the congestion relief taking place in the German transmission system grid. The following assumptions apply to the grid model and the included equipment:

- Projects planned and approved in the Grid Development Plan **NEP 2030 (2019)** have been **fully implemented** and put into operation.
- In addition, **six assumed grid booster systems** (500 MW each, positioning and dimensioning based on InnoSys results) and **two PSTs** (Grohnde and Wahle) have been put into operation.
- **The technical requirements** for implementing the InnoSys system operation process have been **implemented** (fields of action: primary, secondary technology, processes and tools).
- **Absolute current upper limit of 4 kA** for circuits with no underlying operational or technical individual upper limit, taking into account different **reaction time windows**, is coordinated.

The energy scenario used is based on the approved **Scenario C 2030** of the **NEP 2030 (2019)**. Scenario C 2030 assumes a progressive expansion of renewable energies and thus – from the point of view at the time of publication – an ambitious implementation of the climate policy targets. For the rest of Europe, the **Sustainable Transition 2030** scenario according to the Ten Year Network Development Plan 2018 is used.

Based on these scenarios, the following deviating assumptions were made with regard to the installed power and regionalisation of onshore and offshore wind turbines:

- In the control area of 50Hertz Transmission, an increase of 979.1 MW in the installed power of onshore wind turbines is assumed. The regionalisation is not modified, but instead a flat increase of 3.4 % in the installed power of all onshore wind turbines is assumed. This results in an installed generation capacity of onshore wind turbines of 29.77 GW in the 50Hertz control area (C 2030: 28.80 GW) and of 86.48 GW in Germany (C 2030: 85.5 GW).

- The installed power of offshore wind turbines is increased by 4.4 GW to 21.4 GW. In addition, a different location is assumed and 1.1 GW is shifted from the North Sea to the Baltic Sea. Specifically, these are the grid connection systems NOR-9-2 and NOR-10-2, whose connected offshore wind power capacity will be reduced by a total of 1.1 GW, and OST-6-1 and OST-7-1, whose connected offshore wind power capacity will be increased accordingly.

In addition, the following simplifying assumptions were made with regard to grid operations, which are partially resolved in the further course of the simulations:

- No consideration of replacement and collateralisation concepts of curative measures
- Simplified mapping of coordination between grid operators
- No consideration of voltage stability and system stability aspects
- Assumption of perfect but limited temporal foresight
- Use of the full control range of curative measures

Scenario 2030 – Reference scenario

Figure 3-1 shows the results of the annual run simulation for the 2030 scenario – Reference scenario. For each simulated technology concept, the sum of the remaining preventive redispatch (RD) applications of the annual cycle is listed. The total includes the following amounts: the redispatch use of conventional power stations, the curtailment of generation plants based on renewable energies and the use of pumped storage power plants.

The curative application of thermal power plants and distribution grid (VN) flexibility, for which only small potentials for operating point adjustment were assumed here, enables savings of 0.1 TWh and 0.4 TWh respectively. Curative application of PST, grid boosters and HVDC show a clear savings potential due to low reaction times and sufficient potential for operating point adjustment. The combination of curative technology concepts in the innovative scenario shows an additional savings potential for reducing the preventive redispatch demand and achieves a reduction of up to 39%.

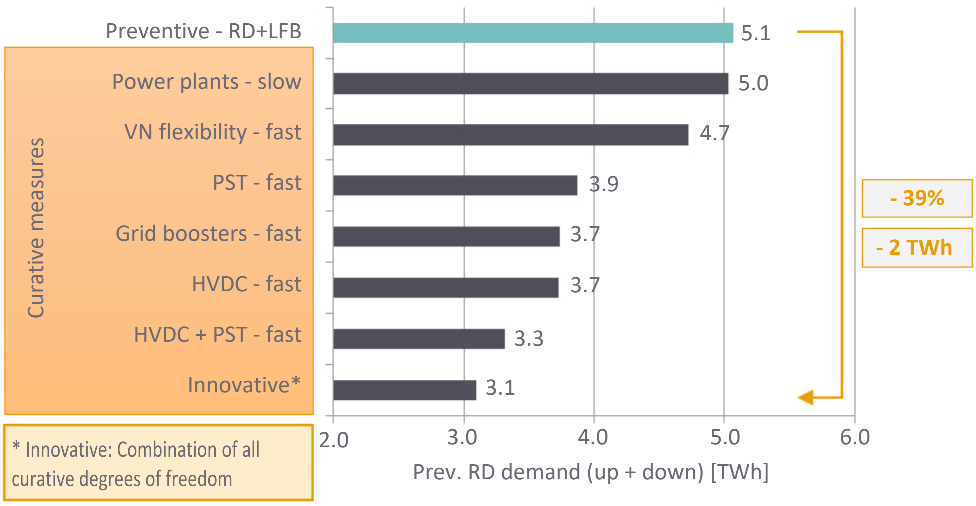


Figure 3-1: Preventive Redispatch (RD) demand Scenario 2030 – Reference scenario

Scenario 2030 – Sensitivity: Limited control range

Motivation:
Investigation of the influence of reduced curative control ranges on the potential of technology concepts for the reduction of preventive redispatch demand

In the previous simulations of the reference scenario, a possible curative operating point adjustment was assumed in the entire control range of the respective curatively applicable technologies. In the following results, the overview of which can be seen in Figure 3-2, the influence of reduced curative control ranges on the potential of technology concepts to reduce preventive redispatch demand was investigated. The aim of the study is to show the influence of taking operational aspects into account when estimating potential. The investigation of reduced curative PST control ranges is motivated by the assumption that in the fast curative time range of up to two minutes, the staging of a PST over the entire control range may not be technically feasible. The HVDC control range is limited for operational reasons, including to reduce the power change from the initial operating point.

The results of the investigation show, on the one hand, the significant influence of the control ranges on the respective potentials. On the other hand, significant reductions in the preventive redispatch demand are already visible with a restricted control range.

