SURVEY OF ROBUSTNESS MEASURES IN ELECTRICAL DESIGNS IN NUCLEAR POWER PLANTS

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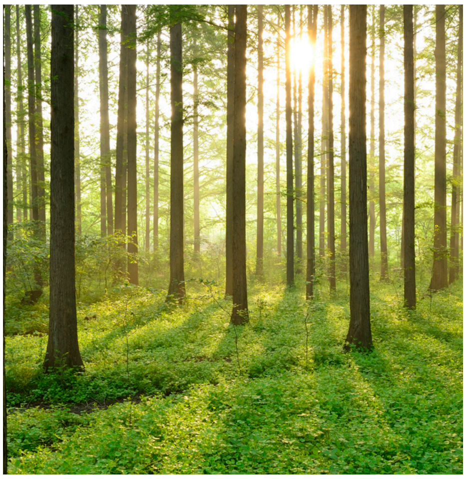

NUCLEAR

GRID INTERFERENCE ON NUCLEAR POWER PLANT OPERATIONS

Energiforsk

Survey of Robustness Measures in Electrical Designs in Nuclear Power Plants

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Foreword

A nuclear power plant needs a stable power supply during both normal and abnormal conditions, both to maintain an acceptable nuclear safety and to support the transmission system to maintain a high electrical quality and its ability to deliver power to customers. There are different solutions to obtain a design that is reliable and robust enough to fulfil such function in an acceptable way.

The aim of the activity is to document different design options for electrical power systems in nuclear power plants, including the option to use alternative sources of energy to achieve the intended function. It was carried out by senior consultants Göran Lindahl and Thorsten Schütte at ABB (former STRI) and Edvin Nyholm, specialist at Engineering4u.

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Sammanfattning

Det huvudsakliga ämnet i denna rapport har varit att belysa möjliga åtgärder som kan öka robustheten och motverka oförutsedda störningar som kan drabba ett kärnkraftblock genom den gemensamma kopplingspunkten mot nätet. Rapporten syftar inte till att ge några rekommendationer eller bedömningar för enskilda block eller anläggningar. Syftet är endast att belysa olika möjliga lösningar som skulle kunna övervägas för enskilda block eller anläggningar.

I den här studien har den elektriska anslutningen av de olika kärnkraftverken i Finland och Sverige granskats med avseende på deras enlinjescheman och hur de är anslutna till nätet. Det finns många likheter mellan blocken men enheterna visar också på ett flertal skillnader i anslutningsmöjligheter till nätet.

Olika sätt att diversifiera anslutningen till nätet med andra kopplingar, såsom korskoppling, anslutning till både huvudnät och reservnät har diskuterats, vilket visar några möjliga sätt att öka robustheten genom att inte ansluta alla subsystem till samma källa.

Användningen av roterande omformare som ett medel för att isolera delar av kärnkraftverkens nät från de yttre näten har undersökts. Detta inkluderar erfarenheter från andra branscher som järnvägssystem, vidare hur de roterande omformarna kan placeras inom ett block eller i anläggning samt vissa aspekter på omformarna såsom verkningsgrad och tröghet. En genomgång av några störningsrapporter från kärnkraftsindustrin avseende operativ erfarenhet av roterande omformare har gjorts. De rapporterade störningarna har visat sig vara av olika karaktär och tillsammans med driftserfarenheter av roterande omformare från några kärnkraftverk har det inte kunnat påvisas att störningar från yttre nätet skulle ge upphov till fel med gemensam orsak som påverkar de roterande omformarna.

Sammanställning av svar från frågeställningar angående robusthet som ställts till industrier utanför kärnkraftsbranschen visar att dessa industrier också är känsliga för elektriska störningar från nätet. Den störningstyp som förefaller ha störst inverkan på dessa industrier är spänningsdippar men även andra störningar har rapporterats kunna ställa till med besvär. Motåtgärder som rapporteras av industrin är till exempel åtgärder som vidtagits på frekvensomriktare eller förbikopplingsmöjlighet av frekvensomriktare. Vissa av industrierna har egengenerering för att försörja anläggningen och utnyttjar denna möjlighet för att i förbyggande syfte gå över i husturbindrift vid åska och därmed öka robustheten mot yttre störningar.

Icke elektrisk kraftförsörjning har diskuterats och betraktelser är gjorda på säkerhetsfunktionerna utifrån några olika perspektiv. Det presenteras en teoretisk bild av den energi som krävs för att utföra säkerhetsfunktionerna, tidsramen i vilken säkerhetsfunktionerna behöver utföras, aktuellt tillståndet för elektriskt beroende eller oberoende, och slutligen presenteras ett förslag där ytterligare minskning av det elektriska beroendet skulle kunna vara av intresse.

Summary

The main topic of this report is to enlighten robustness measures that can be taken to counteract unanticipated electrical disturbances that can reach the nuclear units through a point of common electrical coupling. The report does not intend to give any recommendations or assessments for individual plants or units. It serves only as review of possible measures that could be considered for a specific plant or unit.

In this study the electrical connection of the different nuclear power plants in Finland and Sweden has been reviewed in terms of their single line diagrams and how they are connected to the grid. There are many similarities but the units also show many differences in the connection possibilities to the grid.

Means of diversifying the connection to the grid using other connections, such as cross-coupling, connection to both off-site switchgears etc. has been discussed showing some possible ways of increasing robustness by means of not connecting all electrical trains to the same source.

The use of motor generating sets (MG-sets) as a mean of isolating the electrical system of the plant from the off-site power system has been investigated. This includes experiences from other branches as railway system, how placement of MG-sets within a unit or plant can be done, and some aspects such as efficiency and inertia. Investigation of some disturbance reports from the nuclear industry regarding operating experience of MG-sets has been performed. The disturbances have been found to be of different character and from these disturbance reports and also from operating experience of some nuclear units it has not been possible to find any common cause failure associated with MG-sets related to the off-site power system.

Answers from a questionnaire to the industry outside the nuclear sector reveal that their plants are sensitive to electrical disturbances as well. The disturbances that appear to cause problems to most of the industries are voltage dips but some other disturbances are reported to cause problems as well. Countermeasures reported by the industry are for example actions taken on frequency converters enforcements or by-pass possibilities of frequency converters at disturbances. Some industries have in-house generation to supply the plant and they use this as a countermeasure by disconnecting the plant from the grid at lightning occurrence as preventive action.

Non-electrical power supply has been discussed and it looks at the safety functions from a few different perspectives. It presents a theoretical view of the energy necessary to perform the safety functions, the time frame in which the safety functions needs to be performed, the current state of electrical dependence or independence, and finally presents a suggestion where further reduction of electrical dependence could be of interest.

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1 Introduction

Several different incidents in nuclear power plants around the world has occurred the last decade that has revealed unforeseen stresses to the electrical power systems of the nuclear units. Many of them have had their origin in the off-site power system (grid). The purpose of this work has been to review conditions in Finnish and Swedish nuclear power plants and to give an overview regarding electrical power supply including possible measures to increase robustness to electrical disturbances. In the work solutions both regarding electrical and non-electrical power supply robustness has been illustrated. Robustness to electrical disturbances is important because it has impact on electrical safety system in a unit (nuclear safety systems) because they are normally fed from the outer power system.

There are indications that the development within the power system, (which all NPPs are a part of), to go from centralised power production to decentralised power production, will affect power system stability and reliability ("system challenges"). Therefore, enhancing more independence from the national power system can be a good preventative measure to cope with future power system challenges and the new electrical environment.

In addition to this the conditions in the industry, outside the nuclear sector, has been investigated. This has been done in form of a questionnaire sent to companies in the forest industry, steel and metal industry and in chemical and petrochemical industry.

2 Existing NPPs in Finland and Sweden

To examine the connections to the grid of the different nuclear power plants in Finland and Sweden single line diagrams have been provided by most of the different operators of the plants. In addition operational information on how the plants are normally operated in terms of connection to the grid has been provided for some of the plants. The nuclear reactors represent both boiling water reactors (BWR) and pressurized water reactors (PWR). Some sites may have both sorts while other sites have only one of the types. From an electrical power system point of view the BWR and PWR reactors are quite similar.

Some of the reactors have recently, permanently, been put out-of-operation and some reactor is under construction/commissioning and will be put into operation. Single line diagrams and other information has been provided to the authors. These are however not included in the report for secrecy reasons.

3 Alternative connections and supplies

3.1 ALTERNATIVE CONNECTIONS

3.1.1 Supply from both off-site AC sources

The discussion below is held from a robustness perspective and does not intend to give any general recommendations but just to highlight some prospective solutions. The discussion is generally held from a grid alignment perspective. Different plants and units have different Technical Specifications (operable conditions) which may or may not make these prospective solutions suitable for further considerations.

As mentioned in chapter 2.3 it seems that at least for some units that the operational conditions do not require that the complete unit (all trains) have to be supplied from the same source during power operation of the plant. Diversity in supply from both off-site sources, first and secondary off site sources can therefore for some units be an alternative. One or possibly two of the four trains could during normal operation be supplied from the second off-site source, see Figure 6. Most of the disturbances coming from the off-site power system (or even emanates from the unit grid connection itself) will then not affect all of the trains at the same time and in a similar way. Especially for plants where the electrical distance between the first and second off-site switchgears is large one can anticipate that should one fault at a single point occur in the grid it will appear differently in the different trains. For instance lightning and switching overvoltages arising from the same event cannot be critical to all trains at the same time as they cannot travel long distances without large attenuation. Even over- and under-voltages of power frequency character (of shorter durations) will not affect all of trains equally. If for instance it can be assured that for a fault anywhere in the off-site power system between the first and the secondary off-site switchgear the voltages within the unit auxiliary power system do not drop below the normal lowest acceptable value for normal operation (typically 0.85 p.u. voltage) in all trains, this is may be a feasible solution.

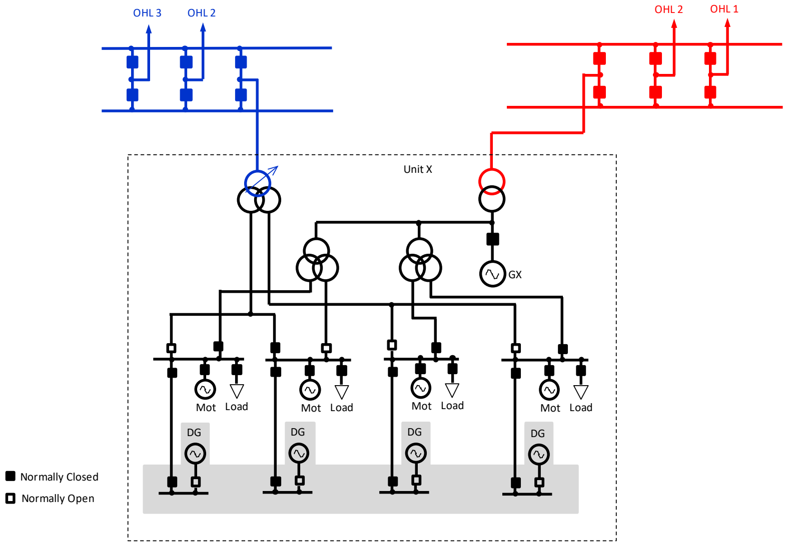

Figure 1. – Schematic sketch showing operation of one train from the second off-site source.

It shall be noted however that the failure rate and the number of disturbances of the second off-site source (sub transmission voltage level) does not necessarily have to be the same as for the first off-site source (transmission voltage level). In fact, as the voltage level is lower, the sub transmission switchgear arrangements can sometimes be in a simpler form and the failure rates of overhead lines is most often higher than for a transmission system. The main reason for this is that the major source of disturbances is in form of lightning strokes. Higher voltage levels have generally better lightning protection in form of shielding wires and less number of strikes will results in a flash-over to the phases. Lower voltage levels (subtransmission) may or may not have shielding wires. For those sub transmission lines that have shielding wires the current amplitude of the lightning stroke that will cause a flash-over to the phases will be lower than for the transmission lines due to the lower insulation level (shorter insulator strings). For those sub-transmission lines that do not have shielding wires most of the faults caused by a lightning stroke will result in a poly-phase fault.
Hence, a comparable higher number of the faults will also be poly-phase faults on the sub transmission lines compared to the transmission lines where the majority of the faults are single phase faults.

Depending on how strong the network behind the secondary off-site switchgear is it may also be challenging to supply the power required if several units in the same plant are having one or two trains supplied from the secondary off-site switchgear. Interdependence between units may have to be considered for instance at start-up of large objects within one unit as it may affect the supply of another unit.
A plant view perspective should be considered as well when assessing a specific solution. However this requires more detailed information about each plant and about individual units including even individual electrical objects within a unit and is beyond the scope of this work.

From an economical point of view also the cost for the power supplied from the secondary off-site source may have to be evaluated since when the auxiliary power

is supplied from the generator it does not need to be purchased.
A further important issue may be how well the unit can cope with the loss of the operational objects in one (or possibly two trains) without causing partial or complete scram of the reactor at total loss of the secondary switchgear (it is assumed that the safety trains will resume operation supplied from their emergency diesel generators).

Further another consideration can be if the supply of the operational part in one train (or possibly two trains) from the secondary off-site switchgear can impact on ability to enter into house-load operation with the main generator supplying the remaining of the operational trains. This may vary from unit to unit.

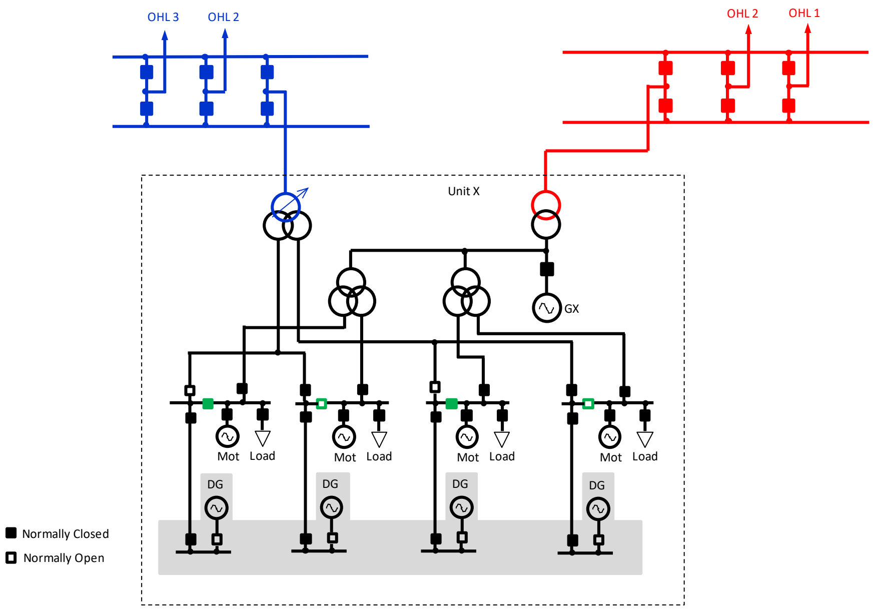

Figure 2. - Schematic sketch showing operation of two safety trains from the second off-site source.

A possible solution, if there are restrictions on how much power output that can be taken from the secondary off-site source and also if operational availability cannot be kept sufficiently high, may be to separate the operational part from the safety part by introducing a bus sectionalizing breaker on the main operational busbars, see Figure 7 above. Alternatively to introduce a direct supply path from the start-up transformer (standby transformer) to some of the safety classed busbars without passing through the operational switchgears. Some of the units described in chapter 2.1 seem to have this facility.

This would allow one or two safety trains to be fed from the secondary off-site switchgear and hence from another source compared to the two remaining safety trains during normal operation. The operational objects in all trains would still be fed from the generator side and would not normally be affected by the secondary off-site source. The power requirement from the safety trains is normally considerably lower compared to the operational parts, typically some maximum 2-6 MVA per safety train based on the size of the diesel generators. The safety busbar(s) supplied from the secondary off-site switchgear may have a different exposure to disturbances from the secondary off-site power system as with this solution (during power operation) the larger operational objects (large motors) are fed from the primary off-site switchgear side. The larger operational objects (large motors) may have a mitigating effect on disturbances coming from the off-site power system as seen from the safety busbar. There may of course be unit specific design consideration from the original design at hand that would require new analysis to be performed before such changes are done.

Frequency excursions of the complete off-site power system is a disturbance that cannot readily be mitigated by supplying different trains from the first and the second off-site switchgears since the complete off-site power system is normally synchronously interconnected throughout a country or region. A major frequency dip or increase will hence affect all trains in about the same way when it comes to the supply frequency. However, the voltage deviation that can often be associated with a major frequency deviation may still be different at the two sources, for instance if a large production unit is suddenly lost close to the first off-site source of the unit.

