USING DECOMMISSIONED NUCLEAR POWER PLANT AS SYSTEM SERVICE PROVIDERS

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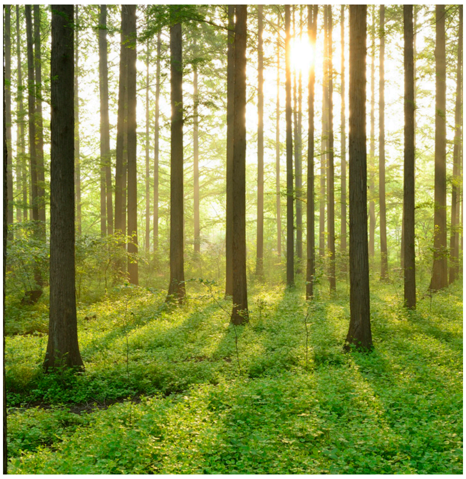

NUCLEAR POWER

Energiforsk

Decommissioned Nuclear Power Plant as System Services Providers

A technical pre-study

VINCENT GLINIEWICZ

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Foreword

The ongoing changes of the power system with decommissioning of several nuclear power plants and large scale introduction of variable power production without direct connected generators will probably result in a situation where there is a lack of reactive power and inertia.

The lack of reactive power could reduce the possibilities to transmit power in the north-south direction, giving a challenging power balance in SE3 and SE4 with electricity trapped in northern Sweden. Lack of inertia could in worst case make it necessary to reduce the output from the largest units, to ensure the grid availability if the largest unit is disconnected.

Decommissioned nuclear power plants could play a role in providing system services, but it would require investments and costs to provide these services. The Energiforsk nuclear portfolio board has initiated this study to make an initial mapping of the technical challenges of providing system services. The main method that has been used in this project is workshops with experienced staff from the nuclear power plants, owner companies and Svenska Kraftnät. Project leader for the study has been Vincent Gliniewicz, consultant at Vattenfall R&D.

Monika Adsten, Energiforsk

Sammanfattning

Kärnkraftverk skulle kunna byggas om för att erbjuda systemtjänster även efter det att de har avvecklats. Energiforsk startade därför detta projekt för att undersöka tekniska utmaningar och möjligheter under hösten 2016. Arbetet har i huvudsak bedrivits genom två workshops, den första vid Vattenfalls huvudkontor i Solna och den andra vid Ringhals, kombinerat med ett besök i anläggningen.

Målet med workshoparna var att diskutera tekniska detaljer kring hur nedlagda kärnkraftverk kan utvecklas för att tillhandahålla systemtjänster. Liknande ombyggnader har gjorts i främst gaseldade ångturbiner, men det finns även några exempel på kärnkraftverk som har byggts om.

Det finns flera argument för att använda nedlagda kärnkraftverk för att erbjuda systemtjänster. En ökande andel av icke-synkrona generatorer i det nordiska kraftsystemet i kombination med en eventuell avveckling av kärnkraftverk i Sverige skulle kunna leda till en farligt låg tröghet i elsystemet och kan också orsaka lokala underskott på reaktiv effekt i delar av Sverige. Att bygga om en befintlig synkrongenerator är förmodligen mer kostnadseffektivt jämfört med att installera nya synkrona kondensatorer, kondensatorbatterier eller statiska VAR kompensatorer (SVC). Dessa nya system skulle kräva markförvärv, nya fundament, ställverk, överföringsledningar och så vidare.

Nya synkrona kondensatorer har diskuterats under seminariet för att inte bara stödja reaktiv effekt men också systemets tröghet, eftersom systemtrögheten riskerar att bli alltför låg när flera kärnkraftverk kommer att avvecklas. För att bibehålla systemets svängmassa, skulle turbinaxeln behållas med undantag för turbinbladen, eftersom de skulle leda till alltför mycket friktion och värmeförluster.

