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Alternative off-site power supply improves nuclear power plant safety

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ABSTRACT

A reliable power system is important for safe operation of the nuclear power plants. The station blackout event is of great importance for nuclear power plant safety. This event is caused by the loss of all alternating current power supply to the safety and non-safety buses of the nuclear power plant. In this study an independent electrical connection between a pumped-storage hydro power plant and a nuclear power plant is assumed as a standpoint for safety and reliability analysis. The pumped-storage hydro power plant is considered as an alternative power supply. The connection with conventional accumulation type of hydro power plant is analysed in addition. The objective of this paper is to investigate the improvement of nuclear power plant safety resulting from the consideration of the alternative power supplies. The safety of the nuclear power plant is analysed through the core damage frequency, a risk measure assess by the probabilistic safety assessment. The presented method upgrades the probabilistic safety assessment from its common traditional use in sense that it considers non-plant sited systems. The obtained results show significant decrease of the core damage frequency, indicating improvement of nuclear safety if hydro power plant is introduced as an alternative off-site power source.

1. Introduction

The nuclear power plant (NPP) safety has attracted paramount attention recently. One of the target areas is the revision of the current safety concepts and adoption of new ideas. Standards and safety analyses confirm the desired safety level (US-NRC, 2007). Probabilistic safety assessment (PSA) is a standard methodology for assessing nuclear power plant risk (Aldemir, 2013; Aneziris et al., 2004; Han and Yang, 2010; Montero-Mayorga et al., 2014; Raimond et al., 2013). Its effectiveness and efficiency – as a tool for NPP risk management – is widely acknowledged.

There is a constant quest for new solutions that will improve NPP safety. An important safety issue is the station blackout (SBO) event, representing the complete loss of all alternating current (AC) power to the safety and non-safety buses in a NPP. The Fukushima Dai-ichi events that took place in March 2011 indicated the importance of the emergency power supply system. This event initiated the conduction of the Stress Tests performed in the European NPPs. The conclusions of these Stress Tests identified the SBO as limiting case for most of the NPPs. One of the approaches for mitigation of SBO is the application of an alternative power source on-site independent of the existing emergency power supply sources.

The existing on-site emergency power supply sources are site-dependent, i.e., they can be jeopardized by common internal and external events such as floods, fires and earthquakes. This implicates the need of an alternative, site-independent and reliable power source.

One of the objectives of this paper is analysis of a concept which considers application of an off-site alternative power source in order to improve NPP safety. The PSA methodology is upgraded from its traditional NPP on-site-constrained use such that it additionally takes credit of the beyond-site non-safety class systems and equipment within the plant PSA modelling. For demonstrative purposes a connections between different types of hydro power plants (HPP) and NPP is considered. In that direction, a HPP is being considered as an off-site alternative power source. Generic reliability data were applied for modelling of the components of the HPPs.

A PSA model of II generation NPP is used as a case study. The NPP core damage frequency is designated as a plant risk measure. A fault tree model, representing the failure of the HPP to provide power to the NPP safety buses, is constructed. The fault tree comprises all of the important HPP components as well as independent electrical connection between the HPP and the NPP. The probability of failure to deliver electrical power to NPP safety buses is considered as the fault tree top event. Subsequently, this top event

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is considered as an additional functional event within the SBO event tree.

Analysis of NPP core damage frequency and the share of the SBO event are quantified. Common cause failures (CCF) of the HPP components are considered in the analysis. Sensitivity analyses are conducted as well. The results show that the introduction of hydro power plant, as an alternative power source, implicates a significant impact to the total NPP core damage frequency. Consequently, this implicates NPP safety improvement.

2. Probabilistic safety assessment

PSA is a standard method for assessing, maintaining, assuring and improving the nuclear power plant safety (U.S.NRC, 1982). It is generally used to find the weak points of a plant and to make recommendations for possible changes in design. PSA relies on two main techniques: fault tree analysis and event tree analysis, both of which have a wide range of applications. Fault tree is a tool to identify and assess all combinations of undesired events in the context of system operation and its environment that can lead to the undesired state of a system (Roberts et al., 1981). An undesired state of the system is represented by a top event. Logical gates connect the basic events to the top event. Basic events are the ultimate parts of the fault tree, which represent undesired events, such as component failures, missed actuation signals, human errors, contributions of testing and maintenance activities and common cause contributions. Event tree is a tool to identify and assess possible scenarios, i.e., accident sequence of safety system functions responses (i.e., system successes or system faults, which are further analysed with the fault trees) to the initiating event (Čepin, 2002; U.S.NRC, 1982). Safety system functions are the means to prevent the accident or to mitigate its consequences. They are modelled as functional events within the event tree. The initiating event is an event, which may lead to the accident consequences. Plant damage states are the end states of the scenarios (U.S.NRC, 1982).