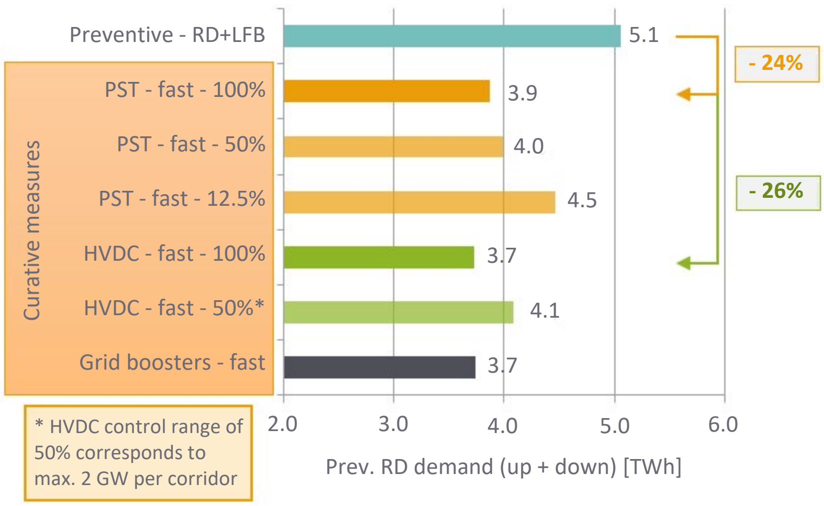


Figure 3-2: Preventive RD Demand Scenario 2030 – Sensitivity: Limited control range

Scenario 2030 – Sensitivity: Redundancy

Motivation:
Evaluation of the influence of simple redundancy/backup concepts on the potential of curative technology concepts to reduce preventive congestion management application

Figure 3-3 shows the results of the sensitivity study regarding redundancy concepts for curative measures. Results from previous studies are also included for better comparability. The redundancy concepts listed consist of disjunctive curative combinations of measures. In addition, restricted control ranges have been specified analogous to the previous investigation. For example, the set of measures "HVDC comb. PST 50%/12.5%" contains the curative application of HVDC and the requirement of an equivalent curative application or redundancy through curative PST use. At the same time, in this set of measures, HVDC operating points can only be curatively adjusted by 50% of the control range of the HVDC and PST operating points by 12.5%.

The results show that curative measures continue to have significant potential for reducing the need for redispatch despite redundancy requirements. By using all three types of plants to provide redundancy to each other, the highest redispatch saving is achieved. The redundancy configuration using disjunctive plant types is a conservative estimate: It can be assumed that further potentials can be raised through more specific redundancy configurations.

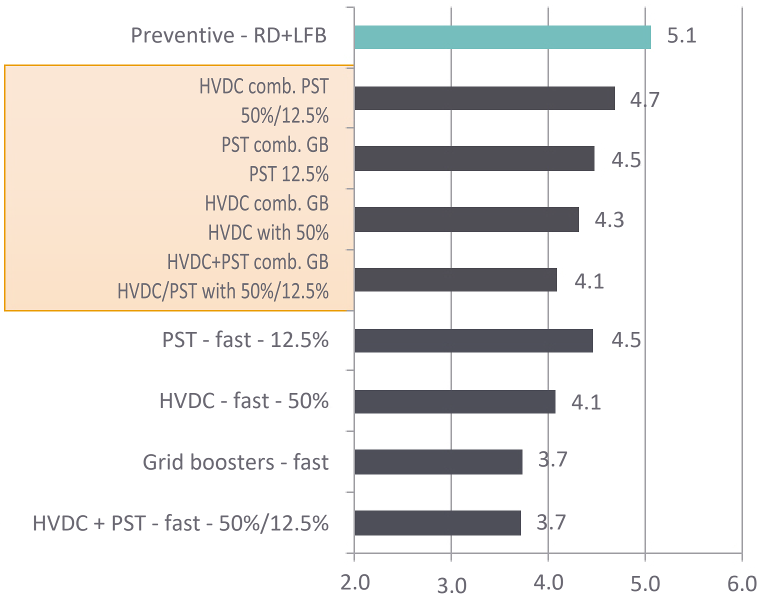


Figure 3-3: Preventive RD Demand Scenario 2030 – Sensitivity: Redundancy requirement

Scenario 2030 – Sensitivity: Congested grid

Motivation:
Demonstrate the effect of curative congestion management assuming a congested grid.

Analogous to the results of the reference scenario shown in Figure 3-1, the potential of the curative technology concepts to reduce the preventive redispatch demand was investigated using a more congested grid.

While retaining the energy scenario, the following assumptions were made for this study with regard to the grid expansion status:

- In the grid development plan **NEP 2030 (2019)**, planned and approved projects could **not** be fully implemented and put into operation – ***AC grid expansion is delayed with status of planned expansion status 2025.***
- **Limit value concept** for the definition of PATL/TATL with **absolute current upper limit of 4 kA** for circuits without an underlying operational or technical individual upper limit taking into account different **reaction time windows**
- No change with regard to HVDC and PST to ensure comparability of the corresponding curative grid operational management concepts.

The study is thus a synthesized extreme case of a delayed AC grid expansion condition for investigating interrelationships.

Figure 3-4 contains the overview of the results of this study. First of all, regardless of curative measures in the congested grid, there is a significantly increased need for preventive redispatch. As in the results of the reference scenario, a moderate savings potential is shown by the curative application of thermal power plants. The curative application of distribution system grid (VN) flexibility and HVDC show increased savings potential. PST and grid boosters show a clear savings potential. The combination of the concepts again shows additional savings potential for reducing the preventive redispatch demand and achieves a potential reduction of up to 15%.