En slutsats av workshoparna var att det förmodligen är enklast och mest ekonomiskt att försöka göra så få ändringar som möjligt i den nuvarande utformningen. Extra massa i form av dummyringar skulle kunna läggas till turbinaxeln, förutsatt att den inte överskrider viktgränsen på den stödjande strukturen. Den nya axelkonstruktionen bör analyseras för att säkerställa att egenfrekvenserna i systemet kan undvikas.

Den nuvarande bristen på ekonomiska incitament gör det mycket osannolikt att nedlagda kärnkraftverk kommer att modifieras för att erbjuda systemtjänster. Investeringar och drift kostar pengar, varför värdet av dessa tjänster på något sätt måste integreras i elmarknaden.

Summary

Nuclear power plants could provide system services even after being decommissioned. For this reason, Energiforsk has set up this project, which has been organised around two workshops during the fall of 2016. The first workshop was held in Vattenfall's main office in Solna and the second one in Ringhals, together with a visit of the plant.

The goal of the workshops was to discuss technical details about using decommissioned nuclear power plants to provide system services. Converting synchronous generators into synchronous converters have been done in the past, mostly for gas fired steam turbines, but some cases of nuclear power plants can be found in literature as well.

There are a lot of arguments in favour of such a conversion. Increasing share of non-synchronous generators in the Nordic power system combined with the possible decommissioning of many nuclear power plants in Sweden could lead to a dangerously low system inertia and could also potentially cause some local deficit of reactive power in some part of Sweden. Moreover, the conversion of an existing synchronous generator is probably more cost-effective compared to the installation of new synchronous condensers, capacitor banks or static VAR compensators (SVC). These new systems would require land acquisition, new foundations, switchgear, transmission line and so forth.

New synchronous condenser designs have been discussed during the workshop to not only provide reactive power support but also system inertia, as a too low system inertia in Sweden could be expected when nuclear power plants will be decommissioned. To maintain the rotational mass of the system, the turbine shaft system would have to be kept, with the exception of the turbine blades, as they would lead to too much friction and heat losses.

A conclusion of the workshops was that it is probably easiest and most economical to try to do as few modifications to the current design as possible. Extra mass in form of dummy rings could be added to the shaft system, as long as it does not exceed the weight limit of the supporting structure. Dynamic analysis of the new shaft design should be performed prior to dimensioning the start-up system to make sure that the eigenfrequencies of the shaft system can be safely avoided.

The current lack of economic incentives makes it highly improbable that nuclear power plants can be modified to provide system services as any of the required modifications would cost a substantial amount of money. To make it happen, the real value of this kind of services must first be recognized by TSOs and somehow integrated into the electricity market.

Acknowledgments

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1 Introduction

1.1 BACKGROUND

Electricity generation at a national level all happens in alternating current at a frequency of 50Hz. The combined inertia of all of the generators in the system is extremely useful to maintain the frequency of the system within acceptable limits in order to avoid damaging electrical equipment or in worst cases, black outs. The loss of a large power station can mean an instant imbalance between electricity generation and demand of the magnitude of gigawatts. The first line of defence against generation failure is system inertia: the more rotational mass there is in the system, the smaller the frequency deviation, i.e. more stable power system.

The system inertia in the Nordic power system is however reducing with the increasing penetration of renewables, as these non-synchronous power plants are meant to replace synchronous ones, such as nuclear power plants. Uniper and Sweco recently warned in a joint report [1] that the wide decommissioning of nuclear power plants in Sweden could lead to a new paradigm where the large decrease in system wide inertia is not enough to sustain big losses of power generation.

It is true that wind turbines with synthetic inertia capabilities could be a solution to prevent deterioration of system stability (it is for example mandatory in Germany for new wind turbines to be able to generate synthetic inertia), but synthetic inertia cannot entirely replace real rotational mass. Indeed, the report [2] states that synthetic inertia delays the frequency recovery and puts higher demand on primary reserve than conventional inertia.

Moreover, the lack of reactive power could reduce the possibilities to transmit power from regions with high power productions, resulting in a challenging power balance for price areas SE03 and SE04. This can be partly compensated with the installation of new power lines, but the need for reactive power would still remain, especially in SE03.

