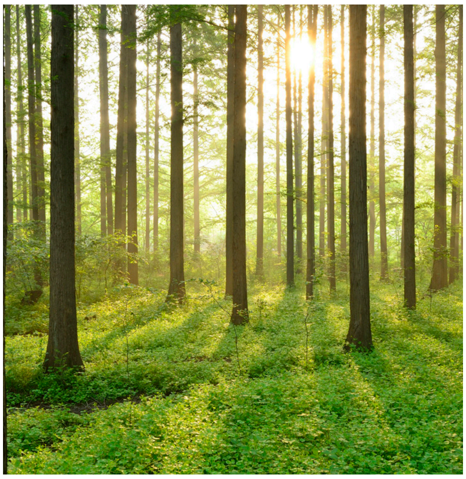
SURVEY ON VIBRATION IMPACT OF FLEXIBLE OPERATION ON NPP

REPORT 2021:774




NUCLEAR

VIBRATIONS IN
NUCLEAR APPLICATIONS


Energiforsk

Survey on Vibration Impact of Flexible Operation on NPP

Based on Operational Experience

TATIANA SALNIKOVA, PETER FORSTER, JUERGEN RUDOLPH, FRANCIS FOMI WAMBA
WALDEMAR GEISSLER, VEIT MARX

ISBN 978-91-7673-774-3 | © Energiforsk May 2021 | Cover Photo: W.Wacker, Wikimedia Commons
Energiforsk AB | Phone: 08-677 25 30 | E-mail: kontakt@energiforsk.se | www.energiforsk.se

Foreword

Nuclear power plants have traditionally been used for base load operation, meaning that plants are generating electricity at stable load and other, more easily adjustable generating units are regulating the grid. However, the significant increase of electricity production of highly intermittent nature, like wind and solar, can lead to a situation where load follow of nuclear power plants will be necessary.

To minimize the risk for deterioration and premature failures caused by high vibrations due to load follow, it is vital to understand what type of problems may occur, how it might affect the main components of the plant and how the problems can be mitigated. In this project senior Framatome experts led by Tatiana Salnikova have interviewed German plant managers and collected hands-on information on experienced vibration problems related to load follow.

The study was carried out within the Energiforsk Vibrations research program. The stakeholders of the Vibrations program are Vattenfall, Uniper, Fortum, TVO, Skellefteå Kraft and Karlstad Energi.

These are the results and conclusions of a project, which is part of a research programme run by Energiforsk. The author/authors are responsible for the content.

Sammanfattning

Syftet med denna rapport är att ge en översikt över hur flexibel drift (FlexOp) påverkar vibrationerna i olika komponenter och system i ett kärnkraftverk. Framatome har genomfört intervjuer med experter och representanter från ledningen i flera tyska kärnkraftverk för att samla tillämpade drifterfarenheter. Representanter från både tryckvattenreaktorer (PWR) och kokvattenreaktorer (BWR) har intervjuats. Relaterade aspekter, såsom påverkan på utmattning eller slitage, har också studerats i denna rapport. För bättre förståelse av resultaten ges också information om vilken typ av flexibilitet som kraftverket har erbjudit samt om specifika egenskaper hos respektive anläggning. Vidare presenteras åtgärder som genomförts för att minska vibrationsproblematiken. Informationen i rapporten kan användas av andra kraftverk som är på väg att gå från baslast till flexibel drift, för att minska risken för att problem uppstår i samband med övergången.

Undersökningen visar att för de flesta kärnkraftverk så definieras en lägsta effektnivå för FlexOp, vanligtvis till 50-60% av den elektriska effekten. Några BWR utförde till och med FlexOp endast mellan full effekt och 70%. Det finns olika skäl till ett sådant beslut. PWR drivs normalt med konstant temperatur i primärsystem, detta för att minska påverkan på komponenterna i primärsystemet och BWR använder mestadels huvudcirkulationspumparna för att undvika deformation av den axiella kraftfördelningsprofilen. Även vibrationsproblematik vid låga effektnivåer kan ha en inverkan på de införda begränsningarna i flexibilitetsintervallet. Förutom dessa uppenbara fördelar för att hålla sig i högre effektområden visade erfarenheten att större och inte alltid förutsebara vibrationer kan uppstå vid lägre effektnivåer. Nödvändiga och lämpliga motåtgärder såsom att undvika vissa effektnivåer eller att införa ytterligare övervakning och utvärdering presenteras. Sådana åtgärder gör det möjligt att övervaka vibrationspåverkan och alltid utföra FlexOp på ett säkert och tillförlitligt sätt.

Det finns omfattande erfarenheter av FlexOp av olika slag finns i tyska kärnkraftverk. Denna rapport sammanfattar kunskap från konstruktion och drift av tyska kraftverk vad gäller hur FlexOp påverkar drift, slitage och andra praktiska erfarenheter.

När det gäller elektriska komponenter spelade inte bara påverkan av FlexOp en roll, utan också övergripande förändrade förhållanden så som exempelvis. spänningsstyrning eller nätinducerade vibrationer. Sådana förhållanden visade sig ha en stark inverkan på generatorer, särskilt i norra Tyskland.

Slutligen presenteras nya innovationer som syftar till att förbättra tillförlitligheten och lönsamheten för den flexibla driften (minska driftskostnaderna för flexibilitet), såsom dataanalys, inklusive lovande resultat från pilotkraftverk som förbereder sig för FlexOp och utförde testtransienter. Idéer om att integrera denna lösning för att komplettera befintliga Energiforsk DIAM-Matrix föreslås. Även nya idéer om vibrationsutmattningsövervakning eller ämnet högcykelutmattning introduceras i rapporten.

Summary

This report has as a main goal to provide a survey of the vibration impact of flexible operation (FlexOp) on different components and systems of NPPs. It is based on the existing operational experience in German Pressurized Water Reactors (PWR) and Boiling Water Reactors (BWR), collected by Framatome via several interviews with experts for operating and shutting down NPPs. Also, other aspects, like impact on fatigue or wear and tear, are mentioned in this report. For better understanding of the results, information about the type of performed flexibility and about some specific features of the plant are provided as well. The mitigation measures applied are described and new R&D results are presented. That information can be used by Nordic NPPs to minimize possible risks in the future.

The survey showed that for the most NPPs the minimum power level for FlexOp is typically defined at 50-60 % REO. Various BWRs even performed FlexOp only between full load and 70 % REO. There are various reasons for such decision. PWRs operate mostly in the range of the constant average coolant temperature to reduce the overall impact on the components and systems and BWRs are mostly using recirculation control to avoid deformation of the axial power distribution profile. But the vibration issues at low power levels were also stated to have an impact on the introduced limitations. Besides these obvious benefits for staying in higher power ranges, experience showed that higher and not always foreseeable vibrations may occur at lower power levels. Necessary and appropriate countermeasures like avoiding certain power levels or additional monitoring and corresponding evaluations are presented. Such measures allow to control vibration impact and to perform FlexOp always in a safe and reliable manner.

Generally, it can be stated that comprehensive experience with FlexOp of various types is available in German NPP for both PWRs and BWRs. The report summarizes the existing knowledge from design and operation of German NPP concerning the FlexOp induced impact besides vibrations on fatigue, wear and tear and several addition topics stressed during the interviews as well.

Regarding electric components not only impact of the FlexOp, but also overall changed conditions like voltage control in underexcited mode or grid induced vibrations played a role. Such conditions were shown in this report to have a strong impact on generators, especially in the north of the country.

Last, but not least, new Framatome developments aiming at the improvement of the reliability and profitability of the flexible operation (reducing operation costs of flexibility), like data analytics solution named CADIS, are presented including promising results from the pilot NPP that is preparing for FlexOp and performed test transients. Ideas to integrate this solution to complete the existing Energiforsk DIAM-Matrix was proposed. Also new ideas of vibration fatigue monitoring or the topic high cycle fatigue were introduced in the report.

Abbreviations

Term	Description
ABB	Asea Brown Boveri
ADAM	Valve diagnostics and evaluation method
AEM	Australian Energy Market
AEMO	Australian Energy Market Operator
ARMA	Auto Regressive Moving Average
aFFR	Frequency Restoration Reserves with Automatic Activation
AGC	Automatic Generation Control
AI	Artificial Intelligence
AIV	Acoustic Induced Vibration
ALFC	Advance Load Following Control
approx.	approximately
ARMA	Auto Regressive Moving Average
ASME	American Society of Mechanical Engineers
BWR	Boiling Water Reactor
CADIS	Central Asset Data Intelligence System
CFD	Computational Fluid Dynamics
CHP	Combined Heat and Power generation
CMS	Central Monitoring System
COMSY	Condition Monitoring System
CRDM	Control Rod Drive Mechanism
CRDS	Control Rod Drive System
CT	Coolant Temperature
CUF	Cumulative Usage Factor
CVCS	Chemical and Volume Control System
DIAM	Detection – Investigation – Analysis - Mitigation
DIN	German Institute for Standardization
DSU	Demand Side Unit
ELPO	Extended Low Power Operation
ENBW	ENBW AG (power station operator)
EPRI	Electric Power Research Institute
FA	Fuel Assembly
FAMOS	Fatigue Monitoring System
FMS	Fatigue Monitoring System
FCAS	Frequency Control Ancillary Services
FCR	Frequency Containment Reserve
FEA	Finite Element Analysis
FEM	Finite Element Method
FIV	Fluid Induced Vibration
FlexOp	Flexible Operation
FC	Frequency Control
FR	Fuel Rod
FRR	Frequency Restoration Reserve
FRT	Fault Ride Through
FSI	Fluid Structure Interaction

H2	Hydrogen
HCF	High Cycle Fatigue
HIV	Health Index Value
HP	High Pressure
IAEA	International Atomic Energy Agency
ISO	International Organization for Standardization
KWU	Kraftwerk-Union (predecessor of Areva, Framatome GmbH)
LFO	Load Follow Operation
LOCA	Loss of all coolant accident
LF	Load Following
LP	Low Pressure
LPMS	Loose Part Monitoring System
LTO	Long Term Operation
mFRR	Frequency Restoration Reserves with Manual Activation
MR	Minute Reserve
MPa	Mega-Pascal
MWel	Mega-Watt (electric)
NEA	Nuclear Energy Agency
NPP	Nuclear Power Plant
OEM	Original Equipment Manufacturer
PCA	Principal Component Analysis
PDD	Power Distribution Detectors
PEL	Preussen Elektra
PCA	Principal Component Analysis
PFC	Primary Frequency Control
PCI	Pellet Cladding Interaction
PN	Nominal Power
PWR	Pressurized Water Reactor
RCC	Recirculation Control Curve
RCCA	Rod Cluster Control Actions
R&D	Research and Development
REO	Rated Electrical Output
RMS	Root-Mean-Square
RPV	Reactor Pressure Vessel
RT	Reactor Trip
RTP	Rated Thermal Power
RUL	Remaining Useful Lifetime
RWE	RWE AG (power station operator)
SFC	Secondary Frequency Control
Smax	Maximum vectorial vibratory displacement (acc. to ISO 20816-1)
VDI	Association of German Engineers
VGB	German Association of Plant Operators
VHCF	Very High Cycle Fatigue
VMS	Vibration Monitoring System
WKK	Wirtschaftsverband Kernbrennstoff-Kreislauf und Kerntechnik

List of content

List of figures

List of tables

1 Introduction

This report provides a survey of the vibration impact of flexible operation on different components and systems of a Nuclear Power Plant (NPP). It is based on the existing operational experience in German Pressurized Water Reactors (PWR) and Boiling Water Reactors (BWR) collected via literature survey and several interviews with experts mostly from NPPs in Germany that are in operation and have about two decades of advanced flexibility behind themselves. Also, NPPs that have been already shut down were interviewed.

Nordic countries are also currently evaluating different types of flexible operation including load following and enhanced low power operation. The Swedish and Finnish nuclear fleet has operated in base load for more than 25 years. Today the integration of the intermittent renewable energy sources increases the need for flexibility. Already the nearest future may increase the required level of flexibility.

The current survey gathers operational experiences regarding flexible operation with a focus on the vibration impact. Particularly analyzed are partial load operation, existing countermeasures and performance of KWU-NPPs.

The Energiforsk Vibrations program supported the project through:

- Reference group with experts from the participating NPPs. They supported with information from the plants, assisted in discussions on delimitations and priorities during the project. Furthermore, they reviewed the draft report.
- Steering group with experts from participating NPPs. They took strategic decisions and reviewed and approved the final version of the report.
- Energiforsk project leader who assisted in the administration of the project.

This project was performed by Framatome GmbH. Framatome itself is an international leader in nuclear energy recognized for its innovative solutions and technologies for the global nuclear fleet. For this study, Framatome provides special competence in flexible operation of nuclear power plants, in the topic of vibrations in general and regarding flexible operation of NPPs. Framatome's team collected the operational experiences of KWU-built NPPs concerning the impact of vibrations on the whole NPP including fuel assemblies. They paid special attention to the possible mitigation measures including the results of the current pilot and R&D projects.

Employees of various departments have participated in this project as consultants: safety, process technic, aging (including consultants with a strong background in measurements), fatigue analysis, corrosion, data evaluation systems, electrical equipment and fuel mechanics. The interviewed persons from German NPPs are representing a wide range of disciplines ranging from technical management of the plant or electric utility to experts in operation and maintenance of primary and secondary circuit components and systems.

German utilities have strongly supported the collection of the required information for section 4.4. Especially, Preussen Elektra and in particular Thomas Fuchs provided information about German PWRs in the North. NPP ISAR 2, represented

by plant manager Carsten Müller and his staff, namely Konrad Schirrmeister, Jens Thomas, Bernd Gerber, Mario Buchholz, kindly agreed to share operational experience, and their figures strongly contributed to section 4.4. Also, RWE, and particularly KRB NPP, represented by the operational manager Gerhard Hackel and his whole team, kindly agreed to discuss BWR operation during an interview, which was carried out directly in the plant. Support of Christoph Heil and EnbW staff, in particular Steffen Riehm and Mathias Stein, were very helpful to get an overall feedback and some concrete examples. Discussions with Jing Wang for the fatigue feedback were fruitful. Also, Vattenfall contributed to the project with Thomas Pahl and Heiko Rades giving feedback from Brunsbüttel NPP which performed flexible operation in the past. The possibility to integrate the results from previously performed Framatome studies in this report, e.g. provided by Alexander Mutz from Swiss NPP Gösgen-Däniken, helped a lot to illustrate possible countermeasures showing their effectiveness.

Keywords

Vibrations in NPPs, Flexible operation of NPPs, vibration impact of flexible operation, mitigation measures for vibrations, surveillance concept for the secondary side, operational experience of German NPPs

2 Background

2.1 INTRODUCTION

NPPs have traditionally been constructed for base load operation, meaning that NPPs are generating electricity at stable (nominal) load and other, more easily adjustable generating units are regulating the Grid. However, the significant increase of electricity production of highly intermittent nature, like wind and solar, can cause a situation where load follow operation of NPPs becomes necessary.

To minimize the risk for deterioration and premature failures caused by high vibrations due to load follow operation, it is vital to have an understanding of what type of problems may occur and how it might affect the main components of the NPP. Apart from understanding the potential problems, it is important to know how to avoid problems or mitigate them. In this way, a safe and reliable long-term operation of the NPP can be assured.

During 2018, Energiforsk has done a research project with Fraunhofer Institute which was focusing more on theoretical part of vibrations relating to the load follow operation. The work is reported in (Nordmann & Ranisch, 2018).

For continuation of the project and additional work within the area, the scope of the current report is focused more on operational experiences, practical mitigation methods and how to estimate possible impact to the component's lifetime due to load follow operation induced vibration changes.

The operational experience in different flexible modes of operation is increasing already over decades. Most valuable experience is existing in France and Germany. As the BWR experience can be found only in Germany, it will be the first country to look at for the overall evaluation feedback. It also has to be mentioned that the level of the proactive monitoring in German plants is very high, so that some effects can be seen already in the early stage.

To illustrate the flexible operation performance of German PWRs and BWRs, the following annular production curves from the year 2009 with strong impact of negative prices can be taken.

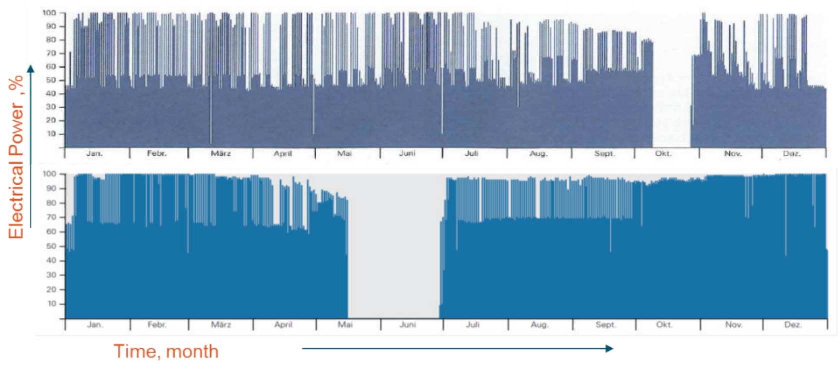


Figure 1: Electric output in % in 2009 of two German NPPs , PWR (top)/ BWR (bottom) (ATW, 2010).

Such curves include various types of grid services provided by NPPs. Thereby, the corresponding operation modes of the plant providing flexibility can be illustrated in a simple way as follows, corresponding to the type of the grid requirement it is dealing with. Voltage control is not included in Figure 2.

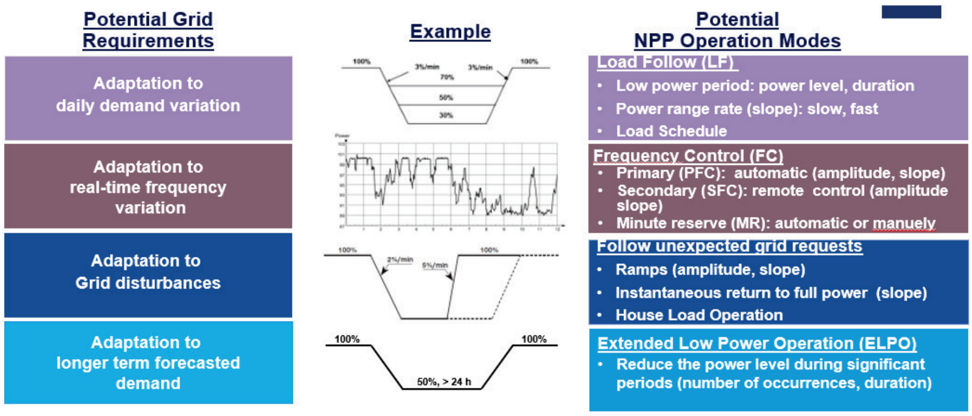


Figure 2: Flexible Operation modes from NPP point of view.

Appendix A gives the definition for such modes and corresponding procured grid services, the way it is activated and the typical range for the plants providing flexibility in Germany, summarized from Table 13 of the survey on power system ancillary services provided by NPPs (Hänninen et al., 2020). This work was carried out by Framatome GmbH during the joint project with VTT LtD and Aalto University for Energiforsk. Such kind of knowledge is valuable for better understanding of the overall level of flexibility of the NPPs interviewed during this project. Various modes are often superposed and the plant operator, in case e.g. of remote controlled operation, can hardly differentiate between different ramping products, e.g. operating in secondary frequency control (SFC) and providing aFRR (automatic Frequency Restauration Reserve), minute reserve (MR) and providing mFRR (manual Frequency Restauration Reserve) or load following (LF) mode used for economical dispatch or redispatch measures. In this case, remote secondary control is activated within predefined power range and with allowed power ramp rates upwards and downwards, respectively.

For this evaluation, it plays no role whether the response is automatic or manual, what is the time before request and whether the service is provided as a result of economic consideration (economical dispatch) or due to grid request (redispatch).

In the following, “FlexOp” will be used as a simplification for all ramping modes providing different services to the grid, except some cases where differentiation is required due to the context.

The vibration performance of the components and systems is assumed to be impacted by FlexOp operation mostly due to the operation at partial load conditions, and this is the case with different modes, only the duration on the partial level is different from minutes and hours up to days and sometimes even months, as in the case of Extended Low Power Operation (ELPO). Also, the power range of the performed services can be different, reaching in some cases even technical minimum power level, as well as the performed ramp rate (slope).

2.2 FLEXIBLE OPERATION IN KWU NPPS

NPPs of the predecessor company of today's Framatome GmbH, German KWU, had already been designed for enhanced capability for load following, primary and secondary frequency control, minute reserve and with partial load capability in the 1980s.

For a long time, these capabilities were only occasionally used to cope with some grid-related events. The strong need for frequent FlexOp has appeared only in the last two decades in order to compensate the rapidly increasing, but fluctuating power generated by renewable energy sources.

These developments led to the first modernization projects related to the improvement of the turbine instrumentation and control systems. Since 2008, the German electricity market allows negative electricity prices. Overall energy and balancing market development leads to new business cases for NPPs and they increased stepwise the ranges for the various grid services to be performed by the plants. Highest levels within the given limits in all phases of the burn-up cycle were achieved by the PWRs that introduced Advanced Load Following Control (ALFC) as an upgrade of the TELEPERM-XS reactor control.

This digital solution covers Xe-calculation, automated reactivity management and optimized axial power distribution control, which inhibits any axial oscillation of the axial power distribution in the beginning. It also allows, if required to perform flexible operation without manual intervention of the operator, corresponding to stochastic load changes (Kuhn, A. & Klaus, P., 2016). Furthermore, ALFC was improved adding predictor technology including, among others features, visualization of the reactivity management (Kuhn, A. & Schirrmeister, K., 2018) and optimization strategies for ELPO. Overall, thanks to ALFC, smoother operation became possible also with respect to FlexOp impact on systems and components. Today Framatome is further developing predictor technology for FlexOp as a separate expert system for each type of plant (Morokhovki, V., 2020).

During FlexOp, various ramping modes are typically activated with a power ramp rate from 10 to 30 MWel per minute and in the range from full power to approximately 50 % of Rated Electrical Output (REO) in PWRs and 60 % REO in BWRs in order to reduce the possible negative impact on the plant. From the I&C point of view higher ramp rates as well as a range from 100 % till minimum load could be achieved, if required. As an example, the commissioning test of ALFC was performed with 40 MWel per minute.

2.2.1 Description of the power change

PWR

The schematic part-load diagram of a KWU PWR (Figure 3) shows the temperature of the coolant (CT) at the reactor pressure vessel (RPV) inlet, the RPV outlet and the average CT across the steam generator as a function of the reactor power (100% = rated power).

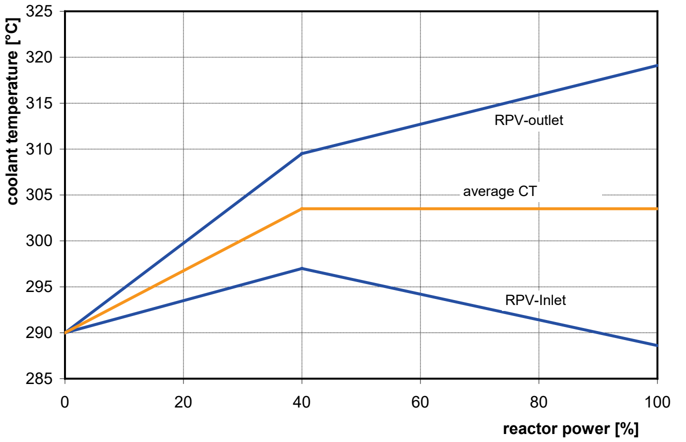


Figure 3: Schematic part-load diagram of a KWU PWR.

The range of the constant average coolant temperature between (in the example) 40 and 100 % can be clearly seen. In the event of a power reduction, the so-called D-bank (4 groups, each comprising 4 control assemblies distributed across the reactor core) is inserted into the reactor core until the desired power change is achieved. The remaining control assemblies (typically 45) are assigned to the so-called L-bank, which always remains at a high position during power operation and thus guarantees the shutdown margin, which is a variable that is important to safety. Slower changes of power distribution in the core, occurring after reaching the desired output, and the concentration of xenon isotopes in the nuclear fuel are compensated by minor movements of the L-bank and changes in boron concentration in the coolant. On an increase of the power, the D-bank is first to be withdrawn from the core. If necessary, the power increase can be boosted by withdrawing the L-bank simultaneously; however, this depends on the position of the L-bank (for an overview of the above components, see Figure 4).

The power gradient for a power increase is limited, for example by the permissible power density. Power reduction is possible at virtually any desired rate.

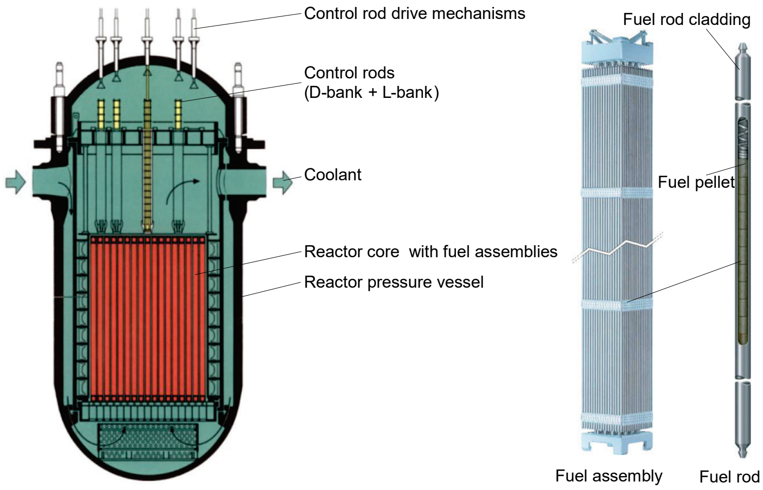


Figure 4: Illustration of typical RPV internals of a PWR.

BWR

The output of boiling water reactors can be regulated either by the maneuvering of control rods or by changing the speed of the forced circulation pumps and, thus, the coolant flow rate (recirculation control). Recirculation control is perfectly suitable for load cycling in the upper power range (about 60 to 100 % of the rated power). The amount of steam in the reactor core increases with a reduction of coolant flow rate, thus reducing both moderator density and reactivity. By contrast, increasing the coolant flow rate leads to an increase in the moderator density and reactivity and thus to an increase in power. Figure 5 shows the characteristic curve for recirculation control (RCC); this plots the reactor power as a function of the core flow for a constant control rod position.

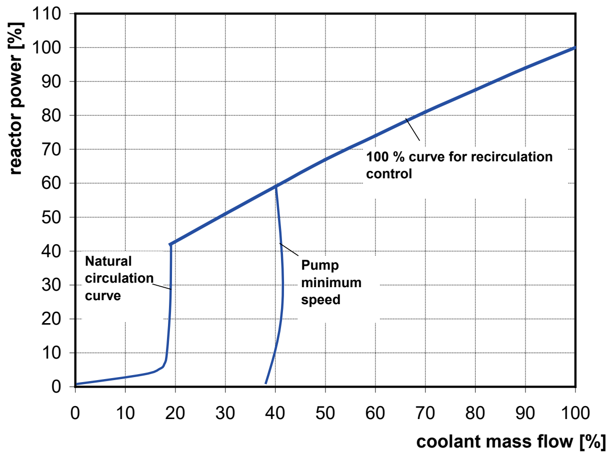


Figure 5: Schematic characteristic curve for recirculation control (BWR).

A major advantage of recirculation-only control is that the relative power distribution in the core is not significantly affected by load changes, because no maneuvering of control rods is required for this purpose. This minimizes stressing of the fuel rods caused by load cycling and consequent changes in temperature in the fuel rod. The maximum feasible load change rates are about 10 % nominal power per minute in the recirculation control power range. Power changes beyond the recirculation control range are done by maneuvering control rods. With optimized control rod maneuvering sequences, power increments totaling between 20 and 100% can be achieved at sufficiently high power gradients (for an overview of the above components, see Figure 6).

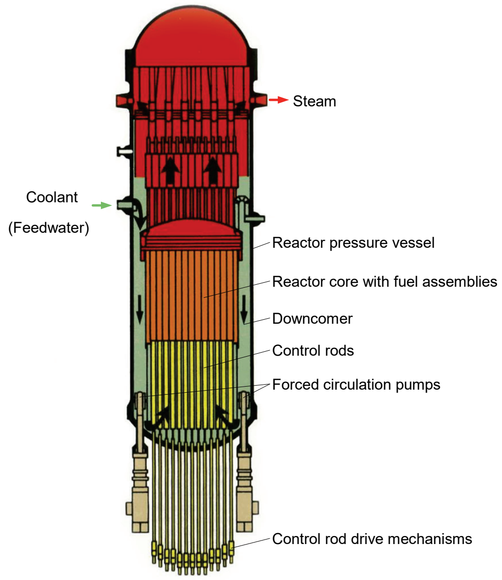


Figure 6: Illustration of typical RPV internals of a BWR.