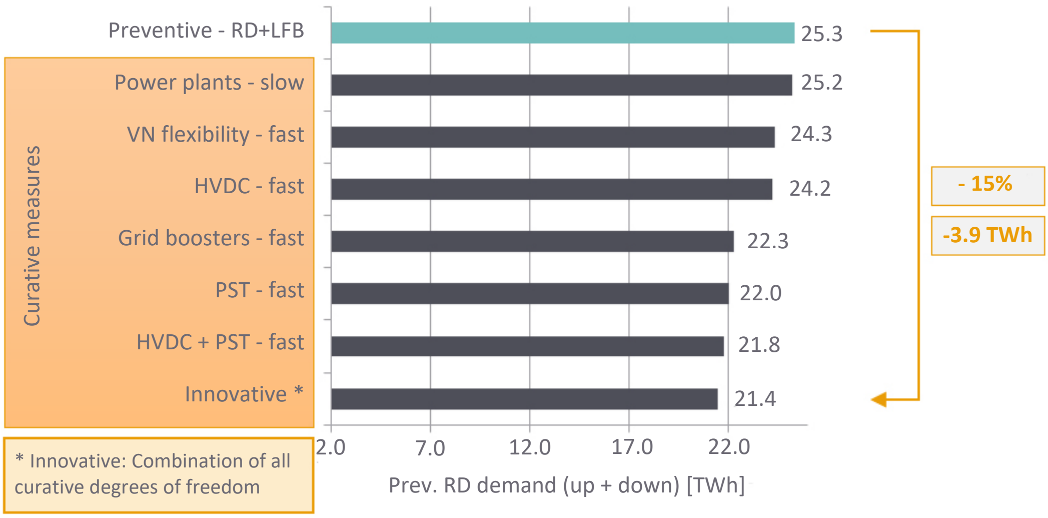


Figure 3-4: Preventive RD Demand Scenario 2030 – Sensitivity: Congested grid

3.2 Practical findings from field tests and demonstrators

In addition to the simulation of grid operation management concepts from chapter 3.1, selected measures were investigated and tested in the form of field tests and demonstrators. In contrast to the simulations, the focus here was not on validating the effectiveness of curative measures, but on aspects such as practicality, scalability and implementation suitability of the measures in a control room or control room-like environment. Three demonstrators and two field tests were created as part of the project. An overview of all field tests and demonstrators with regard to the corresponding core topics as well as the associated partners is shown in Figure 3-5. Demonstrators were located at the Dortmund, Kassel and Ilmenau sites, where a laboratory-scale control room was set up in each case. At the Dortmund site, the focus of the investigations was on the utilisation of the thermal reserve of overhead lines. In addition to the integration of overhead line monitoring in the control system, this also included the development of concepts for the presentation of action periods for system operators. In Kassel, the main focus was on the role of the DSOs in its function as a provider of flexibility potential in the congestion management of the TSO. Methodologies for determining flexibility potentials were investigated and then tested and evaluated for practicability in trials with MITNETZ grid operators. At the demonstrator in Ilmenau, the focus of the investigation was on quantifying the interaction between the system guide and the control system. The experiments here were not tailored to individual measures, but explored structural differences between certain types of measures and highlighted aspects that need to be considered when implementing curative system operation. An investigation of the curative system operation also took place in real systems on the basis of the field tests. In the field test of Amprion and Westnetz, the focus of the investigation was particularly on the coordination between the two grid operators. In its trials, TenneT, together with PSI, expanded its own control system to include a new tool that can calculate effective, cross-technology, curative packages of measures. Both field tests did not take place in the productive system, but evaluated data in listening mode or were fed with historical data.

Figure 3-5: Overview of the field tests and demonstrators

Four core statements have emerged from the investigations during the field tests and demonstrators.

1. **Curative system operation can be implemented as a prototype with due consideration of time, resources, robustness and testing.**

Curative system operation is technically feasible in principle and can be implemented in control rooms. What the trials, especially the field tests, have shown is that the technical maturity of the current implementation is not yet sufficient to be used in a productive system. Accordingly, further resources and time for testing the HEO applications must be planned for transferring these into the real process landscape.

2. **Listening operation both in real time and in operational planning is a suitable tool to prepare for curative system operation.**

The listening mode enables practical testing of the concepts without interfering with the production system to be secured. Processes and interfaces can be set up close by. Within the framework of the field tests, monitoring operation has therefore proved to be a suitable procedure for investigating innovations in (curative) system operation.

3. **A new kind of understanding of the complexity of curative measures is required from the system operator. Support tools and training need to be designed for this.**

The application of curative measures is highly complex due to its strong interlinkage with preventive system operation and the time requirements for resolution. Theses formulated at the start of the project, such as the activation ("arming") of every curative measure by the system operator, also increase the degree of complexity. The conclusion to be drawn from the problems identified is that system operators must be extensively trained in the context of curative system operation. Likewise, the use of assistance systems in the control room to support the system operators should be further investigated.

4. **The embedding in the InnoSys system operation process and thus the consideration of the interaction between operational planning and real time as well as the coordination between the grid operators are aspects that need to be considered more strongly.**

In all studies of field tests and demonstrators, feedback to operational planning has not been taken into account. In the field test, all investigations are based on the regular, preventively operated grids. A meaningfulness with regard to the actual effect of curative measures in real time operation is therefore only given to a limited extent, as the data basis was not designed for their use. Similarly, this meant that there was no coordination between grid operators in the context of operational planning.

A similar problem exists with the demonstrators. The use of generic grids does not cover the representation of operational planning.

4 What are the challenges and risks?

4.1 Preventive and curative system operation concepts from a system security perspective

The system security of the electrical energy system includes a secure and uninterrupted supply at all times, which is ensured by compliance with the standards and the limits of the system. For the evaluation of the system operation concepts developed in InnoSys 2030 in relation to today's security level, the InnoSys system operation process, as shown in Figure 4-1, could not be considered in isolation from the framework conditions that will change in the future. System security in 2030 is influenced by many different aspects, including: new operating equipment affecting power flow, grid expansion, massive expansion of photovoltaic and wind farm installations, and a restructuring of the conventional power station fleet. Furthermore, innovative concepts in system operation influence security in a positive way, as they create additional options for action.

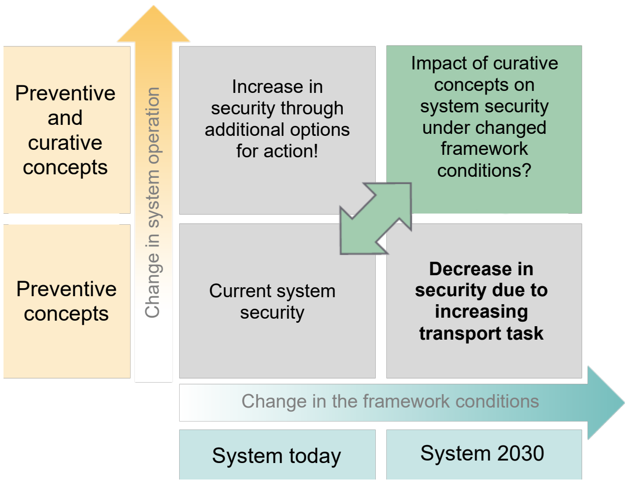


Figure 4-1: Possible influences of the changed framework conditions and system operation concepts on system security

Nevertheless, InnoSys 2030 evaluated how an innovative (preventive + curative) system operation in 2030 would behave in contrast to a purely preventive system operation under today's framework conditions. Based on this comparison, the influences on system security were identified and measures were derived to keep the system security of the innovative concepts at a comparably high level to the current system security.

4.2 Redundancy concepts and the dimensioning of curative measures

A load on the grid operations equipment that lasts longer than permitted or is too high leads to a risk to system security, for example due to overloading and thus damage to equipment or cascading equipment failures. The following conditions thus arise for ensuring curative (n-1) security:

- Application of the curative congestion management measure must function within a specified time window.
  → **A consistent level of system security compared to today's preventive system operation is only achieved if there is redundant execution of detection, control and retrieval as well as curative action.** Figure 4-2 presents two variants for redundant execution of curative measures.

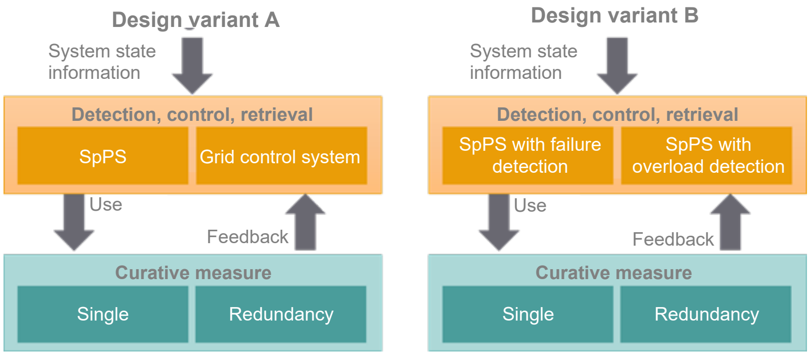


Figure 4-2: Possible realisation of the redundant execution of the curative measures