As a result, modification of decommissioned nuclear power plants (NPPs) in order to provide system services (system inertia and reactive power) could be a cost-effective and sustainable way to phase out nuclear power in Sweden. Some details however still remain to be studied to fully understand the possibilities and feasibility of such conversion.

1.2 PURPOSE

The purpose of this pre-study is to briefly answer the following questions:

- How much reactive power and inertia could be provided by decommissioned NPPs?
- Is there any decommissioned NPPs in the world already providing such services? If so, under which circumstances?
- What is the best way for such generators to provide inertia (Generators only? Generators + shaft? Generators with dummy rings on shaft?)
- Will there be any safety related issues when modifying the NPPs?
- Is contamination in a boiling water reactor a problem?
- Would it be possible to include such units in a reactive power market?

1.3 METHOD

In order to answer these questions, two workshops gathering experts in the fields of mechanical engineering, power system engineering and nuclear power engineering were organised.

- The first one took place in the main office of Vattenfall in Solna, Sweden discussing the following: system needs and general considerations for possible synchronous condenser designs.
- The second workshop took place in the facilities of Ringhals in Sweden. This session focused on arguing the pros and cons of the previously discussed potential designs for synchronous condensers with inertia capabilities.

Finally, prior to the workshops, the author undertook a literature study in order to moderate and highlight certain issues during the workshops with the group of experts.

The documents used for the literature study are publicly available and referred to at the end of this report.

2 Results

2.1 SYNCHRONOUS GENERATOR - SYNCHRONOUS CONDENSER CONVERSION

Retiring a power generation unit can reduce a plant's reactive power capacity, possibly creating a deficit that directly affects the local system's reliability. If a unit is retired, the challenge will be to maintain grid voltage at or near the plant interconnection point to ensure voltage stability and grid reliability. Solutions can involve installing new static volt-amperes reactive (VAR) compensators, shunt capacitor banks and/or synchronous condensers at or near the plant location. However, potentially there is a more economical and effective solution: converting the existing synchronous generator into a synchronous condenser.

There are considerable benefits to making this conversion. Re-using the existing generator, its foundation and building, auxiliary systems and grid connections offers an economical source of reactive power capacity. The reactive power capacity of a synchronous condenser is defined by the generator capability curve, as shown in Figure 1, which defines operation limits in order to avoid over-heating (and therefore damaging) the generator. However, because of the condenser's reduced range of operation (compared to a generator), those operating limits are less likely to be exceeded.

Reactive power produced by a synchronous condenser is considered superior to static VAR solutions; the condenser increases reactive power in response to a system voltage drop while also supplying the local system with significant short circuit support. Moreover, power electronics solutions often create harmonics, a negative impact on the power system. Finally, a synchronous condenser also provides system inertia, due to the rotating mass of the rotor. And if more mass can be kept or added during the conversion process, more system inertia could be provided to the power system.