2.2.2 Design characteristics and impact on process parameter

Flexibility of the German power plants has been reached in a very advanced way thanks to important design characteristics presented in (Ludwig et al., 2010). These are a part-load diagram with the constant average temperature of the coolant in the upper load region, which is frequently used for flexible operation, control rod maneuvering program, axial power distribution control, and an accurate mostly real-time in-core measurement of power distribution, achieving greater operating margins for load following and preventing Pellet Cladding Interaction (PCI), and optimized Primary Coolant Management and Treatment. Regarding BWR, recirculation control and in-core measurements have to be mentioned.

In the following, a short summary on main items related to vibration and fatigue is given, with the main goal to better understand the results and feedback collected during the project from KWU NPPs in chapter 4.2.

Design measures to mitigate and control cyclic loadings (PWR and BWR)

Load cycling within the scope outlined above is predominantly associated with only minor changes in global plant parameters on the primary circuit, such as pressure and temperature in the reactor coolant system. Generally speaking, the resulting additional thermal stress cycles are not excessively relevant to the fatigue of the affected components. Large temperature gradients with correspondingly higher loads can occur when different hot fluids meet in individual components. In addition to a low-stress mode of operation (see part-load diagram), such loadings are well-controlled by a suitable design, namely the choice of suitable materials and appropriate dimensioning or mechanical design to reduce temperature changes, for example in the area of injection nozzles. German nuclear power plants are designed for the stresses associated with load cycling. This design is based on defined numbers of service conditions (in this case load cycles), which cover the frequencies expected during the lifetime of the plant.

Vibration monitoring (PWR and BWR)

In German PWRs, the vibration monitoring of the primary circuit is performed according to DIN 25475, part 2. Figure 7 illustrates the typical positions and number of used sensors for surveying the RPV, the primary loops, the steam generators and the RCPs. Approx. 40 sensors, including neutron flux, are used for an online monitoring and analysis of related vibrations, static displacements, and thus the physical health of the components.

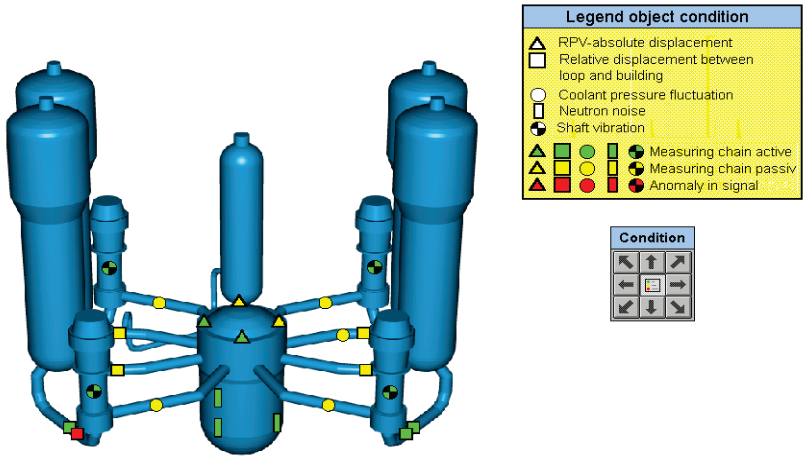


Figure 7: Typical vibration monitoring of a PWR primary system according to DIN 25475 part 2, including neutron flux signals.

Furthermore, approx. 20 sensors from the loose part monitoring system LPMS according to DIN 25475 part 1, placed on the RPV, the steam generators and the RCPs, are used for the detection of loose or loosed particles in the loops, but also for special vibrational effect detection and assessments (Figure 8). This means a broad and independent spectrum of signals from primary components are available for an intense detection of effects and the assessment of component conditions.

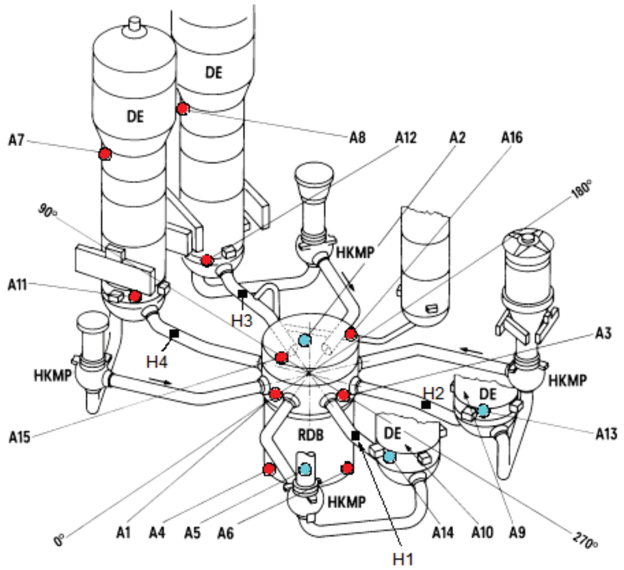


Figure 8: Typical Loose Part Monitoring System of a PWR primary system according to DIN 25475 part 1.

For the BWR reactors, the approach is quite similar like on PWRs, but vibration monitoring has more seldom been installed on the reactors. The LPMS is more often used for an RPV in- and external monitoring during stable and transient operations.

On the secondary side (turbine island), the vibration monitoring is mainly focused on the turbine and the generator train itself, with self-standing systems often provided by the OEMs. Several operators installed vibration monitoring systems on the feedwater or condensate water pumps, e. g. after unwanted events happened.

For safety related or operational valves, a monitoring of the electrical drive parameters and torques is widely used in the plants (Framatome system "ADAM/SIPLUG"). This system provides an extensive information on the mechanical and electrical condition of the drives, for the detection of faults during operation, and thus for an effective planning of maintenance works during outages, based on the component's conditions.

For the water and steam circuits in general, Framatome provides today a highly flexible monitoring system for relevant components on the secondary circuit (e.g. pumps, pipes, motors, valves, heat exchangers, etc.), which is further described below.

Fatigue monitoring (PWR and BWR)

Continuous fatigue monitoring (measuring, recording and analysis of wall temperatures), which facilitates both graduated simplified and fast evaluation as well as detailed fatigue analysis, is available for components susceptible to fatigue. Moreover, by the comparing the history of service conditions, such as load cycles or operational transients, with the design assumptions documented in thermal load specifications, it can be ensured that the component design imposes no restrictions on the operation of the plants. In addition, periodic, non-destructive testing at specified intervals is performed especially for safety-related components.

Despite all of this, if unexpected effects should occur, these would be detected in time.

The core module of fatigue monitoring is a load monitoring system for nuclear power plant components such as nozzles and pipes etc. This is based on continuous measurement of thermal and mechanical loads, locally or more globally (using the standard plant instrumentation and transfer functions). The identified loads can be directly processed by identifying cycles or used for transient counting by comparison of really occurred cycles with transients already defined in stress reports. The measured loads constitute input data for engineering fatigue assessment of different accuracy levels. In this sense, any fatigue monitoring system consists of a hardware and data acquisition part and an engineering part of fatigue assessment methods.

In summary, monitoring of fatigue in reactor components can be visualized by the formula Fatigue Monitoring = Continuous Load Monitoring + Periodic (or Continuous) Engineering Assessment.

In practice the periodic engineering fatigue assessment is often carried out on an annual basis. Upon specific request, online fatigue monitoring capabilities can be implemented.

3 Scope

The objective of this project is to provide the stakeholders of the Vibration program with a survey of operational experience from FlexOp of NPPs, mainly through existing project experience of the team and interviews. The focus of the project described in this report is to identify components that have a potential to face dynamic, i.e. vibration problems in partial load operation and how to avoid or mitigate the problems.

Following main issues are described in the report

- Type of the analyzed and interviewed plant
  - × Short description of the plant type and type of fuel
  - × How are the load changes performed?
- Excitation mechanisms
- What kind of criteria can be used to identify the risks for harmful vibrations?
- Analysis methods to identify the components which are most prone to vibration problems
  - × Calculations
  - × Measurements
- Component classification
  - × Reactor internals
  - × Piping
  - × Turbine island
  - × Other groups of components
- Impact (if any) of type of fuel on vibrations
- Methods how to avoid or mitigate the vibration problems
- Methods how to estimate the reduction of the component lifetime due to higher vibrations

The project team performed internet and literature surveys based on the public available information and moreover interviewed five utilities including collecting practical information from more than ten NPPs (PWRs and BWRs), which performed in the past or perform currently various types of FlexOp. Thereby the corresponding FlexOp was analyzed, and the list of the impacted components set up.

The work is an exploratory study intended to bring to light a realistic understanding of the vibration phenomena under FlexOp conditions in general and corresponding mitigation measures including their effectiveness. The results are indicative and not directly applicable to business applications for Nordic plants as it will require more precise information about each case and the applicability to a particular plant.

Nevertheless, this generic work will be helpful to use the existing lessons learned and allow to avoid or to minimize the risk for the Nordic NPPs in the future if a higher level of flexibility is required.

4 Results

4.1 FLEXIBLE OPERATION MODES OF THE INTERVIEWED NPPS

This subchapter is concentrated mostly on the operating experience with flexible operation of the NPPs that were interviewed during the project and for which the overall vibration impact was further on summarized in Chapter 4.3.2.

4.1.1 BWRs

All German BWRs mentioned in this section have internal variable-speed circulation pumps similar to the ABB-design.

BWR A of approx. 800 MWel

The flexible operation of this BWR was already strongly required by the grid in the 90s due to a special grid connection situation, the night demand reduction of Hamburg city was typically compensated by the NPP. Automated remoted secondary control was activated in the range of 100 MW (whereby the defined ramp rate was at about 20 MWel/min upwards and downwards, even much higher values can be achieved due to the design) with the defined minimal power level at about 60% (recirculation control). The limitation system did not allow the load dispatcher to increase the power more than allowed (20 MW always remained between the maximal power level and the maximal setpoint for the load dispatcher). The load following could be additionally activated via telephone, but also typically in the range of recirculation control.

PFC was qualified at +/- 23 MWel, but not often performed by the NPP. After the owners and grid connection situation changed and the market conditions in the deregulated market became different, primary as well as secondary control were not required anymore for the NPP and only the activation via telephone for the load following operation became feasible. Here the planned reductions during the weekends and holidays became the main type of flexible operation of the NPP. The downward ramps stayed at the same rate of 20 MWel/min and the upwards ramp rates were dependent on the fuel deconditioning. The operation guidelines were provided by the fuel department of the plant based on the individual FA results from the core monitoring computer. The typical ramps were performed between full power and 70 -80 % and the minimal power level was at about 60 % in order to avoid control rod movements. Thereby the positive minute reserve of about 256 MWel was provided by the gas turbine plant, which was originally built to support the black start of the NPP during the loss of offsite power.

The enclosed diagrams of neutron flux signals and recirculation pump speeds show the load changes during nighttime at the end of year, providing automatic secondary control (see Figure 9).

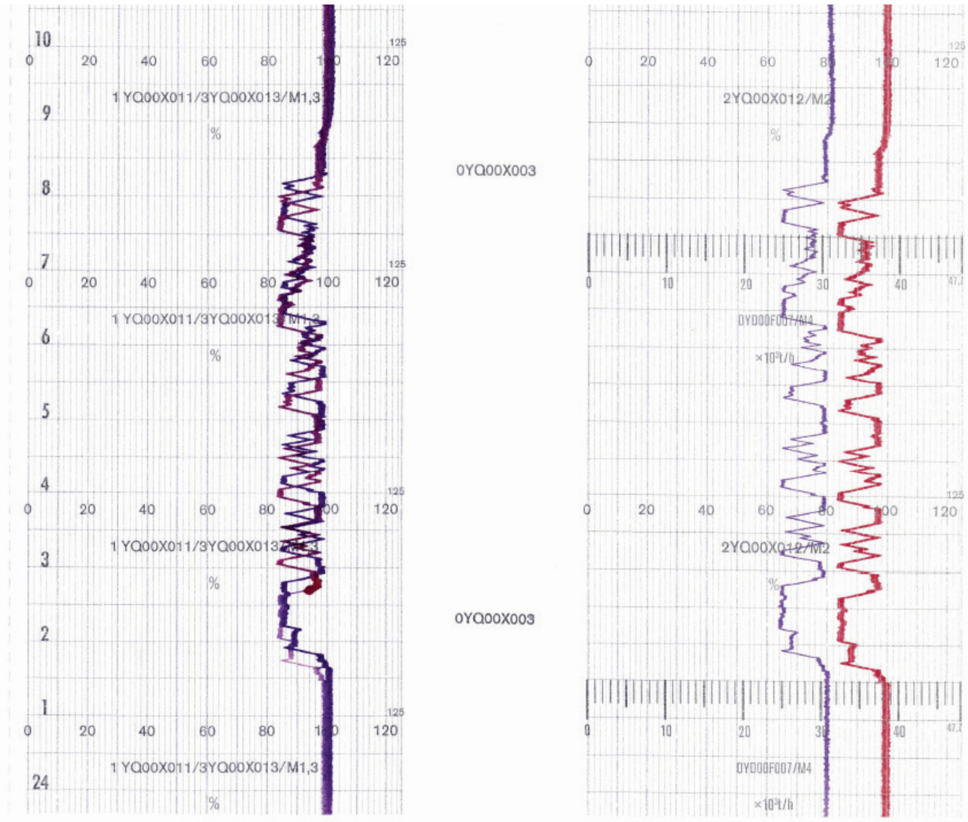


Figure 9: Correlation between Neutron Flux signal (left) and Recirculation pump speeds (right) during FLEXOP in nighttime, end of year 1999.

As an illustration of longer time flexibility provided by BWR A, a one-month figure can be chosen. Thereby all power ramps, except three deep ones to about 50 % of reactor power (blue color) due to maintenance and inspection needs, were required by the load dispatcher. The change of the generator output in MWel is shown by the red curve. To get more general feedback it should be mentioned that in that particular year there were also months without any requests from the dispatcher.

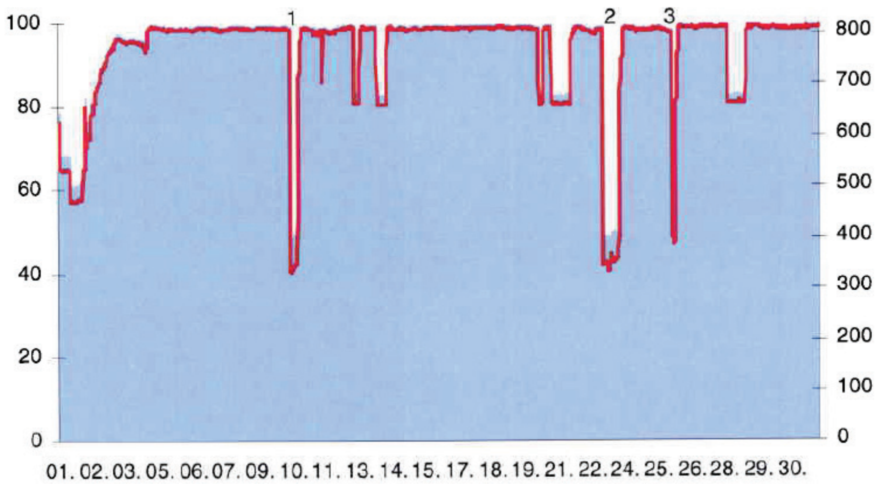


Figure 25: Flexible operation of the BWR A during one-month period of time, end of year 2007.

Special conditions and features related to flexible performance and vibration impact:

- Horizontal preheaters (design feature with influence on fatigue, special attention on loads had to be taken)
- Main steam piping was changed (because of unfavorable pipe material)
- Steam separator was replaced after 2 years (reason was design / material optimization but not the consequences of load following operation).

BWR B of approx. 900 MWel

Primary frequency control was performed by BWR B up to +/- 23 MWel in a power range between 100% and 60 % REO (Frank, M., 2003).

Since about 2002 the ramp rate for the secondary frequency control was specified with 20 MWel/min downward; upwards it was 10 MWel/min between 540 and 780 MWel, and from 780 MWel till full power with 1,5 MWel/min.

Load following was performed with similar gradients and ranges. In case of any fuel damage the secondary frequency control was not performed anymore and load following reduced to the minimal level and ramp rates.

In the months with strong wind generation, the typical operation of the plant is illustrated by the following picture, showing electrical output during one such winter month.

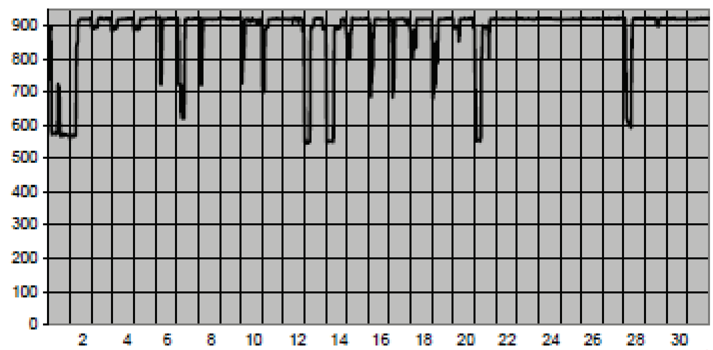


Figure 10: Flexible operation of BWR B corresponding to the load plan over a 1-month period in 2007.

Special conditions and features related to flexible performance and vibration impact:

- Sometimes the reduction of a power level to about 65 % was required due to high temperature of the cooling water in the river.

BWR C of approx. 900 MWel

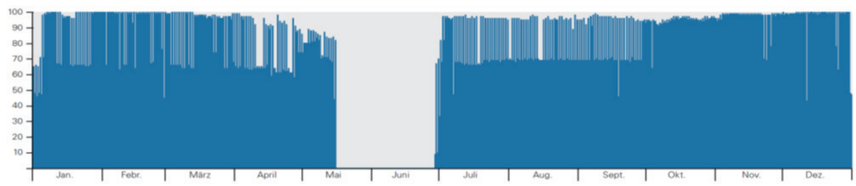


Figure 11: Electrical output in % provided by BWR C over the annular period in 2009 (ATW, 2010).

Energiforsk

BWR C had two control levels for PFC that could be activated successively (-11 MWel and -22 MWel), which was used quite often. This BWR provided only downwards service and performed it mostly between 74 % and 100 % REO.

As the service has to be procured symmetrically, the upwards product was provided by another power plant block. Secondary frequency control was qualified downwards with -30 MWel and MR was qualified for -90 MWel with typical ramp rate of 10-15 MWel/min, but the NPP was not often activated for such services.

Load following was performed till a low level of about 60 % downwards with a ramp rate of 30 MWel/min, but higher ramp rates downwards could have been possible. Upwards the ramp rate was about 10 MWel/min, but about 10 times reduced for the last 5 % before reaching the full load, depending on the duration at the low level. The reduced power was for some few hours, but also weekends at low level were quite common. To give an example of ELPO with a long duration, it was performed at about 48 % REO for more than 12 days in December 2008 and additionally 5 more days in January 2009, as it can be seen in the previous figure.

Some power reductions in the beginning of the year were carried out due to cooling tower operation conditions. Deep reductions a few times per year were carried out due to the periodic tests.

Special conditions/features related to flexible performance and vibration impact:

- This NPP had 100 % cleaning of the condensate that had a positive impact on the chemistry and as a result also positive effect with respect to fuel rod damage. This is an important aspect related to flexible operation, as NPPs with fuel rod leaks are not available anymore for the performance of the Grid services. Core Monitoring System CMS allows to detect core power oscillations * and initiates countermeasures; such as control rod bulk insertion.

  *) BWR stability issue – high power/low flow areas, where oscillations in thermal-hydraulic quantities may induce oscillations in neutron related quantities (mostly, neutron flux), this region will be avoided

BWR D of approx. 1350 MWel

PFC was qualified for +/-40 MWel, but not often requested by the grid. SFC was not introduced in the NPP. The typical ramps were performed between full power and 70-80 % activated via telephone, and the minimal power level was set at about 60 % to avoid control rod movements (recirculation control), with typical duration of about 3 days.

The typical flexible operation for BWR D can be illustrated with the following figure. The ramp rate upwards was typically of 10-15 MWel / min and about 1 % REO / min upwards (depending on the ramp duration at the reduced power level).

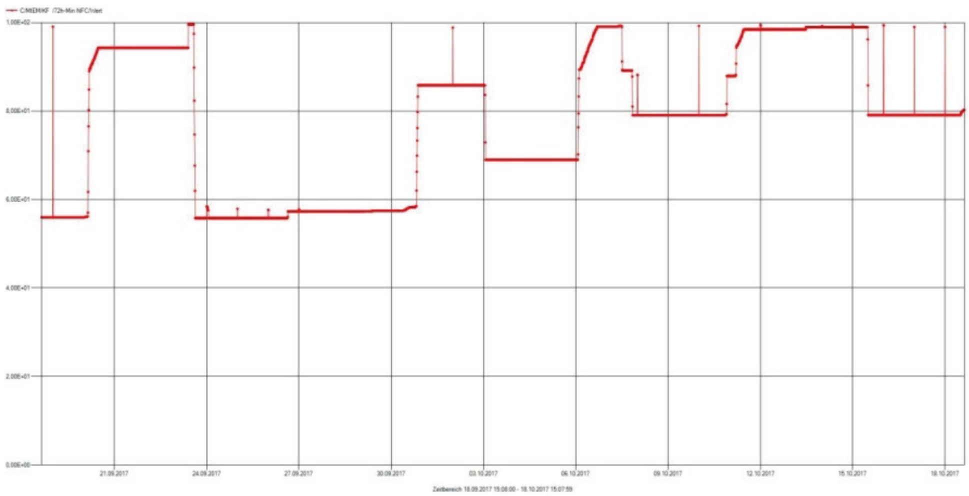


Figure 12: Electrical output in % provided by BWR D over a month period in 2017.

Special conditions and features related to flexible performance and vibration impact:

- The detection limit for Fuel failures is influenced by the existing level of radiation in the systems depending on the previous operational experience (not related to flexible operation). To avoid small fuel failures which are below the existing detection limit, it was decided to operate based on an ambitious fuel reliability program. In order to realize this program, it was decided to minimize the number of performed load changes since 2017.
- The existing material concept including Zinc dosage was used for an optimized water chemistry, having positive impact with respect to optimized crud production on the fuel assembly surface (indirectly for further plant flexibility).
- With the introduction of the spectral shift operation with an increased rod line in the power flow map, multi group rod insertion was introduced as adequate safety measure to avoid / master core power oscillations. Due to this new limitation, the minimum possible power at the highest rod line was increased. This is taken into account performing FlexOp.

4.1.2 PWRs

PWR A of approx. 850 MWel

Figure 13 is illustrating the last decade of operation of the PWR A. It can be seen that since middle of 2007 the plant was running extraordinary sequences of FlexOp during approx. 2.5 years. In 2011, the NPP was shut down.

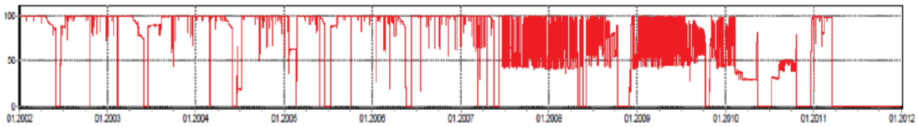


Figure 13: Load diagram of PWR A between 2002 and 2012 (Bolz et al., 2013).

To look inside in more details, Figure 14 is illustrating one particular year with the increased load following during the whole year, and Figure 15 the longest partial load operation. PFC was also performed by the plant.

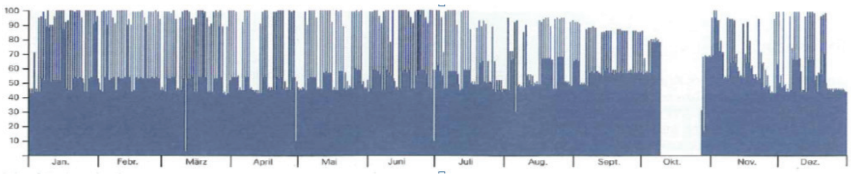


Figure 14: Electrical output in % provided by PWR A over the annular period in 2009 (ATW, 2010).

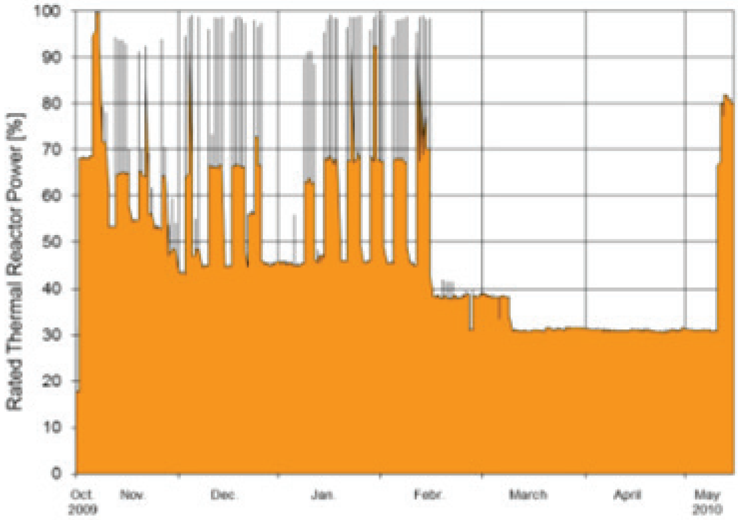


Figure 15: Advanced low power operations over 2,5 months by German PWR A in 2010.

Overall, extensive load follow operation including ELPO took part over about 2,5 years, with daily, weekly and monthly partial load operations at low level. Long time ELPO was performed at less than 40 % reactor power (several months, in 2010), and minimum value was reached at about 30 % load.

Special conditions and features related to flexible performance and vibration impact:

ELPO was performed shutting down the second turbo set (the small traction current generator of about 160 MWel was at zero load and the three-phase generator of about 700 MWel at about 35 % REO).

PWR B of approx. 1400 MWel

PWR B can provide the PFC of 50 MWel and -50 MWel for SFC. Thereby PFC and SFC can be superposed and reach together a maximum of 80 MWel. The typical minimum load for the PFC/SFC/MR is stated to be at about 55 % REO. Thereby, minute reserve could be performed at 100 MWel, and wind reserve (can be required only in the special cases of extreme energy production by wind) at 350 MWel. Load following can be provided till 45 % REO. The downwards ramp rate is defined at 1%/min up to 200 ppm (Boron concentration) in a cycle (the gradient for coming back is reduced to achieving 95% of the load), for the load following the duration of 6 hours at low level is required by fuel department and from 200 ppm to 100 ppm in cycle duration between 12 and 24 h.

Special conditions and features related to flexible performance and vibration impact:

- Load governor for the automatic realization of the load plan provided by load dispatcher.

PWR C of approx. 1400 MWel

Overall, due to the grid requirement in the region and the gas plant providing flexibility, PWR C had a moderate FlexOp experience during the lifetime.

Planned reductions over the holidays are typical. They are even performed till the minimal load, illustrated by the next two pictures.

Figure 16 is showing PWRs and BWRs of various designs in typical load following mode during Christmas 2009, avoiding negative price production due to low demand combined with increased wind energy production. PWR C (light blue curve) is providing a ramp with about 6 h at the reduced level.

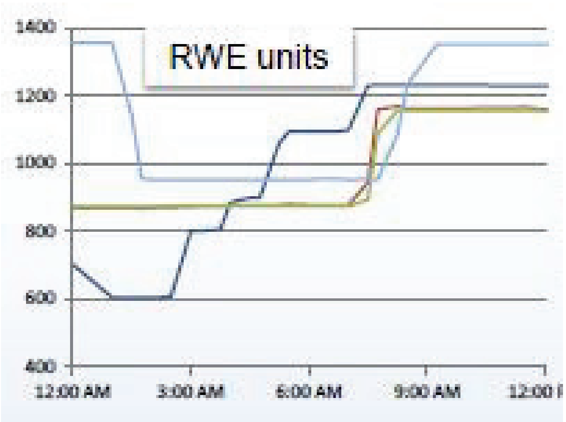


Figure 16: Electrical output in MWel provided by NPPs over 12-hours period of time at Christmas, 2009 (Fuchs, M. and Timpf, W., 2011).

Figure 17 is showing whole fleet in load following mode with the typical rate of 25 MW/min with overall power reduction of 2800 MW, avoiding negative price production on the first day of the year 2011 with PWR C (light blue) mostly achieving the minimum load for few hours.