- The effect of the curative congestion management measures on the congestion must be sufficient. Insufficient impact of curative measures on congestion poses a higher risk than preventive measures.
  → **The risk posed by an insufficient impact of curative measures can be countered, for example, by using appropriate safety margins when dimensioning the measures (related to the congestion value or related to the curative potential).**

4.3 Effects on circuit utilisation, reactive power demand and dynamic stability

The effects of curative congestion management on circuit utilisation, reactive power demand and dynamic stability were investigated in quantitative studies. The most important results and the resulting conclusions are summarised below:

- The investigations showed that the curative concepts, which have a higher potential to reduce the application of preventive congestion relief measures, are associated with higher grid utilisation, as expected. Especially in the curative application of grid boosters, HVDC and PST, a higher number of lines than in the preventive reference scenario more frequently showed a load in a range that is usually critical for system operation. This can be seen in the simulations in both the (n-0) and (n-1) cases. Higher utilisation of the grids reduces the inherent security of the system, irrespective of the system operation concept, because in the event of a fault, equipment that was already more heavily utilised has to assume more power.

  → **Highly utilised grids reduce the inherent security of the system.**

- A comparison of the steady-state voltage-lifting reactive power demand between the reference annual run, in which only preventive redispatch was carried out, and the innovative annual run, in which curative measures were also used in addition to preventive redispatch, showed an additional demand of about 3.8 Gvar in the innovative annual run. From the simulation results, it could be determined that the reactive power demands and flows have increased significantly in some grid groups due to the curative mode of operation and the resulting higher utilisation of the grid. The resulting requirements must be taken into account in grid planning and grid expansion to ensure system security.

  → **Highly loaded grids require the expansion of reactive power compensation systems to ensure operational voltage stability and stability in the event of short circuits.**

- The failure scenarios analysed in terms of system dynamics showed that no additional instabilities occur due to the curative mode of operation. Regardless of the preventive and curative mode of operation, it became clear that the grid is close to the stability limits in individual grid use cases considered and that the mode of operation in the scenarios must be adjusted with regard to the stability limits. The dependence of stability on local reactive power requirements and reserves of the controllable systems also illustrates the relevance of high availability of the reactive power compensation systems.

  → **In highly loaded grids, short-term instabilities can occur with both preventive and curative congestion management.**

4.4 Importance of cyber security for curative system operation

With the introduction of new concepts for curative system operation, the need for information and communication technology (ICT) is also increasing in order to be able to network and automate the measures. However, this also increases the risk of cyber attacks on the grid infrastructure. For this reason, in InnoSys 2030 the curative measures were already systematically examined in the conceptual phase for cyber security risks with a special focus on the communication relationships and the processed data. Through the findings of this comprehensive security analysis, the concepts could be expanded with effective countermeasures and implementation notes, which then form the basis for subsequent secure implementation of the concepts.

One of the most important findings of the security analysis is to reduce the amount of time-critical communication between systems so that in the event of a problem, such as an cyber security incident, there is time to initiate curative measures. Adapted detection methods also play an important role here so that new threats can be recognised in good time. Furthermore, all systems involved must be enabled to recognise manipulations, falsifications and suppressions of measured values and also be able to distinguish these from technical disturbances, such as the inaccessibility of a system. Finally, it is advantageous for systems to behave as deterministically as possible in the event of an error, such as the transition to a secure default state, as this allows all actors involved to better assess the current state and thus avoid negative interactions.

However, the challenge remains that future design and implementation decisions will have a significant impact on the cyber security of the resulting overall system. For this reason, it is essential to consistently implement the lessons learned and to continue to consider the topic of cyber security in the development and implementation of new measures and concepts. Only in this way can the grid infrastructure continue to be effectively armed against the growing space of unknown threats in the future.

5 What is the interaction with the distribution system grid like?

The distribution grid is where most electrical loads and renewable energy plants are connected and can make a supporting contribution to curative congestion management in the transmission system grid by providing flexibility while avoiding congestion shifting to the distribution system grid. For this purpose, it is necessary to understand curative system control as a cross-voltage level approach and to consider the effects on distribution grid security as well as the applicability of curative system control in the distribution system grid. At the same time, operational planning and real-time system operation processes of distribution system operators must be designed in such a way that they are highly compatible with transmission system operator processes. This includes both the exchange of data and the design of common communication interfaces at the border between the distribution and transmission system grid.

5.1 Mutual influence of transmission and distribution system grids

In the case of a meshing between extra-high and high-voltage grid, influence on the high voltage power flow by the extra high voltage power flow is unavoidable (circular flows, as shown in Figure 5-1). Triggers can be unplanned equipment failures as well as planned switching operations or the use of equipment affecting the power flow (Figure 5-2). Curative operation sometimes amplifies these effects, as the grids are now more heavily utilised and power flow shifts can lead to congestion more quickly. Similarly, congestion in the distribution system grid can lead to the curative potential from the distribution system grid that can be used in the transmission system grid being limited. It is therefore essential that the transmission system operator takes greater account of the impact on the downstream distribution system grid in its operational planning processes. At the same time, operational planning processes must be designed in such a way that there is mutual traceability of the reactions to measures in the transmission and distribution system grid.

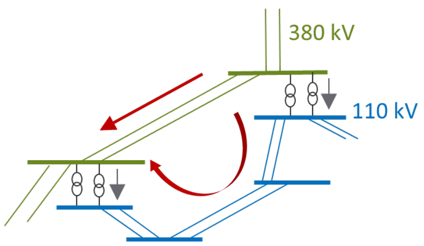


Figure 5-1: Circular flows in the meshed extra-high-voltage grid and high-voltage grid

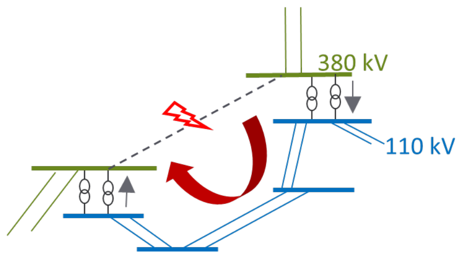


Figure 5-2: Power shifting to the high-voltage grid in the event of an equipment failure in the extra-high-voltage grid

5.2 Processual interfaces between operational planning processes of distribution and transmission system operators

Coordination of curative measures across voltage levels is a prerequisite for avoiding unwanted interactions between the transmission and distribution system grids. Figure 5-3 shows a possible design variant of a system operation process that ensures compatibility with both current Redispatch 2.0 requirements and the InnoSys system operation process: Joint circuit planning is followed by long-term and short-term forecast periods in which preventive and curative measures are planned and dimensioned. This takes into account the Redispatch 2.0 measures in the distribution grid that have been in effect since October 2021, for which available flexibility potentials are initially planned. In the future, overall optimised preventive and curative planning of flexibility potentials at this point is also conceivable. The surpluses in flexibility potential are first reported to the TSO and the TSO earmarks them for curative measures. The rolling exchange of potentials and planned measures between TSOs and DSOs can lead to further updates and refinement until transition to the real-time system operation area. Monitoring of the grid situation and activation of planned measures as well as the return to the (n-1) state take place in the real-time area.