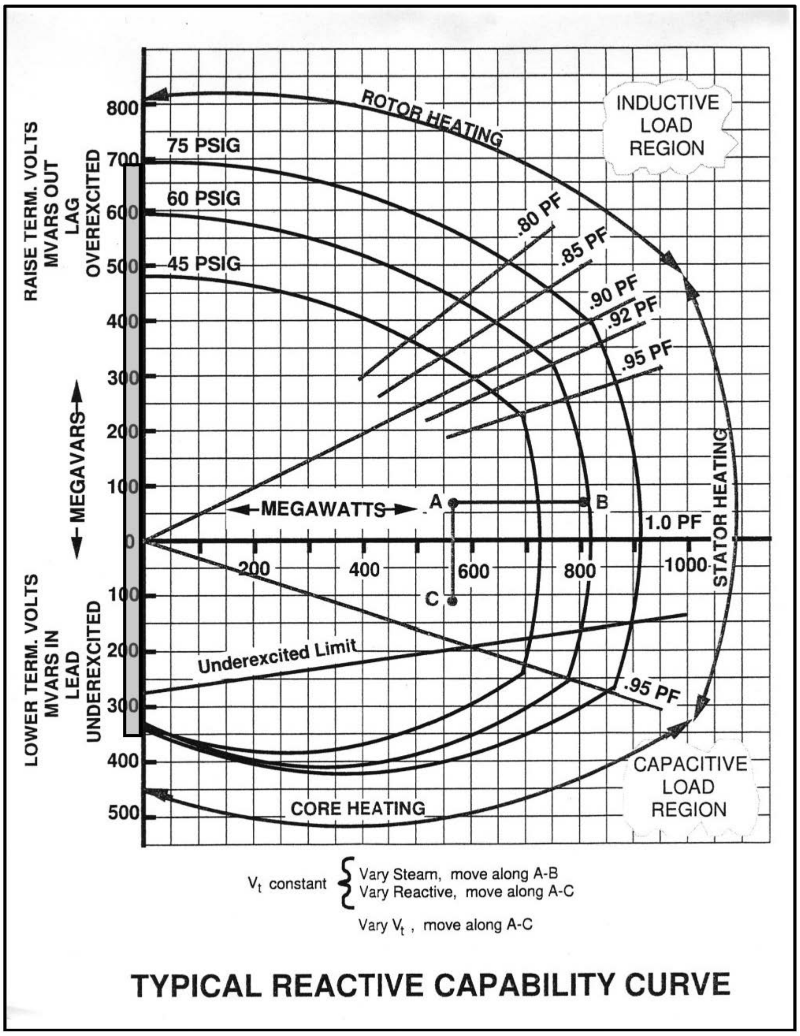


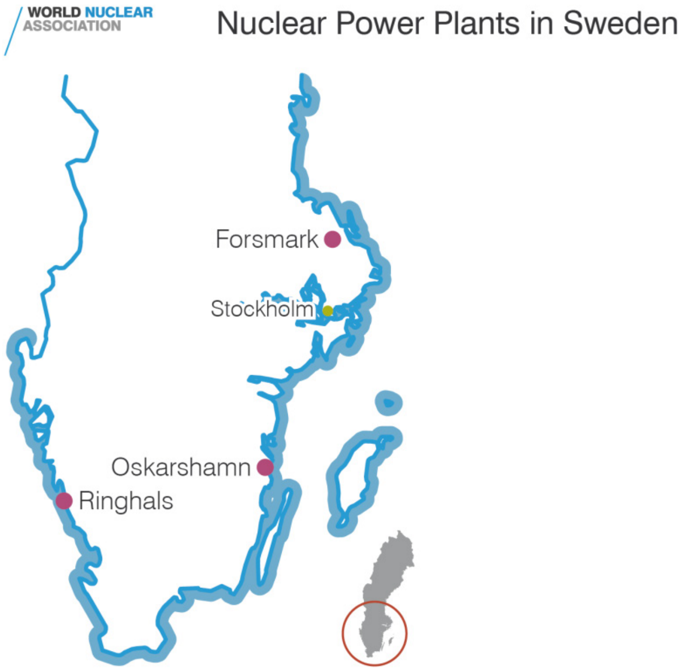
Figure 1: Capability curve of a synchronous machine

2.2 SYSTEM NEEDS

Svenska Kraftnät (SvK) estimates that the biggest challenge for the grid would be the lack of system inertia and therefore the strongest argument for repurposing decommissioned NPPs into synchronous condensers.

The system would benefit from extra inertia regardless of where it is located in the system. This means that all NPPs subject to decommissioning are potential candidates to provide inertia to the system.

Reactive power on the other hand is much more dependent on the local needs of the system. SvK does not see a need in the future for reactive power in the southern part of Sweden as the South West HVDC Link and NordBalt HVDC link could provide sufficient voltage stability in this region. Reactive power would on the other hand be most beneficial to the middle and northern part of Sweden as well as the west coast. From this point of view, Forsmark and Ringhals are very well located while Oskarshamn is less interesting.