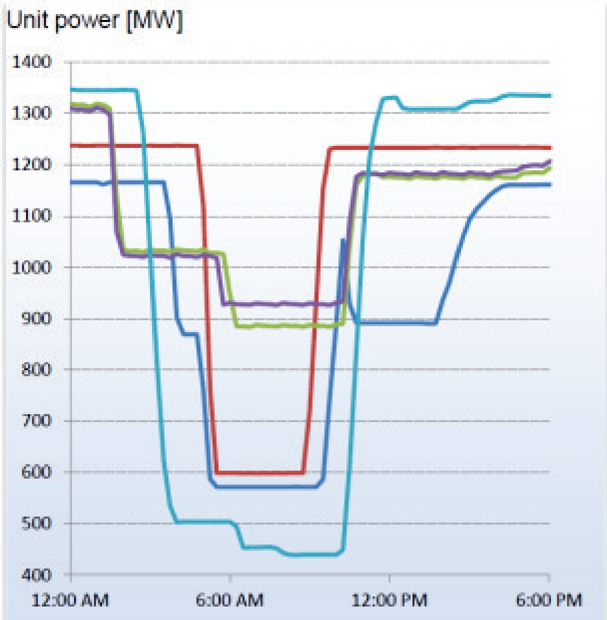


Figure 17: Electrical output in MWel provided by one German utility over an 18-hours period of time at first day of the Year 2011 (Fuchs, M. and Timpf, W., 2011).

PWR D of approx. 1500 MWel

PWR D can provide primary frequency control in the range of +/- 45 MWel (Fuchs, M., 2013), and since 2016 also SFC up to -100 MWel. Overall flexible operation is stated to be performed till 787 MWel (~ 55 % REO). Thereby, the ramp rate is defined up to 20 MW/min. Redispatch measures, reduction of the power requested by the grid (overload management) due to bottle neck situation in the grid in case of too much wind production in the North, also played a relevant role for the plant over the last decade. It is provided in the same way as other ramps.

The next figure is representing the response of the NPP to the grid requirements including various services, in this particular case SFC and load following, whereby also an example of a short ELPO can be given for PWR D (yellow curve). Mostly producing at the constant reduced load for more than 12 hours, also longer periods of about few days can be found in this month. Primary and secondary control will be also activated at the reduced level.

Just to give an example, in February 2020 about 70 % of the time PWR D was activated for PFC and/or SFC, 3 times more compared to the same month 10 years ago. The same relation can be given for the overall number of hours providing flexibility by the NPP. Overall, the NPP has been operating most of the time in the region of the constant average cooling temperature reducing the impact on the primary side.

Figure 18: Electrical output (net) in MWel provided by three German PWRs over an 72-hours period of time in February, 2020.

Special conditions and features related to flexible performance and vibration impact:

- ALFC

PWR E of 1500 MWel

PWR E can provide the PFC +/- 45 MWel (Fuchs, M., 2013) and up to 100 MWel for SFC, and since 2016 +/-100 MWel for minute reserve with a ramp rate of 20 MW/min. For the load following, a ramp rate up to 30 MW/min was performed with the minimal load level specified at ca. 450 MWel (30 % REO). Currently, a ramp rate up to 20 MW/min is activated and the minimal load level is specified at about 60 % REO.

In the previous picture, the black curve is representing flexible operation of PWR E including about 12 hours at mostly constant low level and overall about 2 days at reduced level. After the implementation of ALFC in 2015, up to 40 MW/min could be realized.

Currently, the load following is performed with up to 10 MW/min (the reduction has been applied as a preventive measure due to FA oxidation issue).

Overall, in the year 2019 the flexible operation of PWR E, including redispatch measures, accumulated to about 12,5 full days of production at zero, meanwhile 10 years ago it was only 3,5 full days. The year with the highest number of performed services was 2015 with about 24 full accumulated days with zero production.

Special conditions and features related to flexible performance and vibration impact:

- ALFC, the thermal reactor power during the last three years has been limited to a maximum of 95%, connected to the issue from February 2017 with increased oxide layer thickness on fuel rod cladding tubes of FAs (no fuel rod damage), a limitation for ramp rates of the load following was introduced; currently, the nominal power can be reached again,
- in some warm months also a few output reductions are required in order to comply with water law permit.

PWR F of approx. 1500 MWel

The licensed range of the PFC reached a maximal value of 130 MWel. Typically, the NPP has delivered up to 70 MWel of PFC. Thereby, SFC and MR can be superposed (in this case e.g. with -50 MWel for SFC and -150 MWel for MR). The ramp rates for the ramps downwards and upwards vary strongly with the time in the current cycle (boron concentration), e.g. they can vary from 80 MW/min downwards at the beginning of cycle to 8 MWel /min at the end of cycle, and upwards from 40 MW/min at the beginning of cycle to 1,5 MW/min at the end of cycle. The average value was about 30 MW/min. During down and upward ramps themselves, PFC and SFC were deactivated.

The typical minimum load for MR/load following is stated to be at about 50 % REO. The minimum load for all three types of ancillary services (PFC, SFC and MR) together was defined at about 38 % REO, but the typical minimal value was at about 60 % REO.

Figure 19 is an illustration of 1 month proving continuously primary and secondary control and 4 times deeper load follow operation with the lowest power level for the reduction at about 50 % REO. Such deep reduction is typical for Christmas and new year holidays. In this case it was about 7 hours long. Also, power reductions due to the limitations corresponding to the low water level of the river were performed during the first three days of the month. For example, in 2017 the load follow to the lowest power level of 38 % was requested and lasted for about 22 hours, but it can be seen as an extreme case for this NPP.

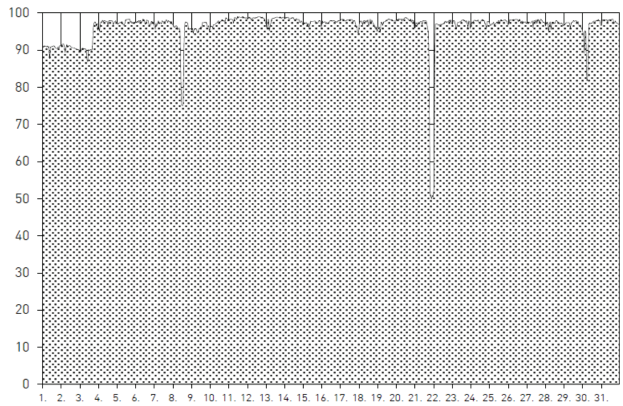


Figure 19: Electrical output in % provided by PWR F over a 31-days period in 2018.

Special conditions and features related to flexible performance and vibration impact:

- ALFC

PWR G of approx. 1500 MWel

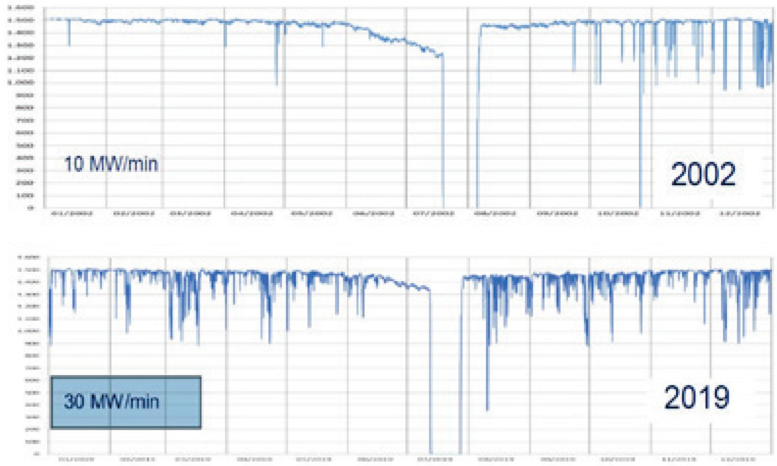


Figure 20: Electrical output in MWel provided by PWR G in year 2019 compared to 2002 (Müller, C., 2020).

This plant has been performing various grid services over the last two decades, and since 2014 in the advanced fully automatic way (IAEA, 2018). Figure 20 is showing the increased requirements over the years. Implementing Advance load following control (Kuhn, A. and Klaus, P., 2016) and further on the predictor technology (Kuhn, A. and Schirrmeister K., 2017), allowed to adapt to the new challenges increasing the reliability and the range of the performed services. Thereby, the flexible operation modes were optimized among other advantages also with respect to smooth plant performance, e.g. with minimization of the boron/demineralized water injections (reducing activation of chemical and volume control system (CVCS)). The ramp rate to achieve was up to 40 MWel/min and the modernizations should allow flexible operation without manual intervention in the whole range between minimum load and 100 %.

With the performed I&C improvements, the NPP achieved one of the most advanced flexibility level worldwide with primary frequency control mode providing FCR up to ± 100 MWel, secondary frequency control mode providing aFRR up to ± 150 MWel, and minute reserve with mFRR typically in the range of ± 300MWel (Hänninen et al., 2020). Such modes are overlapped with load following with a ramp rate of up to 40 MWel/min. Currently the ramp rate is stated to be defined up to 20 MWel/min. The minimal level for the performed services is given for the whole fuel cycle and is typically defined at about 60 % REO.

Figure 21 is illustrating the operation of the plant in the fully automated remote secondary control mode during 2 days in 2019. The graph depicts the changes of the generator output (red curve) within a band of approximately 590 MWel. Thereby, the reactor power (blue curve) is changing within a band of ca. 35 %.

This curve shows the reduction to the low level during weekend which is required for about 1,5 days; due to overlapping of various services, the plant is not operating constantly on the low level, but is responding to the stochastic grid needs.

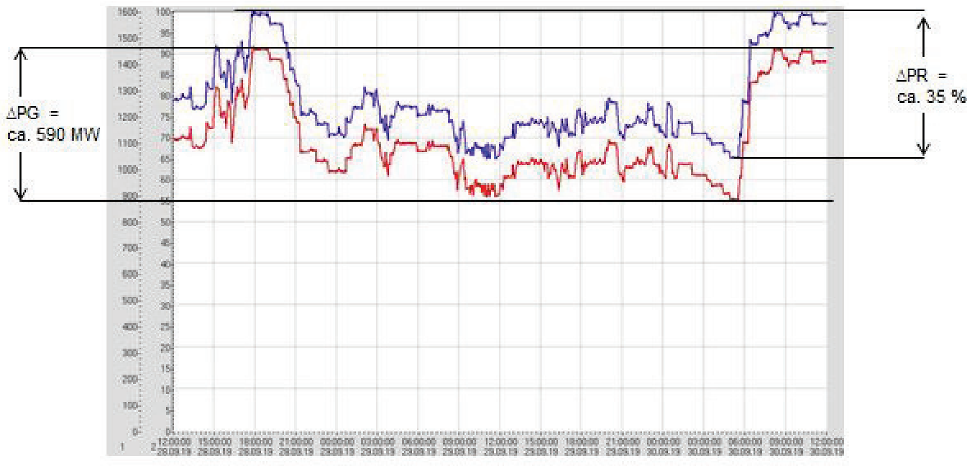


Figure 21: Fully automated remote secondary control by PWR G over a 2-days period, (Petrasch, A. & Salnikova, T., 2019).

The enhanced low power operations at constant low level for a long time in general and especially at low levels much deeper than 60 % level is stated to be a very seldom event and is performed only due to very special grid conditions.

Special conditions and features related to flexible performance and vibration impact:

- ALFC including predictor technology
- spray control valves (continuously)

PWR H of approx. 1000 MWel

PWR H has a proven capability for primary frequency control of ± 20 MWel. PWR H also has carried out proactive pre-studies on potential flexible operation of various scenarios, analyzing possible impact on the whole plant including fuel and corresponding tests. During these tests in 2017, fast load transients were performed, and related operational data collected.

ALFC was introduced in the plant in 2018, and for the predictor technology a commissioning test is being planned for the summer of 2021. The prediction in this case has a new feature that covers various strategies including ELPO of different duration.

The advantages of the automatic system are already acknowledged for the normal operation and the potential flexibly required in the future is taken into account.

4.2 VIBRATION PHENOMENA/PROBLEMS IN NPP COMPONENTS AND SYSTEMS IN GENERAL

Vibrations can have multiple sources, which are presented, e.g. in Nordmann & Ranisch (2018) and Merikoski et al. (2017). Vibrations of NPP components are caused by different excitation mechanisms, which can be mechanical, electrical or fluid flow related. The resulting vibrations of NPP components depend not only on the excitation sources, but also on the dynamical behavior of the NPP component, which can be expressed by corresponding natural frequencies, damping values and mode shapes, compare Figure 22.

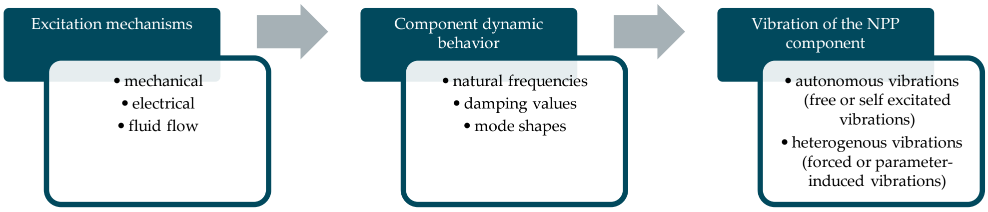


Figure 22: Vibration of NPP component

Table 1 shows a summary of the most known and observed vibration excitation mechanisms in power plants (turbines are excluded).

Table 1: Summary of the most known and observed vibration excitation mechanisms according to component type.

Components	Excitations mechanisms
Rotating machinery (e.g. pumps)	**Rotor excitations** • imbalance excitation → Force proportional to rotating speed • misalignment at coupling → static bearing forces due to non well-aligned coupled shafts which lead to dynamic forces at 1, 2 and 3 times the rotational speed • gearbox or coupling excitation frequencies **Rotor-stator interactions** • hydraulic excitations or fluid forces between rotor (e.g. impeller) and stator (casing) → turbulences, cavitation, hydraulic unbalance • instability or self-excitation in fluid film bearings (e.g. Whirl) • rolling bearing faults • motor or electrical excitations • rotating looseness **Flow induced vibrations as a function of load – cavitation at low load** **Start/run-ups and shut/coast downs (transients)** **Broken components** **System natural frequencies (resonances)** **External or structure borne excitations from the environment through the foundation**
Piping systems	**Mechanical induced vibrations** • excitations forces coming from rotating machineries (incl. transient forces due to run-up or coast down of rotating machineries) or adjacent components • external excitations from the environment though piping supports • structural resonances **Flow induced vibrations which strongly depend on the flow conditions (mass flow, pressure fluctuations, temperature and moisture content and pipe design)** • pump flow pulsations (pump speed dependent) and flow through pressure restrictions

	• vortex shedding at frequency depending on mass flow (which can lead to acoustic or structural resonance) • acoustic resonances at frequencies depending on sound speed and pipe geometry • random hydraulic or pressure excitations due to flow turbulences, cavitation, flashing or non-condensable mixed flow • transient or water hammer induced excitations
Valves	**External/mechanical excitations** • pump excitation forces at characteristic frequencies (e.g. speed frequencies and harmonics) • structural and acoustics resonances of the piping systems or adjacent components • external or structure borne excitations from the environment through the piping supports **Internal fluid induced excitation** • pressure difference between the piping upstream and downstream • flow induced vibrations
Heat exchangers	**Flow induced vibrations** • turbulent buffeting with vibration amplitude depending on mass flow • vortex shedding at frequency depending on mass flow (which can lead to acoustic or structural resonance) • acoustic resonance at frequencies depending on sound speed and component geometry • fluid-elastic instability or coupling depending on the current mass flow compared with the critical mass flow

4.3 VIBRATIONS IN NPP COMPONENTS AND SYSTEMS DUE TO FLEXIBLE OPERATION

4.3.1 Component classification

Table 2 shows the affected components, the excitations due to load follow operation and the usual instrumentation.

Table 2: FLexOp impacted component versus excitations versus instrumentations.

Components	Excitations due to load following	Instrumentation
Main recirculation pumps	Speed dependent rotor excitations Resonances	Acceleration Velocity Displacement Keyphasor
Feedwater pumps	Speed dependent rotor excitations of pump rotor and gearbox with variable speed Flow induced vibrations Cavitation (at low load or flow) Resonances	Acceleration Velocity Displacement Keyphasor

Condensate pumps	Speed dependent rotor excitations Flow induced vibrations Cavitation (at low load or flow) Resonances	Acceleration Velocity Displacement Keyphasor
Heat exchanger	Flow induced excitations	Acceleration Displacement Noise
Piping system	Flow induced excitations Mechanical induced excitations	Acceleration Velocity Displacement
Valves	External mechanical excitations Internal fluid induced and valve position dependent excitations	Valve position Valve load Acceleration Noise
Process conditions	User interactions (process controls) • Change of mass flow → change of pump speed or valve position • Change of temperature • Change of pressure	Mass flow, Temperature, Pressure, Moisture content, Valves position

The following operating parameters of the plant are changed when load following is performed:

- Mass flows
- Temperature
- Pressure
- Moisture content

To control the mass flow during load following, the rotating speed of the feedwater pumps and the valve position/throttling have to be adjusted accordingly.

A change of the pump rotating speed could lead to (see Figure 23):

- a change of the seal pressure difference
- a change of the static loads at pump impellers and therefore on the bearings
- a change of the dynamic behavior of the pump
- speed related vibration excitation mechanisms at the pump level (e.g. unbalance) which will be partly transmitted to the piping systems and valves

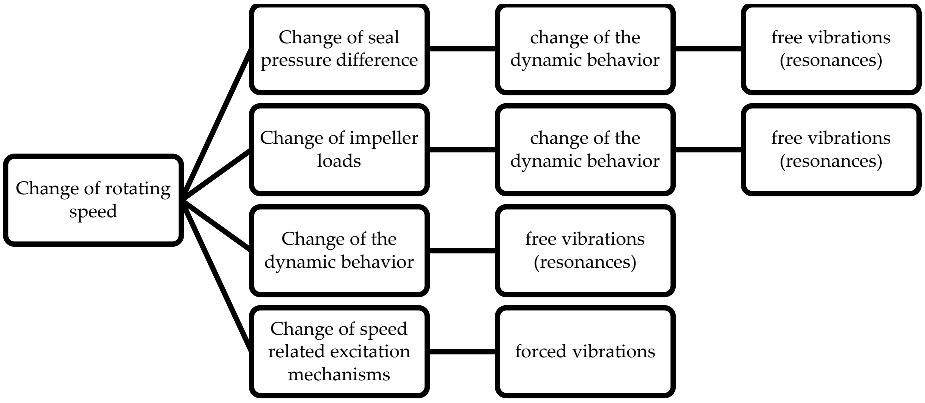


Figure 23: Summary of vibration effects induced by change of rotating speed during FlexOp.

A change of the valve position/throttling could lead to (see Figure 24):

- Mechanical induced vibration at the piping systems and valves
- Internal/fluid/flow induced excitation

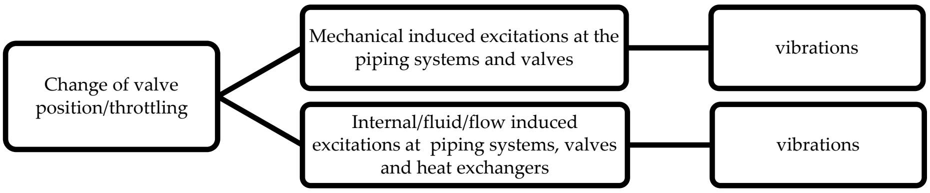


Figure 24: Summary of vibration effects induced by change of valve position during FlexOp.

The plant feedback collected from performed interviews and existing projects is summarized in the following chapters, separating impacts on fuel and on electrical components and giving an overview of the relevance depending on safety class and risk of failure of the impacted components.

4.3.2 Overall feedback on vibration from BWRs and PWRs

The following chapters give an overview of the individual interview feedbacks from utilities and NPPs, with main respect to vibration, but also noise, fatigue or process stability issues tentatively caused by FlexOp incl. ELPO are mentioned as well. Additional observations or countermeasures, which the operators have seen to potentially avoid vibration, fatigue or erosion issues, are listed at the end of each chapter.

4.3.3 BWRs

BWR A of approx. 800 MWel

Main steam piping has been changed in 1998 due to erosion/corrosion/cracks effect, reducing the diameter and improving the steam flow performance (improved material was used). A result was a new design and a quite strong structural support of that pipes, leading to low frequency vibration (independent from FlexOp). As countermeasures, a number of anti-vibration dampers (type Gerb) have been installed on that pipes, reducing the vibrations satisfactorily.

A general experience is that a high load operation (approximately114 % of rod line) led to a higher noise emission in the turbine hall, generated by an undefined number of sources (valves, supports, etc.). Vibrations occurred spontaneously at constant power independent from power level.

It was remarked that an operation with load changes during the cycle was favorable for the control valves because their regular movement did avoid increased local friction marks over the time.

Additional observations:
Preheater trains reacted sensible on fast load transients. It took a longer period of time before stable operation could be observed again. Unstable operations can cause fatigue issues in long term.

BWR B of approx. 900 MWel

More activations of all motor-operated valves in the steam and feedwater system due to FlexOp were observed. The movements were veritable only in a small band of the complete stroke, leading to more partial wear on the stems and gear components.

The brass pipes on the condenser often led to erosion effects by droplets, which led to increased maintenance activities.

In 2008, a guiding sheet break on the steam side of the preheater between LP- and HP-turbine was observed, which led to a power reduction to approx. 90 % before final repair for mostly three months. In that time, the preheater was additionally monitored by vibration and noise sensors for additional degradation (see Figure 25). An extended period of power reduction could be avoided by these measures.

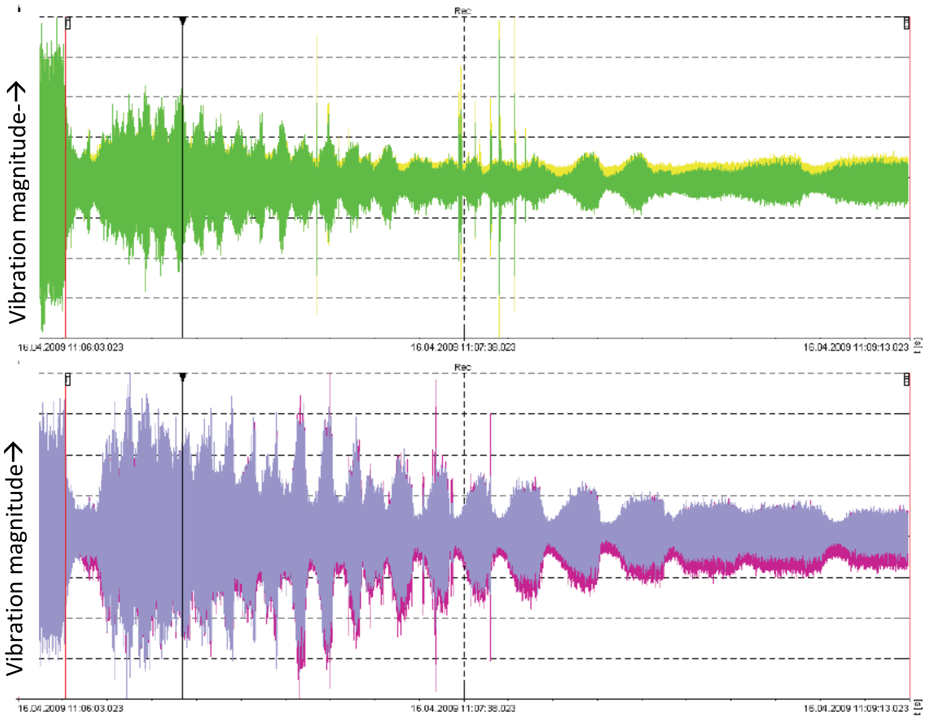


Figure 25: Vibration and noise signals from preheaters during a fast negative load transient (approx. 3 min duration) (Forster, P., 2009).

BWR C of approx. 900 MWel

Overall, the NPP was performing very reliably in flexible operation mode. Main difficulties were connected to reaching again 100 % of power. The generator was operating noisier in flexible mode, but it has to be mentioned that particular generators (the former and the substitute) were noticed to work noisier in normal operation compared to other German BWRs.

BWR D of approx. 1350 MWel

Recirculation pumps:

Auxiliary pipes of the pumps were observed to get into vibration at certain speeds. This was solved by adaption of additional supports, or implementation of vibration dampers.

Steam dryers:

Due to low leakage fuel, during part load operation an impact on the efficiency of the steam drying within the cyclones of the outer circular RPV area was observed. To avoid subsequent erosion effects, an adapted FA-configuration in the outer area was implemented, which solved the problem.

Condensate discharge control:

More vibrations and poor control was observed in partial load operation. An exchange of internal flow restrictors could solve the problem.

Feedwater pumps:

Due to vibrations in part load operation, the minimum flow switch point was changed to avoid of unfavorable resonant speed regions, see Figure 26.

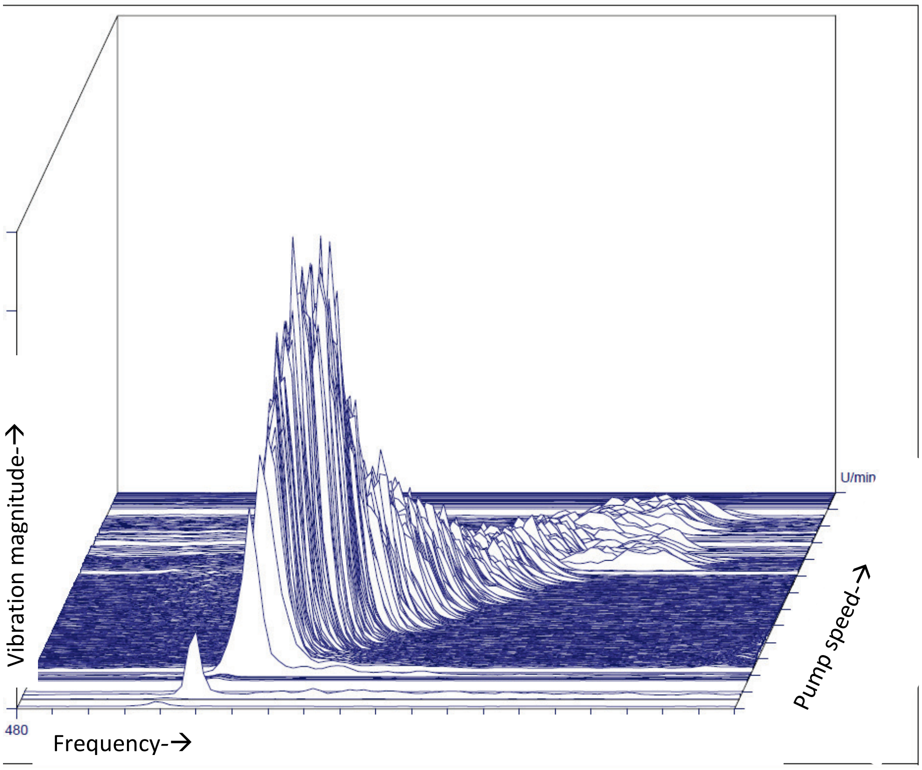


Figure 26: Vibration velocity of a feedwater pump: Resonant elevation at blade passing frequency at certain speeds (Marschner, T., 2001).

Mechanical vibration dampers (BWR):

The operator implemented a significant number of mechanical vibration dampers on relevant piping/components. That he considers as a sufficient measure to avoid vibration on small components at base and part load conditions.

Additional observations:

A change from magnetic to mechanic filter cartridges in the condensate cleaning device led to a reduction of loose particles in the complete system.

4.3.4 PWRs

PWR A of approx. 850 MWel

Since mid of 2007, the plant has been running extraordinary sequences of FlexOp for approx. 2.5 years.

Primary circuit and nuclear island:

During FlexOp, the primary circuit was seen to run very stable.

The operator did not observe problems on the pressurizer, the spraying valves or nozzles due to FlexOp. A generally adapted handling of the plant's operation mode due to FlexOp is considered as the reason for that.

Secondary circuit and turbine island:

However, on the secondary side several observations were made by the operator, which he sees as typical for long FlexOp or part load operation:

1. **Backflow at turbine stages during long low power operations (< 40 % REO):**

   During long idle phases (hours or days), an effect on the LP-turbines occurred, namely a backflow on the inner sections of the last 2 blade stages happened. This effect is due to the part load flow through the blade channels, and smaller pressure ratios within the turbine stages. Resulting effects are erosional degradations of the trailing edges in the lower section of the moving blades, which can lead to an increase of risk for crack initiation. Those turbine blades had been inspected closely and were to be changed after detection of a crack.

   The operator sees that risk also on turbines with thermal heat/steam extraction between the turbine stages in CHP plants.

2. **Pipe rupture in moisture separator/preheater:**

   In 2010, at one of two preheaters several ruptures on the steam piping have been observed, which led to a planning of huge repair activities. Due to the final shutdown of the unit after the Fukushima event, these hardware measures were not conducted.

   The reason is seen in the changes of flow and chemical conditions due to the reduced flow rates and the varying temperature levels. The piping was probably damaged by erosion corrosion. A decrease of chemical passivation with a change of local pH-value due to lower media temperatures is considered as the reason.