For dual turbine units, with more than one unit at the site and depending on how transmission system and HV switchgears are configured, it might be possible to use alternative connections to the first off-site switchgears. See Figure 8 below. At first the transmission lines must be dedicated only to the nuclear units and not to be a part of an existing transmission corridor in the grid aimed for other purposes. Secondly it is preferably best if the transmission lines are not entering the same switchgear at the remote end but are located to different switchgears with some electrical distance in-between. A disturbance emanating from either of the two transmission lines will then mainly affect two of the four trains but in both of the two units.
Another consideration is that if one of the lines is lost the turbine string that looses contact with the off-site power system has to have a high likelihood to resume house-load operation. A further consideration is that the partial decrease in reactor power that is the result of losing a line is equivalent to about half of the load such that not a line fault leads to higher loss of power than would be the case if one complete unit would be lost. Hence it must be assured that this solution will not lead to a larger loss of production than would be the case with a single unit connected to a single line in order not to stress the off-site power system.
Provided that station A and B are not located too close to each other electrically it is likely that only two of the four trains in each unit will be affected equally by a network disturbance such as a voltage dip or swell. The solution does not require a lot of new equipment to be installed but of course some permanently reconnections in the switchgears are necessary.

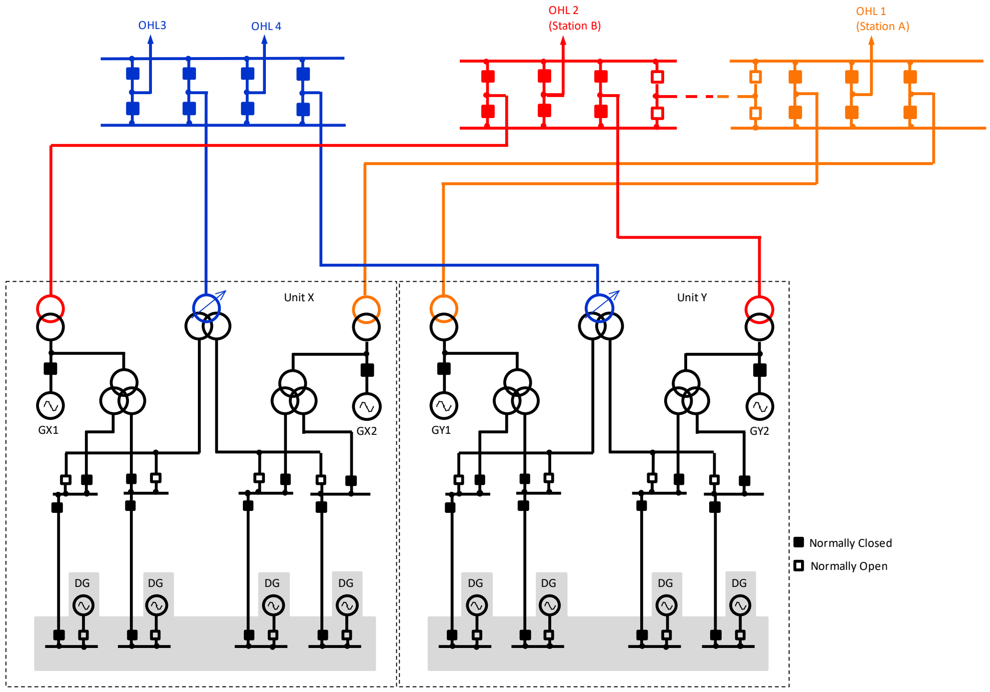

Figure 3. – Schematic sketch showing cross coupling of two two-turbine units.

Other forms of connections can be to add extra station transformers (auxiliary transformers) provided that at least two HV switchgears are available or at least sectionalizing is possible. Then a cross coupling between the units can be established. As shown in Figure 9 one could connect the station service transformer (auxiliary transformer) as an alternative supply to one or two of the safety trains in the adjacent unit which would then require a lower rated apparent power of the extra station service transformers (auxiliary transformers). One or possibly two safety trains are then normally fed from different HV switchgears and it is less likely that all safety trains will be affected in the same way at an external disturbance. There is probably a need for a disconnection/breaking facility on the upstream side of the extra station service transformer (auxiliary transformers) so that maintenance can be done without affecting the hosting unit. Another reason for a breaking device is that a fault on the downstream side (cable to the other unit) can be disconnected without a shutdown of the hosting unit. However, inter-unit dependencies will need particular consideration with this solution.
A corresponding solution with extra station service transformer (auxiliary transformer) connected directly to the HV switchgears as shown in Figure 10 is also possible but of course much more costly as the station service transformers (auxiliary transformers) will have to be designed for high voltage and also since some new bays in the HV switchgears will have to be installed. Still, a similar solution with HV station service transformers (auxiliary transformer) is used for one of the units as shown in chapter 2.1. As the cost will be mostly due to the high voltage rather than the apparent power it is probably no point in choosing the apparent power of the station service transformers (auxiliary transformers) for a too low value. The apparent power could then be the same as the already existing transformers and one could chose to supply one (or possibly two) complete trains

from the extra high voltage station service transformers. It might be favorable to include automatic on load tap-changers on the extra station service transformers (auxiliary transformer) in particular if the hosting unit is out of operation.

Figure 9 and Figure 10 are shown for single turbine units but a similar solution could of course be used on dual turbine units as well.

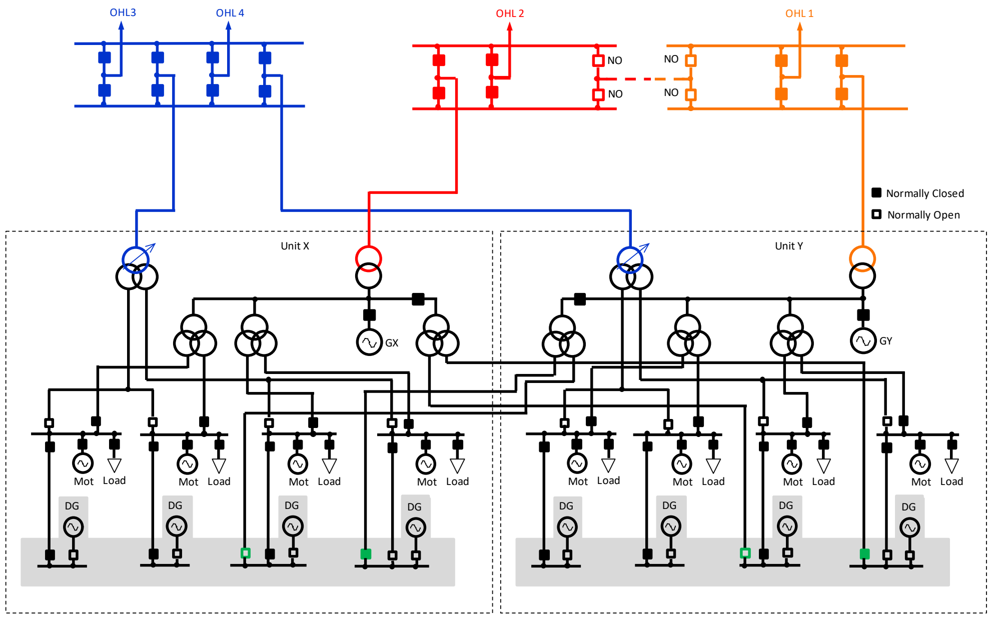

Figure 4. - Schematic sketch showing cross coupling with two extra station service transformers (auxiliary transformers).

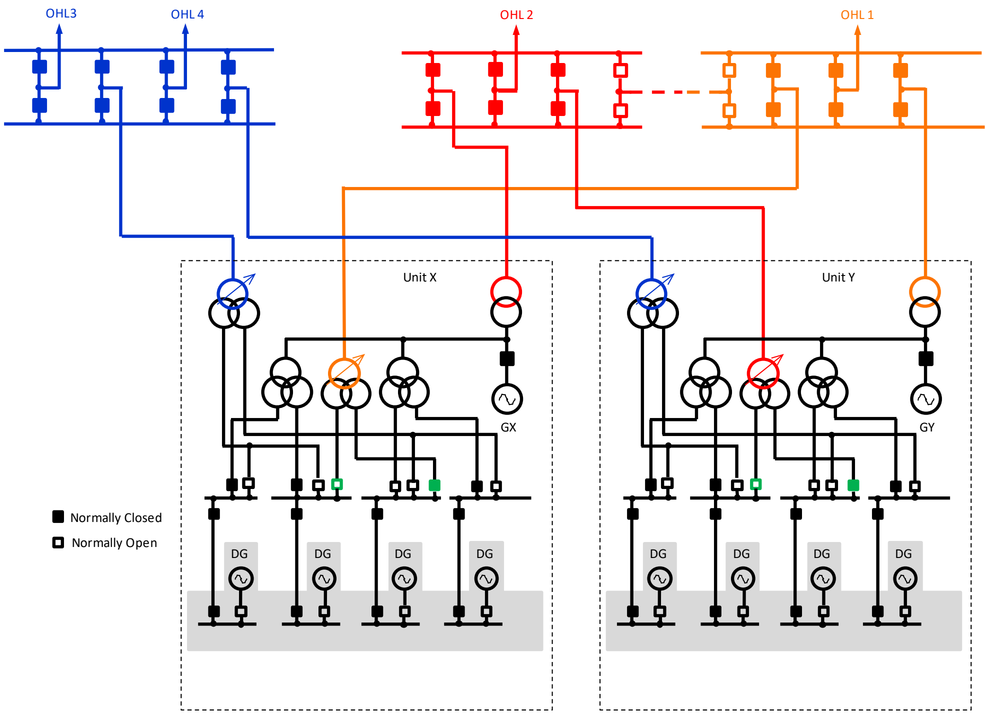

Figure 5. – Schematic sketch showing cross coupling with two extra HV station service transformers (auxiliary transformers).

3.1.2 Considerations regarding disturbances entering the units

In below some prospective solutions are discussed. It shall be pointed out that these are only suggestions in addition to traditional countermeasures such as proper insulation co-ordination (i.e. shielding earth wires, surge arresters etc.) mandatory for nuclear units. Should new protection equipment be introduced it will have to assessed that the equipment do not contribute any new faults modes. Low voltage equipment (such as rectifiers and power electronics) can be sensitive to fast transients entering the unit. The particular needs have to be assessed for the units in concern.

From the single line diagrams in 2.1 it can be seen that the auxiliary power system of all units is fed from transformers and consequently it will be affected by all kinds of disturbances that can penetrate from the external off-site power system into the plant. It is probably not possible to find a single solution with existing transformer supply that could make the units insensitive to all kinds of disturbances. However, if there is a special type of disturbance that one would like to mitigate, it can be possible to find solutions. One example can be transient surge overvoltages that can affect a unit.

Surge arresters are most often installed on the high voltage side of transformers and may often be a part of the transformer delivery. The arresters are likely to be matched with the transformer insulation and often have an insulation co-ordination study been made with the focus on the integrity of the insulation in the high voltage switchgear. However, it is perhaps less likely that the focus of the insulation co-ordination has been to minimize the overvoltages that can enter the auxiliary power system through the transformers. It might therefore be possible to use surge arresters of a higher energy class than may strictly be required from an insulation point of view since the residual voltage (both for switching and lightning) will then decrease. Consequently, also the voltage that can appear over the high voltage winding of the transformer will then decrease.
It might further in some cases be possible to decrease the rated voltage of the surge arrester when a higher energy class is chosen if it can be assured that the temporary overvoltage (TOV) capability of the surge arrester during earth faults can still be kept for the longest earth fault clearing time possible. The TOV capability will generally increase when the energy class is increased.

Additionally, one could also calculate, accurately, the highest earth fault factor (mainly in directly earthed networks) that can actually appear at the plant rather than to use the highest possible value of the earth factor that defines a solidly earthed system (equal to 1.4 times the nominal phase to earth voltage). This may show that a lower rated voltage can be used which also gives a reduction of the residual voltage.

Another way may be to limit the amount of high frequency overvoltage that could penetrate through the transformer. Here especially the capacitive transferred overvoltage of high frequency character can to some extent be affected by the transformer design and of course also by the use of external capacitance such as special protective capacitors. In reality it is the surge capacitance of the winding turns closest to the transformer phase terminals that will be effective in

transferring the overvoltage, see Figure 11.
A rough estimation of the capacitive transferred overvoltage is given in [2],

$U_{T2}=g*h*U_{T1}$

where g is the voltage division of the surge capacitance of the transformer and connected equipment and h is a factor for the superimposed voltage due to the operating voltage. Values of h is given in [2] and depends on the coupling group of the transformer. In [2] also values for g can be found and [3] gives maximum relations of the capacitive voltage division for different primary and secondary voltage values of the transformer.

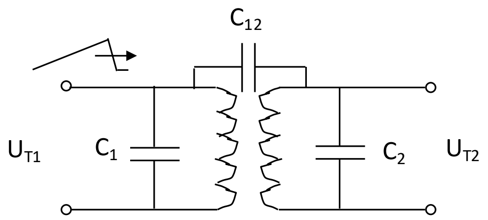

Figure 6. Schematic picture of a transformer for capacitively transferred overvoltage.

The capacitance C_1 and C_2 can according to one transformer manufacturer be varied between quite large ranges of values when designing the transformer windings by means of using different winding designs. For the capacitance between the windings, C_{12}, it is possible to some extent to decrease this value for instance by increasing the distance between the high voltage and low voltage windings. This is however on the account of higher short circuit reactance of the transformer. It might in some cases, if the rated voltages of the transformer windings are not too high, be possible to introduce a grounded screen between the winding to reduce the mutual capacitance. It will increase losses but is claimed to have been used for some designs. It is not unlikely that such solutions could be used for distribution transformers within the plant. It has been reported that at least in one of the plants as discussed in chapter 2, a screen is included for an auxiliary power transformer.

It is of course so that if the transformers are already in place elaborating with transformer capacitances is not an option but it could still be worth considering if transformers are due for replacement.

Surge arresters on the medium voltage side of the supply transformers are indicated on the original single line diagrams for some of the units as described in chapter 2.1 and at least one unit have surge arresters on MV switchgear terminal point. It is probably a good contribution for reducing surge overvoltages. However, as the internal MV system in the nuclear power units is high impedance earthed they will have to be chosen for an earth fault factor of at least 1.73 which requires a correspondingly higher rated voltage. This means a correspondingly higher residual (lightning and switching) overvoltage. A more speculative way of reducing the residual voltage of these surge arresters could be to connect them through a circuit breaker to ground. Then these surge arresters could be chosen with a lower rated voltage and residual voltage value. In case of an earth-fault on the MV system the earth fault protection could trip the circuit breaker associated with the surge arresters in a short time. This prevents thermal stressing of the surge arresters caused by the temporary overvoltage of the earth fault that could persist for a long time.

It is unknown whether surge capacitors are used inside the units except for the generator busducts. If capacitances of cables are low, surge capacitors may be an effective way of decreasing the surge overvoltages of the highest frequencies. A possible place for surge capacitors can be on the low voltage side of the start-up transformers (standby transformers). For this supply route the transformation is just one transformation step from the secondary off-site switchgear. The supply route via the step-up transformer (unit transformer) and the station transformer (auxiliary transformer) will normally limit the capacitively transferred overvoltages due to a double transformation and by the use of already existing protective capacitors on the intermediate generator busducts.

Other ways of decreasing overvoltages arising from lightning is to use shielding earth wires on overhead lines entering the station and to ensure that tower footing resistances are kept sufficiently low if such arrangements are not already in place. Surge arresters are normally always placed close to larger apparatus such as transformers and shunt reactors. But surge-arresters can also be placed at line entrances sometimes in order to use a lower surge protection level of the equipment in the switchgear. However, line surge arrester could also be used to decrease the overvoltage entering the switchgear even though it might not be strictly required for the insulation itself. Using line entrance arresters could hence be a means of reducing high frequency overvoltage that could penetrate into a nuclear unit through its transformers.
Even though it is not perhaps a realistic countermeasure to decrease surge overvoltage it is still worth mentioning that the more parallel objects that are connected to the same switchgear the lower will the overvoltage of the individual objects be. This might be kept in mind for instance if one unit in a plant is going to be dismantled since it might adversely affects the remaining unit(s) if they are fed from the same switchgear. This could for instance be the case with the start-up transformers (standby transformers) which are often fed from the same switchgear (secondary off-site switchgear) should this transformer be removed at dismantling.

3.2 MOTOR GENERATING SETS

In the section below some aspects on motor generating sets (MG-sets) are discussed as this has been one of the tasks with this report. It is intended to look broadly not just limited to nuclear power plants. Therefore a brief overview on railway systems is given as it is the field where MG-sets are still used for higher power applications and where operating experience is extensive.

3.2.1 Application fields of motor generator sets in railway systems (rotary converters)

The probably largest use of motor generator sets above 1 MW is for phase and frequency conversion from 50 - 60 Hz three phase AC to low frequency single phase AC (16 2/3 Hz in Europe, 25 Hz in eastern USA) for electrified railways. To a varying degree also generators in power plants are delivering low frequency single phase AC directly to the railway grid.