Source: World Nuclear Association

Figure 2: Map of the nuclear power plants of Sweden

2.3 PREVIOUS CONVERSION PROJECTS

Some conversion projects of nuclear power plants have successfully been done in the past with the goal to turn the synchronous generators into synchronous condensers:

1. The Zion nuclear station in the USA: 2 (Pressurized Water Reactor) generators of 1100MVA each were converted in 1998 into synchronous condensers (+/-400Mvar each) for an initial running period of 3 years but were kept online for 11 years [3].
2. The Biblis reactor A in Germany (1200MW) was converted by Siemens into a synchronous condenser in 2011 [4].

Both conversions aimed at modifying the nuclear power plants into synchronous condensers for reactive power support. The final condensers were able to provide reactive power amounting about one third (1/3) of the original rated power of the plant. It is fair to assume that Swedish decommissioned generation units could provide the same amount of reactive power as well.

2.4 CURRENT STATE OF NUCLEAR POWER PLANT UNITS

All 8 generators in Ringhals have been partially (stator only) or completely (stator and rotor) refurbished recently. Ringhals 1 has been completely refurbished only a few years ago. In Forsmark, the stator of Forsmark 1 and 2 have been rewound in 1996 and 2007 respectively and the generator at Forsmark 3 is new (done in 2015).

With most generators not having reached their technical useful life if the reactors were to be decommissioned in the near future, it would make sense economically to try to repurpose them.

Using generators as synchronous condensers would mean that current stators are oversized and would therefore probably suffer less stress than in generator mode. The rotor would be subject to approximately the same stress and wear as in generator mode if the rotor is used to provide substantial reactive power. What would considerably affect the life expectancy of the generator (the rotor part) in synchronous condenser mode would be its rate of operation, meaning how often it is switched on and off: a seasonal use would require as much maintenance as what is currently needed in generator mode, but a daily use would require much more extensive maintenance.

2.5 TECHNICAL ASPECT

2.5.1 Reference case: Synchronous condenser

In order to convert a generating unit into a synchronous condenser some questions need first to be answered. Besides the obvious economic viability and strategic location of the plant, some more technical questions need answers. Mainly, during the conversion process, which components or groups of components need to be removed, which need to be maintained and which need to be added?

A very exhaustive report from EPRI [5] lists all the considerations that have to be made in order to know whether the conversion into a synchronous condenser is feasible and viable. The most notable points are presented below:

- The turbine and steam system is not needed for a synchronous condenser.
- Without the mechanical driving force from the steam generator and turbine system, a new start-up system capable of accelerating the condenser up to synchronizing speed needs to be installed.
- The condition of the generator (how new are the stator and rotor) plays a big role in the conversion decision, as the generator is by far the most expensive part in a synchronous condenser.
- The cooling system and lubrication system present on site will be reused for the synchronous condenser. Indeed, the generator will require as much cooling in synchronous condenser mode as in generation mode and any rotating part need lubrication.
- Anytime a turbine generator shaft line element is removed, changed, or added, a dynamic analysis should be performed to make sure the torsional frequencies of the new shaft line is safely away from the system frequencies (50-100Hz).

- Protection equipment must be modified according to the new functions provided by the plant (it will consume power).
- Maintenance costs for a synchronous condenser are essentially related to cooling and lubrication.

2.5.2 Synchronous condenser with inertia capabilities

As described in section 2.2, SvK estimates that maintaining inertia capabilities in the decommissioned nuclear power plants would be most beneficial to the system. This means that the conversion should try to maintain as much rotating mass as possible.

Figure 3 shows a schematic of the rotating system within a nuclear power plant. The generator accounts for only about 10% of the rotating inertia, each low pressure turbine (LT) between 25 and 30% and the high pressure turbine (HT) and the shaft itself the remaining quantity.

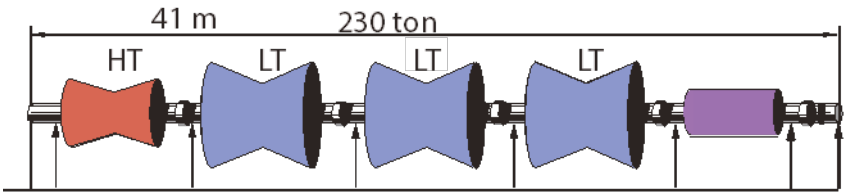


Figure 3: 3 Shaft system of R3, R4, F1 and F2: 3 low pressure turbines, 1 high pressure turbine and a generator are disposed on the shaft.