   As a countermeasure, extensive wall thickness measurements on the pipes have been performed. On longer operation periods a change of the complete preheater piping was envisioned but was not performed due to the plant shut down in 2011.

   Figure 27 gives an overview on the main areas of pipe degradation.

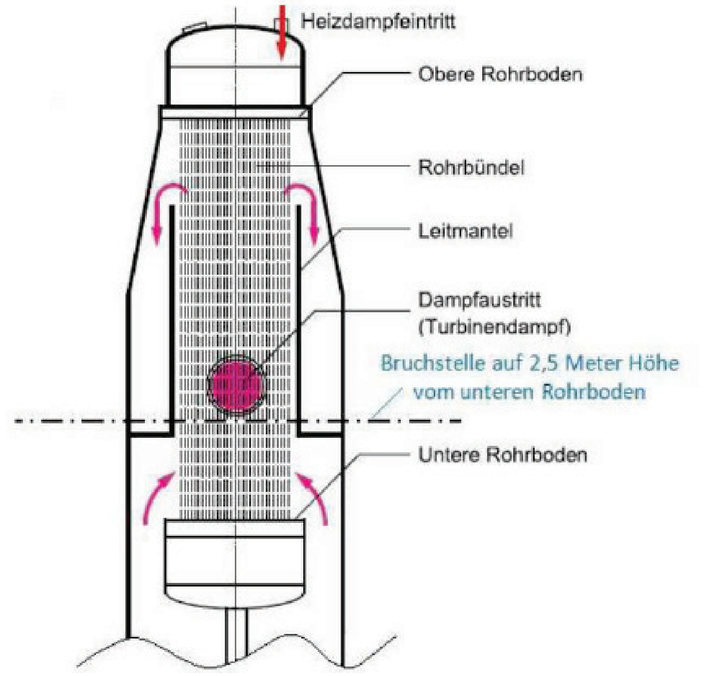


Figure 27: Position of leaked pipes of moisture separator/preheater of PWR A (blue indicated level) after about 2.5 years of advanced FlexOp (Bolz et al., 2013).

3. **Vibrations on Main steam regulation valves**

On low power levels < 40 %, heavy increases of mechanical vibrations in the common main steam regulation and shut down valve casings have been observed. The vibrations occurred quite suddenly when the flow rate through the valves fell below a very particular value and remained near to 0 % power. During normal power up and coast down to this particular flow rate, the vibrations remained within an expected order of magnitude. The operator performed a lot of vibration measurements and analysis on that effect.

Due to the sudden occurrence at dedicated mass flow conditions, a partial load fluidic effect is seen as the origin. As countermeasure, an avoidance of these operation conditions was implemented. In the considered unit these vibrations led to a leakage of a valve casing because inevitable cracks inside the valve material due to the casting process were propagating up to the leakage.

In general, wear on the valve drives due to FlexOp is seen as of minor severity by the operator.

PWR B of approx. 1400 MWel

The operator sees the same general effects on his plant on primary and secondary circuit like on PWR A listed above.

Additionally, some effects are observed in the turbine island:

1. **Cavitation on main feedwater pumps**

   The 3 feedwater pumps (3 x 50 % concept) are running with constant speed, with a throttle valve for mass flow regulation.

   On part load conditions approx. < 50 %, the HP pressure stage of the feedwater pumps is facing fluidic cavitation, with a detectable noise increase.

   As a countermeasure, the operation mode was changed in a way that on such low load condition only one feed water pump will remain in operation, in order to keep its mass flow above an acceptable level.

   As a long-term countermeasure, the operator sees an adjustable speed drive as reasonable for these pumps, like in the French NPP design.

   In general, the operator tries to avoid numerous heavy load changes to decrease power switch-ons and -offs of these pumps due to general fatigue issues, especially in the slide ring seal.

2. **Pipe vibration on main feed water pumps**

   Also, during part load operation < 50 %, visible low frequency vibrations on the intermediate piping between LP and HP volute casings of that pumps have been observed. A reason is seen in an aperiodic eddy shedding in the water flow. Vibration measurements and related stress calculations have been performed. Due to the relatively small, calculated material stresses (approx. 10 MPa) and the confirmed fatigue strength of the piping at this vibration level, no countermeasures have been implemented.

3. **Vibrations on main steam regulation valves**

   Similar to PWR A, vibrations on main steam regulation and shut down valves have been observed during regular power decrease. Load ranges <40 % of power will be avoided during FlexOp. See Figure 28 for an instrumentation example.

Figure 28: Position of a vibration measurement on a Main Steam Regulation and Shut Down Valve in a PWR.

The plant applied an online vibration control system which is used for the vibration detection of the piping systems.

As a general conclusion on fatigue of primary circuit components, no particular issues in terms of occurring damages were reported in the interviews. This was attributed to operational conditions of widely constant loads and small temperature differences. The fatigue management includes detailed fatigue analyses with realistic load data input and resulting reduced Cumulative Usage Factors (CUFs).

Similar conclusions with regard of fatigue of primary circuit components were drawn by the different PWR operators taking part in the interviews.

PWR C of approx. 1400 MWel

Turbine:

At low power levels (< 35 % load), several vibrations were observed. In such cases, the power was increased to avoid those regions in agreement with the grid dispatcher.

PWR D of approx. 1500 MWel

<u>Steam generator:</u>

A small risk of fatigue was seen on the feedwater nozzles to the steam generator. They are monitored by thermal sensors.

<u>Volume control system:</u>

More in- and outflow leads to more thermal transients on the HP heat exchangers. It could result in a long-term fatigue issue and is monitored.

<u>Turbine Control valves:</u>

In part load operation (approx. 50 to 60 % load), flow induced mechanical vibrations could be observed.

<u>Generator:</u>

The generator stator had to be repaired significantly in the past due to combination of various potential causes, e.g. impact of grid conditions, operation mode including flexible operation, but also the design features of the steel sheets themselves. Stator steel sheets had to be changed widely. More dirt could be discovered in H2 cooling system.

As countermeasures, more frequent and more intense visual inspections during outages are planned.

<u>Turbine train:</u>

A rougher vibration behavior was observed during part load operation in the middle power level. This is taken into account performing flexible operation.

PWR E of approx.1500 MWel

<u>Steam generator:</u>

A small risk of fatigue is seen on the feed water nozzles to the steam generator. They are monitored by thermal sensors.

<u>Volume control system:</u>

More in- and outflow leads to more thermal transients on the HP heat exchanger. This could result in a long-term fatigue issue.

<u>Turbine train:</u>

A rougher vibration behavior was observed during part load operation and is known for base load operation as well.

A torsional vibration measurement was installed on the turbine shaft between turbine and generator. Significant torsional excitation could be observed on the shafts, coming from grid disturbances, e.g. continuously generated by wind farm converters.

The torsional shaft vibrations were kept within the required limits but are permanently monitored by analyzing correlated electrical parameters (voltage, current…) of the generator.

PWR F of approx. 1500 MWel

<u>Control Rod Drive System (CRDS)</u>

The plant was facing an increasing number of control rod adjustments, caused by FlexOp. The number of overall control rod movements partly exceeded 1 million steps. This was not the design limit for such type of the plants, but the increased probability of spring fracture of the latch unit was previously shown from the operation experience reaching this value. For checking the performance of the drives, regular assessment of the moving operation by evaluation of the voltage and current shapes was performed. Reassignment of control rods in the control banks to rotate mission time among the CRDSs/CRDM was carried out, and also proactive replacement of CRDSs/CRDMs with increased step number was performed.

<u>Pressurizer spray nozzles</u>

The leading spray train was assigned to all available ones by optimization of controls to reduce specific usage factors on the nozzles. Further a calculative consideration of measured thermal transients, compared to theoretical ones, led to a dramatic decrease of anticipated fatigue usage factors (e.g. 0.9 to 0.1). Main observations were that thermal transients (approx. 20 to 30 K) occurred only in lower range.

<u>Pressurizer Surge Line</u>

More frequent in- and out-surges were observed during FlexOp. However, the thermal transients laid within 20 to 30 K, so not affecting fatigue issues significantly.

<u>Branch to volume control system</u>

This pipe component is seen to be confronted with significant thermal transients during FlexOp and was instrumented with thermal sensors. A fatigue influence is anticipated.

<u>Main coolant pumps</u>

A rising level of vibration could be observed in the past. Though a causal relationship with FlexOp could not be seen, the levels were kept under observation in relation to FlexOp.

<u>Main steam regulation valves:</u>

On loads < 50 %, vibration on these valves were anticipated, based on experience from PWR A.

As countermeasures, the regular inspection periods on that valves were reduced, and loads < 50 % are avoided.

Preheater between HP- and LP-turbine

An insufficient separation of droplets was anticipated (residual humidity >> 0.5 %). Additional perforated sheets had already been implemented. Inspection will be further focused on inner conditions.

Condenser pipes:

More vibration due to FlexOp was anticipated. Several mechanical mitigation means had already been implemented. Normal inspection intervals were kept.

HP- and LP-turbine

More erosion effects on turbine blades were anticipated. Already in former times, better withstanding blade material (more chrome-ratio) was implemented.

On stator vanes, erosion effects occurred. Countermeasures were overlay welding and frequent inspections.

Feedwater pumps:

In part load conditions, only one feedwater pump should perform the operation, because cavitation effects during part load conditions are known on that pump type. As countermeasures, smaller inspection intervals and additional spare part rotors have been addressed.

Feedwater check valves

Long operation periods in part load conditions may lead to an incomplete opening of those valves, which might react with instabilities of the feedwater flow and wear on the internals. More inspections were anticipated.

Preheaters

The heat exchangers are run with lower mass flows, and a higher steam humidity rate. A higher effect on erosion, vibration or fretting could not be excluded. A more frequent inspection was envisioned.

General fatigue assessment

A heavy fatigue impact on primary side even from strong flexible operation was not confirmed. In most circumstances, the temperature differences were much less than 60 K and were at about 20 K, as the plant was performing the flexible operation in the region of the constant average temperature in the primary circuit. Overall, moving to the consideration of the real transients applying online monitoring and more detailed fatigue analyses, allowed to decrease the cumulative usage factor on the mainly impacted components.

In general, considering a potential operation lifetime extension to 60 years, more intense fatigue analyses were seen to be obligatory.

PWR G of approx. 1500 MWel

Control rod drives:

The plant is facing an increasing number of control rod adjustments caused by FlexOp. The number of control rod movements partly exceeded the design number of 1 million. The drives were checked, assessed and are regularly monitored for their drive voltage and current shapes. Together with the manufacturer and authority bodies, the drives were found to be able to run for more than the envisioned steps but are kept under observation.

Pressurizer:

The high number of fast load reductions lead to more and longer periods of spraying into the pressurizer. Especially the spray nozzles are seen to be exposed to a higher thermal load by this prolongation of operation. E.g. in the year when the increased flexibility was started, the overall number of actuations reached about 1.600, 10 times more compared to previous years. It caused a 50 K temperature difference in the spray line, and the fatigue contribution caused by this had to be taken into account for the lifetime management. Further on, I&C measures have been integrated, in order to decrease the transient thermal influences of the spraying on the nozzles (the lead spraying is distributed to more nozzles). The target is to keep the specific usage factor below 0.4 until the envisioned end of operation in 2022. Longer usage would strongly increase the additional, cost intensive effort which needed to be carried out. Beyond this time, even an exchange of those nozzles could become necessary.

Main coolant pumps:

A change of the vibration behavior was observed, depending on the load demand from the grid. Some pumps show higher, some lower vibration values with smaller power demand. Nevertheless, all values are laying within the specified ranges of observation, and finally return to previous values.

Steam generators (PWR):

FlexOp leads to more acoustic noise events in the vicinity of the feedwater intake nozzles. The events appear quite similar and seem to be related to thermal effects due to changes of the primary and feedwater temperatures. Alarm values are not exceeded, or alarms can be avoided by similar noise pattern analysis of the LPMS.

Volume control system (PWR):

FlexOp brings more thermal transients to the recuperative heat-exchangers of the volume control system. Calculative mitigation measures have been performed. One outcome is to keep on running 2 system pumps during secondary load control to decrease thermal transients on the coolers. The target is to keep the usage factor < 0.4 until the end of operation in 2022 (Figure 32).

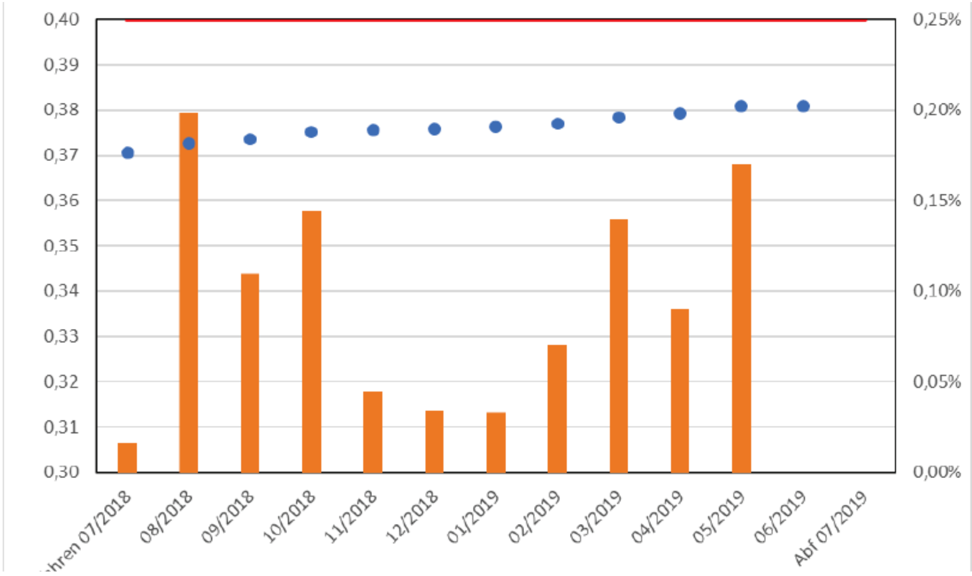


Figure 29: Accumulated fatigue factor (dotted blue) on recuperation heat exchanger between 2018/19 (orange: monthly increase; red: alarm limit) (Müller, C., 2020).

Feedwater pumps (PWR):

The operator sees a changing vibration behavior due to load follow, especially on axial vibrations. Nevertheless, all vibrations lay within specified limits, and return to previous values. The vibrations are monitored regularly.

Valve Drives:

The operator observed a significantly increasing number of valve drive operation steps on all drives in steam- and water circuits. On some systems he went back from a 6-year regular maintenance to a 4-year period. Regular and systematic monitoring of the drives is performed. Figure 33 shows an example for wear due to higher activation numbers during FlexOp.

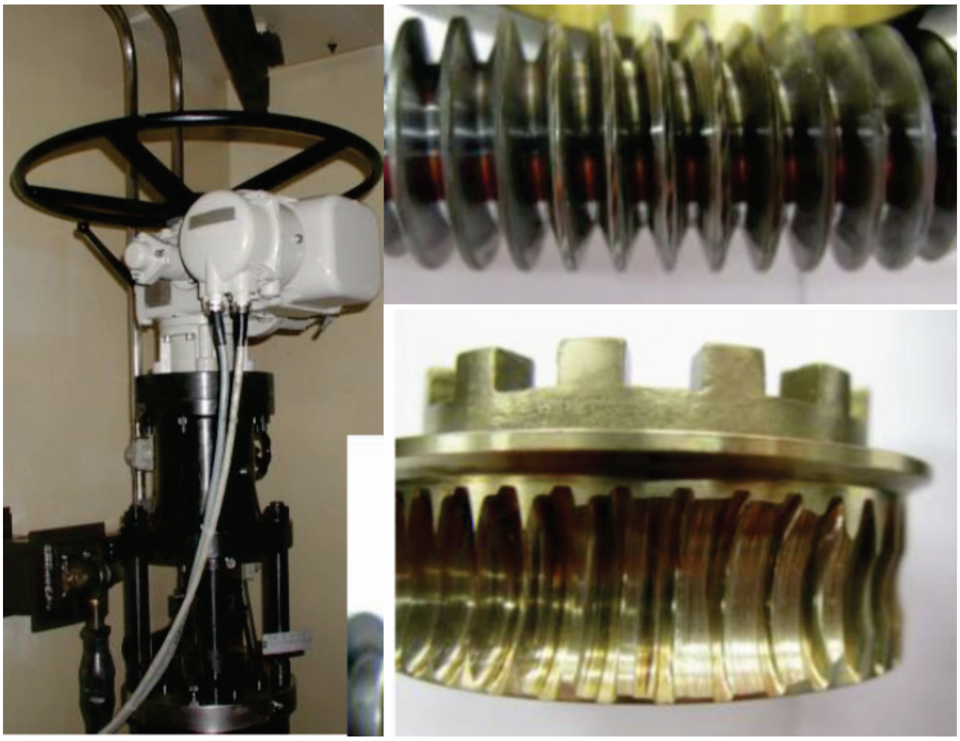


Figure 30: Wear on a valve worm drive due to higher activation numbers during FlexOp (Müller, C., 2020).

PWR H of approx. 1000 MWel

The operator performed an intense study on the influence of FlexOp on the plant performance and reliability in general. This led to recommendations for a deeper evaluation of the influence of FlexOp on several components:

Affected components of primary circuit:

- spray valves and nozzles on the pressurizer
- pressurizer heaters
- T-pipes with mixed temperature flows on auxiliary spray system
- heat exchangers of the volume control system
- related nozzles to the primary circuit
- valve drives and their power units on several systems (volume control, boron and deionized water injection, seal water...)
- pumps (more starts and thermal transients)

Affected components of secondary circuit:

- moisture separator/preheater
- condensate and feedwater preheaters
- general on components with changing water/steam ratios
- valve drives of several systems (condensate control, feedwater ...)
- vibration on the last stage turbine blades
- generator
- operation of cooling tower during wintertime due to part load conditions

A dedicated test monitoring system was created on 5 components of the secondary circuit, combining information from vibration and more than 1100 operational signals.

The instrumented components have been:

- 2 moisture separators / preheaters
- 2 steam driven feedwater preheaters on HP side
- 1 LP condensate pipe

Examples of sensor installation on a moisture separator and the condensate pipe is shown in Figure 34.

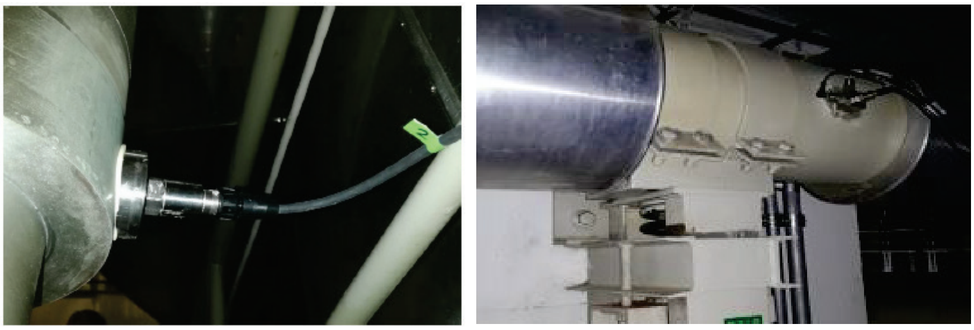


Figure 31: Exemplary sensor installation on a moisture separator (left) and a condensate pipe in PWR H (Forster, P., 2019).

An outcome of these tests have been the highly varying vibration levels on the condensate pipe in power operations (Figure 35), together with a strong spectral variation (Figure 36).

A dedicated FEM stress and fatigue analysis have been subsequently performed on that pipe, with a calculation of related usage factors (see chapter 4.4.6).

Further typical vibration shapes on the moisture separators/preheater during power transients have been observed (Figure 37).

An automated correlation of vibration and operational data led to AI-supported cluster analysis on widely spread parameters to highlight dependencies on separated system parameters (described in chapter 4.2.4).

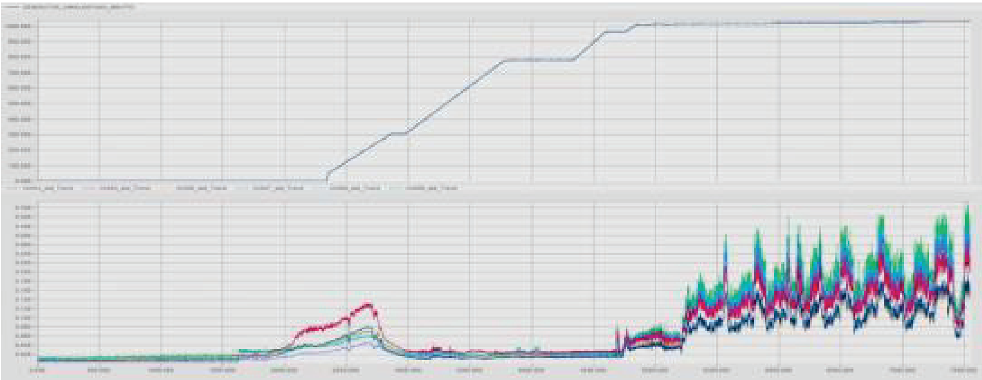


Figure 32: Increasing and pulsing vibration levels on condensate pipe with power in PWR H (Forster, P., 2019).

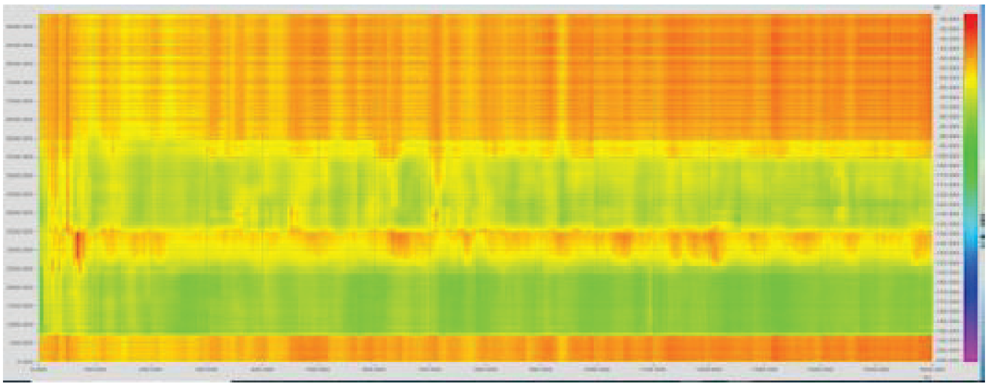


Figure 33: Varying of frequency distribution during test conditions on a condensate pipe in PWR H; vibration amplitudes indicated by color (Forster, P., 2019).

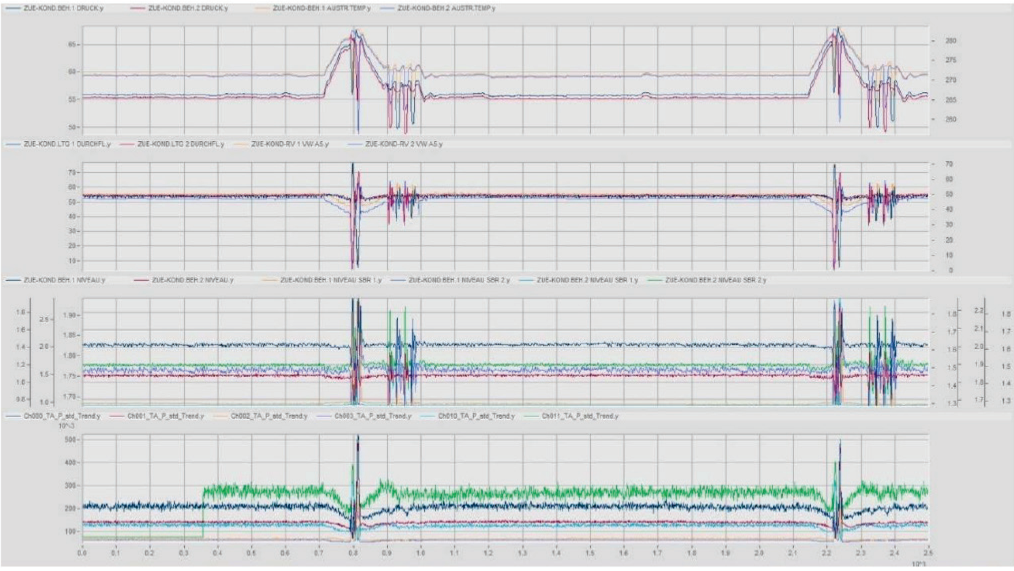


Figure 34: Varying of operational conditions and correlated vibration levels on a moisture separator in PWR H. (Forster, P., 2019).

4.3.5 Fuel assemblies (PWRs and BWRs)

4.3.6 Introduction

In this chapter the effect of FlexOp on the fuel assemblies (FA) will be discussed. The focus of the discussion will be on vibrations that are caused by power operating conditions. Vibrations caused by seismic, LOCA or other accidents are not covered.

Depending on the method to vary the core power the consequences on the fuel can be different. For BWRs the power is mostly changed by the pump speed. In PWRs the core power is mainly changed by RCCA movements and/or Boron concentration changes. In the first case the flow velocity in the core will change. In both cases power changes are always related to temperature changes.

4.3.7 Excitation mechanisms and their consequences

Vibrations of the fuel assembly and its components in the reactor core are under normal operating conditions usually caused by the coolant flow. These vibration phenomena are categorized as flow induced vibrations (FIV).

There are several excitation mechanisms. Always present is the turbulent excitation. It is caused by the fluctuations inherent in turbulent flow. The turbulence is significantly enhanced by the spacer grids and other fuel components. The turbulent excitation level is also influenced by the design of the core internals.

The consequences of turbulent excitation are small vibrations of the fuel assembly and the fuel rods. These vibrations are in the order of 10 to 15 µm (root-mean-square). The excitation spectrum is broad-banded similar to a noise signal.

The resulting vibrations can cause wear at the fuel rod support in the spacer grids (grid-to-rod-fretting). This has to be avoided by a fretting robust design of the fuel rod support. Wear is also possible at the outer straps of the spacer grids if there is a contact to other core components. This risk can be minimized by the design of the spacer grids.

For the turbulent regime, the operation at the nominal power case is covering for FA and FR vibrations. For lower flow velocities and mass flows, the vibration amplitudes are smaller. The effect of small density changes of the coolant due to temperature changes can be neglected.

Another excitation regime is the self-induced vibration. It is related to a strong coupling between the fluid flow and mechanical vibrations (fluid structure interaction – FSI) which allows that energy is periodically transferred from the coolant to the structure. It can be triggered by an unfavorable hydraulic spacer grid design.

The self-induced excitation mechanism can lead to very large vibration amplitudes in the range of 50-200 µm (root-mean-square) of the fuel assembly. Such intense FA vibrations cause strong FR vibrations which can lead under certain conditions to severe grid-to-rod-fretting. Fuel rod failure can happen in a short period of time.

The resulting motion due to a self-induced excitation mechanism is non-chaotic, periodic and highly structured. There is one dominant vibration mode which is typically a higher bending mode of the FA.

While turbulent excitation results in a form of stable forced vibration, in the case of self-induced excitation, strong FSI effects play a major role. These are dependent not only on flow conditions but also on structural parameters of the fuel assembly.

Due to the enormous potential of self-induced excitation mechanisms to cause failure within a short time, adequate testing with respect to sensitivity to self-induced excitation is an essential part of the design assessment methodology. Sensitivity to self-induced excitation has to be eliminated by design measures.

The sensitivity of the fuel with respect to FIV is investigated with flow tests in which the vibratory response of the fuel assembly and the fuel rods is measured for different relevant flow conditions. These tests are usually full-scale tests using real components and parts. Reduced scale testing is in principle also possible.

For the testing it should be considered that self-induced vibrations can occur at flow velocities other than the nominal one. Therefore, a larger range of flow velocities must be covered by the tests. This is usually done by performing sweep tests with continuously varying flow rate.

The effect of cross flows created at the inlet, at the core shroud or due to mixed cores is for PWRs of special interest as excitation source and should be considered for the testing.

State-of-the-art simulations techniques as computational fluid dynamics (CFD) coupled with mechanical models are also gaining ground in the FIV phenomena investigation. Based on the nature of the phenomena, the coupling can be one-way e.g. for turbulent excitation (flow → vibration) or two-way as for self-induced vibration (flow ←→ vibration).

4.3.8 Effect of varying operating conditions on vibrations

Based on the performed interviews with German utilities, there was no indication that FlexOp had a negative impact on the fuel assembly vibrations.

In PWRs, the pump speed remains constant for FlexOp. Therefore, there are nearly no changes in the excitation level created by the coolant flow. The effect of the coolant temperature and density changes on the excitation is negligible. No change of the fuel assembly and fuel rod vibration is expected.