Before the arrival of static frequency converters with semiconductors in the mid-70 ties, rotating frequency converters have been the only means to connect the railway grid with the public grid. And still a significant part of the power needed by the railways is converted by rotating frequency converters, the static ones are filling the growing gap due to increased power needs from the railway and decommissioning of old power plants for low frequency.

There are two main types of rotating converters:

1) Synchronous converters with synchronous machines on both sides giving a fixed frequency ratio e g 3 = 50 Hz / 16 2/3 Hz or 12/5 = 60 Hz / 25 Hz.

2) Asynchronous converters, the three phase machine being rotor fed with the frequency difference from the ratios in 1) allowing the grids on both side to have its own independent frequency regulation.

In the asynchronous case, the rotor of the three-phase machine is fed with the slip frequency [4] to give the wanted frequency ratio. The power transferred here is proportional to the slip ratio and is on older machines (machines put into operation before static power electronics were available) produced by auxiliary machines (Scherbius), on newer and refurbished ones by a static frequency converter.

An intermediate between 1) and 2) are synchronous converters with movable stator to adjust the phase, they have been used in USA for 25/60 Hz [5].

The synchronous solution applies for Norway, Sweden, parts of former Eastern Germany and USA east coast, the asynchronous for Switzerland, Austria and a large part of Germany, these three countries have a common 16 2/3 Hz HV grid.

For the synchronous case, the converters have nominal powers in the range 3 – 10 MVA, usually connecting the three phase grid and the catenary, for the asynchronous case, the power varies between a few MVA and ca 100 MVA as most converters are connecting the HV grids on both sides.

Both converter types are perfectly suited for reverse power flow, e g due to braking trains or, in the asynchronous case, also for deliberate power flow control between the grids, e g optimising the power cost and selling transmission capacity. In some cases, the utilities in Sweden and Norway do not want to handle reverse power flow, in this case the converters are controlled to not reverse the power flow, but this can easily switched off if the rules are changed. Static frequency converters for power flow in both directions have for the mostly used DC-linked type to be equipped with more power electronics (AC to DC to AC), at many locations this additional expense is omitted, stopping the possibility of reversed power flow. Direct converters, both of the older type and the new multimodal design, are intrinsically capable to reverse the power flow.

Pump storage plants are based on easy power flow reversal and are also in use in the railway power grid in Germany [6].

Intuitively one would assume that a rotating machine with its moving parts, especially slip rings and brushes, is less reliable than static converters, but in reality the static converters are less robust and do not have the large overload capacity of the rotating machines. And new technical solutions with brushless magnetization and rewound windings for generation of catenary voltage 15 kV without step-up-transformer result in rotating converters with lower failure rate than static converters [7]. The efficiency of a 5.8 MVA converter converted to 15 kV stator and brushless magnetization increases from 90 to 94 % at full load. Its overload capacity has increased from 6 min at 150 % and 1 min at 200 % of nominal power to 30 and 6 min respectively. Modern rotating converters are also proposed as alternative to static converters, [4] shows a proposal for a 60 MVA 60/25 Hz converter having > 96 % efficiency. More about the efficiency is found below in this text.

As a special case, the hydro power station Pfrombach in Germany [8] had an arrangement of 50 Hz Generator, several Francis turbines, 50 Hz rotor fed machine and 16 2/3 Hz machine on the same shaft which allowed for many different combinations of power flow, from hydropower and from and to the both AC-grids, see Figure 12 below.

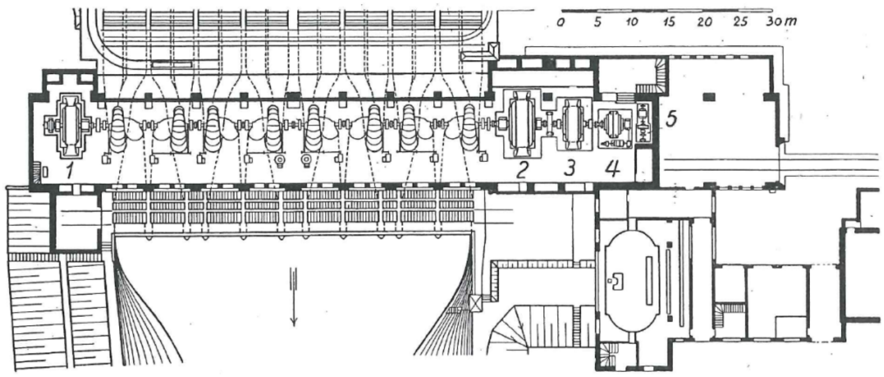

Bild 1. Maschinenanordnung des Kraftwerks Pfrombach. 1 Drehstromsynchrongenerator 17 500 kVA 50 Hz. 2 Einphasensynchronmaschine 20 000 kVA $16^2/_3$ Hz. 3 Drehstromasynchronmaschine 17 500 kVA 50 Hz. 4 Erreger(Schlupf)maschine (mit der Hauptwelle gekuppelt) und Hilfserreger- und Netzerregermaschinen (über 2 Kegelradgetriebe von der Hauptwelle angetrieben). 5 Ersatzerreger- und Anlaßaggregat.

Figure 7. – Overview sketch of combined power plant and converter station (Figure extracted from [8])

This opens for arrangements as [1] in 3.2.2 with both rotating machines and combustion engine on the same shaft.

One major reason to maintain a certain proportion of rotating converters in the railway context is that they contribute to rotating mass, while static converters do not. Rotating masses give higher stability and ride through capability for short power outages. The railway converters are comparatively heavy with high inertia mass which in this context is an advantage.

As the low frequency electrified railway is the major user of large rotating converters, the accumulated experience there is of high value for other presumptive users as nuclear power stations. In Sweden, there are two workshops for maintenance of rotation converters, TGOJ in Åmål, now Euromaint and ABB Service in Luleå, now Luleå Generator Service [9]. The change to 15 kV stator for 16 2/3 Hz and brushless magnetization was performed by VG Power [12].

The synchronous converters are mobile on railways which make this central maintenance possible simply by moving them on the railway instead of repairing them on their location.

The larger synchronous converter types will not be obsolete in the near future, but the smallest ones (Q24) with ca 3 MVA are gradually withdrawn due to their low power. In the context here, perhaps 3 MVA are a very convenient size? Maybe one may think to split two Q24 and reunite the 50 Hz machines from both on a common shaft to a 50/50 Hz synchronous converter. This should be checked up soon before the decommissioned converters are scrapped. First contacts to TrV gave encouraging answers, the idea seems viable. A big challenge is to get some information on the costs, see below, a guess is that a new rotating converter would be more expensive, but a converter based on part of converters for railway use at scrap prize may have a reasonable price tag. If large power is needed, one also can look for scrapped 10 MVA converters (Q48 copies) from NE-Germany, but here both the Norwegian and the Swedish railway are concurrent buyers. There is also a third size with 5.8 MVA, the Q38 converter, but they are all used and will remain in use, parts of them modernized with brushless magnetization and 15 kV rewound stator on the single phase side. And then we have the Swedish and Norwegian railways own 10 MVA converters of type Q48 which all will stay in use. If re-used railway MG-sets are considered for use in nuclear power plants one have to take notice of safety qualification requirements (e.g. seismic).

A very crude prize guess for a converter built from two 3.1 MVA converters of type Q24 [10] by combining their 50 Hz engine on a common shaft is about 5 MSEK or 1,7 MSEK/MVA, using pessimistic assumptions [12]. Here also an introduction of brushless magnetization is included as it makes the engine much more reliable. The experiences with that at the Norwegian and Swedish Railways are very good [12]. The maximum efficiency of this converter based on old material will be about 92 % (estimate based on assuming 50 Hz three phase losses as ½ of the 16 2/3 Hz single phase losses and 88 % efficiency for the original converter). Thus 8 % losses have to be capitalized for comparison with new rotating converters and static converters. The weight of a Q24 converter with its own railway wagon is 85 ton, two 50 Hz halves without wagon should be lighter than that, perhaps 50 ton. The weight of a Q38 is 102 ton, of a Q48 138 ton. The maximum efficiency of a Q38 is 91 %, approximately 94 % for the 50/50 Hz version giving 6 % losses to capitalize, for the Q48 94% respectively 96 %, giving 4 % losses [10].
Figure 13 shows the efficiency of a Q24 converter with a shallow maximum near the rated power.

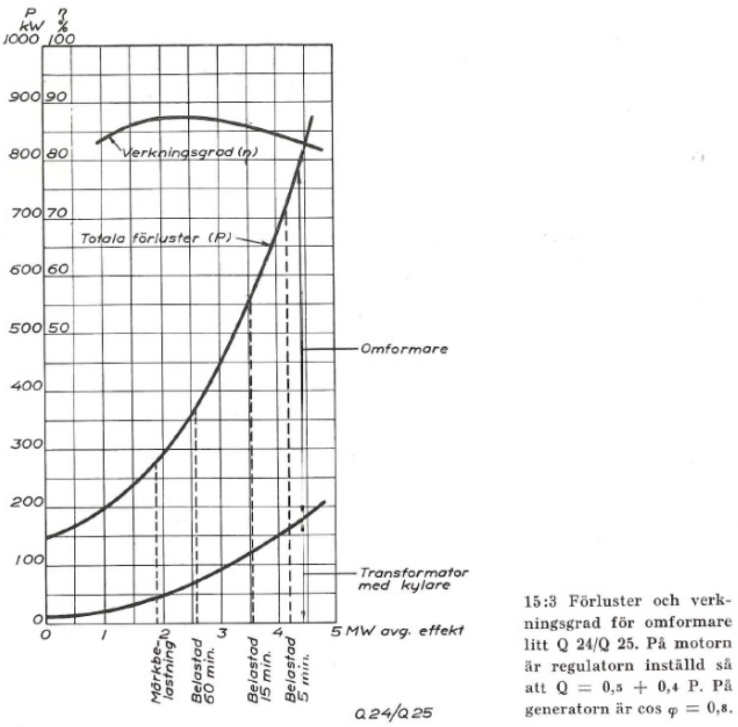

Figure 8. - Losses and efficiency of rotary converter Q24/Q25 (Picture extracted from [10])

The curves for the other converter types Q38 and Q 48 are similar with even shallower maxima. When knowing the actual power and its variation in an actual case, from these curves better predictions for the losses can be made. Due to the shallow maxima, accuracy for the power is not that critical.

All converters have a considerable overload capacity. The 6 min overload is 4.8 MVA for a Q24, 8 MVA for a Q38 and 14 MVA for a Q48. For 1 minute they can deliver about the double rated power and for short power dips, the inertia of their large rotating mass (two rotors + axis) gives a ride through capability already without additional flywheel. The moment of inertia of a Q24 is 8500 kgm^2 for both rotors together. This corresponds to an inertia constant H= 3.76 MWs/MVA (referred to the 50 Hz system).

The single phase rotor is somewhat heavier than the three phase rotor, thus for a rebuilt converter with two 50 Hz rotors, the inertia moment is expected to be 10 – 20 % lower. No electrical transient can pass over between the two sides of the converter, the only shared property is the through the shaft transmitted active power. On both sides, reactive power can be generated or consumed at wish by proper magnetization. Thus the converter can be an active part in handling reactive power on both sides.

For all converter types, the voltage on the 50 Hz stator is 6.3 kV, a standard voltage for which transformers should be easy to fix. Otherwise, the rotor can be rewound for the voltage wanted.

The power stations in question have no railway connected which would have made the transport of the converter an easy task. But still the limitations of the railway load gauge give the converter a compact size and the railway wagon a good frame for mounting of the converter at place. The rotating converters are usually run in parallel with several others in railway feeding stations. Thus, if e g the power needed is about 6 MVA, two Q24 can be used in parallel. All types of converters (Q24, 38, 48) can be run in parallel as their characteristics are similar.

Should re-built railway converters be used in nuclear power stations they are likely to be installed outdoor or in special building due to their weight.

The Q24, 38 and 48 are followed by a transformer wagon with among others a starting transformer, reducing the starting voltage from 6.3 to 2.2 or 2.6 kV for a softer start.
The east German 10 MVA machines, otherwise being copies of the Swedish ones, do not have that “luxus”, they are delivered without transformer wagon. The converter is in both cases started from the 50 Hz side with eddy currents in the massive poles instead of damping windings (which are found on the single phase side).

Regarding the starting of asynchronous motors with converter fed slip ring rotor, as used for instance in Germany, one starting method is described in [14]. At starting the stator (at that time disconnected from the grid) of the asynchronous motor is short-circuited and the rotor through the slip ring is supplied through the converter. The machine is accelerated up to about 180 rpm (full speed is 500 rpm). The converter is then disconnected from the motor and connected to the (1-phase

16 2/3 Hz) generator stator and the machine is brought up to little more than full speed and then synchronized on the 50 Hz side.

A more speculative new type of rotating machine is the “Written Pole Machine” WPM where the rotor poles are imprinted, “written”, by magnetization windings in the stator giving large flexibility [11].

3.2.2 Motor generator setups/applications from literature

Motor generating sets have been utilized in the past in many different configurations. In [1] a system is described that in its function is fairly similar to a modern UPS. It constitutes of an induction motor, a synchronous generator, a flywheel, a magnetic clutch and a combustion engine. See, Figure 14 below.

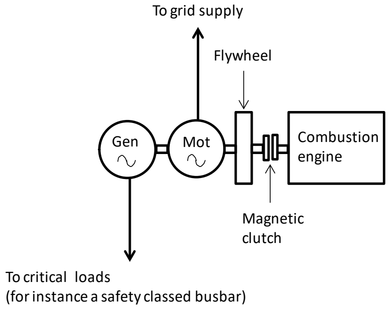

Figure 9. – Principal sketch of a combined MG-set and combustion engine

In the description of reference [1] the important aspect of total isolation of line transients from the grid, long periods of grid power outages and uninterruptable power supply is claimed.
Looking into the different components the generator constitutes of a synchronous generator (with independent supply similar to a brushless exciter). The motor used here is an asynchronous machine of the squirrel cage type. This means that the when the electric motor is driving the generator the output frequency will be slightly less than synchronous frequency. In the application it is described that the motor is designed to have a maximum slip of 1% at full load to minimize the deviation from the synchronous frequency.

The flywheel is continuously connected to the electric motor and generator. The flywheel has in this application two purpose; one is to smooth out short term disturbances in the power system supply voltage, hence energy is delivered from the flywheel to the generator which will protect the loads connected to the generator from these disturbances. The second purpose of the flywheel is, if the supply of the grid disappears, to deliver energy in order to crank and start the combustion engine and to maintain energy delivery to the generator. This will dimension the flywheel depending on how much the frequency is allowed to decay and how long time it will take to start the combustion engine. The starting of the motor appears to be initiated by low voltage criteria in any of the phases (90-95%) which initiates the clutch to connect the flywheel to the combustion engine. The energy for the magnetic clutch is taken from the generator. Should the grid supply voltage remain below the low voltage criteria the combustion engine will now supply the generator. Should the voltage of the grid come back to a level above the required voltage criteria the switch over to the electrical motor supply will be delayed (approx. 15 minutes) to let the power system supply stabilize and not to have repeated combustion motor starts transferring back and forth between electric motor and combustion engine supply. The delay is also used to assure a 15 minute warm up period of the motor after each start.

In the application as a flywheel is utilised the combustion engine is also used to start the unit from standstill. The reason claimed for this is that a start from the electric motor will lead to a prolonged time of inrush current during starting. The unit is started with an inertia starter through a speed increasing gear box attached (which is manually initiated) to the generator exciter shaft. When the speed is sufficient high (less than normal speed) the magnetic clutch is energised (through battery supply) and the combustion engine is started through the flywheel. The unit is then brought up to full speed by the combustion engine and electric motor is connected. The combustion engine is disconnected through the clutch and stopped.

One application for this set is claimed in [1] for supply of microwave relay sites, often situated in remote site where reliability requirements are high.

Naturally, within reasonable voltage levels, there is no need for a transformer and the voltage of the motor and the generator does not have to be the same. The voltage can then for instance be on medium voltage level for the motor and low voltage level for the generator, unless of course a direct by-pass of the unit is considered necessary.

A limitation mentioned in [1] is that it is not recommended to run units in parallel because should electric supply fail to one of the units the two generators may not be kept in synchronism when one of the unit is starting its combustion engine.

A unit like this could for instance also be used as an extra source of on-site standby supply, perhaps as a back-up for a part of the load of an ordinary diesel generator in a nuclear power plant.

Unfortunately, not so much more of modern literature regarding motor-generating sets has been found apart from some railway application articles (see previous section 3.2.1.). This is probably due to the fact that static solution is nowadays the dominating solution for conversion.

3.2.3 Motor generator sets used in the Finnish and Swedish NPPs

With reference to the plants in chapter 2, two units in one plant and two units in another plant utilise motor generating sets.