While getting rid of the turbines makes sense from a reactive power point of view, it is quite clear that removing such a high amount of rotating mass will provide much less inertia.

On the other hand, keeping the turbines as they presently are is not a viable option either. For example, the blades of the turbines used to give the shaft its rotational speed would, in the case of a synchronous condenser, offer a strong rotating resistance and therefore prevent the shaft to rotate as freely as possible, generate excess heat and consume unnecessary power. Moreover, the vacuum system currently in place at each turbine housing should be kept in order to minimize heat losses.

Three possible designs were discussed during the workshops:

1. Case 1: Synchronous condenser (reference case) with turbine shaft and turbines without blades.
2. Case 2: Synchronous condenser with turbine shaft and low pressure turbines without blades and extra mass through the addition of dummy rings
3. Case 3: Synchronous condenser without turbine shaft. Instead, a flywheel is installed to provide inertia.

2.5.3 Start-up system

The only difference between a start-up system for the reference case (synchronous condenser only) and the three cases presented in the previous section is the added mass.

This means that a start-up system such as the one presented for the Biblis conversion [4] could be used, with the difference that the hydraulic system responsible of setting the mass into motion should probably be more powerful (since a lot more mass is present).

Another idea discussed during the workshops was the use of an external motor to start the system. Motors of such kind could be present on site and would therefore be a more economical alternative to the start-up system used for the Biblis case.

It should be noted that a dynamic analysis of the new shaft design should be performed prior to dimensioning the start-up system in order to make sure that the eigenfrequencies of the rotor/shaft system can be safely managed.

2.5.4 Case 1: Remove the blades of the turbines

In a project aimed at reducing the power output of one of its generating plants, Mälarenergi has removed the blades of one of its low pressure turbine [6], thus indicating that this solution is technically feasible.

The main drawback with removing the blades of the turbine is that some rotational mass (and moreover the one farthest away from the axis of rotation) is lost. Experts at Ringhals estimate that removing the blades of all low pressure turbines would reduce the inertia of the system by approximately 30-50%.

Removing turbine blades is fairly straightforward for pressurised water reactor (PWR) nuclear power plants, but for boiling water reactor (BWR) nuclear power plants, such as Ringhals 1, the turbines and turbine area are contaminated, meaning that they must first be cleaned from radiation before any modification can be done. This unfortunately means that the conversion process will be more expensive for BWR type plants compared to PWR type plants. The

2.5.5 Case 2: Remove the blades and add dummy rings to increase inertia

The difference with this case compared with case 1 is only the added mass through the use of dummy rings. This means that the contamination problem for BWR type plants is relevant for case 2 as well.

Theoretically speaking, it is possible to achieve a greater moment of inertia of this system by adding rotational mass or reallocating it further away from the axis of rotation. One cannot however add an unlimited amount of mass, as the bearings and the foundations supporting the shaft and its components have been designed to support a limited mass. Exceeding the limit would mean having to change all the supporting structures of the shaft, probably at great cost. It is however safe to say that replacing the blades with dummy rings of equal mass will not have a negative impact on the supporting structure of the shaft.

Finally, the shaft (and what is on it) will be rotating at synchronous speed, 3000 rpm. Any modification done on the shaft (removal of blades, addition of mass) means that the shaft structure must be carefully balanced, in order to avoid otherwise dangerous vibrations or worst, mechanical instability. The balance test is often done at the manufacturer's site, as it requires specific equipment that is not present on the nuclear power plant site. This means that any modification done on the shaft structure will require this heavy piece of equipment to be moved from the site for testing at a substantial cost.

Participants of the workshops discussed however whether balancing the shaft structure after only removing the turbine blades could be done on site. This could be explained by the fact that no over-speed test is needed for synchronous condensers as they cannot exceed 3000 rpm set by the grid.