For FlexOp in BWRs, the reactor power is mostly controlled by the pump speed. If the power has to be reduced from the nominal state, the flow is reduced. This leads to a lower turbulent excitation resulting in smaller vibration amplitudes.

In BWRs, the excitation level is smaller compared to PWRs. This is also due to the design of the fuel assembly, e.g. the surrounding fuel channel which reduces the risk of large cross flows inside the FA. Turbulent excitation is the main source of vibrations. Self-induced vibration at lower mass flows than the nominal is prevented mainly by damping. With a robustly designed rod support, the risk of grid-to-rod-fretting is low.

In a Germany BWR using FlexOp there were no observations that fuel vibrations have changed.

Overall, there was no feedback from the German utilities that FlexOp had negative impact on FA vibrations for heterogeneous cores from different suppliers.

4.3.9 Relevance depending on component safety class and risk of failure

In IAEA Specific Safety Requirements No. SSR-2/1 (Rev.1), Requirement 4: Fundamental safety functions, it is stated:

> "Fulfilment of the following fundamental safety functions for a nuclear power plant shall be ensured for all plant states: (i) control of reactivity; (ii) removal of heat from the reactor and from the fuel store; and (iii) confinement of radioactive material, shielding against radiation and control of planned radioactive releases, as well as limitation of accidental radioactive releases.
>
> 4.1. A systematic approach shall be taken to identifying those items important to safety that are necessary to fulfil the fundamental safety functions and to identifying the inherent features that are contributing to fulfilling, or that are affecting, the fundamental safety functions for all plant states.
>
> 4.2. Means of monitoring the status of the plant shall be provided for ensuring that the required safety functions are fulfilled."

Regarding flexible operation, this requirement implies that if indications on SSCs are detected, they have to be assessed regarding their safety significance and measures have to be taken to ensure the required safety functions.

Indications on operational components in general do not have safety significance but they may have a significant impact on the availability of the plant and on the frequency of initiating events.

- Example: On the secondary side, mass flows are controlled by throttling of flow. This may induce vibrations on main feedwater control valves or turbine inlet control valves. Vibrations in pipes of operational secondary systems are not safety important but may lead to operational problems. Therefore, it is reasonable to monitor such vibrations.
- Such effects can also finally lead to initiating events like "loss of main feedwater" or "loss of main heat sink". Even if the safety systems which are required to cope with such events are not affected by flexible operation, an increased frequency of such events would have a negative impact on plant safety and an impact on the probabilistic safety analysis too.

Indications on safety systems require actions like e.g. repair or replacement of the component in order to recover the required redundancy.

- Example: During load follow operation, the number of steps of the control rods in PWRs is increased which may lead to increased loads on the rods. This may lead to malfunctions like rod drop. A monitoring system that counts and records control rod motion (i.e. number of steps) is suitable for comparison to design lifetime resp. for definition of increased maintenance frequency.

Vibrations may have an impact on civil structures. That means certain civil structures also have to be included in the safety assessment.

In IAEA Nuclear Energy Series No. NP-T-3.23 "Non-baseload Operation in Nuclear Power Plants: Load Following and Frequency Control Modes of Flexible Operation", potential impacts, possible solutions and recommendations for flexible operation and implementation in nuclear power plants are discussed (e.g. Sections 5.3.2, 5.3.3, 5.3.4, 5.3.12 of this guide).

In appendix B, the impacts of FlexOp in NPPs with respect to vibration and wear are summarized and affected components are listed based on the experience of the German plants.

Only one listed component is related to an active safety function (Control rod drives). Adverse consequences due to flexible operation can be mitigated by intensive monitoring and inspection, e.g. online fatigue monitoring and specific tracking

The following listed components of nuclear island are passive components contributing to the fulfillment of safety functions:

- Steam generator
- Recuperative heat-exchanger
- Pressurizer spray nozzle
- Fuel Assembly (no impact on vibration)

All other components listed in appendix B are only related to operational systems and components. Such components may have an effect on plant availability and in some cases on the frequency of initiating events.

The countermeasures and mitigation measures described in appendix B are suitable to identify increasing degradation in due time and to avoid undesired consequences.

4.1 OVERALL IMPACT ON ELECTRICAL COMPONENTS

This subchapter is dealing with electrical components, including main generator, regarding the impact of overall changed operation requirements and grid conditions.

The preferred consideration of renewable energy as power sources for the grid, especially windmills and photovoltaic, has an impact on the operation mode of the NPPs. It leads particularly to FlexOp operation requirements, and also changed requirements corresponding to the reactive power delivery to and absorption from the grid and also effects in the grid, e.g. regarding harmonics.

In the following the different consequences are shortly described.

4.1.1 Flexible operation providing active power

Electrical components:

The electrical components of the Unit Auxiliary Power Supply System are generally minimally affected by the flexible active operation of the plant. Experience has shown that especially power contactors in defined control circuits have to be substituted in a shorter interval than before (e.g. 2 years) and a higher maintenance effort could be necessary.

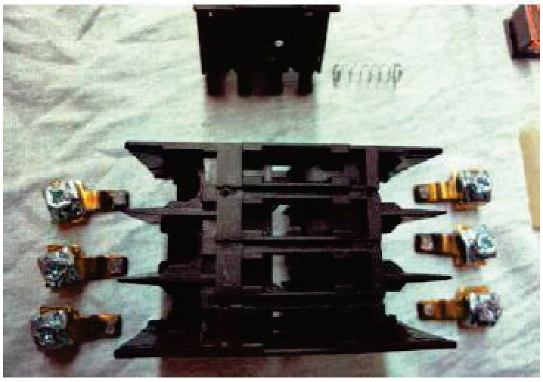


Figure 35: Power contactor with higher demand (Müller, C., 2020).

Main generator:

Vibrations may be introduced by the turbine to the main generator. Experience in Germany has shown that this depends on the special characteristics of the Turbo-Generator and the conditions of the connecting point to the grid.

In the NPP with the highest level of vibration, a measuring system was installed. On the turbine shaft a measuring system for the torsion vibration was installed and additionally electrical measurements on the grid connection. With the results, an "empiric-mathematic model" was elaborated. With this model it is possible to calculate mechanical vibrations considering the electrical input data. The "empiric-mathematic model" has no active influence in the unit protection but gives alarms if limit values are reached. The shift has to decide about eventual further actions.

In order to avoid possible stress for the generator, the NPP has limited the allowed power ramp rates.

4.1.2 Voltage regulation with NPPs

Over the years, a change of the power factor (from overexcited to underexcited operation) can be seen in various German NPPs.

During the design and construction phase of NPPs, the foreseen operation of the main generator was in an overexcited (inductive) mode, as shown in Figure 39 with a power factor of 0.9 inductive.

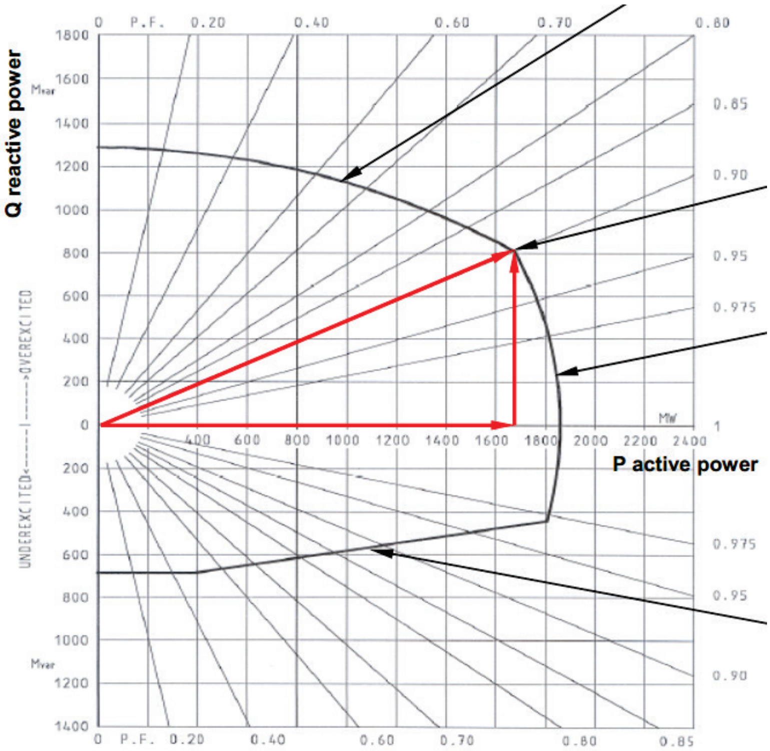


Figure 36: Generator diagram with “standard operational point”.

Depending on the local grid conditions of an NPP, in many cases the operation of the generator is carried out mainly in an underexcited (capacitive) mode, as shown in the following Figure 40. This operation mode is necessary because renewables, especially photovoltaic sources, may create a high voltage in the grid, which has to be reduced by the conventional plants with underexcited (capacitive) operation mode. If the electric utility has no other conventional alternatives, this has to be done by NPPs. Otherwise, with fossil fuel fired plants available in the operating park, NPPs are used only in rare cases in the underexcited (capacitive) operation mode.

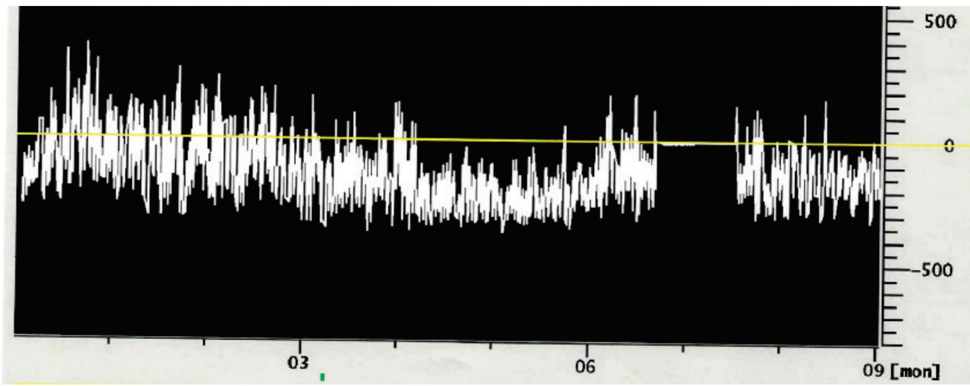


Figure 37: Reactive power (inductive/capacitive) of PWR G over 9 months.

The underexcited (capacitive) operation mode is afflicted with some technical constraints, as described in the following:

a). Active power production may be affected.

The generator curve presented in Figure 39 shows that with a power factor (capacitive) lower than 0.975, the active power production has to be reduced. This is also shown in Figure 41 for a specific plant. The maximum capacitive reactive power which can be produced without reduction of the active power for PWR G is approx. 400 MVAr

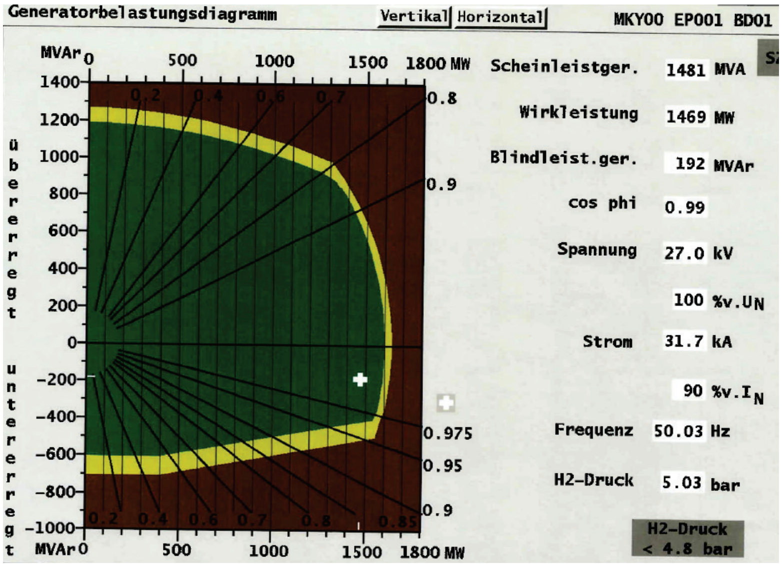


Figure 38: Generator diagram of PWR G.

b). Instability of the generator in case of a short circuit in the grid (fault ride through, FRT).

In case of a short circuit in the grid, the unit has to remain connected to the grid with stable generator until the fault clearance time (150 ms in Central Europe, 250 ms in the NORDEL area). With the same fault clearance time, the generator of a capacitive operated plant gets faster instable than a plant operated at the nominal point of Power factor 0.9 inductive.

c). Initiation of switch-over to standby grid in case of short circuit in the grid, depending on power factor.

The initiation of the switch-over of the unit auxiliary power supply to the standby grid is initiated in many plants from the unit protection, due to underfrequency and undervoltage.

In case of a short circuit in the grid, the plant has to remain operable and connected to the grid under conditions defined by the Grid Code. Additionally, to the risk that the generator gets instable, the initiation of the switch-over to standby grid by the undervoltage protection is high. As shown in Figure 42, the voltage sag after fault clearance (150 ms in this case) depends on the power factor. During underexcited operation (capacitive power factor), the time until voltage recovery increases significantly. The risk that a power plant will be disconnected in case of a fault in the grid increases while the generator is performing in underexcited mode.

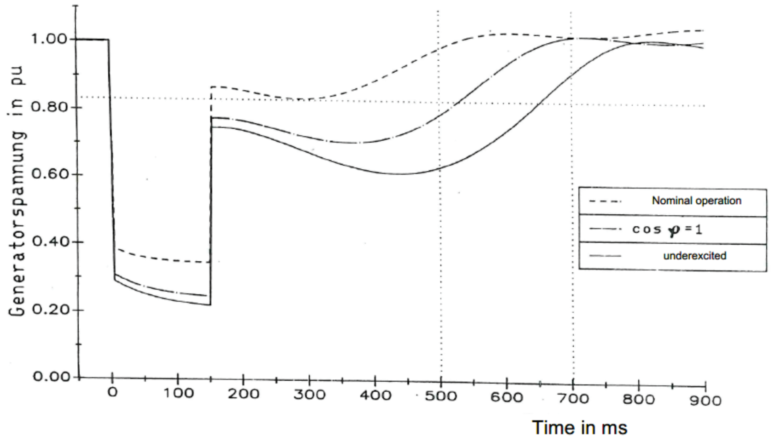


Figure 39: Typical generator voltage in case of a short circuit in the grid, depending on the power factor.

Remark: At load conditions with very high capacitive reactive power, the stator core and especially the end zones could be subjected to higher thermal and vibrational stresses, which should be avoided to assure a reliable operation of the generator.

4.1.3 Other influences from the Grid

Due to the influence of the renewable energy sources, the stability in the grid has lowered. The windmill parks supply their energy to the grid via fast reacting static inverters, which produce a “non-perfect” sinus with influence on the generator. The harmonics may produce vibrations in the stator lamination.

Compared to the past, the Power System Stabilizer acts more often (approximately 10x). This creates also stress for the generator.

4.1.4 General operational feedback: example of North-Germany

All operators in North-Germany are facing a higher number of harmonic waves and peaks in the grid voltage, which are seen to come from great wind farm grid converters. Also, the operation of a new cable link to Norway seems to increase the volatility in the grid. Two generator stators appeared to have a high number of loosened isolation material, so they had to be exchanged completely.

Overall, through the combination of various potential courses, such as some construction features, aging effects, voltage peaks coming from wind farm converters, voltage transients during switching process, the voltage regulation impacted generator performance in various NPP in North of Germany. Flexible operation is also discussed as one of the possible additional courses.

4.2 MEASUREMENTS AND NUMERICAL METHODS TO IDENTIFY COMPONENTS WITH POTENTIAL VIBRATION PROBLEMS

There are several proven methods to identify components with potential vibration problems:

- Human detection
- Numerical methods
- Sensorial detection / vibration measurements

These methods are mostly used in combination.

4.2.1 Human detection

Though not absolutely objective, the detection of new or extraordinary sound and vibration by human ears, eyes or hands is often a first indication triggering deeper analysis. E. g. the ASME-code OM-S/G-2007 describes measures for getting a first impression with some help for a more countable assessment. Also, many plant operators rely on this method by simply performing regular walk downs in the plant during constant or transient load operations.

Visually detectable vibrations are often seen on large and weakly supported structures, like piping or baffle plates, mostly in the low frequency range up to approx. 20 Hz.

Audible detectable vibration patterns lay in the frequency range of 20 to 2000 Hz, but lead sometimes to misinterpretations, because acoustic noise depends on sound velocity of a surface and its vibrating area. So, if the emitting surface is large enough, a misleading acoustical impression can arise.

4.2.2 Numerical methods

A recommended first step for a better understanding of the behavior of a power plant component is to create a numerical model of the component using structural, acoustic or fluid dynamic simulation tools, e.g., Finite Element Methods. Often such models have already been created during the design phase of the component.

The numerical models, usually based on material and design data of the component, are typically used for the following purposes:

- Static load analysis to determine high stress and strain areas.
- Modal analysis to find natural frequencies and mode shapes of the structure.
- What-If investigations where the effects of design changes (material or geometry) on the static or dynamic properties of the structure are analyzed.
- Dynamic loads analysis where time histories of the structural response to dynamic loads are simulated.
- Digital twin or simulation of a structure using data measured on the actual component.

A numerical model is only an approximation of the static and dynamic behavior of the real component or structure, for example, a FEM model. Therefore, verification and validation of the model through measurements and testing of the real structure is commonly done in praxis. The most widely used tool for this purpose is experimental modal analysis and model updating, for example, with ME'scope according to Mobius Institute (Mobius Institute Training and Examination Center, 2017). Figure 43 resumes the process.

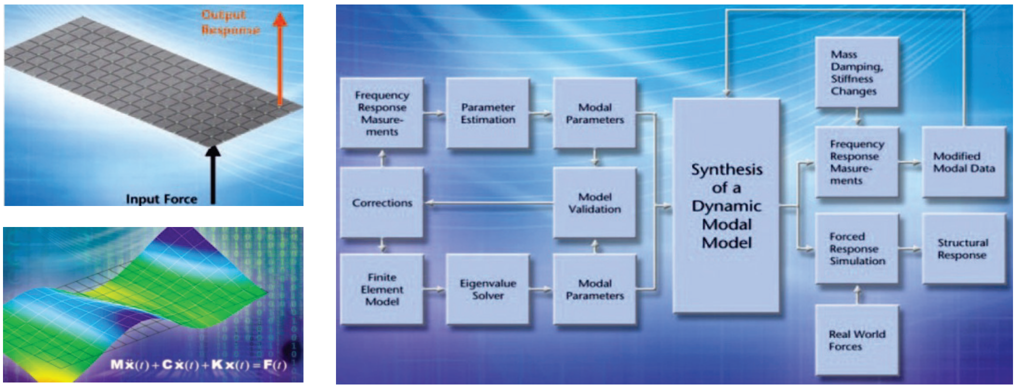


Figure 40: FEM model testing, validation and optimization.

During testing, measurement data on the real structure are acquired for following purposes:

- Verification of the numerical or analytical model by comparison of modal parameters from experiment and model.
- Evaluation of design changes on prototypes before production changes.
- Troubleshooting of noise and vibration problems on structures or machines which are already in service.

Figure 44 shows an example from a Framatome project where numerical methods have been used for model-based diagnostics of a main coolant pump. The same procedure can be applied to any kind of rotating machine.

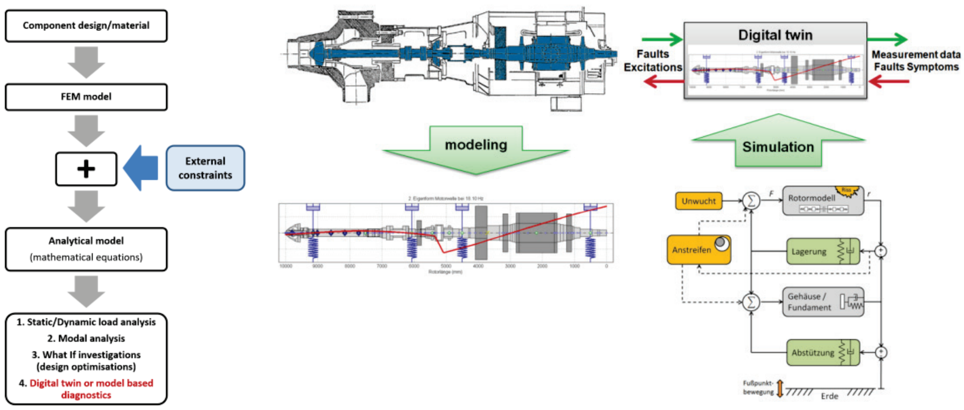


Figure 41: Application of numerical methods for model-based diagnostics (digital twin).

Another application example is the finite element analysis of a piping system to identify the dynamic behavior (natural frequencies, damping values and mode shapes) and to derive the installation positions of the vibration sensors according to predefined observability criteria (-> nodal points) see Figure 63.

4.2.3 Sensorial detection or vibration measurement

A large variety of vibration sensors are available on the market, with typical properties and application ranges:

Table 3: Overview of vibration sensors commonly used in condition monitoring.

Sensor Type	Short description
Displacement sensors	• Useful for frequency ranges between 0 and 1000 Hz (static position + vibrations) and measurement range from 0.1 to 10 mm. • Allow relative vibration measurements (e.g. displacement/position of the shaft in a journal bearing). • Can be used for radial position measurements (orbit measurements), axial position measurements and as key phasor (speed measurement) of rotating shafts and also for measurement of rotor/stator differential thermal dilation (e.g. on turbo machinery) • Mostly used for rotating machines with journal bearings. • Most expensive vibration measurement method using eddy current technology
Acceleration sensors	• Very useful for frequency ranges between approx. 0.5 and 20.000 Hz • Allow absolute vibration measurements (e.g. casing vibrations of rotating machinery or vibration on non-rotating structures like piping, vessels, or heat exchangers). • Mostly used on rotating machines with roller bearings. • Robust vibration measurement technique, widely used in industry • Most economic vibration measurement method using piezo technology
Velocity sensors	• Useful for frequency ranges between 2 and 2000 Hz, using the electrodynamic principle for vibration measurement • Allow absolute vibration measurements (e.g. casing vibrations of rotating machinery). • Mostly used by rotating machines with journal bearings for casing vibration measurements. • Decreasing number of applications in the industry, due to more robust and economic acceleration sensors

It is recommended to get vibration information as close as possible to the excitation source, which means a close adaption of the sensor to the component in question, and also to consider the frequency range of the vibrating component to be measured by choosing the suitable sensor for the task.

Since it is expected that load follow operation induced vibrations will change with flow conditions, it is also recommended to gather all relevant process information together with vibration measurements:

- Flow conditions (temperature, pressure, mass flow, …) at inlet and outlet of all identified NPP components which are impacted by load follow operation
- Mechanical conditions of active (or motor operated) components like pumps and valves (speed, power, position, …)
- Electrical conditions of active (or motor operated) components like pumps and valves (voltage, current)

For an efficient correlation analyses during the data evaluation and diagnosis, it is recommended to get all data (vibrations and process data) aligned in time, i.e., time synchronization of the decentralized data collectors with the plant master clock and time stamped measurement data are mandatory.

Figure 45 shows an overview of the solution to put in place in order to get vibration and process data, time synchronously, for an efficient monitoring, diagnosis and prognosis for components impacted by load follow operation.

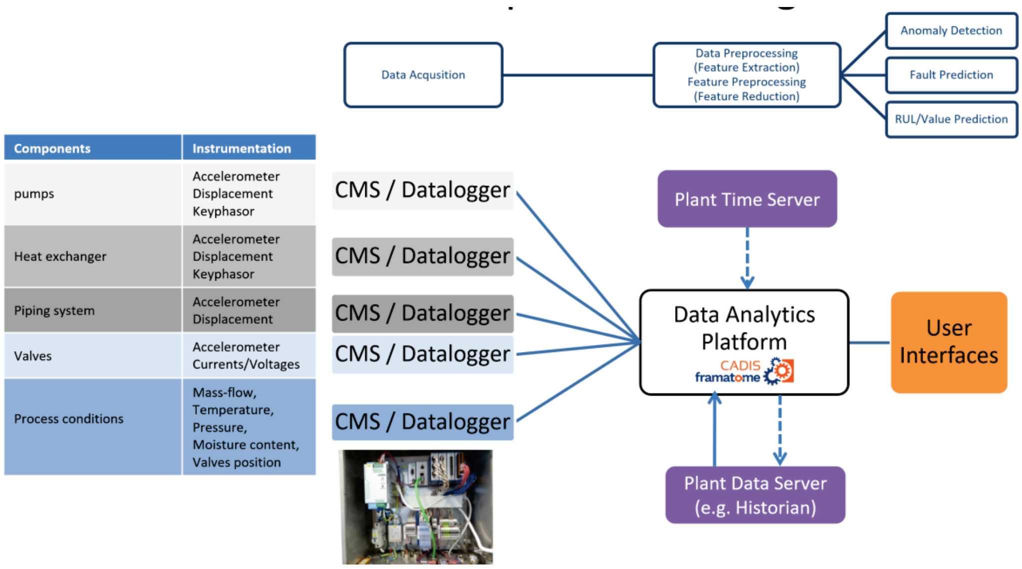


Figure 42: Proposed solution for time synchronously data collection for monitoring, diagnosis and prognosis purposes.

In order to deploy the above-mentioned solution, it is recommended to follow related standards:

- ISO 17359 (Condition monitoring and diagnostics of machines — General guidelines) presents an overview of a generic procedure recommended to be used when implementing a condition monitoring program and provides details on the key steps to be followed. It introduces the concept of directing condition monitoring activities towards detecting failure modes and describes the generic approach to setting alarm criteria, carrying out diagnosis and prognosis, and improving the confidence in diagnosis and prognosis.

- ISO 13379-1 (Condition monitoring and diagnostics of machines — Data interpretation and diagnostics techniques — Part 1: General guidelines) gives:

    (1) a general procedure that can be used to determine the condition of a machine relative to a set of baseline parameters. Changes of the baseline values and comparison to alarm criteria are used to indicate anomalous behavior and to generate alarms → condition monitoring or fault detection, and

    (2) guidelines for the data interpretation and diagnostics of machines. Additionally, procedures that identify the cause(s) of the anomalous behavior are given in order to support the determination of the proper corrective action → diagnostics or fault identification.

The above mentioned standards can be resumed to the process flow diagram in

Table 4: Process flow diagram for condition monitoring and diagnostics programs.

Step	Step Description
1) Selection of measurement positions	a. Standards (e.g. ISO 7919, ISO 20816), b. Numerical investigations (mode shape observability criteria) c. Failure Mode Symptom Analysis method (ISO 13379-1)
2) Selection of relevant plant process data	a. Flow condition data (mass flow, temperature, pressure, moisture content) b. Valve positions c. Pump speeds d. Generated power
3) Configuration of the data logger for time synchronous data acquisition	a. Suitable sampling frequency / monitoring time window b. Signal pre-processing, e.g., re-sampling, filtering, … c. Monitoring parameter per signal and limit values (e.g. RMS) d. Data storage strategy i. Trigger conditions (cyclical (e.g. hourly), by operating condition change (e.g. speed), by threshold violation) ii. Measurement record length (Pre-trigger, Post-trigger)
4) Data analytics (Diagnosis / Prognosis)	a. Data pre-processing for feature extraction (transform unstructured raw data to time series features) b. Feature pre-processing for feature cleaning, enrichment and reduction c. Anomaly detection i. Live monitoring of extracted features with different limit levels and alert notifications ii. Descriptive analytics (find out what happened, when, where and how using clustering methods) d. Fault prediction (predict what may happen, fault prediction using classification methods) e. Prediction of the Remaining Useful Lifetime using regression methods f. Expert or knowledge based diagnostics

The resulting solution after implementing the above-mentioned process diagram will look like follows, see Figure 46:

- Process = load follow operation impacted NPP component with its sensors
- Monitoring = vibration and operational data acquisition + processing + monitoring (threshold violation check) + data storage + alarm notification
- Diagnosis = measurement data collection + data processing + descriptive/ predictive analytics (data driven diagnostics) + knowledge/expert-based diagnostics

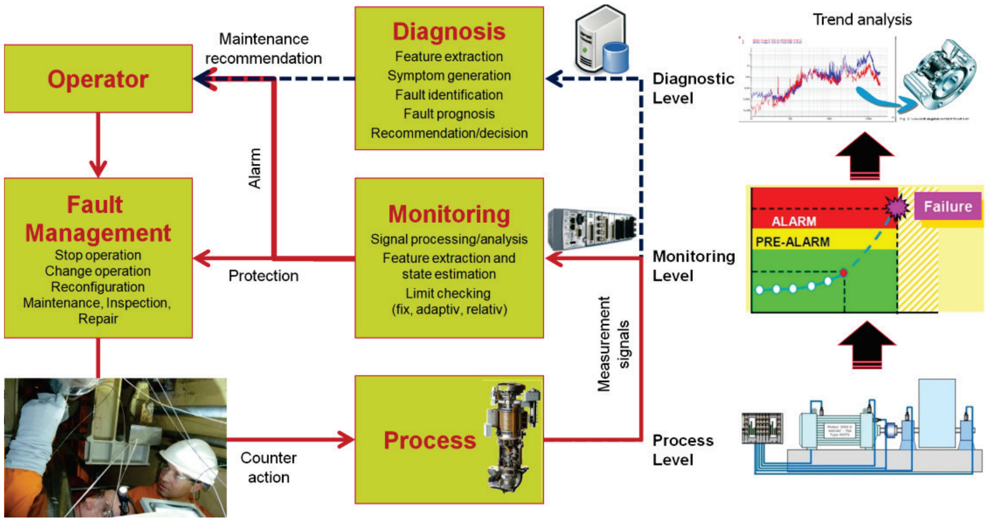


Figure 43: Condition Monitoring and Diagnostics according to ISO 13379-1 and ISO 17359.