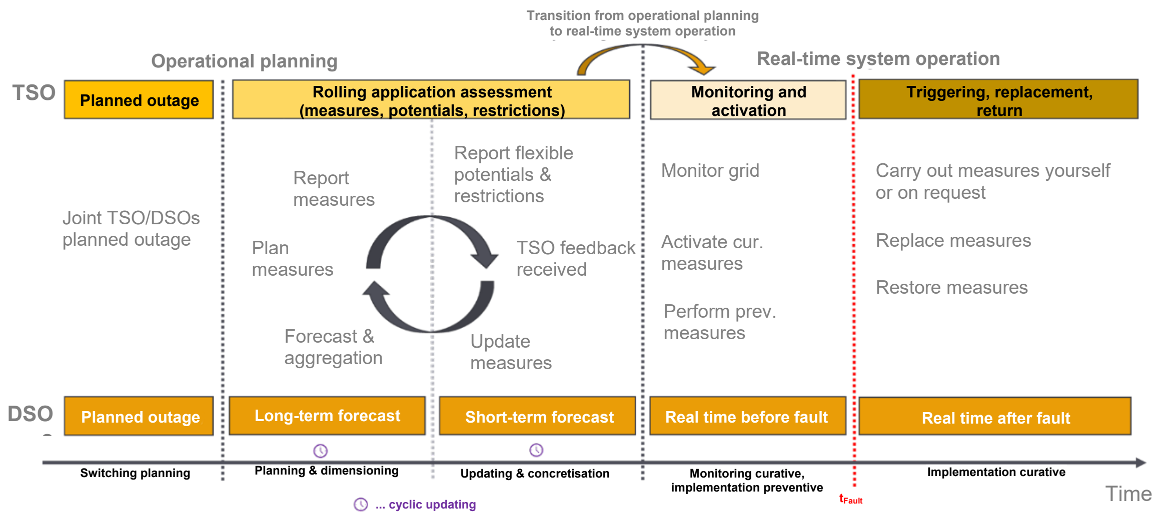


Figure 5-3: Possible DSOs system operation process with interfaces to the InnoSys system operation process

5.3 Transferability of innovative system operation to the distribution grid

In the InnoSys 2030 project, system and grid management concepts were developed with the aim of enabling higher utilisation of the transmission system grid in particular while maintaining at least the same level of system security. A qualitative analysis carried out by the distribution system operators Avacon Netz, MITNETZ Strom, Netze BW and Westnetz on the applicability of the technologies, concepts and effective mechanisms investigated in InnoSys 2030 shows that the curative system operation approach considered in the project can also be transferred to the high-voltage grid. Depending on the characteristics, implementation requires further investigations or developments. The conclusions of the analysis are explained below.

The principle of curative system operation can be implemented in principle in the HV grid. Process-related aspects, such as the system operation process or the curative limit value concept, are transferable in principle. The exact design as well as technological adaptations are to be reviewed depending on the area of application. The approach chosen in InnoSys 2030 of showing evolutionary stages, i.e. development steps from partial to full implementation, is also an approach to strive for in the distribution grid. Solutions with a relatively low level of complexity can use existing primary and secondary technology and require only minor further technological and process developments.

An area-wide application of curative system operation concepts in the distribution grid requires further investigations and developments regarding the specific characteristics of distribution grids.

In particular, the mutual influence of planned curative measures in the transmission and distribution grid must be considered in detail and taken into account in terms of process. In this respect, it also needs to be clarified to what extent the effects of the use of flexibility potentials in the distribution grid can be taken into account by TSO optimisation tools or whether own optimisation tools need to be (further) developed at distribution grid level.

With an increasing application of curative measures in the distribution grid, the importance of sufficiently accurate forecasts of power flows and available (curative) flexibility will increase significantly. In addition, the regulatory framework conditions require an in-depth analysis, especially with regard to the (curative) use of flexibility or of (decentralised) grid boosters, but also with regard to other legal framework conditions such as emission limits.

Furthermore, the benefits and economic efficiency of curative system operation in the distribution grid itself have not been considered so far. It must be investigated under which conditions and for which applications such an approach is appropriate.

Within the framework of an implementation, in particular, of curative plant management in the distribution system grid, the transmission system grids can take an active role.

In order to maximise the effect of higher utilisation of the entire electricity grid, potentials and measures of the transmission system grid with high sensitivity to the distribution grid can also be used for higher utilisation of the distribution grid where possible. These include large conventional power stations and grid booster plants, which can be used to balance out distribution grid flexibility in terms of energy. The opposite case, i.e. replacement, redundancy and energy balancing through distribution grid flexibility, is already considered in the concepts for grid booster application and curative redispatch with conventional power stations.

In the context of a decentralised grid booster approach (e.g. as battery storage in the distribution grid), synergy effects could also possibly be tapped with regard to joint but coordinated curative application.

6 What happens after InnoSys?

In InnoSys 2030, a roadmap was developed that describes how the developed concepts can be realised by 2030 and beyond. A phased approach was proposed for implementation, which takes place in six fields of action. The most important stages of the roadmap are briefly presented in the following sub-chapters.

6.1 The InnoSys 2030 roadmap for the implementation of innovative system operation

The implementation of the concepts within the fields of action should take place step by step. The roadmap envisages three evolutionary stages for this, as shown in Figure 6-1.