The traditional application of PSA for NPP safety evaluation does not take into account systems which are not located at the NPP site. This defines the conservative nature of the PSA for NPP. In this paper an upgrade of the traditional PSA for NPPs is proposed such that that the method takes into consideration systems that are classified as non-safety related and located at a certain distance outside the NPP. This modification is allowing the PSA to evaluate the impact to core damage frequency of the NPP from systems that can be used in emergency scenarios such as SBO.

3. Hydro power plants and correlation with nuclear power plants

Hydroelectricity is the most widely used form of renewable energy (OECD/IEA, 2010). Hydro power plants are producing electrical power using the gravitational force of the falling or flowing water. Given the way in which power of the water is transformed into electrical power the following hydro power plant designs exist: conventional (dams), run-of-the-river, pumped-storage, tide and underground. The conventional HPPs, where dams are used to store large amounts of water, are the most widely used HPPs. They are converting the potential energy of the water in to electrical energy using water turbine and generator. Run-of-the-river HPPs are those HPPs which employ small or no reservoirs. In such a way the water coming from upstream must be used for generation at the given moment or must be allowed to bypass the turbine-generator system. Pumped storage hydroelectricity is a way of storing and producing electricity to supply high peak demands by moving water between reservoirs at different elevations (Hadjipaschalis et al., 2009). This type of HPPs will be of special interest in this study.

3.1. Pumped-storage hydro power plants

Pumped storage hydropower plants are storing and producing electricity to supply high peak demands by using water reservoirs positioned on different elevation connected between each other with pipes under pressure. They are the largest and most mature form of energy storage currently available. However, the capital costs required for pumped-storage hydro plant (PSHP) are large and the availability of suitable sites is decreasing (Connolly et al., 2010).

Taking into account the evaporation losses from the exposed water surface and conversion losses, approximately 70–85% of the electrical energy used to pump the water into the elevated reservoir can be regained (Hadjipaschalis et al., 2009). Along with energy management, PSHP help control electrical network frequency and provide reserve generation. Pumped storage plants can respond to load changes within seconds.

3.1.1. Pumped-storage hydro plants as energy storage capacities for base-load units

One of today's NPP characteristics is that their capital costs are higher than the capital cost of an equivalent size fossil-fuel plant. However, the operating costs of the NPPs are substantially lower than those of the fossil-fuel plants (Knapp, 1969). The result is total power costs for the NPPs that compare favourably with fossil-fuel power generating costs. The low incremental energy cost of power from the NPPs makes the consideration of PSHP very attractive as energy storage devices.

The PSHPs can be designed in such a manner that it can be brought on the line rapidly enough to be classed as a reliable source of spinning or assured reserve capacity at all times. Furthermore, its ability to accept or reject load almost instantaneously makes it much more flexible than other types of generation, peaking or base load. It can follow the sharp peak-load fluctuations that occur on a minute-to-minute basis in any large system. This same ability to follow the peaks of the system load permits more uniform and efficient loading on the fossil-fuelled and NPPs that are operating as base-load units in conjunction with the PSHPs (Knapp, 1969). If the terrain permits its use, the pumped-storage hydro plant can be valuable for providing an improved plant factor for the large-base-load nuclear generating units. One example of such application of PSHP is the Northfield Mountain Pumped Storage Project in New England USA (Knapp, 1969). When preparing the project it was determined that the PSHP, working in conjunction with the base-load NPPs, produces the lowest overall production cost for the system. It was determined that only the pumped-hydro unit is sufficiently flexible to permit it to be classed as assured reserve in New England (Knapp, 1969).

However, this is not the only benefit that the power system and more specifically the base-load units such as NPPs can have from application of PSHPs. In this study an application of PSHP for NPP safety improvements is proposed.

3.1.2. Pumped-storage power plants as an off-site alternative power source

The installation of PSHP as a mean of meeting the system peaks permits an overall reduction in the installed reserve required on the system. This reduction is possible because of the better reliability of the PSHP compared to alternative types of peaking generation (Knapp, 1969). Nevertheless, the PSHPs can be used as an external (off-site) alternative power source, connected with the NPPs using separate power lines if the distance allows that. All types of hydro power plants, located in the vicinity of an NPP, can be used as an alternative power sources if an independent electrical connection is made. The idea in this paper is based on the consideration of off-site power source (e.g. PSHPs) as an