In the first plant, two units are equipped with MG-sets and they are used in UPS systems feeding un-interruptible AC busbars in the safety-classed trains. The UPS at those units consists of a static rectifier which feeds both the DC batteries and the inverter that feeds the MG-set. The MG-set itself is a combined synchronous motor and synchronous generator including a brushless excitation and a pony motor which is used to start the rotating parts. This pony motor is supplied from the AC

on-site grid but can also be supplied through the batteries via an inverter for black-start purposes.
Regarding operating experience two equipment failures shortly after commissioning of the UPS have been reported. They are told be caused by inadequate components or design. Due to the failures the UPS were rebuilt by the supplier. Other operating experience is that some earth fault supervision units related to the UPS has been replaced. A part from this the operating experience with UPS is reported to be very good.

In the second plant two units have MG-sets in UPS in safety classed systems. The size of the generator machine is given to be 125 kVA. The MG-set connects a DC busbar with a 400 V AC uninterruptable busbar. The DC busbar is connected to batteries and is normally supplied through static rectifiers from a safety classed AC busbar. The MG-set is always running (except when unavailable). The motor of the MG-set is a DC motor of the shunt field type. The starting of the MG-set is done from the DC side through starting resistor and the DC motor is accelerated to its rated speed without any load on generator side. The MG-set is synchronised on the AC with the spare supply. The speed control is told to be on the motor DC side. The DC motor is dimensioned for operation down to -15% of the battery voltage. It is unknown whether the motor or the batteries sets the limit for low voltage operation. The generator is equipped with a PMG fed brushless excitation.
The losses of the UPS are given to be about 20-30% depending on the load power. It has not been possible to get any information of the cost for MG-set or cost for maintenance.

The reported operation experience with MG-set tells that they have been working very well taken the running hours into account. Some previous problems reported have been related to vibrations of the MG-set which has been overcome with modification of the beddings of the sets. Some operating experience is also reported with respect auxiliary relays associated with MG-set caused by ageing and small crawling of the generator voltage regulator. Hence, no common cause failure with respect to network disturbances has been reported for these MG-sets.

In addition, the plant also has another MG-set which is connected to one of the medium voltage (non-safety) classed busbars. The MG-set is used as back-up supply for the excitation system of the main generator. However, no further information about this set has been revealed.

3.2.4 Motor generator sets used in other NPPs

A nuclear power plant (outside Finland and Sweden) is reported to use MG-sets. Two different kinds of MG-sets are told to be used in that plant.
The first type of MG-set is having a low voltage three phase motor driving a single phase generator. The generators supplies power to the protections circuits of the reactor. The MG-set is using a flywheel for inertia purpose.

The second type of MG-set has a three phase medium voltage motor which is driving through a hydraulic coupling a three phase generator. The generator supplies electric power to the reactor re-circulation pumps. The excitation system is using a rotating DC generator for it supply and the excitation system is designed to control ratio of the voltage to frequency.

3.2.5 Aspects on the electrical machines of the MG-set

For most of the cases the generator in the MG-set is likely to be a synchronous machine such that the voltage can be controlled on the supplied busbar and that sufficient short circuit power can be delivered for instance for motor starting purpose and for fault current contribution sufficient for existing protective relays. The motor type however may depend on where in unit or the plant the MG-set is located and what is requirement of the MG-set. Hence the motor can be chosen more freely. It is therefore worth mentioning that principally many alternatives can do the about the same job. Such alternatives are; the directly connected synchronous motor, the squirrel cage asynchronous motor with or without frequency converter, the slip ring asynchronous motor, and the rotor converter fed slip ring asynchronous motor, converter fed DC motor, frequency converter fed permanent magnet motor, etc. Some of these alternatives may be less feasible for larger power (as DC machines or PMG drives often practical limitations in power) or due to that they require equipment in series that possibly could reduce robustness (for instance frequency converter squirrel cage asynchronous machines). Some of the more likely choices are discussed in section 3.2.8.

3.2.6 Efficiency

Efficiency of conventional MG-sets depends on the type of electrical machines used. If synchronous machines are used both as motor and generator (stand alone electrical machines) the efficiency would approximately be the product of the efficiency of the two machines although the exciter and PMG machines will reduce the efficiency further a bit. Numerical values will depend on the MVA rating of the unit. Large size synchronous machines (~30 MVA) may have a typical full load rated efficiency of 97.5-98.5% which would then yield a total MG-set efficiency of 95-97%. The efficiency is likely to depend on the number of poles chosen and with many poles it tends to decrease somewhat. Too high or too low rated voltage in relation to the rated MVA size may decrease the efficiency. Partial load efficiency of a synchronous machine of the same size is lower and a typical value at 25% of rated load may be 96-97% which would result in approximately some 92-94% efficiency for the MG-set. If the MG-set is primary used to supply loads within a nuclear power plant it is not unlikely that one can accept $\cos\varphi=1.0$ (power factor) which means zero MVARs exchange with the feeding off-site power system. A higher power factor means somewhat lower losses perhaps in the order of 0.1-0.3 % compared to a rated power factor of 0.9-0.85 p.u.

Smaller synchronous machines (~0.5-2 MVA) may have a typical efficiency of 94.5-96.5(97)% provided that the speed is not too low and that the voltage is not too high (say smaller machines with a rated speed less than 500 rpm and rated voltage above 10 kV). This would give a rated load efficiency of 89-93% for a MG-set. Again partial load efficiency for a single synchronous machine is lower and at 25% of rated load it may typically be in the range of 90-94% resulting in a MG-set efficiency of 81-88%.

Squirrel cage induction machines as the driving motor may be an option provided that one can accept a lower than nominal frequency on the generator side. However, with an induction machine the power is perhaps limited to below some 10-15 MW if standard designed machined are to be used. Smaller sizes of squirrel cage induction motors may still have quite high full load efficiency. Typical full load efficiency for a 500 kW (high efficiency class) motor can be some 96-96.5% (2-8 pole machines). Larger induction motors (>5000 kW) of medium voltage type may have a full load efficiency exceeding 97%.

Regarding converter slip ring fed asynchronous machines it is more difficult to give efficiency as it also includes the converter and possibly a converter transformer. The efficiency of the slip ring fed asynchronous machine itself compared to a squirrel cage asynchronous machine appears to be about the same at least for larger motors (>5000 kW). The total efficiency should however be somewhat lower due to the converter losses.

One supplier of rotating MG-set offer a solution with a connection from the AC power grid with a coupling choke (some kind inductive coupling transformer or similar) which is the main supply. In parallel with this is a synchronous motor-generator set with a common stator (for both motor and generator) and a single brushless rotor (for both motor and generator). The motor generator is acting in parallel with the coupling choke and enables voltage control. The motor generator also has the possibility to connect through a clutch to a diesel engine. It is also claimed to have the provision to use a dedicated flywheel generator or batteries to supply the motor through a converter to override supply failures of the supplying grid and to let the diesel engine start. It is said to have a very high efficiency of up to 97%. This perhaps due to the fact that most of the power goes through the coupling choke and that only one stator and rotor is present in the MG-set. In addition it is also claimed to have low harmonics on the output due to the low short-circuit impedance and effective damper winding of the combined rotor.

Some comments to this technique is however that it cannot be seen at classic MG-set as the motor generator is in fact not a separate electric motor and separate electric generator where a full electro-mechanical transformation occurs. Magnetic coupling is present in this combined motor generator set (virtually a synchronous machine with two separate stator windings) as well as in the coupling choke. For instance an unbalance in the supply will to some extent be coupled by the stator and is likely to be seen also on the generator side.

3.2.7 Inertia

The moment of inertia (J) of the electrical machines of the MG-sets is depending on which type of machine that is used. Normally the moment of inertia is related to MVA rating of the machine taking the rotational speed into account defining inertia constant as

$$H = \frac{0.5 * J * (2 * \omega_s / N_p)^2}{S} \text{ [MWs/MVA]}$$

where ω_s is the synchronous angular speed, N_P is the number poles and S is the rated apparent power.

Standardised horizontal synchronous machines in the power range of 1500-5000 kW may typically have an inertia constant of H=0.15-0.4 MWs/MVA depending on the frame size and also on the speed of the unit. This means that for a total set based on two synchronous machines for both motor and generator the inertia of the total MG-set should be doubled, i.e. resulting in H=0.3-0.8 MWs/MVA. For the synchronous machines the inertia will be somewhat higher provided that the machines are fitted with brushless excitation (exciter and PMG machine).

For asynchronous squirrel cage motors of about the same power size the inertia constant seem to be about the same as for the synchronous machines. Slip-ring fed asynchronous machines of the same power range of 1500-5000 kW will give slightly higher inertia than squirrel cage machines typically in the range of 0.4-0.6 MWs/MVA.

Larger (horizontal) synchronous machines in the range of 30-50 MVA may have an inertia constant H=0.7-1.0 MWs/MVA (4-6 pole machines). For larger designed type synchronous machines it is sometimes possible (within reasonable limits) to alter the inertia when designing the machine.

For MG-sets using a synchronous machine as motor one important aspect is that the inertia is sufficiently large that the synchronous motor will not lose synchronism when a fault appears on the supply side. Most often this can be considered to be a fault on the HV side of the step-up transformer (unit transformer) or the HV side of the start-up transformer (standby transformer). However a fault on a parallel object, connected to the same busbar as the MG-set, disconnected by its ordinary short circuit protection should also be a case to consider. The inertia is of course not the only parameter determining if the MG-set will stay in synchronism or not, reactances of the machine and excitation system performance is important as well.

The inertia is important in minimizing the impact of faults in the off-site power system as seen on the load side of the MG-set as well. With sufficiently high inertia of the MG-set the fault ride trough can be improved.

As an example of the impact of the inertia a simplified simulation has been performed. The example shows the speed variation and the mechanical power delivered to the generator of the MG-set. It has been assumed for simplicity that the load of the generator in the MG set can be represented by constant mechanical torque. The example shows the impact of inertia both for a synchronous motor and a squirrel cage asynchronous motor. The motors used have typical electrical data in terms of reactances, resistances and time constant and has the same apparent power
(2 MVA). In the simulation it has been assumed that the mechanical power delivered to the generator is the same. As the asynchronous motor is operating at asynchronous speed the mechanical torque required is consequently larger. The initial operating point in terms of delivered mechanical power in the simulation is equivalent to slightly less than half the apparent power (0.476 p.u.). Further regarding the synchronous motor, for simplicity reasons, it has been assumed that the field voltage is kept constant with a zero exchange of reactive power to the feeding off-site power system. The system is perturbed with a 3-phase short circuit

applied on the busbar that feeds the motors. The fault is cleared after 100 ms and has a fault resistance such that voltage drops down to about 20% of the nominal feeding voltage during the fault. A short circuit power that is "normal" for an operational medium voltage busbar has been used. The inertia constant has been varied between 0.5-8.0 MWs/MVA. In the simulation parallel loads are present as well.

Figure 15 and Figure 16 below shows the speed and the mechanical power delivered to the generator. It can be seen that the inertia constant has a considerable impact on the speed and mechanical power delivered to the generator. Further it is noticed that the synchronous motor gives a more oscillating character at a disturbance compared to the asynchronous motor. It can be noticed that for a low inertia (H=0.5 MWs/MVA) the speed and mechanical oscillation are quite large and would to some extent affect the load side. For an inertia of 4.0 MWs/MVA the lowest speed will still be within the limits the plant shall continuously cope with according to [17]. It is likely that an MG-set with this magnitude of inertia could cope with many of the "normal" disturbances in the off-site power system without any severe impact on the loads of the generator side. It can further be noticed that the inertia of the railway converters (Q24/Q25) as described in chapter 3.2.1 has a comparable inertia of H=3.76 MWs/MVA which has proved to give satisfactory operation experience.

With even larger inertia, H=8.0 MWs/MVA, the disturbance in speed and mechanical power is insignificant. However, it shall be noted that such large inertia can hardly be accommodated within the electrical machines themselves using "natural" MVA ratings. Hence if very large inertia is used it will be a machine that is over-dimensioned in form of its "natural" MVA rating or it will be an MG-set using a flywheel to increase the inertia.

For the synchronous motor the use of an automatic voltage regulator will in reality improve the conditions which can contribute to increase synchronising torque and to decrease the oscillations during a disturbance.

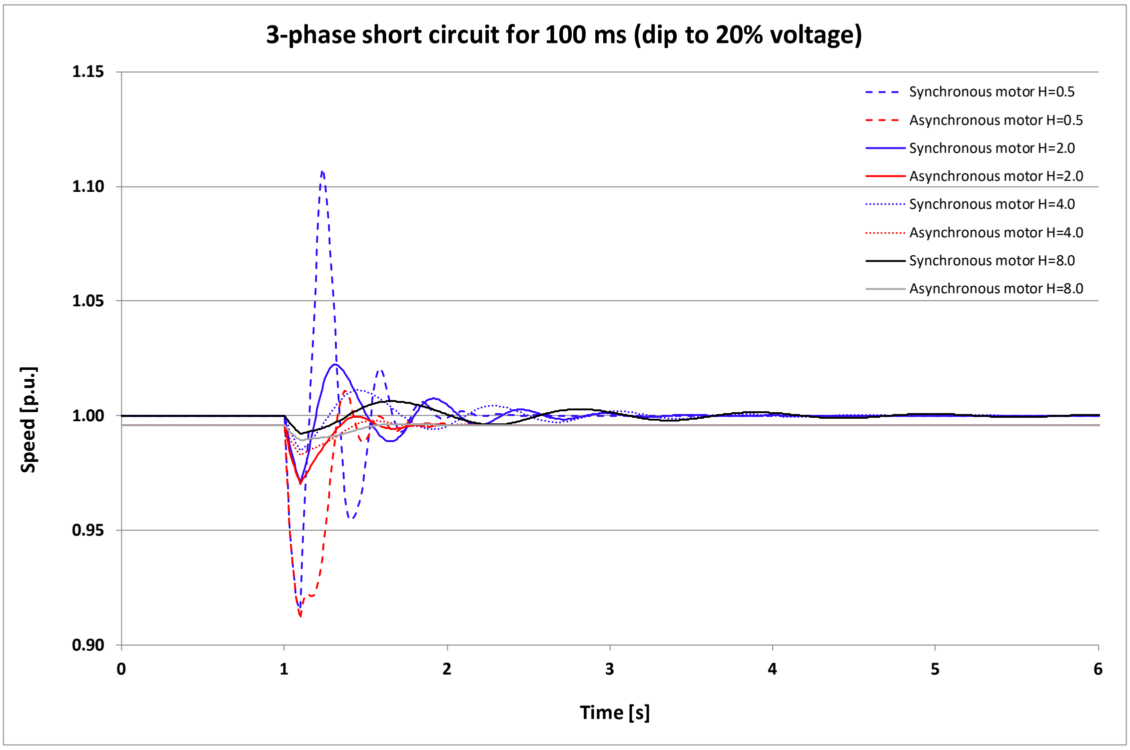

Figure 10. – Speed of motor as function of inertia.

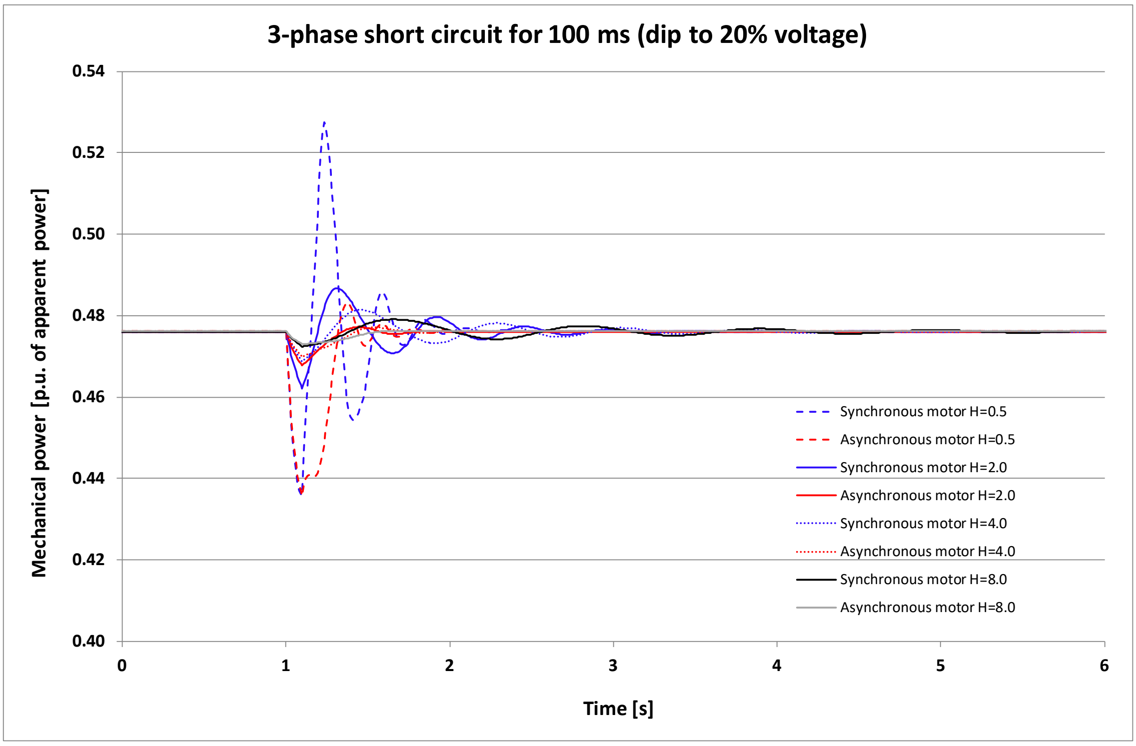

Figure 11. – Mechanical power of motor as function of inertia.