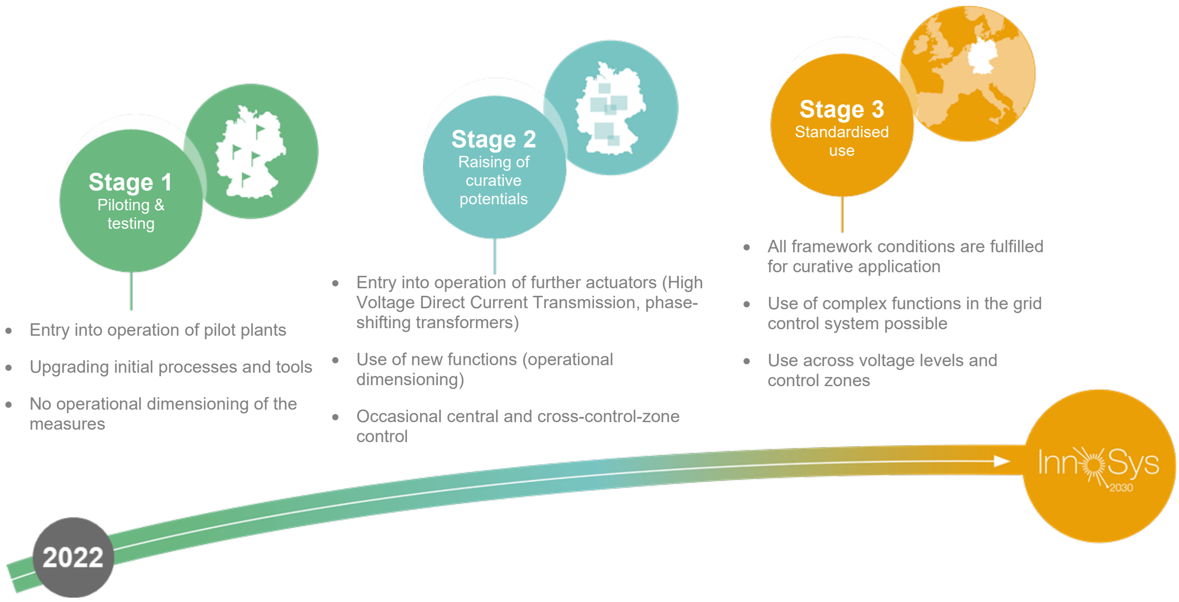


Figure 6-1: Step-by-step implementation of the InnoSys concepts

For the first stage "Piloting & testing", initial systems and processes are being upgraded and experience gained in pilot projects. Further activities are being initialised, primarily to define the framework conditions for curative application. Building on this, actuators such as phase-shifting transformers and HVDC systems are put into operation in the second stage, "Raising of curative potentials", which offer the grid operator further degrees of freedom to relieve power circuits curatively. Due to the increasing complexity, new systems or an extension of existing systems are required, which, for example, allow for an operational dimensioning of the measures. With the third stage "Standardised use", the corresponding developments and activities have been completed to such an extent that curative application has established itself as an integral part of congestion management. The framework conditions for all technologies are defined so that each of the six technology concepts addressed in InnoSys 2030 can be applied. The implementation of curative congestion management is not yet complete after reaching the third stage. Subsequently, it will be a matter of continuously putting further measures for curative application into operation in order to be able to use the potential demonstrated in InnoSys in the long term.

6.2 Fields of action and relevant stakeholders

The concepts developed in InnoSys 2030 can make an important contribution to the energy transition, as they enable a higher utilisation of the transmission grid through power flow control and the curative application of congestion management measures, thus allowing a faster integration of renewable energy. The realisation of the concepts is partly associated with high resource and development costs and takes place in different areas. Six fields of action were identified in the project, which include the most important development steps (see Figure 6-2).

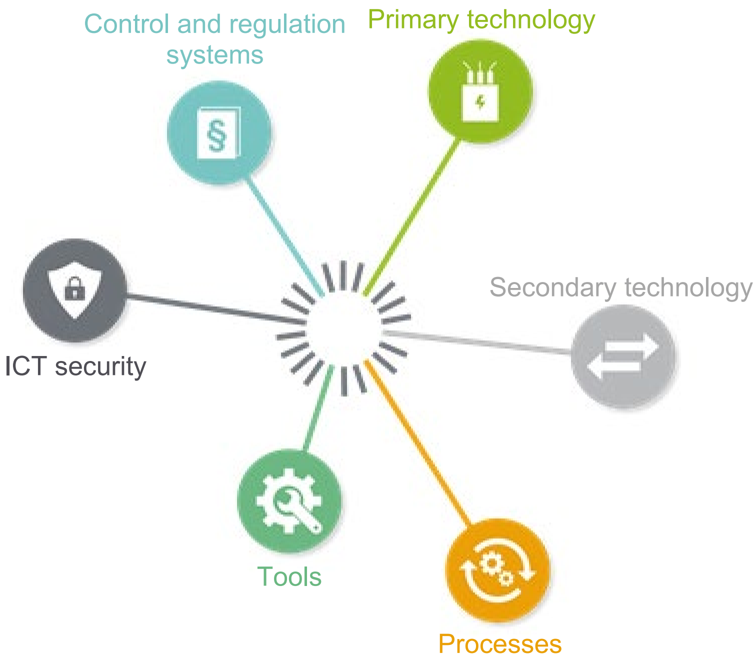


Figure 6-2: InnoSys fields of action for the implementation of curative congestion management

In the field of action Primary technology and technologies for curative application, two aspects are addressed. On the one hand, the existing grid must be upgraded in order to be able to fully utilise the potential for higher capacity utilisation. Some of the bay components have to be replaced for this. The possibility of temporarily using existing equipment to a higher capacity – beyond the permanently permissible limits – can reduce the cost of upgrading bays. This requires the development of appropriate standards.

On the other hand, actuators are to be put into operation that can be considered for curative application. Some actuators, such as conventional power stations and renewable energy plants, are already available. Other actuators such as PSTs and HVDCs are already firmly planned by the past grid development plans and will be realised in the next few years. In perspective, it makes sense to consider curative measures in the grid planning in order to reduce the required grid expansion in the long term and to optimally position the actuators also according to their curative benefit.

In addition to the actuators, additional power compensation devices are also required to ensure the voltage stability of the electrical grid in the event of higher utilisation.

The secondary technology field of action addresses four development areas. In the area of “Connection of actuators”, the need for additional action is relatively low because most actuators are connected to the process grid of the respective grid operator as part of entry into operation anyway. Special features arise when connecting power stations that usually cannot be controlled directly via the grid operator’s grid control system. If necessary, this can be based on the findings from the power-frequency control, which can be used to automatically adjust the power when a signal is received from the grid control system.

In addition to the actuators, additional sensors are also required. The transmission system grid already has very good observability, as current and voltage transformers are installed in every field. For validation purposes, however, it can be useful to provide additional sensors, e.g. to measure the temperature of the equipment. In addition, the expansion of the Wide Area Monitoring System with corresponding Phasor Measurement Units can bring advantages in the evaluation of success (e.g. high-frequency system state detection using hybrid state estimation) and in the further development of special protection schemes. Observability in the subordinate voltage levels is of great importance for a secure call-up of flexibility from the distribution grid. While there is generally good observability in high voltage, many distribution system operators are working on expanding observability (e.g. also in medium voltage) independently of curative system operation.

Another field of development in the field of secondary technology is the so-called Special Protection Schemes, which are a core component in the very fast, automated triggering of curative measures. In order to meet future requirements, the systems need to be further developed to allow for a more flexible and cross-regulatory use.

The project showed that protection limits can limit the higher utilisation of circuits. The first step is to identify circuits to which this applies and, based on this, to check the extent to which protection limits can be raised. This is to be seen as a continuous process that will be carried out together with the grid expansion. In order to ensure that the grid can be operated securely despite higher protection limit values, online monitoring of the settings for protection excitation (protection excitation polygon) is recommended in the future.

The field of action Processes deals with the implementation of the system operation process developed in InnoSys 2030 (see also 2.2 The InnoSys system operation process). Building on the established process landscape of the transmission system operators, preventive and curative measures must be jointly dimensioned in the future. In addition, depending on the technology, there are new processes for determining replacement and return measures. For real-time operation, processes for monitoring, triggering and success control must be developed.