4.2.4 Selection of vibration measurement positions

The selection of vibration measurement locations can be done according to the following rules:

Table 5: Method for selecting the measurement location.

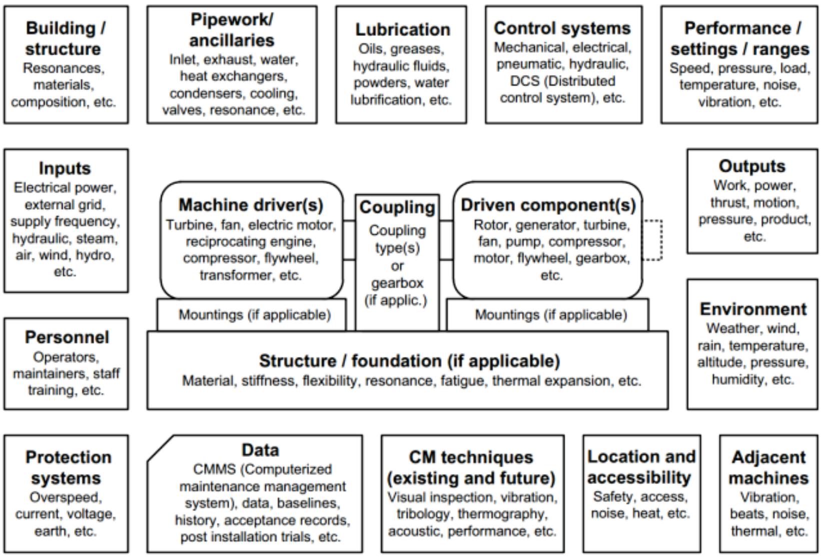
Method	Field of application
Based on standards	E.g. ISO 7919, ISO 20816 for rotating machinery
Based on numerical investigations (mode shape observability criteria)	For flexible structures like piping systems, elastic shafts, etc.
Based on Failure Mode Symptom Analysis	ISO 13379-1 for all power plant components

4.2.5 Selection of relevant plant process data

The selection of the relevant process data can be done according to Table 6 (ISO 17359), which presents the factors influencing the operating and vibration condition of a component.

All information which can influence the operating and vibration condition of the component must be continuously collected and monitored together with the vibration data. Basically, all interactions of the NPP components with its environment must be identified and all measurement data or information at the identified interfaces must be collected.

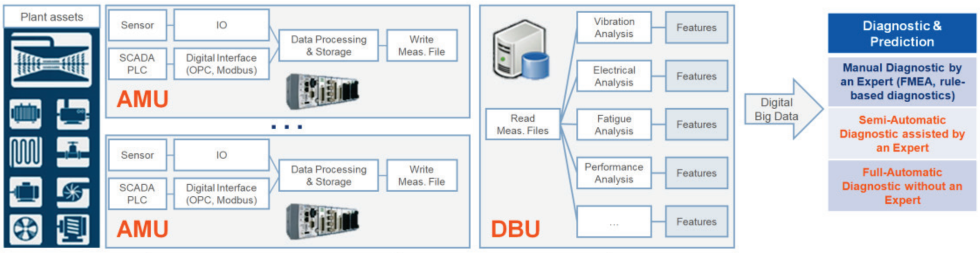
Table 6: Selection of relevant plant process data.



4.2.6 Configuration of the data logger for time synchronous data acquisition, monitoring and data storage

Framatome has built in the past years an universal data logger system (see Table 7) capable to connect to many industrial sensors available on the market. The aim of the system is to gather data of different types of NPP components with the same hardware solution and by this means reduce the costs for condition monitoring.

Table 7: CADIS Data loggers



	Dynamic Signals (1 to 100 kHz or 1MHz)				Static Signals (1 to 100 Hz)			SCADA Interfaces
Data logger, Condition, Performance, Fatigue & Structural Monitoring	Vibration Noise	Load Strain Torque	Current Voltage	Acoustic emission Ultrasonics	Temperature Pressure Flow Position	Thermo-graphy	Oil Lubrication	OPC, Modbus, EtherCat, ProfiNet, Profibus, CANopen
Rotating machines	x		x	x	x	x	x	x
Valves	x		x					x
Non rotating machines, Pipes, Vessel	x			x	x			x
Boiler, heat exchanger	x	x		x	x	x		X
Concrete structures	x	x		x	x	x		X

AMU: Acquisition and Monitoring Unit
DBU: Data Base Unit

The scalable data logger combines multiple monitoring tasks:

- condition monitoring using vibration, acoustic, and electrical signatures,
- fatigue monitoring using temperature, load or vibration data
- and performance monitoring using process data

of different kind of plant equipment (rotating structures like pumps, motors, etc. and non-rotating structures like pipes, and heat exchangers) in one system.

Each NPP equipment has its typical characteristics like design, function, failure modes, operating modes. Based on these characteristics, an individual Failure Mode Symptom Analysis is performed, which identifies all relevant failure modes with their diagnostic indicators. The result of this analysis helps to design and configure the online monitoring system concerning the selection of sensors, signal conditioning modules, monitoring parameters, data storage strategies, and data analyses for feature extraction. The commissioning of the online monitoring system should take place during commissioning of the equipment or after a maintenance intervention. In a learning phase, the baseline or reference measurements are recorded. Their analyses help to characterize the equipment by defining the reference and threshold values for the different operating modes. During the operating phase, the measurement data (vibration and process data) are acquired and monitored permanently to detect events such as change in operating mode or in health condition. The measurement data are stored both cyclically and event-triggered on the online monitoring device and are then automatically transferred to the Data Server (CADIS Data Storage) using standard network-based communication interfaces.

A machine with a condition monitoring system tailored to its specific characteristics and permanently capable of communicating via Ethernet or internet to a centralized Data Server can be called an intelligent machine. It is able to monitor and diagnose itself to report events such as monitoring alarms or system errors and to regularly archive their measurement data on the predefined data storage platform. Using the universal data logger system all Load follow operation impacted NPP components will be transformed into intelligent components.

Deviations from the baseline values and comparison to alarm criteria are used to indicate anomalous behavior of components and to generate alarms: this is usually designated as condition monitoring according to ISO 17359 and this is together with the cyclic and event-based measurement file creation the purpose of the universal data logger.

Additionally, procedures that identify the cause(s) of the anomalous behavior in order to assist in the determination of the proper corrective action is usually designated as diagnostics according to ISO 17359 and this is explained in the next section 4.2.4.

4.2.7 Data driven and knowledge based diagnosis

The following information is mandatory for an optimal diagnosis according to ISO 13379-1 and should be continuously collected into the data server:

1. Condition monitoring data
    a. Dynamic measurement (e.g. vibrations) and their extracted time series features,
    b. Operational parameters like speed, power, mass flows, pressures, temperatures,

2. Component design data such as natural frequencies, kinematics data, bearing types, motor types,
3. Component history: a record of the fault history, operational history and maintenance history of the component in order to take these facts into account for diagnostics.

Two main approaches can be used for diagnosing the condition of a component according to ISO 13379-1.

a) Data driven approaches (simple trending, neural network, pattern recognition, statistical approach or other numerical approaches). These methods are generally automated, do not require deep knowledge of the mechanism of fault initiation and propagation, but do require training the algorithm using a large set of observed fault data.

b) Knowledge based approaches, which rely on an explicit representation fault behavior or symptoms through, for example, fault models, correct behavior models or case description.

These approaches which are implemented in the Framatome Data Analytics Solution called CADIS (Fomi et al., 2019) may overlap, and solutions may be developed which utilize a combination of several approaches.

The load follow operation impacted NPP component is continuously monitored using the universal data logger. Relevant measurement data (vibration and process) are recorded when necessary (cyclically or event based). Anomalies are detected automatically during the monitoring process using pre-configured monitoring thresholds. Monitoring results and alarm notification are forwarded to the main control room. The measurement files are collected on the data server and analyzed automatically by the data analytics modules in order to extract information and insights which are used for data driven and knowledge based diagnostics.

All component data (historical and current data, raw data, processed data, operational logs, fault history) should be accessible to the CADIS data analytics module at any time. This provides the possibility to use signal processing, data mining, statistics, and machine and deep learning methods, and to automatically extract meaningful information and insights like fault pattern recognitions, fault predictions and RUL predictions. See Figure 47.

The extracted information and insights can be put at the disposal of diagnostic experts, who can confirm the data driven diagnostics results and create recommendation reports with counter measures for the identified component faults.

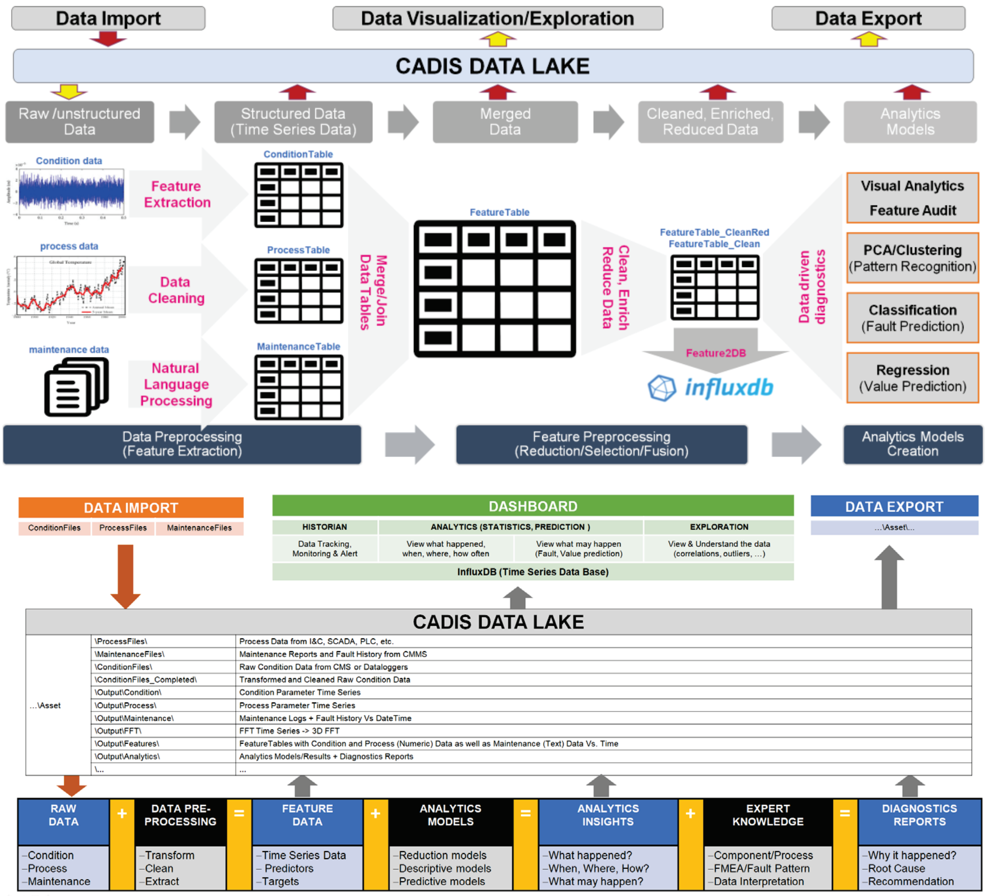


Figure 44: Data driven and Knowledge based Diagnostics with CADIS.

4.2.8 Data analytics application examples

4.2.9 Example 1: Anomaly detection using vibration and process data on a rotating machine

The first step consists of the extraction of time series features using signal processing algorithms from vibration data and to merge the gained vibration features with cleaned time series process data in order to obtain a so-called feature table, see Figure 48.

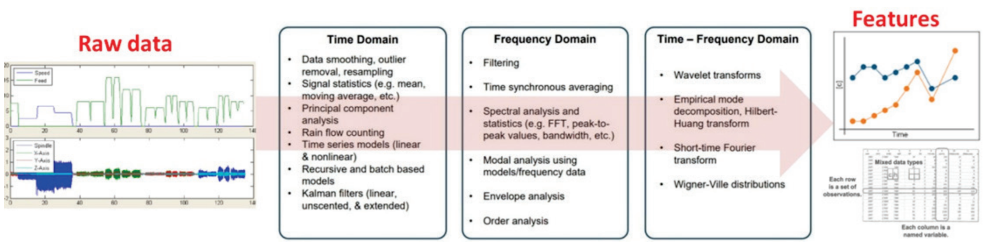


Figure 45: Example of Signal Processing for Feature Extraction using the CADIS.

The next step is to identify statistic clusters or groups inside the data. Then the identified statistic clusters are compared with process induced clusters according to rotating speed changes. All remaining clusters or changes which are not process induced are component fault related and represent a vibration issue or anomaly. Figure 49 shows statistical clusters and process induced clusters.

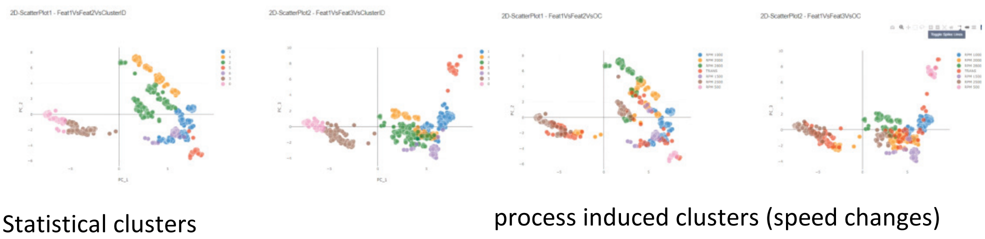


Figure 46: Cluster analysis for anomaly detection on rotating machinery.

From each cluster, one can get the information when (time period in which the cluster occurs) and where (sensor and parameter linked to the cluster) an event occurred. Using this information, a review of time series data using expert visualization tools will give an explanation of the cluster occurrence.

4.2.10 Example 2: Anomaly detection on primary circuit using functional test data

During hot functional test on a NPP primary circuit, vibration and process data have been collected. The temperature and pressure of the coolant have been step by step increased from 60 °C to 303 °C and vibration data have been collected.

Using the same procedure as in example 1, the results depicted in Figure 50 have been obtained.

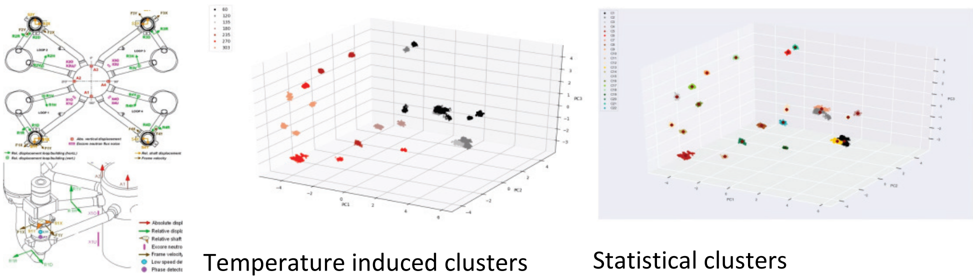
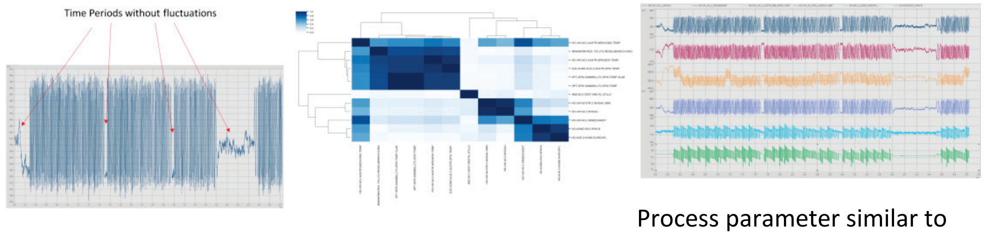


Figure 47: Cluster analysis for anomaly detection on reactor coolant system.

The figure shows statistical clusters and process induced clusters. For a given temperature level, there can be several clusters. The analysis why there are several clusters for a specific temperature level (steady state process operation) gives hints about vibration excitations mechanisms which may exist at this temperature level.

4.2.11 Example 3: Fault pattern recognition and problem localization using process data

A water level fluctuation problem has been observed for several months in a NPP heat exchanger. The knowledge-based diagnosis of the problem was not successful. It has been decided to use the CADIS data analytics platform for analyzing this problem. Over 1000 different process parameter data taken from different components have been provided. After importing the data in the CADIS platform, the data have been cleaned and reduced to components which may be related to the observed problem (approx. 300 process parameters remaining). Then a correlation and cluster analysis (so-called cluster map) has been carried out to find process parameters which are similar to the water level fluctuation signature, see Figure 51.



Water level fluctuation | Cluster map results | Process parameter similar to water level fluctuation

Figure 48: Correlation and cluster map analysis for problem localization.

CADIS was able to pinpoint the components linked to the problem and to give hints about the origin of the problem: A valve was defect and did not close/open fully when triggered.

4.2.12 Model based fault diagnosis / digital twin

With the availability of high-performance computers and low-cost sensor data, model-based fault diagnosis or digital twin is becoming more and more an economically rentable way to monitor components, detect anomalies and diagnose faults. Model based fault diagnosis is a combination of data driven and expert based diagnostics. Instead of using methods built on available historical data like in the data driven diagnostics, the model-based diagnostics uses a validated analytical model of the equipment.

There are two ways to create a validated analytical model of a component:

(1) Black Box Model which simply describes the functional relationships between system inputs and system outputs. The model has unknown physical parameters and can be idealized as linear or nonlinear mathematical function. A variety of techniques may be used to identify the parameters of black box models. Least-squares-based algorithms are, however, the technique most used. Within the nonlinear category, time series features are found together with neural-network-based models. The use of neural networks in black box model building has increased with the availability of low-cost computing power.

(2) Grey Box Model which combines physical knowledge in form of an analytical model with measurement data. The model (e.g. reduced FEM model, Transfer Function model and/or Differential Equations model) is partly or completely described by physical equations, where parameters are physically interpretable.

Figure 52 shows the model-based diagnostics approach. In parallel to the real process where the real NPP component is operating at specified operating conditions and measurement data (e.g. vibrations) are collected, a validated simulation model (digital twin) of the component is running. The measurement results of the real system are compared to those of the digital twin in order to detect anomalies. The results of the anomaly detection as well as information from digital twin model and real system are used by the diagnosis module (which is usually artificial intelligence based) in order to identify the failure mode and predict the remaining useful lifetime of the component.

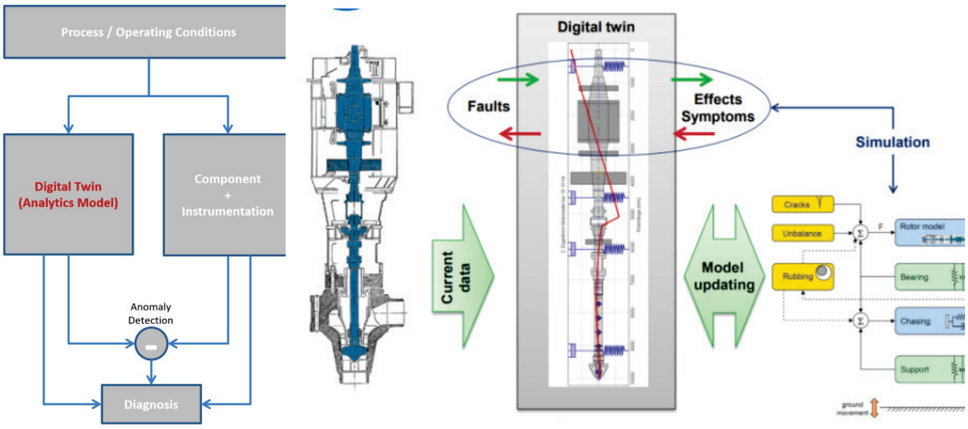


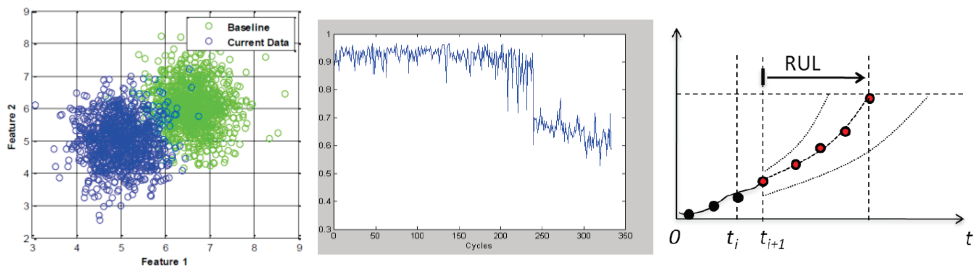
Figure 49: Model-based diagnostics (digital twin).

4.2.13 RUL prediction (Prognosis)

CADIS RUL Prediction using labelled data

The CADIS RUL prediction module uses labelled data, i.e. historical data including fault history of the component to create a fault prediction model which describes the relationships between predictors (condition and process features) and responses (e.g. fault types) as labelled clusters. Then it computes a Health Index Value (HIV) according to

HIV = 1 - D2R/D2F (1)



1. Relationships between predictors and responses
2. Health Index computation using distance between distributions
3. Health Index Value Prediction using regression methods

Figure 50: CADIS RUL Prediction using labelled data.

Herein D2R is the distance between the current distribution center and the reference distribution center, and D2F is the distance between the fault distribution center and reference distribution center. Figure 53 provides an example. The time series of the HIV is finally used as input in regression methods to predict the RUL. The remaining useful lifetime ends when the HIV will be equal zero.

Figure 54 gives an overview of the basic steps to predict the RUL using labelled data. Table 8 provides further information about the models applied in RUL prediction.

RUL Prediction methods according to Matlab® Predictive Maintenance Toolbox™

The Matlab Predictive Maintenance Toolbox offers additional RUL prediction methods which can also be used in CADIS.

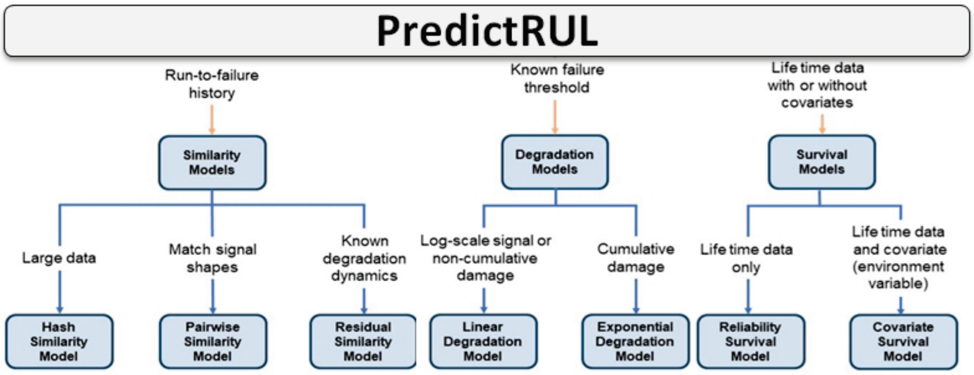


Figure 51: Predict RUL methods.

Table 8: RUL prediction Models.

Similarity models:	– Such models can be applied when degradation profiles or run-to-failure data from similar systems (components) are available. – Hashed-feature similarity model transforms historical degradation data into condensed information such as the mean, total power, maximum or minimum values, and is useful when you have large amounts of degradation data. – Pairwise similarity model determines RUL by finding the components whose historical degradation paths are most correlated to that of the test component. It delivers better results than the hash similarity model if the degradation profile changes over time. – Residual similarity models fit prior data to model such as an ARMA model or a model that is linear or exponential in usage time and computes the residuals between data predicted and the data from the test component. Useful when the knowledge of the system includes a form for the degradation model.
Degradation models:	– Such models work with a single condition indicator → use of PCA to generate a fused condition indicator. – Linear degradation models are useful when the system does not experience cumulative degradation. – Exponential degradation models are useful when the test component experiences cumulative degradation.
Survival models:	– These are statistical methods used to model time-to-event data. They are useful when run-to-failure histories are incomplete: – Use ReliabilitySurvivalModel if data about the life span of similar components is available, e.g. number of miles or hours the engine ran before failure or maintenance. – Use CovariateSurvivalModel if both life spans and some other variable data (covariates) are available such as the component supplier, regimes in which the component was used, or manufacturing batch that correlates with the RUL.

4.3 CRITERIA TO IDENTIFY RISKS FOR HARMFUL VIBRATIONS OF NPP COMPONENTS CAUSED BY FLEXIBLE OPERATION

Continuous monitoring aims at identifying risks of harmful vibrations. There are different methods how to define criteria for detection of harmful vibrations summarized in Table 9

Table 9: Methods for detecting harmful vibrations.

Method		Description
A	International standards	Application if methods B and C are not possible. Vibration limit criteria from standard like: ISO 20816, 7919 for rotating machinery VDI Standard 3842:2004-06 for piping systems
B	Numerical methods and dimensioning results	Application when component design, material and load conditions are available. Static and Dynamic Load Analyses and Simulations → max. stresses and strains → max. forces, accelerations, velocities and displacements → vibration limit criteria (component position specific)
C	Historical data and operational experiences from OEMs or from component operators	Application when historical data and operational experience with similar equipment in similar load conditions are available Use historical data and statistical and clustering methods to derive vibration limit criteria → run to failure history → known failure threshold limit (critical limits) → known life time data (with environmental conditions)

4.3.1 International standards

The use of international standard is a good basis for vibration issue detection. Monitoring thresholds from standards are often used when there is neither additional information from OEM, nor historical data nor operational experiences from the component.

Using international standards, only overall vibration parameters like RMS, Peak, Peak2Peak or Smax values can be monitored and only at given power or rotating speed levels. There are no monitoring thresholds for more sophisticated diagnostic parameters like the amplitude of the speed frequency which is an indicator for unbalance. Different operating conditions are not specified in the standards either.

4.3.2 Numerical methods and dimensioning results

Using numerical methods (see 4.2.2), it is possible to extract component specific information like maximum stresses and strains which can be converted to maximum forces, accelerations, velocities or displacements and, thus to vibration limit criteria.

The numerical methods offer also the advantage to deliver limit values which are measurement position specific., e.g., the limit values at the upper bearing of a motor may be different from the limit values at its lower bearing)

4.3.3 Historical data and operational experiences

A proven method to identify risks for harmful vibrations of NPP components is the use of historical data and operational experiences from OEM or component operators.

Available historical and current data including fault history, operational and maintenance logs of the component are used with statistical and clustering methods to define criteria for good, acceptable and critical vibrations.

Since not all data of all components is available, the PredictRUL Matlab® methods (see chapter 4.1) are a good starting approach for defining criteria for good, acceptable and critical vibrations for similar components in similar load conditions.

4.3.4 Application of a vibrational fatigue monitoring system

NPP components, like other industrial structures, are subjected to vibrations and the material fatigue induced by these phenomena can be the limiting factor of their lifetime. Without monitoring the occurring loads, there is a lack of knowledge about the actual remaining lifetime of the structure. This gap of knowledge cannot be closed by the application of structural health monitoring systems which aim to detect the appearance of an unexpected fatigue damage in a system. To this end, a system is needed which is able to predict fatigue damage before it occurs.

The FAMOS-V system, developed by Framatome, gives a real time assessment of the remaining lifetime of structures submitted to vibration induced fatigue. Using a numerical model, only one or a few acceleration measurements are necessary to re-construct the complete stress history in the whole structure, including on welds or bolted connections that could not have been directly instrumented. From this stress history, a fatigue analysis with a rain flow counting algorithm is conducted and the cumulative usage factor of each concerned structure is determined. The remaining life duration is then estimated as it is shown exemplary in Figure 55.