Adding this extra mass will come at a non-negligible cost. If balancing tests are required both for case 1 and case 2, the main determinant for choosing between both cases would be the price of system inertia.

2.5.6 Case 3: Remove the turbines and replace them with flywheel(s) of equivalent rotating inertia.

This alternative is the only one discussed that does not keep the turbine shaft as it is. This has the benefit of putting PWR and BWR type plant on an equal basis, since the contaminated turbines would not be used.

On the other hand, many drawbacks were found for this design: even though it is theoretically possible to add a flywheel to the generator to add inertia to the system, this would require major changes in the whole structure. Indeed, the flywheel would probably require, among other changes, a new vacuum chamber, new supporting bearings, as well as moving and modifying the lubrication and cooling system currently installed around the turbine shaft. Every modification in the current design will require many systems to be adjusted or modified as well, inducing great costs.

A conclusion of the workshop was that it is probably easiest and most economically efficient to try to do as few modifications to the current design as possible. The flywheel design should thus probably be excluded from further considerations.

2.5.7 Site clearance & Safety

The turbine hall should be cleaned up and the site cleared (friklassad in Swedish) before any reconversion project can take place. This clearance process will probably take longer for BWR type reactors than for PWR type reactors, therefore delaying the reconversion operations for this type of reactor.

Clearing the turbine hall has the benefit of allowing reconversion operations to be conducted by any qualified personnel, as opposed to authorized personnel (meeting nuclear safety requirements) only otherwise.

2.6 SYSTEM SERVICES MARKET

There is currently no planned compensation scheme for providing system inertia. However, as more and more zero marginal cost sources of energy enter the energy market, it is becoming more likely that other markets such as capacity market or system services market will emerge in the future. The Irish TSO Eirgrid e.g. estimates a fourfold increase in system services payments [7] within the five coming years. System inertia and reactive power support are named as potential services in such a market, two services that a repurposed decommissioned nuclear power plant could provide and could be compensated for if there is a scheme in place.

Further research is needed in order to clearly identify the value of system inertia, e.g. by studying the cost of providing synthetic inertia. Following, one must also determine the most efficient way to incentivise these system services, be it through a dedicated market or direct compensation from the TSO.

3 Conclusions

The conversion of an existing synchronous generator is probably much more cost-effective compared to the installation of new synchronous condensers, capacitor banks or static VAR equipment since these new systems could require for example land acquisition, new foundations, switchgear and connection to transmission lines.

New synchronous condenser designs have been discussed during the workshops in order to not only provide reactive power support but also system inertia, as a too low system inertia in Sweden and the Nordic synchronous system could be expected if its nuclear plants were decommissioned. In order to maintain the rotational mass of the system, the turbine shaft system would have to be maintained, with the exception of the turbine blades, as they would induce too much heat losses. A conclusion of the workshops was that it is probably easiest and most economically efficient to try to do as few modifications to the current design as possible. Extra mass in form of dummy rings could be added to the shaft system, as long as it does not exceed the weight limit of the supporting structure. Dynamic analysis of the new shaft design should be performed prior to dimensioning the start-up system in order to make sure that the eigenfrequencies of the shaft system can be safely avoided.

Finally, converting a nuclear power plant's generating unit into a synchronous condenser requires substantial investments that need to be compensated for. Current system services market do not provide sufficient economic incentive to motivate such a conversion.

In order to make it happen, the real value of this kind of services must first be identified, recognized by TSOs and somehow integrated into the electricity market.

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A conclusion of the workshops performed within this project was that it is probably easiest and most economical to try to do as few modifications to the current design as possible. Extra mass in form of dummy rings could be added to the shaft system, as long as it does not exceed the weight limit of the supporting structure. Dynamic analysis of the new shaft design should be performed prior to dimensioning the start-up system to make sure that the eigenfrequencies of the shaft system can be safely avoided.

The current lack of economic incentives makes it highly improbable that nuclear power plants will be modified to provide system services as any of the required modifications would cost a substantial amount of money. To make it happen, the real value of this kind of services must first be recognized by TSOs and somehow integrated into the electricity market.

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