For the necessary fast coordination and communication in the real-time processes, the prerequisites must be created so that the necessary information can be exchanged automatically and reliably between the grid operators. In addition to the interfaces, the data formats must be expanded or adapted in order to be able to take into account the additional information for curative application.

An important aspect with regard to the further development of the national and local processes is that they are in line with the planned international developments on congestion management.

The field of action Tools for system operation covers the adaptation and development of new tools and functions required for curative congestion management in operational planning and real-time operation. Operational planning is mainly about tools that are used to determine application. The tools for power flow optimisation must be adapted so that preventive and curative measures can be identified in a coherent manner. In addition, tools for determining TATL limits, replacement measures, redundancy and return measures must be developed in operational planning. To take curative distribution grid flexibility into account, exchange platforms and control centre couplings need to be upgraded, via which the forecast potentials can be communicated and measures triggered. The DSOs need appropriate tools to determine the potentials.

The system analysis and system optimisation functions must be upgraded for real-time operation. The grid security calculation must be able to map the effectiveness of curative measures in order to avoid unnecessary preventive measures and negative interactions. The variables determined in operational planning (e.g. TATL, reaction matrix) are to be updated in real-time operation via corresponding assistance systems in order to be able to react as efficiently as possible to failure situations. Modules in the grid control systems that enable central curative control are to be provided for triggering the measures. For secure operation in the higher utilised grid, DSA[8] tools are also needed for real-time operation, which are applied in line with the steady-state grid security calculation.

Mainly non-technical development steps are shown in the field of action Regulatory and legal framework, standards and contracts. The existing regulatory framework, especially with regard to §13 EnWG, also allows the application of curative measures. Regulatory challenges are seen above all in the concepts of grid boosters and curative redispatch from the distribution system grid.

[8] DSA: Dynamic Security Assessment

As the application of curative measures leads to a higher utilisation of the transmission system grid, approvals may be required due to the higher electromagnetic immissions and interference with the external grid. This depends primarily on whether the curative application concept is classified as a change to the operational concept according to §43f EnWG. In principle, the obstacles to implementation should be removed by current regulations (e.g. in the TA-Lärm [German Noise Prevention Code]) in order to enable faster approval procedures. In the context of approvals, as many synergies as possible should also be used with the implementation and application of weather-dependent overhead line operation.

In order to ensure that grid operators have the necessary data basis for curative application planning, guidelines may need to be expanded. Furthermore, the implementation of curative congestion management can be advanced more quickly if the principles of curative application are described in higher-level guidelines (e.g. FNN guidelines). Already installed systems may not have the necessary technical requirements for curative application. To ensure this for new installations, the technical connection rules must be adapted. In principle, it is important that curative application is considered and taken into account when adapting existing guidelines or creating new ones.

The field of action cyber Security addresses three areas of development. The first area addresses the validation and plausibility of measured values and commands. Appropriate methodology is to be developed and systems are to be upgraded to protect the communication network from the manipulation of measured values and commands. If manipulations nevertheless occur, they must be reliably detected by means of a comparison with the expected value.

The second area is about resilience against delays, accessibility errors and suppression. As part of the implementation of the InnoSys system operation concepts, it must be checked to what extent the communication networks used meet the necessary high reliability requirements or whether further redundancy measures are necessary.

The third area deals with classic ICT protection measures. This includes segmenting and securing grid areas to make cyber attacks more difficult, legitimacy checks on messages and changes in the grid and securing remote maintenance access.

6.3 Open research questions

In the InnoSys 2030 research project, the developed system operation concepts were elaborated in detail, examined in extensive simulations and finally evaluated on the basis of the criteria. Nevertheless, beyond InnoSys 2030, there are further important research topics and open questions in the context of higher utilisation and curative congestion management, which are briefly described below:

- Thermal modelling of equipment: In the project, the thermal consideration for calculating the TATL limits focused on the overhead line. There is a need for further research into thermal modelling for primary technical equipment such as switchgear and converters.

- Power flow optimisation: In the power flow optimisation, all technology concepts except for those of the topology switching measures were considered in combination. Due to the complexity of topology optimisation, innovative approaches are needed to solve such optimisation problems.
- DSA: In InnoSys 2030, the subordinate grids were considered in aggregated form in the dynamic simulation. For a more accurate representation of the distribution grid, corresponding dynamic models of the distribution grid are required.

Other open issues include:

- Economic benefit: In InnoSys 2030, the benefits of curative congestion management were presented in terms of redispatch savings. Initial quantitative estimates of cost savings were made based on historical data. Further studies are needed to assess the overall economic benefits.
- A detailed consideration of the interactions between the transmission and distribution grid has not been carried out in the project. This applies in particular to the possible constraint of curative measures and the use of power flow control equipment due to technical restrictions in the distribution grid. With regard to the implementation of curative system operation, further individual case studies are therefore necessary.
- The analysis of a curative grid management to control congestion in the distribution grid was not part of the project. However, conceptual analyses have shown that the solution approaches developed in InnoSys 2030 can in principle also be transferred to the high-voltage grid. Further studies are required to specify the need for further development and concrete applications on the one hand, and to assess the technical and economic benefits on the other.

6.4 Conclusion and first steps after InnoSys 2030

In the InnoSys 2030 project, the theoretical foundations for curative congestion management were described and dealt with in detail. With the project ending in December 2021, it is important for a quick implementation that the results are directly followed up and the first activities are started. Fundamental to successful implementation will be pilot projects that, building on the initial experience, will help transmission system operators to improve the concepts and enable faster realisation of further concepts. Projects such as the net booster pilots are already in the concrete planning stage. Further uses for curative application will be internally evaluated by the grid operator after the end of the project.

The fields of action and development steps described in the roadmap are to be concretised together with the stakeholders involved so that activities can be initialised on this basis. The grid operators involved have already started to think about this. For successful implementation, it is important that curative congestion management is further developed in an interdisciplinary manner. Various platforms (conferences, workshops, etc.) are used to publicise the concepts and to engage in exchange with the stakeholders involved. In addition, further research projects are in the pipeline that will build on the results of InnoSys 2030. In order to maintain the discourse on curative congestion management with the stakeholders already involved (InnoSys advisory board) beyond InnoSys 2030, a regular stakeholder meeting is already planned.

7 Appendix

7.1 Presentation of the Stakeholders Involved (InnoSys Advisory Board)

An intensive professional exchange with the InnoSys Advisory Board was already maintained during the project. Interim results were discussed, intersections and additions to further studies were identified. The InnoSys Advisory Board consists of the following nine ministries, organisations and companies.