The disadvantage of using high inertia is mainly at starting, in particular if the MG-set is directly started. Higher inertia will proportionally increase the starting time. Long starting time will decrease the voltage for other objects fed from the same busbar during a longer period of time. Another aspect of high inertia is that it will also affect the weight of the MG-set, this may be an important aspect to consider in existing nuclear units where restrictions on weight and volume are present.

A direct on line start of an asynchronous motor has been simulated (the same motor as used above). In Figure 17 below the speed of the motor and the voltage on the feeding busbar are shown for the different inertia values of the asynchronous motor. The object (MG-set) is started without any mechanical load presuming that the generator is not loaded until full speed is reached.

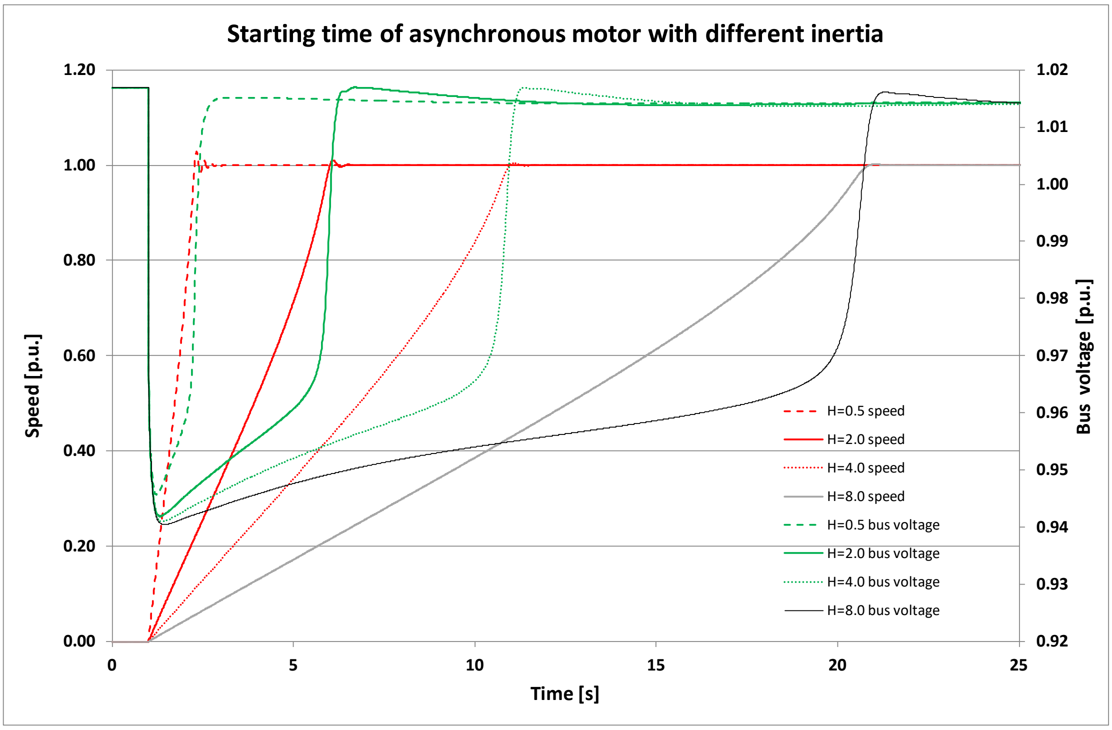

Figure 12. – Speed of asynchronous motor and busbar voltage at direct on line starting.

It can be seen that the starting time of the MG-set depends proportionally on the inertia. For inertia of up to H=2.0 MWs/MVA the starting time is approximately in the vicinity of what other already existing motor objects have in normal starting time (with nominal voltage) and should not considerably affect the behavior of the plant. The voltage drop is not considerably high and should be acceptable. Other larger motor objects in the units are expected to give even larger voltage drops. With an inertia constant of H=4.0 MWs/MVA the starting time is about 10 s. This starting time could probably be accommodated by the motor because it is in the same order magnitude as the time indicated when starting an asynchronous motor with with quadratic torque speed characteristic of the load equivalent to a final load of 90% of the machine rating (as given in a catalogue from one motor manufacturer). A starting time of 10 s may be an important time to keep because it is normally the maximum allowable time required for an emergency diesel generator to start and pick-up load. Hence, if the MG-set is connected between the operational and the safety classed busbars it will have a chance to be started before the emergency diesel generator pick up the load should the supply voltage disappear. In practice however the starting time of diesel generators (the time to pick-up load) is often shorter than 10 s so it might be that MG-set will have to comply with a shorter staring time to avoid that the diesel generator will be connected instead of the MG-set.

For a high inertia of H=8.0 MWs/MVA it is questionable if the motor itself can withstand this high starting current for so long time. Should a high inertia like H=8.0 MWs/MVA be required it is likely that some other starting method as for instance reduced voltage (auto-transformer start or equivalent) will have to be used. This will of course increase the starting time further but reduce the current to acceptable levels.

Starting synchronous motors could also be done in form of direct on line start (asynchronous starting). The design of the rotor in form of solid poles with or without damper bars (or even laminated poles with damper bars) and the use of discharge resistors in the field will all affect the torque during the starting process. The starting time will therefore vary depending on the design of the motor. It is perhaps likely that the starting time will be somewhat longer for a synchronous motor compared to an asynchronous motor as the synchronous motor will have to be synchronised applying the field voltage before it can pick-up load.

3.2.8 Where in the nuclear plant to use the motor generator sets

There are several places within a plant or a unit where motor generating sets could be placed depending on what is going to be achieved. The main objective for using MG-sets here independent of where they are placed is to break up the electrical connection between the outer power system and the auxiliary power system in various degrees. It serves to decrease the risk that disturbances emanating from the power off-site power system shall affect the complete auxiliary power system.

In Figure 18 below some locations (electrically) within a unit is shown. At least four different locations can be found denoted A-D corresponding to existing solution with transformers A'-D'. It is of course so that only one of these locations is chosen at time. In Figure 18 two trains are shown with conventional transformer solution and two trains is shown with MG-sets. The choice on how many of the trains that should be equipped with MG-sets is an open question. Two trains as shown here may be a balance between investments and the advantageous of having a full electromagnetic isolation of more than one train. All trains equipped with MG-set will increase investment cost and probably increase maintenance cost as well compared to static solutions. There is always a risk of common cause failure using the same solution in all trains, for MG-sets perhaps a higher risk of failure due to seismic impact compared to a transformer solution could be expected as rotational parts are present in MG-sets. Hence MG-sets in all trains are probably not the best solution.

The first solution A corresponds to the station service transformers (auxiliary transformers) A'. This solution will then have one motor and two generators supplying two trains. In reality this solution is perhaps less likely as it will be an expensive solution but it decouples two trains completely from the off-site power system and it also decouples the two trains from each other electrically. On the generator side, a synchronous generator with a brushless PMG excitation would be the most likely choice. Exact and independent voltage regulation could then be achieved for each train and it is not unlikely choosing the generators with sufficiently low reactances that starting of large objects within a train could be done with even smaller voltage dips affecting parallel loads than what can be achieved with a conventional transformer solution. On the motor side one alternative is a synchronous motor with brushless excitation PMG. Starting of a synchronous motor will probably have to be done with reduced voltage through a starting transformer or frequency converter or possibly a pony motor. Direct asynchronous start of larger synchronous machines as will be the case here substituting a station service transformer (auxiliary transformer) (up to about 60 MVA) will probably cause too high voltage drop especially if other transformers are connected to the same generator busbar.

Another solution is to use a converter fed asynchronous slip ring motor. With reference to [4] it is told that for railway supply, rotary converters with asynchronous slip-ring motors of up to 80 MVA are in operation. Even larger units of up to 400 MVA such as in pump storage plants have asynchronous slip ring motors with rotor converters
[13]. In such a pump storage plant it is possible to adjust the speed and have the same stator frequency, this is also what is used as a standard solution in wind-

turbines (double fed induction generators DFIG), hence they are frequency elastic systems. One distinct advantage of using a slip-ring asynchronous motor with a converter in the rotor circuit is then that it is possible to use this elastic feature in the “opposite” direction i.e. if the network frequency changes (within reasonable limits) it is still possible to keep the speed constant. This means, at least in steady state, that the generator supplying the auxiliary power supply can also be decoupled from the off-site power system in terms of frequency. Starting of the asynchronous slip ring motor could probably be arranged using variable starting resistors. With high resistance in the rotor circuit during start the rotor current will decrease and consequently the stator current.

Irrespective if a synchronous motor or an asynchronous converter fed slip ring motor is used the motor when placed at A will have to be built for the same voltage as main generator which is probably far from optimal for a motor of this size. A breaker is also necessary for synchronizing and disconnection possibilities. It will however be difficult or even impossible to find a circuit breaker that will be able to break a prospective fault current from both the main generator and the generator step-up transformer (unit transformer).

The second solution denoted B will be of the same MVA size as solution A if the MG-sets are going to be operated continuously when supplied from the secondary off-site switchgear although at some units the starting transformer (standby transformer) is somewhat different in MVA rating compared to the station transformers (auxiliary transformer). It will also likely have the same possibilities with respect to choosing the type machines in the MG-set.
With the B solution a transformer is required to bring down the voltage from the secondary off-site switchgear and for this reason voltage can be chosen freely suitable for the required MVA rating, perhaps with the same voltage for the two machines. This may be favorable in terms of maintenance and spare parts. As anyhow a transformer is required from the secondary off-site switchgear a third winding can be incorporated as well with a suitable reduced voltage for starting purposes. This is shown with dotted lines in Figure 18. Supplying operational trains from the MG-sets may be beneficial as voltage dips and swells can be reduced in particular if the inertia of the MG set is high enough. Some equipment in the operational trains may be sensitive to interruptions as for instance the frequency converter main circulation pumps in BWRs. The inertia of the MG-set will add to the already existing energy storage as often included in such converter systems.
If the main purpose is to supply only the safety trains through MG-sets a direct connection to the safety buses from the two generators is also possible. This solution will considerably reduce the MVA rating of the MG-set. This is shown with dashed lines including also transformers to the safety buses (here as low voltage). However these transformers can of course be omitted if a suitable lower generator voltage of the MG-set is selected. Further as the MVA rating will only correspond to two safety trains a direct on line start of the motor (synchronous) is within reach.

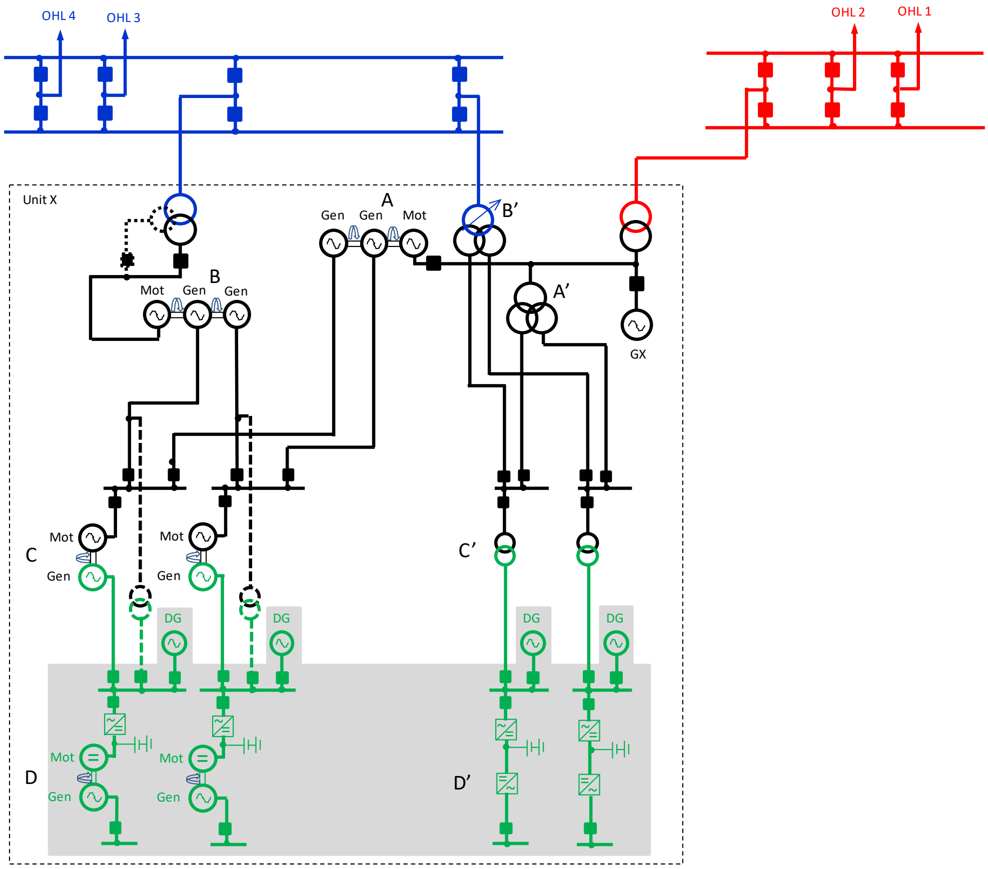

Figure 13. – Possible places in a unit to connect motor generating sets.

Solution C with placement between the operational and safety trains is perhaps a natural boundary to place MG-sets. The MVA sizes will here be reduced to some few MVA per safety trains. With this size a robust solution may be with a synchronous motor and synchronous generator. The size suits well (at least for some units) with what has been proposed in chapter 3.2.1 possibly re-using the motors of existing Q24 railway sets. For this MVA size there are also standard MG-sets available on the market [15], [16] which are claimed to fulfill the American safety class 1E.

Starting currents of the total loads downstream the generator side have to be considered and some sequence staring is likely to be needed in a similar way as when the safety busbar is supplied (energised) from the diesel generator. If the motor of the MG-set is a synchronous motor and is supplied from the off-site power system the frequency will not be affected by the starting of the safety busbar. Hence, the starting sequence will be less demanding focusing mainly on the voltage drops. This compared to when starting from the diesel generator where both voltage and speed have to be considered in the start sequence.

For the MG-set placed here it is important that excitation equipment of the generator have the possibility for reactive “backward” compensation as such that the diesel generator and the MG-set can be connected to the busbar at same time without hunting. This could for instance be at periodic “exercise” of the diesel generating sets against the grid.

Another possibility could even be to use a squirrel cage induction motor. This is perhaps the most simple and robust motor choice that one could think of. The disadvantage is that the frequency on the generator side will depend on the slip of the induction motor and the frequency will always be bit lower than system frequency. Typical slip for a few MVA rating squirrel cage induction motor is about 0.006 (four pole machine) with probably a bit higher slip for lower speed machines. At nominal network frequency this should still be within what the downstream loads could tolerate in steady state. However, when the network frequency is at its lower limit the generator frequency will be outside the limit of the downstream loads. Anyhow should a squirrel cage motor be used the downstream loads will have to be qualified for a somewhat lower frequency than what can be anticipated when fed directly from the off-site power system.
At this MVA size direct on line start should be possible since the MVA size of the MG-set if often in the same order of magnitude as the largest induction machines connected to the medium voltage operational busbars. These induction machines are most often directly started. Direct on line start of the MG-set will then cause about the same voltage drop at start on the feeding system as the largest induction machine already in place.

Figure 19 below show some variants C1 and C2 with MG-sets using two motors on the same shaft in combination with different couplings. In C1 one motor is connected on one sectionalising half of the operational switchgear and the other motor on the other half. With the sectionalising breaker normally opened there are two simultaneous sources available for the supply. Here the choices of motors have some impact. If both motors are synchronous motors there will be an active power transfer path between the two sections if both motors are connected depending on the angle between the two sources. That may not be desirable (although small regulation of the pole angle can be made with excitation equipment). Anyhow even if only one motor is connected and is lost or disturbed the other one could quickly be connected taking up the load as it rotates and could likely be pulled into synchronism applying excitation if the speed has not decreased too much.
Another possible solution would be to use two different types of motors for the two supplies. If a synchronous motor is used on one side, for instance on the start-up transformer (standby transformer) side, and a asynchronous squirrel cage motor is used on the other side both motors could be connected at the same time without any power transfer in between the two systems. The reason is that the asynchronous squirrel cage motor operating at synchronous speed is not able to transfer any torque as there is no current induced in the rotor at synchronous speed. The asynchronous squirrel cage motor will then only draw excitation current for its stator from its source. The provision for this is of course that both sources are connected to the same system so that the frequency is the same. Using two motors will cause extra losses in form of the no-load excitation losses (stator iron losses) and ventilation/friction losses of the idle motor and this will reduce the efficiency. Typical values of no-load losses for a medium voltage squirrel cage motor at synchronous speed and rated voltage may be some 1-3 % of full load input electrical power depending on the MVA size and the speed. The ventilation/friction losses should be added to this but they are normally smaller, typically an order magnitude smaller (~0.3 %). An advantage on the other hand is increased inertia.