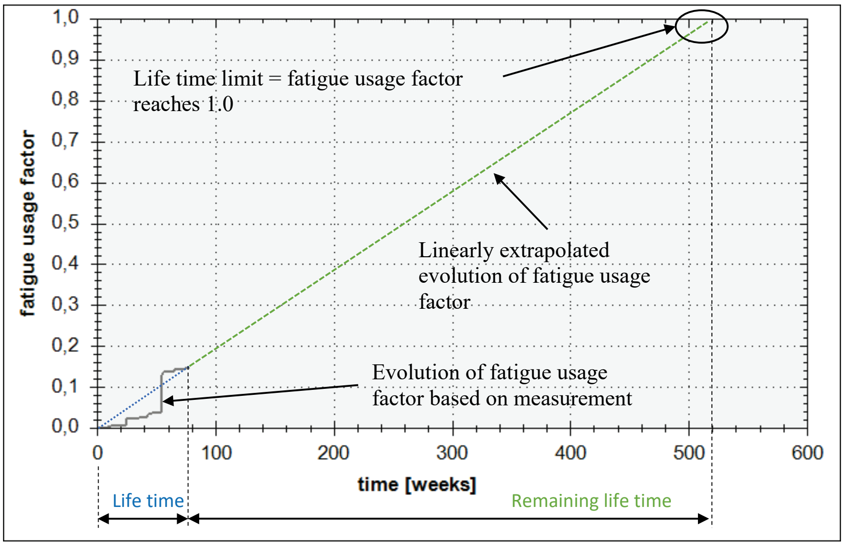


Figure 52: Follow-up of usage factor and life duration estimation.

Framatome disposes of the system's software for the detailed vibrational fatigue monitoring of vibrations of components. It calculates actual fatigue usage factors and implements a trending function. FAMOS-V fragments the vibrational measurement signal into its relevant modal fractions. The fragmented single signals are scaled by modal elementary load stresses and subsequently superposed again. This process results in a stress tensor as a function of time which can be directly used for the derivation of the fatigue usage. This vibrational system constitutes the best and most realistic solution for the vibrational fatigue assessment of components thanks to the direct processing of the measuring signals. The method can be used both in online and in offline mode. Additionally, the remaining lifetime is displayed based on the calculated fatigue usage factors. Based on this information, the operator is in the position of operating the component in a fatigue friendly manner. In case of already existing fatigue cracks, FAMOS-V can be extended in the sense of a fatigue crack propagation prognosis. The system is customized to customer specific needs.

FAMOS-V is composed of a hardware part and a software part: The hardware consists of simple and robust accelerometers or displacement sensors that measure the vibration at a few selected key points of the structure. The software identifies the contribution of each dynamic vibration mode in the measured vibrations and transforms this information into an estimation of remaining lifetime at each weld or other locations of interest. This transformation is customized by Framatome experts for each particular structure. It is installed on a server and then run in an autonomous mode. An accompanying service package is proposed to the customer on a case-by-case basis, including technical support for the hardware and software, additional expertise or big data analysis. For structures submitted to both thermal and vibration induced fatigue, a coupling of FAMOS-V with the thermomechanical FAMOSi system is easily possible.

The monitoring and control of Very High Cycle (VHCF) fatigue phenomena in industrial structures constitutes a further future application.

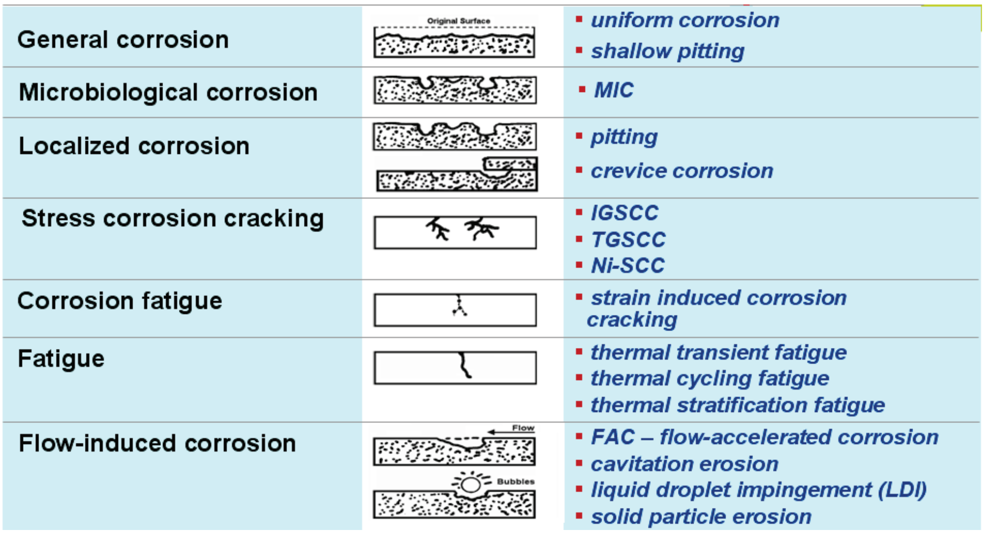
Further technical details, e.g. details on the methodology for re-creating stress time histories, the numerical validation and addition of pseudo-static correction, the stress cycle counting and calculation of cumulative usage factor and the on-site application, can be taken from (Moussalam et. al., 2019)

4.3.5 Corrosion affected degradation

The load follow operation poses many technical challenges as the plants need to be operated reliably for the entire operational lifetime, 50 and more years. It is therefore necessary to deal with the degradation behavior of equipment and its predictability in order to cut maintenance costs and ensure high availability at the same time. All potential degradation mechanisms need to be considered properly.

One of the key objectives of aging and plant life management is the early identification of possible degradation mechanisms, which may compromise safety or availability. The relevant aging mechanisms need to be identified for each relevant component in order to ensure that maintenance programs and NDT are performed using appropriate testing technology and inspection intervals.

The potential degradation mechanisms of mechanical components are shown in Figure 56.



General corrosion	▪ uniform corrosion ▪ shallow pitting
Microbiological corrosion	▪ MIC
Localized corrosion	▪ pitting ▪ crevice corrosion
Stress corrosion cracking	▪ IGSCC ▪ TGSCC ▪ Ni-SCC
Corrosion fatigue	▪ strain induced corrosion cracking
Fatigue	▪ thermal transient fatigue ▪ thermal cycling fatigue ▪ thermal stratification fatigue
Flow-induced corrosion	▪ FAC – flow-accelerated corrosion ▪ cavitation erosion ▪ liquid droplet impingement (LDI) ▪ solid particle erosion

Figure 53: Degradation mechanisms of mechanical components.

It is crucial to understand the main parameters of influence for the different degradation mechanisms, i.e. the elaboration of reliable predictive degradation models requires a detailed understanding of the type of degradation concerned, as well as in-depth understanding of the functional interactions of the relevant parameters which influence the rate of damage propagation.

Laboratory tests and damage analyses have been conducted at Framatome for more than 30 years for this purpose. The results from these investigations have been compiled in analytical as well as semi-empirical degradation models for each degradation mechanism.

Based on the environmental conditions e.g. operating parameters, water chemistry conditions and the component specific materials, the possible degradation mechanism, and furthermore, the degradation progress can be evaluated. For mechanical components models have been developed for 16 different degradation mechanisms.

The requirements for a comprehensive aging management require a sound knowledge base for the periodic evaluation of systems, structures and components with respect to degradation effects. Applied systematically, an aging management program provides remarkable economic benefits. To support aging and life management activities, Framatome has developed the software tool COMSY. This software solution supports the process of aging and life management for mechanical, electrical and civil Systems, Structures and Components (SSCs) and provides a systematic surveillance strategy for aging effects.

Thus, the knowledge base includes relevant information concerning the design concept, safety and availability requirements, manufacturing and service history of the equipment concerned. It determines possible degradation mechanisms and supports appropriate monitoring and testing methods, including the evaluation of the results. Overall, this system ensures that the aging and life management process is built on a periodically updated database of the actual technical state of the plant, thus providing reliable long-term surveillance of aging effects. Based on reliable trend analyses, the safety, maintenance management and plant availability can be optimized progressively. The knowledge base also supports Long Term planning for the safe and efficient operation of the plant and preservation of know how.

Operational experience:

The knowledge of a typical behavior of a component or a system is a helpful basis for its assessment. Subjective criteria like audible noise, visible vibration or e.g. leakage give first hints of an abnormal status, but are poor for a true comparison. With today's computerized information and knowledge storage possibilities, new detection and analysis methods are possible, for an online or quite fast detection of abnormal operation conditions. The aim is to place "operation experience" in a matrix of numbers and values regarding operation, thermal, flow, position, vibration or noise conditions, and define them as good in a first step. If the component is run under the same (or similar) operation conditions as registered before, a computerized comparison will be started on changes in the operation behavior, which will result in a known category (within ranges), or in a deviating result. After an analysis, the deviation may lead to an extension of already known operation ranges (classes) to a definition of a new operation class, or in a postulation of an unknown effect or failure on the component. This procedure can be applied on any component under observation, and criteria definitions changed or enhanced by user friendly support algorithms, e. g. by simply defining relative tolerances bands. The economic availability of applicative sensors, in combination with operational results, combined and assessed on server-based algorithms, provide a new feature on collecting and securing of a huge and deep operation experience on any single component in operation.

Latest R&D Results on Very High Cycle Fatigue (VHCF) of NPP components

The fatigue assessment of safety relevant components in the low cycle (LCF), high cycle (HCF) and very high cycle (VHCF) regime is of importance for ageing management with regard to safety and reliability of nuclear power plants. Reactor internals are examples of concerned components. For reactor internals, austenitic stainless steels are often used due to their excellent mechanical and technological properties as well as their corrosion resistance. During operation the material is subject to loadings in the Low Cycle Fatigue (LCF) regime due to start up and shut down procedures as well as high frequency loadings in the Very High Cycle Fatigue (VHCF) regime induced e.g. by stresses due to fast cyclic thermal fluctuations triggered by fluid dynamic processes. While the LCF behavior of austenitic steels is already well investigated the fatigue behavior in the VHCF regime has not been characterized in detail so far. Accordingly, the fatigue curves in the applicable international design codes have been extended by extrapolation to the range of highest load cycles.

The aim of an ongoing cooperative R&D project of the Technical University Kaiserslautern Institute of Materials Science and Engineering (WKK), Materials Testing Institute (MPA) Stuttgart and Framatome GmbH, Germany is to create a comprehensive database up to the highest load cycles $N = 2 \cdot 10^9$ for austenitic stainless steels. For this, fatigue tests on metastable austenitic steel AISI 347 / 1.4550 / X6CrNiNb1810 as well as on austenitic welds (Fox SAS 2-A) were performed with an ultrasonic testing system at a test frequency of 20 000 Hz to realize acceptable testing times. In addition, an induction generator was implemented in the test system to investigate the influence of operation relevant temperature of 300 °C on the fatigue behavior. The ultrasonic testing system works under displacement control. Therefore, for reliable statements on fatigue life according NUREG/CR-6909 and using of S-N-curve (total-strain amplitude vs. cycle to failure), a fictitious-elastic and elastically-plastic numerical material model was used for calculation of total-strain amplitudes based on experimental data. The results show that at ambient temperature and 300 °C no specimen failure occurred in the VHCF regime neither for the base material nor for the welds. Consequently, for these materials a real endurance limit exists.

Additionally, in a continuative test a specimen with a pre-autoclaving period in high temperature water (HTW) of 2.500 hours was tested in air at a total strain amplitude of 0.1 % in the VHCF-regime up to a number of cycles $N = 1\ 10^9$ using an ultrasonic fatigue testing system. The chemical composition of the HTW for the pre-autoclaving period is comparable to near operation conditions. Afterwards, by using of scanning electron microscope, no defects or cracks were detected in the oxide layer.

The project layout and intermediate results of this project VHCF-I can be taken from two ASME PVP papers (Schuler et. al., 2018) and (Daniel et. al., 2020).

A follow-up project VHCF-II is going to be launched in 2021.

4.4 METHODS FOR THE MITIGATION OF VIBRATION PROBLEMS IN NPPS CAUSED BY FLEXIBLE OPERATION

4.4.1 Mitigation of vibration problems – overview and examples

According to ISO 18436-2 and Mobius Institute (Mobius Institute Training and Examination Center, 2017), there are several vibration corrective actions which are to be known by vibration specialists and can be applied to components with vibration problems:

- Shaft alignment
- Shaft balancing
- Replacement of machine parts
- Flow control
- Isolation and damping
- Resonance control
- Basic maintenance action (e.g. lubrication)

Nordmann & Ranisch (2018) gives a short theoretical description of the different vibration correction methods which can be clustered as follows:

Table 10: Group of methods for mitigation of vibration problems.

Method	Description	Field of application

Excitation reduction	• Reduction of excitation force through:
	  • balancing and/or alignment
	  • rotating speed control
	  • reduction of fluid pressure loads
		Rotating machines
		Piping systems

System de-tuning	• Change mass or stiffness to shift the natural frequency and avoid resonance problems
	  • increase the mass to reduce the natural frequency
	  • increase the stiffness to increase the natural frequency
		Rotating machines
		Piping systems

Vibration reduction	• Adding damping to reduce the amplitude at the resonance frequency => Friction, Hysteresis, Viscous
	• Vibration isolation
	  • to reduce the excitation from the structure to the environment (source isolation)
	  • to reduce the excitation from the environment into the structure (receiver isolation)
	• Reduce vibrations through absorbers or neutralizer
	  • vibration tuned absorber
	  • tuned mass damper
		Foundations and supports of rotating machines
		and piping systems

Active vibration control	• Forced base excitations with specific frequencies • Adaptive damping • Adaptive stiffness • Excitation reduction using balancing actuators	Foundations and supports of rotating machines and piping systems

Mobius Institute (Mobius Institute Training and Examination Center, 2017) gives good practical examples with case studies in its vibration expert training documentation on how to correct vibration problems:

- By correcting resonances via rotating speed control and stiffness modification: 3 different approaches to modify the stiffness using Finite Element Analysis, Modal Analysis and Structural Modification Investigations are explained. A description how to add damping, how to utilize tuned absorbers and how to solve isolation issues by dimensioning the isolator elements are provided. Figure 57 shows an example for a stiffness modification.

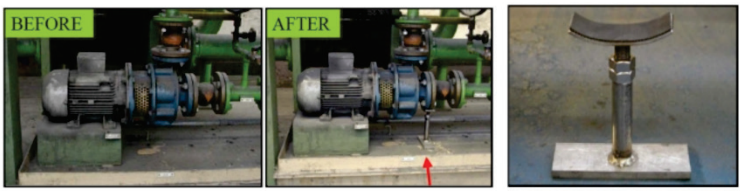


Figure 54: Example for a stiffness modification.

- By balancing rotating machines using different procedures

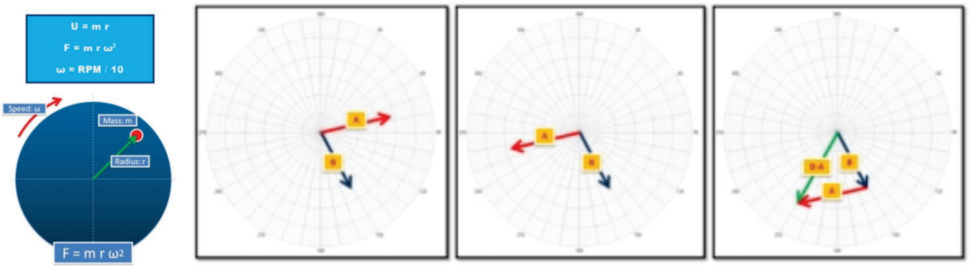


Figure 55: Examples for balancing procedures.

- By aligning coupled rotating shafts

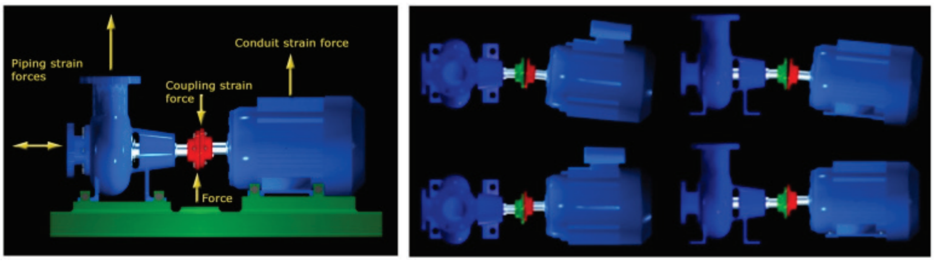


Figure 56: Example for aligning coupled rotating shafts.

4.4.2 Avoidance of vibrating operation conditions

The first reaction after detection of highly vibrating structures and components is to get out of the relevant operation range. In some cases, the operation curves of aggregates can be adapted to lesser vibration conditions by providing same or similar operation features (e.g. flow, pressure, power …).

On redundant systems, a reconfiguration of train switch points or operation ranges can avoid vibration or fatigue critical performance.

A permanent monitoring of the components vibration will not reduce them, but provides a basis for calculated usage factors, not based on (conservative) assumptions, but on real measurements.

4.4.3 Optimization of support and damping concepts

The second and third approach after the detection of highly vibrating or fatigue induced components is to reduce the vibration amplitudes by additional means.

Additional supports with mechanical dampers applied to vibrating sections normally lead to reduced vibrations. Nevertheless, these dampers have to be fixed against rigid non vibrating counterparts, which have to withstand the related loads, and lead to additional loads on both sides. Thus, a recalculation of the mechanical behavior may become necessary to secure the fulfillment of operational and design criteria.

4.4.4 Modal adaption

A simple addition of mass on vibrating components leads to lower natural frequencies on them, which can shift or divide overlapping resonant vibration regions. Nevertheless, higher mechanical loads are normally generated by these measures.

4.4.5 Use of vibration absorbers

The use of vibration absorbers does not lead to fixations on the walls or floors but need a detailed knowledge of the vibration behavior of the component, best if based on measurement results, and a numerical adaption of mass absorbers to the component itself. Several parameters of these absorbers are adjustable (mass, stiffness, damping coefficients, degree of freedoms ...), so that a reliable calculation before implementation is necessary. The result will be reduced vibration amplitudes in a certain frequency range, depending on the chosen parameters. A use of several mass dampers on components will require detailed calculations on their impacts and cross-correlations.

4.4.6 Mitigation of fatigue failure mechanisms, operating experience and calculation methods

Operating experiences are very helpful in order to understand the fatigue failure mechanisms that pose a threat to various types of plant equipment, particularly concerning the vibrational fatigue mechanism. It is recommendable to take cost-effective measures to monitor and correct fatigue problems before they lead to forced outages. All occurring fatigue failures should be documented properly. The two EPRI documents (MRP-235, 2015) and (MRP-138, 2005) are of interest in this context.

Figure 60 taken from (MRP-138, 2005) underlines the outstanding importance of the vibrational fatigue issue. E.g., the reported number of failures outnumbers by far the reported number of thermal fatigue failures.

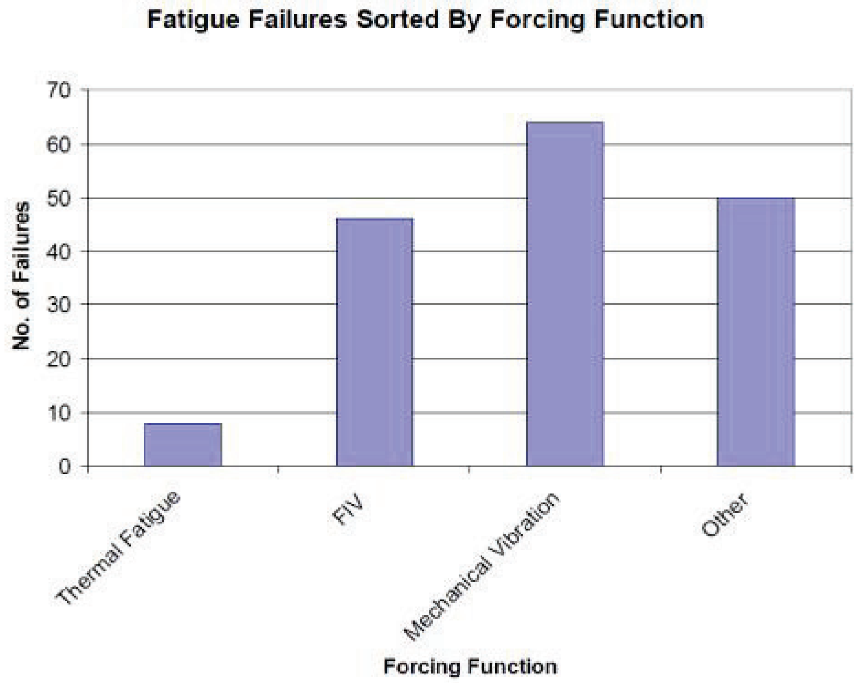


Figure 57: Fatigue mechanisms in (MRP-138, 2005).

Flow Induced Vibration (FIV) and Acoustically Induced Vibration (AIV) are issues which may cause High Cycle Fatigue (HCF) damage. Typical occurrences are in small bore socket welded piping. BWR typical damages were observed in steam dryers due to FIV and vibrational fatigue failures of jet pumps.

The effects of socket welds on vibrational fatigue life are extensively considered in (MRP-235, 2015): Fatigue Management Handbook. This concerns welds as shown in Figure 61.

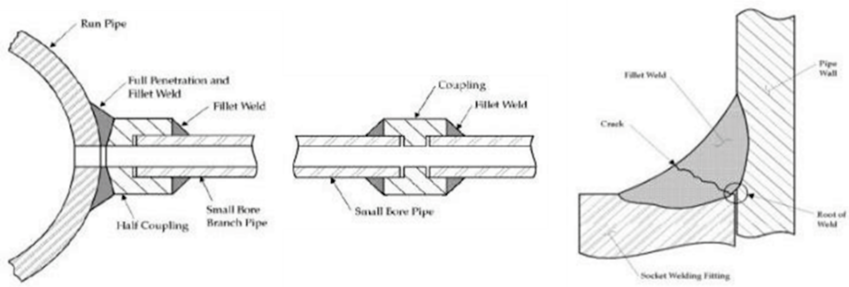


Figure 58: Socket welds according to (MRP-235, 2015).

These socket welds are critical components in small bore piping with regard to HCF. Usually, circumferential cracks occur in the pipe initiated on the outside of the pipe near the toe of the fillet weld. A significant number of the failures occurred in the root of fillet (weld defects such as lack-of-penetration at root of weld).

According to (MRP-235, 2015), operating experience databases (with focus on US plants) have recorded over 200 vibration fatigue failures.

EPRI 3002005510 (MRP-235, 2015) defines a methodology to develop a fatigue management program. In a first step, pipelines are identified which could be susceptible to vibration fatigue. The identified pipelines are classified in two geometries: cantilever type pipelines and complex pipelines. For each geometry, MRP-235 allows to define screening criteria to determine its susceptibility to vibration fatigue problems. It allows to establish the maximum allowable acceleration for cantilever pipelines and the maximum allowable velocity for complex pipelines. The method is considered to be conservative. In this step, real vibration data of the identified pipelines are collected.

In a further step, the real vibration data are obtained by transducers for strain, acceleration, pressure, displacement, or by accelerometers. The measured real acceleration or velocity is compared to the allowable values. If these criteria are not met, it is recommended to carry out a detailed piping evaluation with the use of a piping model. It shall be verified that the maximum stress range due to vibrational loads is lower than the endurance limit. Hence, an endurance limit check is done.

Nowadays, highly effective fatigue monitoring systems can be installed in order to monitor the fatigue behavior at fatigue prone positions online. Recently, Framatome developed the FAMOS-V vibrational fatigue monitoring system which is described in more detail in section 4.3.4.

A simplified version of this vibrational fatigue monitoring method can be applied for the calculation of the fatigue contribution due to piping vibrations, e.g. in the secondary circuit of NPPs at locations with available measuring data. The fatigue assessment can be based on the first measured principal vibration. Higher modes can be neglected in this approach. The piping calculation methods of the European design code EN13480-3 can be applied for the Eigenvalue and stress calculation. Fatigue assessment can be based on the fatigue curves for welded components given in the European design code EN13445-3. The time series of measured accelerations are transferred to frequency spectra in order to determine the excitation frequency and align them with the calculated natural frequencies of a finite element model. The finite element model can be based on pipe elements. The first measured principal mode can easily be aligned this way. The time series of accelerations are converted to time series of displacements by filtering on the relevant frequency range and by correction of the drift.

An example of a resulting time series of displacements is shown in Figure 62.

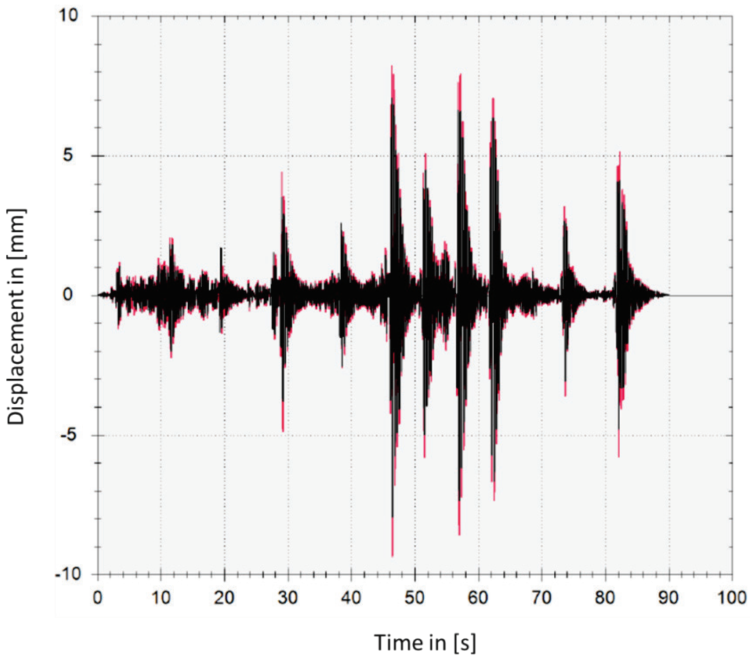


Figure 59: Exemplary time series of 2 displacements signals.

The displacements can be directly correlated to the bending moments at the locations of interest.

Figure 64 shows an example of displacements resulting from Finite Elements analysis.

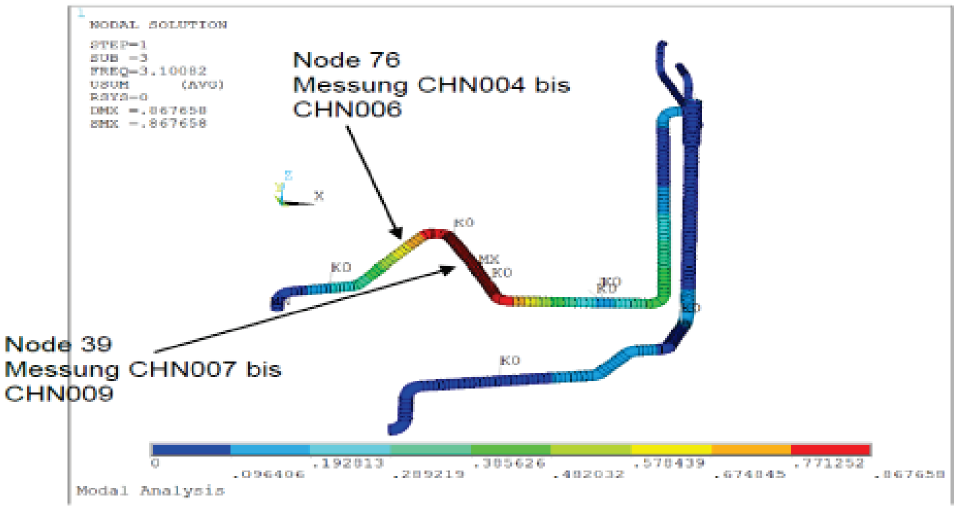


Figure 60: Exemplary FEA results in terms of total displacement.

The time series of stresses which are required for the fatigue assessment and determination of partial and cumulative usage factors (CUF's) are determined based on the time series of displacements and bending moments (using the pipe stress formulae given in EN13480-3) and the scaling of the natural frequency and mode shape. Stress ranges are determined by application of the rainflow cycle counting method and stress ranges are used to determine the fatigue contributions by application of the appropriate fatigue curve given in EN13445-3 (see Figure 64).