Federal Ministry for Economic Affairs and Climate Action (BMWK)	German Federal Network Agency (BNetzA)
B E T Büro für Energiewirtschaft und technische Planung GmbH *on behalf of the BMWK*	Austrian Power Grid AG (APG)
Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV)	Agora Energiewende
Federal Office for Information Security (BSI)	Deutsche Energie-Agentur GmbH (dena)
Federal Environmental Agency (UBA)	

Figure 7-1: InnoSys Advisory Board

7.2 Overview of the scientific publications in InnoSys 2030

To be read with the abstract and the link to the publication on the website http://www.InnoSys2030.de:

No.	Title	Authors	Place of publication	Date
1	Curative actions in the power system operation to 2030	Dirk Westermann, Steffen Schlegel, Florian Saas, Robert Schwerdfeger, Andreas Wasserrab, Ulf Häger, Stefan Dalhues, Charlotte Biele, Andreas Kubis, Jan Hachenberger	ETG Congress	May 2019
2	Planungsorientierte Simulation kurativer Maßnahmen im Deutschen Übertragungsnetz [Planning-oriented simulation of curative measures in the German transmission system grid]	Katharina Kollenda, André Hoffrichter, Maximilian Schneider, Alexander Schrief, Albert Moser	16th Symposium on Energy Innovations	February 2020
3	Integration kurativer Maßnahmen in das Engpassmanagement im deutschen Übertragungsnetz [Integration of curative measures into congestion management in the German transmission system grid]	Tobias van Leeuwen, Ann-Kathrin Meinerzhagen, Stephan Raths, Andreas Roehder	16th Symposium on Energy Innovations	February 2020
4	Probabilistische Analyse der betrieblichen Spannungshaltung im Übertragungsnetz [Probabilistic analysis of operational voltage stability in the transmission system grid]	Markus Knittel, Stefanie Samaan, Sascha Bauer, Albert Moser	16th Symposium on Energy Innovations	February 2020
5	Secure and dependable protection relay behavior in extremely high loaded transmission systems	Jakob Schindler, Jonas Prommetta, Johann Jäger	DPSP 2020	March 2020
6	Power Factor Improvement by Active Distribution Networks During Voltage Emergency Situations	Luis David Pabón Ospina, Thierry Van Cutsem	XXI Power Systems Computation Conference	Jul 2020
7	Preventive and Curative Actions by Meshed Bipolar HVDC-Overlay-Systems	Tom Sennewald, Franz Linke, Dirk Westermann	IEEE Transactions on Power Delivery	Jul 2020
8	Superposition-based Modelling of Series FACTS in Nonlinear Mathematical Optimized Grid Operation	Denis Mende, David Sebastian Stock, Lutz Hofmann	ISGT Europe	October 2020
9	Parameter Optimization of Differential Evolution and Particle Swarm Optimization in the Context of Optimal Power Flow	Tom Sennewald, Franz Linke, Jakob Reck, Dirk Westermann	ISGT Europe	October 2020

No.	Title	Authors	Place of publication	Date
10	The contribution of distributed flexibility potentials to corrective transmission system operation for strongly renewable energy systems	Till Kolster, Rainer Krebs, Stefan Niessen, Mathias Duckheim	Applied Energy	December 2020
11	Security Assessment for higher loaded power system operation to 2030	Alexander Raab, Gert Mehlmann, Jakob Schindler, Matthias Luther, Matthias Abel, Stefan Horn, Chris Heyde, Pascal Wiest, Rainer Krebs, Andreas Kubis	ETG Congress	May 2021
12	Development of a Preventive and Curative Congestion Management Module for Close to Real-Time Transmission System Operations	Jan Hachenberger, Richard Küsters, Andreas Kubis, Tatjana Rzymek, Matthias Abel, Christian Greiten, Andreas Gumbel, Robert Schwerdfeger, Andreas Wasserrab, Peter Hoffmann	ETG Congress	May 2021
13	Approach to the Identification of Critical Contingencies for the Stability Analysis of Innovative Operational Concepts	Stefanie Samaan, Motjaba Momeni, Markus Knittel, Carola Meier, Albert Moser, Moritz Mittelsteadt, Stephan Winck	ETG Congress	May 2021
14	Load Encroachment in the Presence of Single-Phase Autoreclosure and Bulk Power Transmission	Jonas Prommetta, Jakob Schindler, Johann Jäger, Christian Romeis, Timo Keil	IEEE PowerTech	June 2021
15	Steady-State and Dynamic Security Assessment for System Operation	Alexander Raab, Gert Mehlmann, Matthias Luther, Tom Sennewald, Steffen Schlegel, Dirk Westermann	SEST 2021	September 2021
16	Adaptive Power Control of VSC-HVDV as a Corrective Measure	Alexander Raab, Dominik Frauenknecht, David Riebesel, Gert Mehlmann, Matthias Luther	ICPEA 2021	October 2021
17	Corrective congestion management in transmission networks using fast-responding generation, load and storage	Martin Lindner, Ulf Häger, Andreas Wasserrab, Ilhami Sacar, Mitra Ariatabar, Tobias van Leeuwen, Denis Mende, Marcus Lässig, Christian Lakenbrink	2021 IEEE Electrical Power and Energy Conference (EPEC)	October 2021
18	Kurative Systemführung – Gemeinsame Herausforderungen für Übertragungs- und Verteilnetzbetreiber bei der Umsetzung eines höherausgelasteten Stromnetzbetriebs [Curative System Operation – Common Challenges for Transmission and Distribution System Operators in Implementing Higher Load Electricity System Operation]	Julian Vielemeyer, Marcus Lässig, Christian Lakenbrink, Thomas Schmidt, Sebastian Sengen	ETG-CIRED Workshop “Innovationen im Verteilernetz / Innovations in the Distribution System Grid”	November 2021

No.	Title	Authors	Place of publication	Date
19	Best Practice for Creating Dynamic Network Models based on Power Flow Models for DSA Applications	Johannis Porst, Ilya Burlakin, Elisabeth Scheiner, Matthias Luther, Stefanie Samaan, Markus Knittel, Mojtaba Momeni, Albert Moser, Hendrik Just, Stefan Horn	17th Symposium on Energy Innovation	February 2022
20	Verteilnetze als Freiheitsgrad für kurative Systemführung [Distribution system grids as a degree of freedom for curative system operation]	Christian Lakenbrink, Denis Mende, Julian Vielemeyer, Thomas Schmidt, Till Kolster, Mathias Duckheim, Marcus Lässig	ew-Magazin	May 2022
21	Curative measures identification in congestion management	Katharina Kollenda, Alexander Schrief, Charlotte Biele, Martin Lindner, Niklas Sundorf, André Hoffrichter, Andreas Roehder, Albert Moser, Christian Rehtanz	IET Gener. Transm. Distrib.. 1–13 (2022)	May 2022

7.3 Further information and documents regarding InnoSys 2030

Factsheets

- Mechanism of Curative Remedial Actions
- InnoSys System Operation Process
- InnoSys Roadmap

Reports

- Final Report
- Executive Summary of Final Report
- InnoSys System Operation Process
- InnoSys Roadmap

Presentations

- Project Profile
- InnoSys Core Messages

All content can be found at www.InnoSys2030.de. Please contact us at innosys@tennet.eu.

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