Should either supply source fail or be disconnected the other side will take over immediately nearly as an UPS (but without any energy storage). If the supply to the asynchronous squirrel cage motor is interrupted nothing will happen. Should the supply to the synchronous machine fail the asynchronous squirrel cage motor will pick up load as soon as the speed decreases. The load will be supplied although with a somewhat lower frequency. The asynchronous squirrel cage motor will also serve as the natural starting device with direct on line starting and the synchronous motor will be put into synchronism by applying excitation.

Further, another possibility with more than one unit at the site could be to take the supply to one of the motors from another unit like shown for solution C2 in Figure 19. With this solution there will be three grid sources available to feed the MG-set.

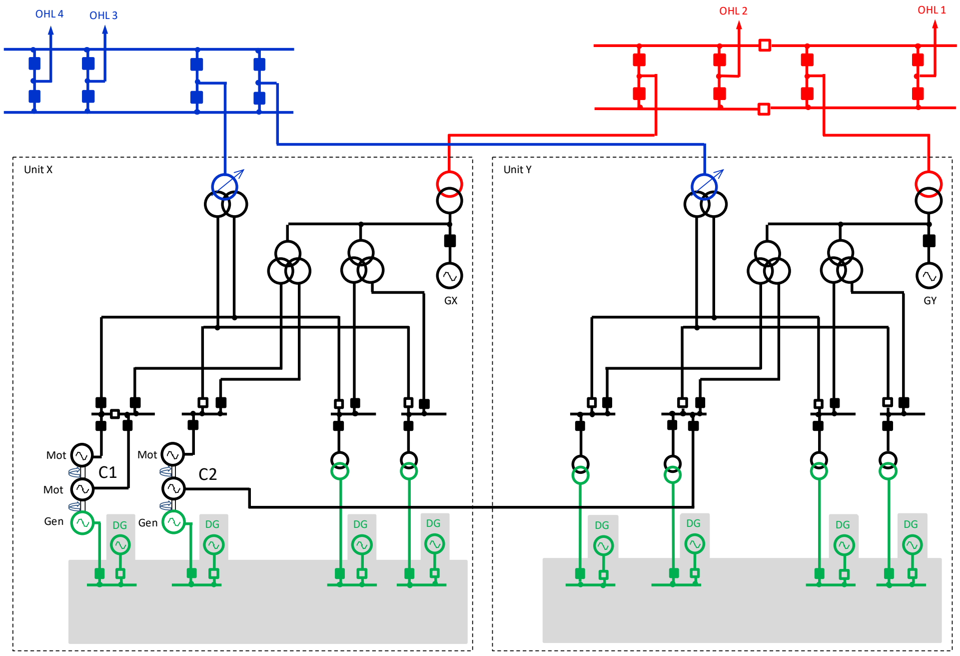

Figure 14 – Possible places in combination with extended connection.

Solution D in Figure 18 is to be considered for uninterruptible power supply (UPS) including energy storage, most often in form of batteries, where a safe an independent AC voltage (mainly for control and small power purposes) is then enabled. Such solutions are already in place at some of the units as described in chapter 3.2.3. In Figure 18 the solution is shown with DC motor but other solutions with AC motors fed from inverters are possible as well. As long as the UPS AC busbar is supplied through the MG-set a safe AC supply independent from grid disturbance is present. However, the solution may still be sensitive to off-site power system disturbances since the battery charger is often of a static type. In some cases UPS systems can be provided with a static switch (thyristor breaker) as a fast by-pass which potentially could be sensitive to disturbances. Hence using a static switch which also connects the feeding AC source may compromise the use of the MG-set in this solution.

The harmonics generated by power electronics (six pulse converters) connected on the downstream side of the generator may affect the size of the MG-set (generator).

Apart from placing motor generating sets within a unit it could also be possible to apply a motor generating set outside the unit. In plants with more than one unit a MG-set could serve several units. It be placed between the secondary off-site switchgear and the units or it could also be placed as a "sectionalizing solution" of the switchgear. Solutions like that are shown in Figure 20. Solution E shows a common MG-set which is connected in parallel with the sectionalizing breaker. With this placement of the MG-set it is possible to feed the start-up transformers (standby transformers) of several units without any electromagnetic coupling from the secondary off-site power system and it is still possible to use direct connection or a mix of them both for redundancy. The MVA size can be chosen depending on if it shall be capable of supplying all trains in all of the units or if only a few of the trains in all units is sufficient.

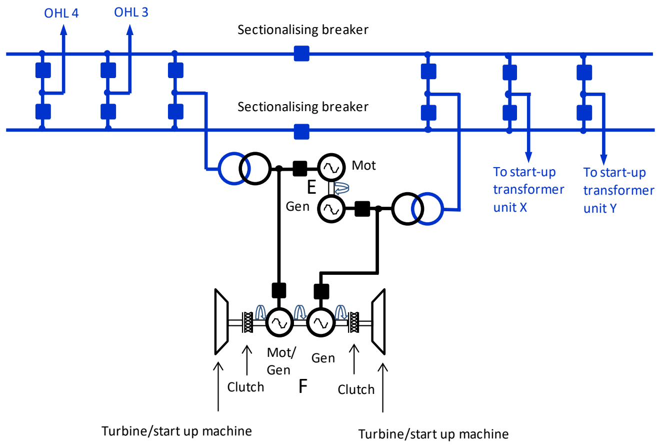

Figure 15. – Possible places and solutions outside a unit to connect a motor generating set.

The choice of machines for the motor is the same as for solution A and for the generator a synchronous machine with brushless excitation is the best choice.
An alternative solution indicated with F in Figure 20 shows a combination of a MG-set with turbines, possibly gas turbines or larger combustion engines (as larger diesel sets). This solution is not so different from the existing gas turbines which are located within some of the plants as described in chapter 2. These gas turbines have two halves connected to the same generator but on the two sides of the generator shaft. They do have provisions for just running one of the turbine halves at time and they are also designed to use one of the halves as a "start-up" motor to accelerate the synchronous machine and to synchronise it. Afterwards the turbine half can be disconnect through the clutch enabling synchronous condenser operation of the synchronous machine against the off-site power system. An extra synchronous machine connected to the same shaft and an extra transformer and breaker bays is what is missing compared to solution F.
With the solution F the starting of the MG-set is course one of the main advantages as it does not have to have any extra starting facilities for starting from the grid.

3.2.9 Operating experience from motor generating sets in nuclear power plants

Incidents in NPPs

In below are short descriptions of some incidents that have been reported on an international basis (IAEA IRS database) and that has occurred in nuclear power plants with regard to motor generator sets. None of the incidents are related to any of the nuclear power plants as described in chapter 2 of this report.

Incident A
(IRS Number: 8646)

For a nuclear reactor an operating experience on a motor generating set feeding a no-break board has been reported. In the report an incident is described causing an overvoltage condition caused a by phase-fail relay due to incorrect contact ratings that caused some fuses to blow. This in turn led to that the feedback voltage to MG set generator to disappear which resulted in an increase of voltage (likely caused by low feed-back voltage to the generator voltage regulator). It was also reported that the frequency increased during the incident and that the MG-set was tripped by over-speed condition as the phase-fail relay did not trip on delay time. It was further reported that there was no overvoltage protection installed to protect against overvoltage. Some damages to equipment supplied from the no-break board were reported. Some corrective actions reported are installation of overvoltage protection for the MG-set and replacement of the phase-fail relays.

A reflection regarding the reported incident is, although no exact information is available on how the MG-set is designed in this particular case, that the generator of the MG-set must be treated as any other generator with when it comes to operating conditions and possible fault states. Loss of supply voltage to a voltage regulator which is not correctly detected will lead to overvoltage unless the voltage regulator is blocked or initiated to a different control mode (for instance field current regulation). As no overvoltage protection was installed on the generator a single failure led to this condition.

Incident B
(IRS Number: 6350)

For this nuclear reactor an operating experience on a motor generator set feeding a DC panel has been reported. The incident reported is about a short circuit in the armature winding of the DC machine. The supply circuit breaker between the DC machine failed to operate and as consequence the DC voltage was far from normal on the DC panel. This lead in turn to current oscillations which caused operation of other breakers, for instance of the reactor protection system which led to a reactor scram. Also the breaker from the storage battery tripped in an unselective manner. Some objects received signals to start, such as diesel generators but did not start as consequence of the loss of DC. The MG-set seem to have been tripped by its circuit breaker on the AC-side.
Safe operating conditions were violated in this incident but did not lead to any severe accident as the reactor was at low thermal power and as it was possible to

restore the DC supply from another DC panel some 20 minutes after the initial event.

It is reported that ageing of the insulation and non correct determination of extended life time of the MG-set was two of the causes of the incident directly related with the MG-set.

A comment regarding this incident is that it did not occur as any consequence of off-site power disturbances but as a consequence of a local fault. The protection of DC machine did not work as expected and it seemed that no back-up protection was installed. It appears that the loss of DC had large impact on safety system and control systems and that design faults revealed common cause failure (CCF) of all safety system related to the DC system. However, it cannot be concluded that the MG-generator set alone was the origin of this CCF but rather the design of the DC system.

Incident C
(IRS Number: 1064)

For this nuclear reactor a MG-set supplying a recirculation pump tripped by its differential protection. The trip was caused by high resistance in one of phases of the current transformer secondary coils caused by poor contact, which initiated the trip of the differential protection. Hence, there was no primary fault in the MG-set or in the recirculation pump motor.

The tripped caused a power reduction of the reactor to about half of the initial power value. The reactor was manually shut down for inspection. The countermeasure was replacement of the current transformers.

A comment regarding this incident is that it is a typical case of unwanted tripping. It appears that this incident is not directly caused by the MG-set but it could as well have happened with any electrical object equipped with current transformers feeding a differential relay.

Incident D

(IRS Number: 1010)

For this nuclear reactor a failure of the field circuit breaker occurred of a motor generator set. The MG-set is used to supply the recirculation pumps of the reactor. In scheme the reactor recirculation pump trip appears to be initiated by the tripping of the field circuit breaker of the MG-set. The field breaker failed during a normal shutdown of the reactor after a manual trip the recirculation pump. The root cause seemed to be inadequate preventive maintenance and failure to follow maintenance instructions as recommended by manufacturer of the field circuit breaker and endorsed by the regulatory authority.

A reflection regarding this incident is that the MG-set excitation is likely not to be of the brushless type as it is described that the field circuit breaker is also used for connecting discharge resistor. Another reflection is, if it is sufficient to use only the field circuit breaker as the only means to disconnect the energy (in this case to recirculation pumps) without having any back-up breaker installed should not the primary breaker (in this case the field circuit breaker) operate as designed.

Incident E
(IRS Number: 380)

For this nuclear reactor a MG-set failed to maintain the regulation of the output frequency when it was switched over to its DC power source. This happened when the nuclear unit was operating at full power but with low off-site power system voltage and low main generator voltage. As a consequence of this one essential bus in the plant was also operating at low voltage (at a lower voltage than was anticipated at a previous made analysis). During this low voltage another motor object was started on the same essential bus and as consequence operation of degraded voltage relays occurred resulting in start-up of diesel generator and switch over of the essential loads to supply from the diesel generator. It appears that MG-set was not any essential load and it was switched over to its DC source. As a consequence of not maintaining the output frequency several malfunctions of instrumentation and control systems occurred. Countermeasures reported was primary enhanced analysis related to voltage restrictions on the essential buses.

A reflection from this incident is that no investigation seems to have been reported on why the supply of the MG-set from its DC source resulted in unstable output frequency. This as switch over to DC supply seemed to be a designed function that was intended to happen if the AC source disappeared. It may raise some concerns of the robustness of the MG-set when it comes to switch over to another supply.

Incident F
(IRS Number: 6397)

This incident is related to two nuclear units and is in fact not a single incident but describes unavailability of reversible MG-sets that occurred during several occasions. It appears that the unavailability was caused by control equipment and thyristor breakers associated with the MG-sets. The main root causes were deficiencies in manufacture of control equipment and the inability of the organization to handle acceptance test of the associated control and thyristor breaker equipment.

A comment regarding this is that the control equipment of the MG-set may be a source of decreased availability rather than the rotating machines of the MG-set. The MG-set should probably be as simple as possible not to decrease robustness and availability that could be the case with too much of control and ancillary equipment.

Observations and reflections on the reported incident related to MG-sets

All except one of the incident related to MG-set seem not to have been caused by any disturbances or condition associated with the off-site power system. Many of the faults seem to have been known types of faults that can virtually affect any rotating machine with associated equipment (breakers, protections, excitation system etc.). There is hence no firm indication of a common cause failure, caused by off-site power system disturbance, affecting several MG-sets at the same time in these reports.

4 Solutions for robustness outside the nuclear industry

4.1 PREVIOUSLY PERFORMED WORK REGARDING DISTURBANCES IN INDUSTRY

Work against the forest industry was performed by STRI in the early and mid years of 2000 regarding the sensitivity to external network disturbances, mainly focusing on voltage dips caused by events in the grid. It was concluded that lightning strokes was the major cause of event for voltage dips. Some areas related to this were investigated such as the impact of lightning strokes and how the type of overheadline tower designs is affecting the fault ratio. This could be the type of structure such as steel and wooden tower, the impact of earthing of cross-arms and tower footing impedance, the impact of whether shielding earth-wires on the overhead line are present or not, the impact of line surge-arrester placement etc.

Another mitigating method investigated was the use of filters connected to the feeding lines of the supplying busbar. Such solution is using a reactor and a capacitor in series with same reactances for the nominal frequency. At normal operating the filter shows very little impedance. However, at a short circuit on the line the current through the capacitor is bridged through a varistor or the capacitor short circuit which means that the reactance to the fault increases and fault current decreases. This is in turn keeps the voltage on the supplying busbar at a higher voltage. Consequently, other loads connected to the busbar is exposed to a smaller voltage dip compared to the case should the line would have been directly connected to the busbar without any filter.

4.2 INQUIREY REGARDING ROBUSTNESS IN INDUSTRY

In order to investigate how other electrical power consuming industries outside the nuclear branch is dealing with robustness of electrical supply from the outer grid contacts have been established. Some question regarding robustness measures were compiled and sent to these contacts within the industry. Questions were sent to 14 different industries and answers were received from 10 of them.

The names of companies and the names industries are not revealed in this report for anonymous reasons. However, questions were sent companies in wooden industry (pulp and paper), to companies in metal industry and to companies in chemical industry, all of them within Sweden. The questions were written in Swedish and answers were also received in Swedish. The questions and answers have been translated into English in this report. However, names of places or names of industries have been removed in the translation in order to keep the answers anonymous. Any fault or misinterpretations in the translated answers is the responsibility of the author of this report.