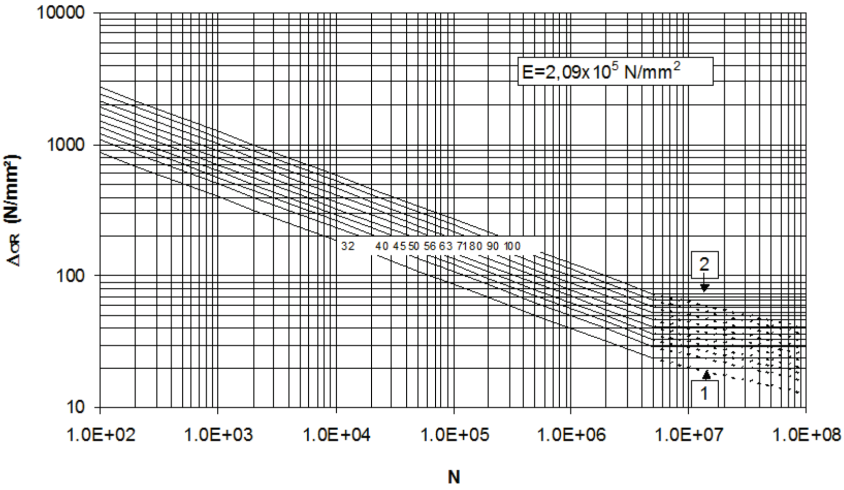


Figure 61: Fatigue curves for welded components in EN13445-3.

4.5 VIBRATION IMPACT ON THE LIFETIME OF NPP COMPONENTS AND SYSTEMS

The methods and tools described in the previous sections are adaptable to each single customer's specific needs and requirements. Based on a detailed preliminary study they are obviously applicable in the Nordic grid context.

5 Conclusions and future work following this project

In this chapter, single topics are summarized, and main conclusions are given, including ideas of the further projects that can help to increase the overall understanding of the vibration impact during part load operation, allow more detailed view on the existing operational experience and help to transfer the lessons learned to the Nordic NPPs, which evaluate the theoretical impact now.

5.1 CONCLUSIONS WITH RESPECT TO FLEXIBLE OPERATION MODES

Table 11 summarizes the overall collected information about the performed FlexOp modes and the corresponding provided services by interviewed NPPs.

Table 11: Classification of the flexible operation by NPPs incl. ancillary service products.

Plant mode/ Service	Aim	Time Frame for activation	Range	Typical values	Minimum power level
Primary frequency control/ FCR	Contain the frequency	up to 30 sec	from 2 % to 10 % REO	± 50 MWel	50% - 60% REO
Secondary frequency control/ aFRR and Minute reserve/ mFRR	Return frequency to nominal	up to 5 mins / up to 15 mins	Ramp rate 10 - 30 MWel/min	± 50 MWel / ± 150 MWel	50% - 60% REO
Load Following/ Redispatch measures	Economical dispatch or overload management	Corresponding to the ramp rate	Ramp rate 10 - 30 MWel/min	till 50 % - 60 % REO	50% - 60% REO
Extended Low Power Operation	Long time (> 12 h) demand variation	Corresponding to the ramp rate	can be slow	till 50 % - 60 % REO	Single example: till min. load 30-40 %

Thereby, the general conclusion with respect to flexible operation modes is that the NPPs are trying to avoid FlexOp at low power levels, the minimum power level for all services is defined typically at 50-60 % REO. For various BWRs, it can be even stated that the frequently performed level is till 70 %. Depending on the grid situation there are some exclusions from this overall tendency and also operation for few hours/days at minimal load and even for months can be found in the plant history. Such cases are of special interest and the impact among others on vibrations was analysed.

5.2 CONCLUSIONS AND FUTURE WORK WITH RESPECT TO VIBRATION IMPACTS

Comprehensive experience with flexible operation in German NPP is available:

- Significant vibration impact (e.g. in form of relevant increase) was observed on various components (nozzles, heat exchangers, pumps, pipes, drives, valves, turbine...) in flexible operation, but appear to be also often plant specific.
- Main components of vibrational and wear impact are:
    - Pressurizer
    - Control rod drives
    - Recuperative heat-exchangers
    - Moisture separator, Preheaters
    - Main steam regulation valves
    - Main feedwater pumps
    - Valve drives
    - Turbine
    - Generator
- Tables of the impact on main components in nuclear and turbine island, included realized and potential countermeasures, are summarized in appendix B

Proven countermeasures are:

- Limitation of NPP operation to uncritical power ranges (typical 50 % - 60 % to 100 % REO)
- Intense analysis of transient affected components
- Collection of vibrational and operational data in a central diagnosis system

For the future work, the following measures can be worth performing:

- Comprehensive vibration data analysis for the most impacted components of KWU NPPs (nozzles, heat exchangers, pumps, pipes, drives, valves, turbines, ...).
- Surveillance concept on most FlexOp affected components on primary and secondary circuits (motor/drives, pumps, heaters, pipes, ...), combination of dynamic vibration and static operational data

5.3 CONCLUSIONS AND FUTURE WORK WITH RESPECT TO EFFECT ON FUEL

Based on the operating experience from the German plants, it has been seen that the effect of FlexOp on vibrations of the fuel assembly and the fuel rods is minor. This applies to PWR and BWR.

The nominal operating state is covering for the vibrations caused by turbulent excitation during FlexOp.

This principal statement needs to be confirmed for the differently designed Scandinavian plants.

It is recommended to review the available design analysis and test results whether there are hints that a sensitivity of the fuel assembly to flow induced vibrations exists. This has to be done for every FA design which is in the core considering also a potential mixed core state. In particular, the case of self-induced vibrations at certain relevant operating points needs to be excluded.

Core power changes are also related to a higher activity of the control rods. This can lead to additional dynamic loads and can influence the life time of the control rods. These potential fatigue effects need to be investigated.

Beyond the effect on vibrations of the fuel assembly, the existing design analysis shall be reviewed regarding whether the different core temperatures resulting from FlexOp are covered and if existing fatigue analysis need to be extended.

The mentioned temperature changes alone do not lead to mechanical vibrations. The effect of additional thermal cycles on the lifetime needs to be investigated.

5.4 CONCLUSIONS AND FUTURE WORK WITH RESPECT TO ELECTRICAL SYSTEMS AND MAIN GENERATOR

The effect of FlexOp on the electrical equipment of the unit's auxiliary power supply system is generally low.

Impacts on the main generator are depending on local grid conditions and special characteristics of the generator.

Other requirements coming from a change of grid conditions (for example underexcited operation of the main generator) have an impact on the plant behavior in case of grid failures (fault ride through) and switch-over to the standby grid.

In case of vibrations on the main generator induced by the grid, the installation of measurement systems for the elaboration of an "empiric-mathematic" model has to be taken into account.

5.5 CONCLUSIONS AND FUTURE WITH RESPECT TO EFFECT ON DIAGNOSIS

From the discussions with members of the Energiforsk steering group, condition monitoring systems including diagnosis, prognosis and health management for NPP components are not used because models, corresponding algorithms and input data are not available. The practical monitoring is therefore mainly based on the observations of vibration signals and monitoring of changes of vibration signals (Nordmann & Ranisch, 2018).

In the past 4 years, Framatome has developed a data analytics solution named CADIS for automated data driven diagnostics using component data like condition, process and log data with the aim of supporting the expert- or knowledge-based diagnostics. Detailed information about CADIS can be found in (Fomi et al., 2019).

Further step can be a research and development project with the objective to develop a data driven diagnostic platform that will complete the existing DIAM Matrix (Energiforsk Knowledge Database for Fault Detection, Identification, Analysis and Mitigation) currently under development. An analytics platform like CADIS can be used to develop data driven diagnostic models with available component data:

- Clustering models for Fault Detection,
- Classification models for Fault Prediction and
- Regression models for Value/RUL prediction.

5.6 CONCLUSIONS WITH RESPECT TO FATIGUE

Fatigue constitutes a crucial damage mechanism in the context of flexible operation. Nevertheless, according to the operational experience reported in the interviews, a strong additional fatigue impact on primary side even from strong flexible operation was not confirmed. In most circumstances, the temperature differences were about 20 K, much less than 60 K, as the plant was performing the flexible operation in the region of the constant average temperature in the primary circuit.

Overall, moving to the estimation of the real transients, applying online monitoring and more detailed fatigue analyses allowed to decrease the cumulative usage factor on the main impacted components. Is has to be pointed out as well that flexible operation was included in the design and the number of the performed transients of various types was counted and had enough margins even with respect to further operation in such mode.

The main impact, as stated by the most NPPs, is on the volume control system (RCVS).

In general, for a potential operation lifetime extension to 60 years more intense fatigue analyses were seen to be obligatory.

Thermo-mechanical and particularly vibrational fatigue issues have to be addressed by application of appropriate fatigue management measures such as the implementation of monitoring and surveillance concepts. Both thermo-mechanical and vibrational fatigue have to be managed.

In this context, vibrational fatigue monitoring and associated fatigue monitoring systems are going to be part of future projects:

- Adaptation to all kind of vibrations in industrial structures (e.g. NPP piping)
- Online monitoring systems and digital twins of affected structures

Another future issue is the management of Very High Cycle Fatigue (VHCF). This includes the consolidation of the endurance limit in complex damage accumulation situations (e.g. reactor internals) and the overall sensitivity of applied materials to VHCF. The interaction of low cycle (LCF), high cycle (HCF) and very high cycle fatigue (VHCF) in the sense of realistic damage accumulation constitutes a challenging task of fatigue assessment. Ongoing R&D activities contribute to related solutions.

5.7 OVERALL CONCLUSIONS

The analyzed experience and performed interviews show that plant by plant evaluations together with lessons learned from other NPPs allowed German NPPs to develop an operation with minimal impact on vibrations. Monitoring and maintenance concepts were adapted to such flexibility and allow safe and reliable flexible operation in various available modes.

6 References

ASME OM-S/G-2007. Standards and Guides for Operation and Maintenance of Nuclear Power Plants; ASME 2006

ATW, 2009. http://www.kernenergie.de/kernenergie-wAssets/docs/service/602atw-betriebsergebnisse-kkw2009.pdf

ATW, 2010. http://www.kernenergie.de/kernenergie-wAssets/docs/service/602atw-betriebsergebnisse-kkw2010.pdf

Bolz., M., et al, 2013. ATW, Einfluss des Lastfolgebetriebs auf die Chemie des Primär- und Sekundärkreislaufs eines Kernkraftwerks mit Druckwassserreaktor, Vol. 58, Issue 7, July, 2013

Daniel, T.; Smaga, M.; Beck, T.; Schopf, T.; Stumpfrock, L.; Weihe, S.; Rudolph, J., 2020. Investigation of the very high cycle fatigue (VHCF) behavior of austenitic stainless steels and their welds for reactor internals at ambient temperature and 300 °C. Proceedings of the ASME 2020 Pressure Vessels & Piping Conference. PVP2020,
July 19-24, 2020, Minneapolis, Minnesota, USA. Paper No. 21460

DIN 25475-2 Nuclear facilities –Operational monitoring –Part 2:
Vibration monitoring for early detection of changes in the vibrational behavior of the primary coolant circuit in pressurized water reactors

Fomi Wamba, F., 2015. Zielgerichtete Instandhaltung, SPS Magazin, 12/2015

Fomi Wamba, F., et al., 2019. Operation optimization using data analytics CADIS - a Framatome solution, 39th Annual Conference of the Canadian Nuclear Society and 43 rd Annual CNS/CNA Student Conference WestinOttawa Hotel, Ottawa, Canada, June, 2019

Forster, P., et al., 2009. KKI1: Schwingungs- und Körperschallüberwachung der Zwischenüberhitzer RB01-B101 und RB02-B101 im 22. Brennelementzyklus, AREVA GmbH, July, 2009 (internal report)

Forster, P., Keck., et al.,2019. Diverse reports on system implementation and signal analysis on turbine island components during transient load conditions; Framatome GmbH, 2019 (internal reports)

Frank, M., 2003. Lastfolgebetrieb und Primärregelung - Erfahrung mit dem Verhalten des Reaktors, Isar 1, 2003, https://www.ktg.org/ktg-wAssets/docs/fg-bet-rph-lastfolgebetrieb-kki1.pdf

Fuchs, M. & Timpf, W., 2011. Presentation from VGB Congress POWER PLANTS 2011, The Load Change Ability of Nuclear Power Plants – Experience and Outlook, 9/2011

Fuchs, M., 2013. Atoms for future, Load follow from operator point of view, October 21, 2013

Hänninen, S., et al., 2020. Survey on power system ancillary services, Report 2020:708, Chapter 4.7 https://energiforsk.se/program/paverkan-av-yttre-nat-in-i-karnkraftsanlaggningen-gino/rapporter/survey-on-power-system-ancillary-services-2020-708/

IAEA, 2018. Non-baseload Operation in Nuclear Power Plants: Load Following and Frequency Control Modes of Flexible Operation, https://www-pub.iaea.org/MTCD/Publications/PDF/P1756_web.pdf

ISO 13379
Condition monitoring and diagnostics of machines — Data interpretation and diagnostics techniques —Part 1:General guidelines, 2012

ISO 17359
Condition monitoring and diagnostics of machines — General guidelines, 2011
Kuhn, A. & Klaus, P., 2016. VGB Power Tech, 2016. Improving automated load flexibility of nuclear plants with ALFC, 5/2016

Kuhn, A. & Schirrmeister, K., 2018. Advanced Load Following Control, Nuclear Engineering International magazine, November, 2018. https://neimagazine.globaltrademedia.com/features/featureadvancing-load-following-control-6015633/

Ludwig, H., Salnikova T., & Waas, U., 2010. "Lastwechselfähigkeit deutscher KKW," ATW, vol. 55., Issue 8/9, 2010

MRP-235, 2015. Materials Reliability Program: Fatigue Management Handbook, Revision 2, (MRP-235). EPRI, Palo Alto, CA: 3002005510

MRP-138, 2005. Materials Reliability Program: Fatigue Issues Assessment, (MRP-138), EPRI, Palo Alto, CA: 2005. 1011442

Merikoski, M., 2017. Pipe Vibrations in Nuclear Applications, Energiforsk, 2017

Mobius Institute Training and Examination Center, 2017. Master Vibration Analysis Category IV, slide book provided to attendees at Mobius Institute Training Course, 2017

Morokhovki, V., 2020. Reactor Core Control Based on Artificial Intelligence", ATW, vol. 65, Issue 6/7, 2020

Moussalam, N.; Ziegler, R.; Bergholz, S.; Rudolph, J., 2019. A method for monitoring vibrational fatigue of structures and components. Transactions, SMiRT-25, Charlotte, NC, USA, August 4-9, 2019, Division IX

Müller, C., 2020. Presentation at the Forum Kerntechnik, Berlin, 2020 (Postponed due to COVID-19). Erfahrungen aus dem Lastfolgebetrieb, Kernkraftwerk Isar 2, Preussen Elektra

Müller, K., 2003. Lastfolgebetrieb und Primärregelung - Erfahrung mit dem Verhalten des Reaktors, Isar 2, 2003, https://www.ktg.org/ktg-wAssets/docs/fg-bet-rph-lastfolgebetrieb-kki2.pdf

NEA, 2011. Technical and Economic Aspects of Load Following with Nuclear Power Plants, June 2011, https://www.oecd-nea.org/ndd/reports/2011/load-following-npp.pdf

Nordmann, R. & Ranisch, C., 2018. Vibrations caused by load-follow in NPPs, Energiforsk 2018:521, https://energiforsk.se/en/programme/vibrations-in-nuclear-power/reports/vibrations-caused-by-load-follow-in-npps-impact-on-the-dynamic-behavior-of-significant-systems-structures-and-components/

PEL, 2018. Pressemitteilung PreussenElektra, Eiszeit oder Heißzeit: Kernkraftwerke der PreussenElektra bilden solide Stütze für die Stromversorgung in Deutschland, August, 2018, https://www.preussenelektra.de/de/unser-Uternehmen/newsroom/pressemitteilungen/2018/KKWbildensolideStuetefuerStromversorgung.html

Salnikova, T., 2017. Editorial - VGB PowerTech Journal 5/2017, Flexible operation of nuclear power plants – first steps for paradigm change worldwide? https://www.vgb.org/en/editorial_pt_5_2017.html

Schuler, X.; Schopf, T.; Beck, T.; Smaga, M.; Daniel, T.; Rudolph, J.; Buchholz, B., 2018. Investigation of the Fatigue Behavior of Austenitic Stainless Steels and their Welds for Reactor Internals under Combined Low Cycle (LCF), High Cycle (HCF) and Very High Cycle (VHCF) Operational Loading Conditions.
Proceedings of the ASME 2018 Pressure Vessels and Piping Conference PVP2018 July 15-20, 2018, Prague, Czech Republic. Paper No. 85028

Sperlich., M., et.al., 2019. Presentation at the IAEA Technical Meeting on PCI/SCC in Flexible Operation, PCI/SCC Loads in BWR and PWR: German Operating Conditions and Experience", France, Aix-en-Provence, 8th, August, 2019

Timpf, W., and Fuchs, M.,2012. Lastwechselfähigkeiten von Kernkraftwerken - Erfahrungen und Ausblick," atw, Issue 5 2012, ISSN 1431-5254; v. 57(5); p. 313-316

Zander, A.: Degradation and Corrosion Assessment against the Backdrop of New Energy Policy Framework Conditions.
3rd Meeting of the European HRSG Forum May 09th – 12th , 2016; Prague

Zander, A.; Nopper, H.: The COMSY - code for the Detecting of Piping Degradation due to Flow-accelerated Corrosion.
Proceedings of PVP20082008 ASME Pressure Vessels and Piping Division Conference, July 27-31, 2008, Chicago, Illinois, USA

Zander, A.; Schmitt, R.; Nopper, H.: AREVA Aging Management Platform. Proceedings of International conference, National Forum On Maintenance 2015, 2 – 3 June, 2015, VysokéTatry, ŠtrbskéPleso

Appendix A: Definition of the existing flexible operation modes

Table 12: Definition of the existing flexible operation modes including German examples.

NPP Mode/Grid Service in Germany	Description and Examples
primary frequency control (PFC) providing **PCR / FCR**	Depends on the current grid demand, performed as a step change of the grid supply or in the load • German transmission code requires ± 2 % REO linear provided in 30 s, in accordance with European grid code (German transmission code, 2007), can be positive and negative. • Grid frequency is linked directly to the turbine power controller in order to compensate the energy misbalance in the grid directly. • The prequalified range for PFC varies considerably plant by plant, from 2 % to 10 % REO (maximum for a German NPPs was realized during the test for a load drop of 14 %). Typical range would be ±50 MWel. • Depending on the optimum dispatch, the typical response is often lower than the prequalified level. • PFC is initiated by the plant shift on demand of grid dispatcher, resulting from market auction & TSO requirements. • PFC can be performed within a specified power level range, thereby the minimum power level is typically defined at 50% - 60% REO
secondary frequency control (SFC) providing **SCR/aFRR**	Depends on current grid demand (stochastic load changes, supplier outages) and is performed as an automatic remote controlled ramp in a specified power range (by the grid dispatcher) • SFC is an automatic response in 5 minutes, can be positive and negative. • The activation of the SFC is carried out by the plant shift on request of the grid dispatcher, resulting from market auction & TSO requirements. • Ramp rate (rate of change in power) is also set by the reactor operator and is typically in the range between 10 and 30 MW/min in Germany. • The dispatcher directly governs the target setpoint of the turbine load within the mentioned range (limited in the turbine control). • Some NPPs are taking part mostly or only on the negative SFC. • SFC can be performed within a specified power level range, thereby the minimum power level is typically defined at 50% - 60% REO
Minute Reserve (MR) providing	Depends on current grid demand and can be performed as an automatic or manual actuated ramp • The activation time of this reserve is between 7.5 and 15 min and the duration is from 15 minutes to a few hours. It can be

NPP Mode/Grid Service in Germany	**Description and Examples**
MR / mFRR	requested, at the latest, 7.5 min in advance, can be positive and negative. • The activation of the MR is carried out by a plant shift on request of the grid dispatcher, resulting from market auction & TSO requirements. • The ramp rate is also set by the reactor operator and is typically, in Germany, in the range between 10 and 30 MW/min (depending on the ramp duration at the low level). • Often NPPs are taking part only on the negative MR. • PFC, SFC and MR can be superimposed. • MR can be performed within a specified power level range, thereby the minimum power level is specified and typically defined at 50% - 60% REO
Load Following (LF) as a result of portfolio optimization **(Economic dispatch)**	Depends on demand/supply balance • LF works on the predefined variable load programs, i.e., reductions or increases in power output agreed in advance. • The load program is defined by the load dispatcher (day ahead) according to availability and cost optimization for all generators of this electric utility (portfolio optimization). Results from the Intraday-market can change the load plan several times during the day. • It is typically requested more than one hour in advance. • It can be performed manually or automatically with the help of corresponding software. The ramp rate is set by the reactor operator on request of the load dispatcher and is typically in the range of 10 to 30 MWel/min – and could be lower, e.g., depending on the time in the fuel cycle. • Minimum power level is specified in advance. • LF could be performed by a German NPP from full power till minimum load, approximately 30%- 40%, but typically the minimum level for LF is defined at about 50%-60% REO for PWRs and approximately 60% REO for BWRs to reduce the possible impact on the plant.
Redispatch (Overload management)	Defined as a shift in the planned power production to avoid network bottleneck, leading to a Short Term agreed change in the predefined load program - single power reduction • Start of ramp down by the plant shift on demand of grid dispatcher, resulting from TSO requirements • Ramp rate and minimum power level is specified • Typically, the same ramps and power levels as for economical dispatch are defined

NPP Mode/Grid Service in Germany	Description and Examples
Extended Low Power Operation (ELPO) as a result of portfolio optimization **(Economic dispatch)**	Performed with single power reduction, and is applied to adapt to a longer term demand forecast • Power level and duration are forecast. After performing the ramp, the NPP returns back to full power on request of the load dispatcher • Definition is country dependent with typical duration of > 24 h • Fuel conditioning / deconditioning is an important limitation factor for the return to full load • The ramp rate and minimal power level is set by the reactor operator on request of the load dispatcher • The ramp rate depends on the Boron concentration and strongly differs between up- and downwards. • Existing operation experience for daily, weekly, monthly ELPO, e.g., several months, at less than 40% RTP (100% = RTP - rated thermal power) in addition to extensive load following for about 2,5 years • Overall, ELPO at minimum power level is used only in some German NPPs and in very specific cases (e.g. very high negative prices)
Emergency access	Applied in the case of grid emergency situation (imminent danger, danger of grid safety) • Expanded control rights are given to the grid dispatcher/authority to issue an instruction to reduce power (via telephone) • A minimum load level is specified. • The grid dispatcher typically gives info about the level, the required ramp rate, the reason and the planned duration Maximal ramp rates are at maximal design values e.g. 10% /min for PWRs and 30% /min for BWRs, lower rates can be agreed, e.g., 60 WM/min for BWR (1344 MWel)

Voltage regulation
 	
providing
 	
reactive power
	Secures voltage stability of the grid
	• Activated by Short Term grid dispatcher request via telephone
	• The grid dispatcher can have access to the tap changer of the NPP
	• Currently, various are operating in the underexcited mode most of the time, e.g. annual participation in voltage regulation of a single NPP
	    ◦ typical inductive activation of approximately 150 Mvar (up to approx. 450 Mvar)
	    ◦ mostly in under excited mode, typical activation of about approx. 200 Mvar (up to approx. 350 Mvar)

Appendix B: Impacts of FLEXOP to NPPs with respect to vibration and wear

Table 13: Impact of vibration and wear on NPPs in Nuclear Island.

NPP type	Component	Vibration / Aging mechanism	Operator's observations (typical/often/ rarely)	Realised Counter-measures	Life time impact	Possible Mitigation measure
PWR	Pressurizer spray nozzles	Thermal fatigue	Thermal transients alter material (t)	I&C measures to spread load	Usage factor reached at 2023	Online Fatigue monitoring
BWR PWR	Recuperative heat exchanger	Thermal fatigue	Thermal transients alter material (t)	Operation of more trains	Usage factor rising significantly	Online Fatigue monitoring
PWR	Control rod drives	Mechanical degradation	Control rod drives move more often due to FlexOP (t)	Calculative measures for LTE	Number of design activations overstepped	Intense monitoring and inspection
PWR	Steam generator	Vibration impacts by fluid	More noise events during load transients (t)	More often inspection, monitoring	Currently none detected	Specific tracking by monitoring

Table 14: Impact of vibration and wear on NPPs in Turbine Island I.

NPP type	Component	Vibration / Aging mechanism	Operator's observations (typical/often/rarely)	Realised Counter-measures	Life time impact	Possible Mitigation measure
BWR PWR	Motor operated valve drives	Activation due to load transients	Mechanical degradation on gear parts or stems (t)	More often inspection and maintenance	High (> 20 x more controls)	Online Monitoring
BWR PWR	Main steam regulation valves	Fluid activated vibrations	High vibration < 40 % load (o)	Avoiding of load ranges	Currently not defined	Vibration and fatigue monitoring
BWR	Main feedwater pumps	Forced structural vibration	In part load conditions resonant excition (o)	Avoidance of operation range/more pumps in activation	Middle	Vibration monitoring
PWR	Main feedwater pumps	Cavitation at part load	HP-stages of pumps are facing cavitation for < 50 % load (r)	Avoidance of operation range / less pumps in activation	Middle	Noise monitoring
BWR *	Main feedwater pumps	Speed dependent rotor excitation	In low load conditions on pump and gearbox with varible speed drive (o)	Intense balancing of rotors	Middle	Vibration monitoring
BWR * PWR	Feedwater and Condensate pumps	Fluid induced vibrations	In part or full load conditions (r)	Change / redesign of exciting component	Middle	Vibration monitoring

(*: Additional Information from a Swedish BWR.)

Table 15: Impact of vibration and wear on NPPs in Turbine Island II.

NPP type	Component	Vibration / Aging mechanism	Operator's observations (typical/often/rarely)	Realised Counter-measures	Life time impact	Possible Mitigation measure
BWR PWR	LP turbine end stages	Erosion on lower blade sections	Back flow on last 2 blade stages due to part flow conditions (o)	Inspection / change of blades	High	Inspection / avoidance of low loads
BWR PWR	Turbine shaft	Torsional vibration excitation	Electric grid peaks excite shaft vibration (o)	Mechanical and electrical monitoring	Currently seen low	Vibration and fatigue monitoring
BWR PWR	Moisture separator / preheater	Corrosion, mechanical load	At part low condition change of pipe passivation (o)	Intense repair	High (large areas concerned)	Avoiding of part load / change of piping material
BWR PWR	Preheaters	Erosion due to changed flow conditions	Changed flow, pressure or humidity condition can cause erosion (o)	Regular inspection, cladding with resistive material	Middle	Regular inspection, additonal cladding

Table 16: Impact of vibration and wear on NPPs in Turbine Island III.

NPP type	Component	Vibration / Aging mechanism	Operator's observations (typical/often/rarely)	Realised Counter-measures	Life time impact	Mitigation measures
BWR PWR	Electrical components of the Unit Auxiliary Power Supply System	Mechanical degradation	Minimally affected (r)	More often inspection at some power contactors in defined control circuits	No, due to counter-measures	Monitoring of motor, gear, stems
BWR PWR	Main generator	Torsional vibration	Affected (o)	measurements referring vibrations and electrical measurements on the grid connection	No, due to mitigation measures	"empiric-mathematic model", gives alarms to the shift
PWR	Generator Cooling tubes	Higher O_2 content generator cooling water – corrosion of copper tubes	Single NPP (r)	Maintenance activities	No, due to counter-measures	Maintenance

Table 17: Impact vibration and wear on NPPs on fuel assemblies and erosion/corrosion in general.

NPP type	Component	Vibration / Aging mechanism	Operator's observations (typical/rarely)	Realised Counter-measures	Life time impact	Possible Mitigation measure
BWR PWR	Fuel	Flow induced vibrations	Not affected (r)	Robust, fretting resistive design	Currently not defined	n. A.
BWR PWR	Various in secondary circuit	Erosion corrosion	Significant effects already before partial load operation (t)	Individual expert evaluation	No, due to mitigation measures	Monitoring, software tools like COMSY

SURVEY ON VIBRATION IMPACT OF FLEXIBLE OPERATION ON NPP

Nuclear power plants have traditionally been used for base load operation, meaning that plants are generating electricity at stable load and other, more easily adjustable generating units are regulating the grid. However, the significant increase of electricity production of highly intermittent nature, like wind and solar, can lead to a situation where load follow of nuclear power plants will be necessary.

To minimize the risk for deterioration and premature failures caused by high vibrations due to load follow, it is vital to understand what type of problems may occur, how it might affect the main components of the plant and how the problems can be mitigated. In this project senior experts have interviewed German plant managers and collected hands-on information on experienced vibration problems related to load follow.

Energiforsk is the Swedish Energy Research Centre – an industrially owned body dedicated to meeting the common energy challenges faced by industries, authorities and society. Our vision is to be hub of Swedish energy research and our mission is to make the world of energy smarter!

Energiforsk