4.2.1 Questions asked and answers received from the industry

1. *Do you have any special solutions regarding the feeding of sensitive parts within your internal auxiliary power grid, which makes it robust to disturbances from the external network? For example, this could be feeding different parts of the plant from different points in the external network which are relatively independent of each other; or feeding some parts with internal generation (if, for example, there is an excess of process steam); or special reserve power units (diesels, gas turbines, UPS[1], other) which take over some critical loads in case of disturbances; or rotary converters that isolate the system electrically from the network; any filters; or different operating modes depending on the disturbance; or something else not previously listed?*

   a. Pulp-, paper- and paper manufacturing industry
      i. The factory is divided into an A-network and a B-network. The A-network can be disconnected from the incoming feeder and switched to islanded operation. In that case the A-network is fed from two steam turbine generators. In addition, there are around 30 UPSs, ranging 10-80 kVA.
      ii. Unable to sustain any kind of production without external power supply. Internally there are two backpressure-steam driven generators but only one is running, which supplies only about half of the facility's power demand. Furthermore, the facility lacks the possibility to operate in islanded mode or perform black start. Additionally, there are four diesel generators that can supply about two percent of the facility's demand, rated between 200-700kW each. It takes approximately 10 to 15 seconds to start these units.
      iii. Possible to operate in islanded mode, in other words run completely without external network support and even deliver our surplus to the network. This is practiced approximately 20-30 times a year when there is risk of lightning strikes in the area. Today, there are four generators, of which three are sufficient to meet the internal power demand, which means that the fourth generator can be connected to the external network. Internally, there are also UPS units for important monitoring and control tasks, which are backed up using a diesel generator, however, major drives cannot be operated on these UPSs.
      iv. Some UPS units ensure power supply for different process and administrative computer systems, as well as two diesel generators to supply power to certain parts. These are also used for emergency lighting.
      v. Two different factories. Two incoming 130 kV lines to each factory, that come from different locations in the regional network.
         One factory can be operated in islanded mode by means of backpressure steam driven generators, that cover the entire power demand, i.e. the factory can be disconnected from the network and maintain islanded operation. Additionally,

[1] Uninterrupted Power Supply

there are diesel generators to ensure a safe turn-off of important boilers in case of total power outage.
The other factory has only a small turbine to produce power from excess steam, covering about 5% of the facility's demand. There are no diesel generators available, which means that all processes stop during power outage.
Both factories have UPS systems available to provide manoeuvring voltages to switchgear, PLC systems, IT equipment, networks, etc. The first factory can use the internal generation capacity to switch to islanded operation when there is risk of lighting in the area, a function which is used several times a year. Furthermore, the UPS system in this factory is backed-up by diesel generators and can last long periods of time. The second factory has no reserve to back-up the UPS system and can only supply the facility for about 15-30 minutes.
The UPSs also make the facilities less sensitive to voltage dips in the network.

    vi. Inhouse power generation with some switchgears prepared for islanded operation. We are self-supplied to about 50%.

b. Steel and metal industry
    i. Three incoming 130 kV lines, one of them is equipped with shielding earth wires. In addition, inhouse power generation ranging 10-60 MW, by means of twelve diesel generators dispersed throughout the plant.
    ii. Reserve power plants, UPSs, and redundant power supply.

c. Chemical/Petrochemical industry
    i. Two different factories within the site. One has four feeding nodes, and the other has three. The connection voltage levels are 10, 40 and 130 kV. That implies that disturbances in the regional network only affect part of our operations. Reserve power is available but only for control and monitoring tasks, the reserve is unable to sustain our main operations.
    ii. By default, redundancy throughout our entire electricity distribution system by means of A and B transformers, switchgear, etc. This does not help against external disturbances, but some work has been done to increase resilience to the most common disturbances, i.e. voltage dips usually caused by lightning but also, to earth fault, or component failure, etc.
    In practice, this means that the plant loads can handle dips in the network up to 600 ms (by riding through longer times). In addition, the network must be strong in all necessary places when restarting or for coming back to nominal speed after the fault has been cleared. In the event of an outage, we cannot keep the production running but only to shut it down safely. The power required for this is obtained from steam, UPS and emergency diesel generators.

2. *Are your facilities mainly fed directly from the transmission network (220-400 kV), from regional networks (70-130 kV), or from local area networks (<70 kV)? Do you have the possibility of supply from several points?*
    a. A. Pulp-, paper- and paper manufacturing industry
        i. Dual 130kV cable connection.
        ii. Regional network 130kV via two lines coming from different places.
        iii. Regional network 130kV with two incoming overhead lines from two different places. However, the lines share the same towers approximately 10 km before reaching the facility.
        iv. From 130 kV regional network with two incoming overhead lines.
        v. See above (Two 130 kV lines from different parts of the regional network, see 1v.)
        vi. One main input from the regional network, 130 kV. Reserve power from a 40 kV (local) network that can be switched in without interruption. The reserve power network can handle full production
    b. Steel and metal industry
        i. Three incoming lines from the regional network 130 kV
        ii. Three incoming lines, regional network 130kV
    c. Chemical/Petrochemical industry
        i. Regional network 130 kV, but also from 10 kV and 40 kV (local) networks.
        ii. Regional network 130kV

3. *Are there any critical time where parts of the plan cannot be without power supply (e.g. fractions of seconds, few seconds, minutes) such that it has serious consequences for the process, and how long is it?*
    a. Pulp-, paper- and paper manufacturing industry
        i. Approximately 70-80% the supply voltage in 100 ms without the process being disturbed.
        ii. Basically, all control and monitoring systems are powered from UPSs. Water for fire-fighting is fed from reserve power supply switchgear. Some cisterns require the stirrers do not to stand still for too long time.
        iii. In general, the factory cannot handle major disturbances during normal operation without a significant impact on the production, therefore the internal power grid has been designed for operation in islanded mode. The most important machine part in this facility is the recovery boiler, which if stopped by less than a second, would mean a factory shutdown with impact of likely a three-day production loss.
        iv. The process stops immediately in case of disturbance (fractions of a second).
        v. The processes stop at about 100 ms with sustained voltage dips under 75% of the nominal voltage. The first factory the process is stopped, and shutdown safely, using the diesel generators power if the outage last longer periods of time (longer than what it can be supplied with in islanded mode, see previous answers). On the other hand, the consequences for the second factory are that paper web is ruptured, the refiners stop, and in the worst case, destroy parts of the paper machines.
        vi. The boilers for steam generation enter a shutdown sequence and cause a total stop of the factory.
    b. Steel and metal industry
        i. Some parts shut down for voltage dips lower than 70%, while other parts then take a day to start up. If the power outage lasts more than 8 hours, the pyrolytic coal plant breaks down, incurring a two billion SEK loss, besides all the additional inconveniences.
        ii. Yes. Large parts of the production.
    c. Chemical/Petrochemical industry
        i. Large motors shutdown in case of power outage (fractions of a second).
        ii. The plant can likely handle voltage dips of up to 600ms duration, but in practice this time is probably shorter. However, it is known that the plant is capable of handling three-phase large voltage dips of at least 150 ms.

4. *Is the facility sensitive to any particular type of disturbance from the external network? For example: voltage dips, voltage swells, harmonics, transient overvoltages (lightning or switching overvoltages), over/underfrequency, frequency derivative, asymmetries in supply voltage (e.g. caused by shunt or serial faults), or something else not previously specified.*
    a. Pulp-, paper- and paper manufacturing industry
        i. Based on experience, it is voltage dips that affects the most.
        ii. Very few known disturbances both internally and externally, the network is not particularly sensitive to lightning, but it may occur within a few years interval. The UPS systems protect the electronics from voltage transients.
        The raw water pump station is fed through overhead lines (20 kV) and may be sensitive to lightning. The frequency converters for speed controls are equipped with automatic synchronisation for by-pass and switching to direct operation and control of the flow via the control valve (fully open at frequency operation mode).
        The availability and reliability increase due to the ability to operate without the frequency converter (in case of it malfunctioning). Additionally, there is overvoltage protection installed on the raw water pump frequency converter.
        iii. The plant is mainly sensitive to lightning, but also under/over frequency influences greatly. Under "normal factory" operation, the factory can be automatically disconnected from external network in case of external disturbances.
        iv. Yes, the facility is sensitive.
        v. Voltage dips have been detected. Previously, transient surge voltages (switching overvoltages in the external network) caused problems with (the facilities') GIS switchgear, but this problem has been solved the regional network operator.
        vi. Lightning is probably the only known disturbance source (of any concern) that has affected the plant in recent years.
    b. Steel and metal industry
        i. Sensitive to voltage dips (lightning and other things that produce dips).
        ii. Yes, for all the above reasons.
    c. Chemical/Petrochemical industry
        i. Primarily voltage dips, but also problems with asymmetries have been experienced.
        ii. There are dips that we are exposed to and built up a good protection against.

5. *Does the plant completely or partially (sensitive parts) be provided by inhouse generation (or reserve power units) if the external network would become unavailable?*
   a. Pulp-, paper- and paper manufacturing industry
      i. If the power supply from the external network is unavailable for a long time, the boilers can run out of fuel, which means that the A-network cannot be sustained over time (see the answer 1i).
      ii. No production can be maintained, some sensitive auxiliary systems are run by means of the diesel engines.
      iii. See previous answers (Factory designed to be operated islanded in case of external disturbances, UPS system for monitoring and control (see 1iii)).
      iv. Impossible to carry any production at all on power failure.
      v. See previous answers. (One factory yes, the other no)
      vi. There might be a possibility to operate parts of the factory in islanded mode, provided that some modifications are made to the steam grid. The parts selected are the sections that are most time-consuming to get started after a shutdown.
   b. Steel and metal industry
      i. To a very limited extent.
      ii. No.
   c. Chemical/Petrochemical industry
      i. Some inhouse generation available but only for normal operation. Critical support systems are supplied with steam turbines that take over in case of power outage, but also a gas turbine and diesel motors.
      ii. We only have emergency power to handle the most important and it is to safely shut down the plant. Loads in need of emergency power are usually: part of the lighting, servers, firefighting equipment, security systems and manoeuvring systems, etc.

6. *If the power supply is completely or partially unavailable, or if it is affected by abnormal quality, does it mainly affect production or are there any sensitive processes that depend on cooling, ventilation or anything else that could damage the facility if it is disturbed?*
    a. Pulp-, paper- and paper manufacturing industry
        i. Production is sensitive to disturbances and any disturbance becomes costly, i.e. production loss. The facility might be damaged or become hazardous if the cooling water system is not operating.
        ii. The production is affected by disturbances on the power grid. The alarm system for monitoring e.g. environment, fire and personal protection is fed with UPS power.
        iii. Implies total production stop with high start-up costs.
        iv. Affects the production.
        v. See previous answer
        vi. It is not uncommon that power electronic equipment fails because of heavy lightning.
    b. Steel and metal industry
        i. See the answers to the previous questions, we are completely dependent on electricity.
        ii. Mainly against production and corresponding refrigeration plants
    c. Chemical/Petrochemical industry
        i. The production cannot be maintained without cooling systems, such as cooling water systems.
        ii. Primarily against our production but at the same time it is not good for a refinery to be "stopped" so urgently and without warning. It is desirable to get electricity back as quickly as possible as it helps in the extinguishing work. Then when the plant is in a controlled stage, it is time to try to start-up again, which usually takes about a week before everything is up and running again. Disturbances can also create events that can cause clogging in the refinery or damage the catalyst, etc. This will add extra time for start-up, or maybe problems will be noticed only after start-up. Then it is necessary to bring down the process again for corrections.

7. *Could it be possible to access simplified single-line diagrams that describes/shows how the system is fed from the external network, especially if there is any solution in the system that increases the robustness of electrical power from the network?*
   a. Pulp-, paper- and paper manufacturing industry
      i. (No answer given)
      ii. (A simplified single line diagram was provided but it is not available in this report due to secrecy concerns.)
      The 20 kV switchgears powered from the transformers have duplex system (A and B busbars), enabling load redistribution at different operating modes. In case of failure or maintenance of one of the incoming transformers, loads can be redistributed between the switchgears using cross-coupling possibilities. The sub-switchgears that are fed from the main switchgears have only one busbar, but spare feeding can usually be provided from another sub-switchgear.
      iii. (A simplified single line diagram was provided but it is not available in this report due to secrecy concerns.)
      The power surplus at normal power production is about 20-40 MW, which is supplied to the external grid. The largest single contribution to robustness comes from the inhouse generators.
      iv. (A simplified single line diagram was provided but it is not available in this report due to secrecy concerns.)
      There are two incoming lines and eleven 130/10 kV 63 MWA – transformers, that feed a 10 kV to the switchgears for further distribution into the factory.
      v. Single line diagram not provided but could be requested.
      vi. (A simplified single line diagram was provided but it is not available in this report due to secrecy concerns.)
      Surge arresters allocated at various selected places to cope with surge overvoltages.
   b. Steel and metal industry
      i. No.
      ii. Yes, can be requested.
   c. Chemical/Petrochemical industry
      i. Several feeding points, redundancy in the incoming transformers.
      ii. As previously described A and B redundancy throughout the system. Two incoming 130 kV lines, transformed to 22 kV, which is further transformed down to the appropriate voltage depending on the loads, e.g. 6.3 kV for 200 kW-1.5 MW loads, and 0.4 kV for 0 - 200 kW loads.

8. *Do you have any fault/disturbance recorders so that you can monitor the power supply disruptions that have affected your facility?*
    a. Pulp-, paper- and paper manufacturing industry
        i. Four fault recorders.
        ii. Yes, a fault recorder to see if the disturbances come from outside or inside.
        iii. MicroScada at medium and high voltage.
        iv. No.
        v. We have several measuring instruments with automatic fault reporting on all incoming points. In most parts of the factory's internal power grid, there is relay protection with integrated fault/disturbance recorders.
        vi. Energy meters and analysers have been installed in the incoming bays to the factory in all high and medium voltage bays. These meters also detect disturbances and save them for later analysis.
    b. Steel and metal industry
        i. Yes, we have advanced measurements scattered throughout the network, we document all the disturbances
        ii. Yes, about 600 units of class A fault/disturbance recorders / power quality meters installed.
    c. Chemical/Petrochemical industry
        i. At some connection points.
        ii. Yes.

9. *Given that you have identified any part that is vulnerable to disturbances, have you taken any special measures to make the plant more resistant to disturbances from the external network, and what does this measure consists of?*
    a. Pulp-, paper- and paper manufacturing industry
        i. For example, allow a greater variation in the intermediary part of the frequency converter.
        ii. See the answer to question/answer 4ii regarding the raw water pump station.
        iii. Replacement of faulty power cables, affected by water treeing problems. Also, directional protection relays have been added. Currently, it is planned to replace the 130kV cables between our receiving station and the T1 and T2 transformers.
        iv. No. Just some actions that help to start-up faster.
        v. See previous answers, the most important thing is to feed all controls from the UPS.
        vi. Frequency converters are usually quite sensitive to disturbances. In recent years we have purchased these converters with extra-large capacitors to maintain the voltage at dips and undervoltage conditions. All computer equipment is powered by UPS and important 400V- and 230V-equipment are supplied via a special disturbance protection transformer with a static screen.
    b. Steel and metal industry
        i. Yes, the converters limits have been adjusted, some part of the plant are fed via UPS, batteries, diesel generators. Different parts of the plants have been divided into different categories, depending on how important these are.
        ii. UPS, reserve power and automatic change-over facilities.
    c. Chemical/Petrochemical industry
        i. (..)[2]
        ii. Most facilities are sensitive thus preventive measures are performed at several places.

[2] The actual question was not provided to this industry actor.

4.2.2 Comments to answers regarding robustness

From the answers it appears that most of the industries are supplied from the regional 130 kV grid. Only three of the plants are reported to be supplied also from lower voltage levels (local grids). One plant has the possibility switch over from the regional 130 kV grid to 40 kV local grid.

Most of the plants appear to have at least two incoming lines to the outer switchgears. Only a few of the industries supplied single line diagrams. The single line diagram will not be a part of this report due to secrecy reasons. The single line diagrams provided do show that there are lots of transformers connecting the plant with the supplying grid, in one case more than ten transformers. The transformers supply different parts of the plants but it appears from the single line diagrams that there are several possibilities for back-up supply within the plants with cross-connection between internal switchgears. However, when it comes to the supplying (130 kV) switchgears, the transformers are connected in parallel and normally not operated sectionalised and all incoming overheadlines are connected to the same busbar as the transformers. In this sense the plants appears to be sensitive to a busbar fault. In at least two of the industries the incoming overheadlines are fitted with surge-arresters on the line side of the line breakers. This indicates increased lightning protection and thereby higher robustness to surge overvoltages also within the plant.

Some of the plants within the pulp-, paper- and paper manufacturing industry have in-house generation. Some of these factories have power production that covers only a part of the plant load whereas some can supply the total load even with a surplus to be delivered to the grid. Several of the plants with in-house generation have the ability to operate in island mode.

All of the answers indicate that UPS systems are in operation. Some of the UPS system are supplied from diesel generator whereas some do only rely on batteries and has thereby limited endurance.

As can be seen from the answers it appears as the disturbance that causes problems to most of the plants are voltage dips. However there are also indications of sensitivity to over- and underfrequency disturbances as well unbalance from some plants.

Countermeasures reported to increase robustness are improvement of inverters (withstanding voltage dips better) and installation of shielding earth wires on incoming 130 kV lines.

One very distinct robustness measure practiced by at least two of the plants is, at risk for lightning, to switch over to island mode (house-load operation) as a preventive action. This is reported to be performed several times a year. A corresponding measure in a nuclear power plant is of course not suitable with the main generators as withdrawing (possibly several) large units from the power off-site power system may jeopardize safe operation of power system. However, operating one (or some) of the diesel generators supplying the safety busbars isolated from the off-site power system may, at lightning in vicinity of the plant, give corresponding robustness to the safety systems for some units. For other nuclear units it may not be appropriate action.

It is reported that the majority of the industries have disturbance recorders, some of them to quite a large extent enabling supervision of both external and internal disturbances. This can be a valuable method of learning which kind of disturbances that are entering the plant. In particular those disturbances which do not lead to any large disturbance because they can be a valuable indication of which kind of disturbances that are the most common ones entering the plant.

5 Non-electrical power supply

Apart from studying different design options for electrical power systems in nuclear power plants, another objective of the study was to study options to use alternative sources of energy to fulfill safety functions generally. Electrical independence is as such studied as a principle decoupled with measures for increased robustness discussed elsewhere in the report.
This chapter looks at the safety functions from a few different perspectives. It presents a theoretical view of the order of magnitude of the energy necessary to perform the safety functions, the order of magnitude of the time frame in which the safety functions needs to be performed, and the current state of electrical dependence or independence. Finally it tries to identify where electrical independence on a system/function level could be feasible.

5.1 ENERGY REQUIREMENTS FOR DIFFERENT SAFETY FUNCTIONS

To study the feasibility, and which energy source can be applied, it is of interest to look at the energy required to perform the different safety functions from a purely theoretical perspective.
Since most of the safety functions deals with the reactor pressure vessel (RPV), the energy required can be expressed as a volume work in the form $P * \Delta V$. Assuming the RPV pressure is constant, a comparison can be made looking only at the volume which needs to be displaced, or injected into the RPV.
Depressurization of the RPV will, in most cases, have the effect of lowering the required energy by an order of magnitude.

Isolation

Isolation of the RCPB is achieved through the closing of isolation valves. An approximation of the energy necessary to close a valve is the volume encompassed inside the pipe by the movement of the closing stroke.
Assuming a pipe diameter of 0,3 m (DN300), and a stroke the length of the pipe diameter, the displaced volume is $\pi *0{,}3^2 / 4 * 0{,}3 = 0{,}02\ m^3$.

Closing as many as 50 valves would only equate to a displaced volume of 1 m^3. Furthermore, many valves close in the direction of the flow, and use the pressure of the RPV to actuate the isolation. This is a common feature in fail-to-safe configured valves where the safe state is closed.

The isolation of the containment is performed against a much lower pressure and the energy requirement for the actuation is low.

Overpressure protection

Like with isolation above overpressure protection is performed by the operation of valves. The valves are smaller in diameter and lower in number than those necessary for isolation. Assuming half the diameter and number of valves, the displaced volume required to open each valve once would be approximately 0,05 m^3.

Reactivity control

Reactivity control can be achieved either by inserting control rods of injecting a boron solution.

Control rods

There are approximately 160 control rods, most of which needs to be inserted into the core to ensure reactivity control. The displaced RPV volume is the volume of the rods in the guide tubes to which the control rods are mounted, since the control rods are inside the RPV at all times. The distance into the core they need to be inserted depends on the current control rod configuration.

An easier and more pragmatic view is to look at the already existing hydraulic system for inserting the control rods into the core, which has a volume of approximately 3 m^3 for a BWR.

Boron

The amount of boron which needs to be injected into the RPV to ensure a sub-critical state depends on the concentration of the boron, and assumptions regarding how much that boron is diluted. The theoretical value as such becomes dependent on boron concentration, whether the boron is diluted by feed and bleed of the RPV during injection, the final water level in the RPV, and whether local concentration differences occur in steam generator loops in a PWR.

Back to simple and pragmatic. For a BWR the volume of the boron tank is in the order of 20 m^3.

Emergency core cooling

Unlike isolation and reactivity control, which mainly are one off requirements[3], core cooling is needed continuously after an initiating event. The volume needed for the first 24 hours is in the order of magnitude of 1000 m^3.
Note that if depressurization of the RPV occurs, the volume needed is still approximately the same, but the energy required to inject the water drops by an order of magnitude.

Residual heat removal

If residual heat removal is achieved through transfer of steam, like that from steam generators on a PWR, or the residual heat removal from the RPV to the containment for a BWR, the external energy requirement is close to zero, or at most equivalent of that required to open a few valves. The energy required is in these cases the same which was used to perform core cooling.

Residual heat removal from the containment via cooling chains is different from the safety functions above, in that it’s not connected to the RPV, and simply looking at displaced volume can’t be done. The energy required is that which is needed to pump water through three separate systems containing two heat exchangers.

[3] Some boron injection is needed with time for PWR, but a smaller amount than that which is initially needed in conjunction with sub-criticality and a potential depressurization.

An approximation, assuming the average flow in each of the three systems is 0,1 m^3/s, the pressure drop is 5 bar, 7,5 bar, and 2,5 bar respectively[4], is that the energy needed for 24 hours of operation is equal to that of displacing 1850[5] m^3 of water at the pressure 70 bar. The energy requirement for residual heat removal from the containment is not effected by depressurization of the RPV.
The approximated value is further that of one cooling chain, which may lead to containment temperatures for a short time being higher than design temperature.

Summary of energy requirements

The theoretical relative energy requirement for different safety functions have been summarized in Table 1 below.

Table 1. – Safety functions and energy requirement

Safety function	Energy requirement, relative	Energy requirement at low pressure, relative
Isolation	1	0,1
Overpressure protection	0,05	0,005
Reactivity control, control rods	3	0,3
Reactivity control, boron	20	2
Emergency core cooling	1000	100
Residual heat removal, one cooling chain	1850	1850

It’s well worth to keep in mind these are theoretical values used to show order of magnitude and give an idea and understanding what type of energy carrier are necessary to perform the safety functions. For example control rods are inserted by a hydraulic system, and while core cooling could be accomplished by hydraulics, the size of the system would have to be a few hundred times larger. For practical purposes the solution for powering core cooling has to be another energy carrying media that that applicable to reactivity control.

A further comment about these being theoretical values is that the systems performing the functions, for practical reasons, often expend more energy. Core cooling pumps are always in operation after an event, the flow direction is regulated by the operation of valves. The reason for this technical solution is reliability; repeatedly starting/stopping pumps increases the risk for failure. The continuous operation does however increase the energy expenditure of the core cooling function over the theoretical value when in practical use.

5.2 CRITICAL TIMES FOR THE DIFFERENT SAFETY FUNCTIONS

Due to inherent physical properties in the design of the reactor, the different safety functions have a varying time window after which the function needs to be activated. These time windows varies between BWR and PWR, it further depends on the initiating event the safety function is handling, whether a deterministic or

[4] The actual pressure drops depends on type of heat exchangers, length of the piping and more.
[5] 0,1 * (5+7,5+2,5)/70 * 3600 *24

realistic analysis is made, and between different reactors of the same type due to factors such as thermal effect and more. As such the times given are indications of order of magnitude.

Isolation

For isolation it is mainly a question of a pipe break, and the loss of coolant from the RPV. The physical properties in question are the size of the pipe and resulting flow rate after a break, and the amount of water above the core. Isolation needs to be performed within approximately tenths of seconds to a minute.

Overpressure protection

For overpressure protection the inherent physical properties are the volume of steam in the RPV, for PWR also steam generators, the thermal effect of the core, and the margin between operating pressure and design pressure. For a BWR steam is inherently existent in the RPV, while a PWR has a specifically designed structure to achieve the same water/steam interface. In the case of an isolation of the RPV, the overpressure protection needs to be activated within seconds.

Reactivity control

The time window for reactivity control is highly dependent on the function of the other safety systems. The time window at face value is dependent on the physical properties thermal effect, the volume of water above the core, and void coefficient feedback on the thermal effect.
To manage all acceptance criteria the time window is short, the function needs to be performed within seconds.

Emergency core cooling

Emergency core cooling depends on the thermal, or residual, effect of the core, and the volume of water above it for a BWR. For a PWR also the volume of water in the steam generators.
The function is needed after about tens of minutes up to an hour, the longer time for PWR with a higher amount of water available in steam generators.

Residual heat removal

Residual heat removal from the core in a BWR or steam generators in a PWR is practically the same as the core cooling system, with the same time windows attached to them.
When it comes to residual heat removal from the containment the physical properties are residual heat from the core, the volume of water in the condensation pool, and the mass of metal and concrete in the containment which is being heated. Without any residual heat removal from the containment, the time before the acceptance criteria is reached is several hours.

Summary of critical times

The critical times for different safety functions have been summarized in Table 2 below.

Table 2. – Safety functions and critical times

Safety function	Critical time
Isolation	Tens of seconds
Overpressure protection	Seconds
Reactivity control	Seconds
Emergency core cooling	Tens of minutes to an hour
Residual heat removal	Several hours

Looking at some sort of structure, the critical times available for isolation, overpressure protection, and reactivity control are short. Emergency core cooling has an intermediate time frame and residual heat removal has a long time frame.

5.3 CURRENT ELECTRICAL INDEPENDENCE OF SAFETY SYSTEMS

The current design of the safety systems already contain electrical independence to a significant degree, as described below.

Isolation

Isolation is to a large degree achieved by valves operated by their own media. For in-flow lines check valves are used, which when the direction of the flow changes closes using the force of that flow. For effluent lines similar principles are used where the valves are normally held open either by electrical or pneumatics. A failure in the energy supply leads to the valve closing, usually referred to as the fail-to-safe principle.

In short, a loss of electrical power will lead to sufficient containment isolation given that the fail-to-safe principle is applied to at least one of the normally two isolation valves.

Overpressure protection

Overpressure protection can be performed using different types of valves, which somewhat overlapping tasks. The tasks of the overpressure protection system can be divided into overpressure protection and depressurization.

The overpressure protection is performed by valves operating in steam, whose main valve can be entirely operated by its own media and mechanical forces, overpressure protection is thus performed after a complete loss of electrical power.

Depressurization of BWRs requires opening of pilot valves operated by an external power source, currently electrical, or opening of water blowing main-valves by electrical motors. PWRs have manually operated valves for depressurization of the steam generators and as such can perform both overpressure protection and depressurization independent of electrical power supply.

Reactivity control

Reactivity control via control rod insertion can be performed, and will be performed, at a loss of electrical supply. The insertion is performed via a hydraulic system which activates at a loss of electrical power due to a fail-to-safe configuration. For PWR this is further enhanced by a design where the control rods are normally held in place by electrical magnets, and fall into the core at a loss of electrical power supply.

Emergency core cooling

For older BWR reactors in Sweden, electrical independent systems in the form of condensers and steam driven pumps were part of the design. This is however only the case for reactors which are slated for closure at or before 2020.
PWR reactors are fitted with a steam driven emergency core cooling system. While the main power source of the system is the steam from the steam generators, the system has a small dependence on electricity for operation and control.

For plants operating in Sweden of Finland past 2020, a new emergency core cooling system is being installed due to regulatory requirements. The new emergency core cooling system will enhance the independence from electrical power supply.

Residual heat removal

For PWRs the residual heat removal from the core is performed by natural convection in the circulation loops towards the steam generators. The residual heat removal from the steam generators to the atmosphere is performed by the electrically independent overpressure protection valves.

For BWRs the residual heat removal from the RPV to the containment is similarly electrically independent due to the electrically independent opening of the overpressure protection valves. However the residual heat removal from the containment is dependent on supply of both AC and DC power for the operation of the cooling chains to keep within the acceptance level temperature.

Summary of current electrical independence of safety systems

With the current design of the plants most of the safety functions, due to the fail-to-safe design principle, will be performed at a loss of electrical supply. The main exceptions are core cooling and residual heat removal for BWRs. For PWRs the situation is better although a small[6] dependence exists for operating the steam powered core cooling system.

5.4 DISCUSSION REGARDING THE CURRENT LEVEL OF ELECTRICAL INDEPENDENCE OF SAFETY SYSTEMS

The level of electrical independence of the safety systems range from complete independence to a high reliance on electrical power. The safety functions which are already independent of electrical power supply have two common denominators,

[6] Assuming the gasket issue in the main circulation pumps is solved.

the external energy required to fulfill the function is low, and the critical time before the function is needed is short.

Electrical dependence is most apparent in the safety functions emergency core cooling, and for BWRs in the residual heat removal system.
For emergency core cooling, efforts are already underway to install new systems to fulfill the function.
For residual heat removal, it is the function with the highest energy demand and the longest time period before which the system function is required. While an electrical independent residual heat removal system would be possible, the energy demand gives a rough idea of the scope of such a project. It would be of a similar, or slightly larger, size to the current project for installing independent core cooling. With this in mind the question has to be raised if attempting to construct an electrically independent residual heat removal system makes sense. The possibilities of protecting all safety functions, by the alternative connections discussed in chapter 3, would strengthen all safety functions, including the more time critical ones.

5.5 ELECTRICAL DEPENDENCE IN DEFENSE IN DEPTH LEVEL 4 FOR BWR

Since no feasible candidate for increased electrical independence was identified among the regular safety functions, it may also be of interest to look at electrical dependencies in other safety related systems, and especially the systems credited to handle design extension conditions in defense in depth level 4. Here limited in scope to look at BWRs.

The plants have previously been retrofitted to handle two new scenarios. A pipe break with a degraded pressure suppression function, which is a more challenging mechanical failure than in original design, and a core meltdown scenario.

The functions installed were:

- Unfiltered depressurization of the containment to prevent containment breach in fast events
- Filtered depressurization of the containment to prevent containment breach in slow events
- Water filling of the lower drywell
- Protection of penetrations in the lower drywell
- Water filling of the containment by sprinkling the upper drywell

Of the above functions the unfiltered depressurization function handles the pipe break with degraded pressure suppression function, and the other functions handle the core meltdown scenario. The actuating power of the above function ranges from passive, via pneumatic, to DC and finally DC backed AC, and varies between plants.

Electrical dependencies in handling a core meltdown scenario

The following text is limited to having examined the core meltdown analysis on a few BWR reactors only, and may not be directly applicable to other sites and plants.

The current analysis of core meltdown assumes a loss of the diesel powered AC, but takes credit for DC and DC backed AC systems. As such there are a few electrically powered functions that are credited in the analysis:

- Reactivity control via insertion of control rods, isolation of the containment, and overpressure protection. As mentioned above these occur at a loss of electrical power and would be performed after a complete loss of electricity.
- Depressurization of the RPV via the overpressure protection system. This would require DC backed AC power operating the valves in question.
- Water filling of the lower drywell. In one case operated by DC backed AC power.
- The function of the reactor protection system for as long as battery power is credited to activate the above functions.

If the loss of diesel powered AC in the analysis was replaced by a more severe event, complete loss of all electrical power, as a way to identify electrical dependencies, none of the reactors studied would be able to handle the event. In one case the RPV would remain at high pressure at the time of RPV failure, resulting in a high-pressure core melt through. In another case the lower drywell wouldn't be water filled, leading to no fragmentation of the core melt and a non-coolable core configuration in the containment.

While the author in no way suggest the core meltdown scenario should be changed to a complete loss of electrical power, it is striking that the exact same function is electrically independent on one reactor, but electrically dependent on another.

Potential for electrical independence in defense in depth level 4

The functions needed in handling a core meltdown scenario are powered by natural forces. Depressurization of the RPV is driven by the pressure difference between the RPV and the containment, filling the lower drywell is powered by gravity and differences in water levels. However along the piping needed to perform the function there are valves which need to change position to actuate the function. As has been described above valves require a low amount of energy to operate, and they can be made to be electrically independent.

For filling the lower drywell one plant already has a system with pneumatic valves which can be operated by pressurized gas bottles using manual actions, completely independent of electricity, which is a proof of feasibility.

For the depressurization of the RPV one case of a fail-to-open valve exists, which proves feasibility. However changing fail-to-safe configuration on another plant may have ramifications on analysis within the design base.
Alternatives would be to exchange the actuators of water blowing valves to pneumatic, or exchange an electrically powered pilot valve for a pneumatic. It's been identified that at least one plant has two electrical pilot valves which are seemingly not part of the reactor protection system, and as such only manually operated. While any project or change inside the containment isn't easy, overall it seems feasible to exchange electrical pilot valves for pneumatic ones. Combined with a manual interface for operators similar to that for water filling of the lower

drywell a complete electrical independence for defense in depth level 4 functions seems possible to achieve.

Potential issues with manually operated functions

Even if all functions necessary in defense in depth level 4 could be made to operate without electrical power supply, there are a few issues that would have to be considered.

One clear issue would be operator information. In such a situation the control room staff would be in a complete information vacuum, a situation that would be very hard to navigate. While the actual function could be electrically independent, an operator would not easily be able to identify the need for the function. Would not be able to verify either the function of the system, or whether the safety objective was performed, unless the operator information was also made electrically independent.

The current functions in defense in depth level 4 are single failure proof for components in difficult to reach positions, which valves inside the containment definitely would be. Having two manually activated depressurization valves would increase the consequences of an erroneous manual action, so it's not clear whether redundancy would be the best for overall safety in such a function.

Further, manual actions are currently not credited in the first 8 hours to mitigate severe accidents. Although there is no strict requirement regarding the time frame, apart from it being shown to be sufficiently long, the time frame 8 hours is commonly used. If an emergency standby force was implemented, there could be cause to reexamine this time frame. If the time frame was adjusted it could have implications for the use of other functions in DiD level 4, notably the water filling and time frame for pH-adjustment of the containment.

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SURVEY OF ROBUSTNESS MEASURES IN ELECTRICAL DESIGNS IN NUCLEAR POWER PLANTS

In this study the electrical connection of the different nuclear power plants in Finland and Sweden has been reviewed in terms of their single line diagrams and how they are connected to the grid.

Means of diversifying the connection to the grid using other connections, such as cross-coupling, connection to both off-site switchgears etc. has been discussed showing some possible ways of increasing robustness by means of not connecting all electrical trains to the same source.

Motor generating sets, MG-sets, as a mean of isolating the electrical system of the plant from the off-site power system has been identified as a good measure and no common cause failures have been identified.

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