Power system regularity challenges connected to electrification of large scale offshore installations form land

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ABSTRACT: As a consequence of the increased focus on reducing carbon emissions to the environment, more and more offshore oil and gas installations are now being realized with power supplied from the onshore power system. Many oil and gas installations are located from 10 -100 km from shore. This fact alone creates a major challenge concerning design of reliable and cost efficient land based power supply systems. A large portion of the challenge lays in calculating the impact this new and dominating point loads have on the existing power systems. The onshore grids are not designed for handling large and sudden load increases in a single load point. These grids are also commonly complex and highly meshed which increase considerably the complexity concerning analysis of supply reliability. Furthermore, these extensions of the onshore grids are traditionally only evaluated from an electrical point of view, not from a total system regularity point of view. In Norway we have practical experience regarding this problem. A large part of the power system in the middle of Norway has shown a decrease in power system regularity. This decrease in regularity is a consequence of connecting a large offshore oil and gas installation to the onshore power system. This presentation will show methodology and analysis results concerning analysis of power delivery reliability produced by the recently developed simulation program PROMAPS. The presentation is based on experiences from regularity studies related to electrification of offshore oil and gas installations form land in Norway.

1 INTRODUCTION

As a consequence of the increased focus on reduction of carbon emissions to the environment, more and more offshore oil and gas installations are now being analyzed for and also realized with power supplied from the onshore Norwegian power system. These projects, from the early studies to realization, involve several challenges that have to be managed by the oil and gas companies. Central challenges are the offshore installation power delivery reliability and the impact these large loads have on the existing onshore power system.

This paper presents a general method for analyzing the reliability of power delivery in electrical power systems. Focus in the presentation is electrification of offshore oil and gas installation by connection to onshore power systems. Chapter 2 discuss challenges concerning the Transmission System Operators (TSO's), the Norwegian power system control authority (NVE) and the oil and gas companies. Chapter 3 presents a general theoretical background concerning reliability and regularity analysis of power grids. Chapter 4 shows application of the regularity analysis. Chapter 5 discusses project experiences. Chapter 6 contains comments and discussions and chapter 7 mention some application of the method on other systems.

2 THE INVOLVED PARTS POINT OF VIEW

2.1 *The transmission system operator (TSO)*

The Transmission System Operator (TSO) is faced with increasing requirements regarding the reliability of power delivery. The cost of not delivering agreed energy can be substantial. In Norway there is a CENSE-cost connected to energy not delivered. If a grid company has low power delivery reliability in the power grid, the company will experience a reduction in the allowed fix income related to the power system rent that every consumer pays.
The need for powerful analyses tools is therefore obvious. Tools for power flow calculations, dynamic analyses etc. are some of the most important tools for the TSO. In addition, to be able to analyze the load delivery reliability, a suitable power system reliability analysis tool is needed.

In Norway the TSO is obligated to allow a consumer to connect load points to their power systems. Even if the oil and gas company finance the connection from offshore to the power system connection onshore, the TSO is faced with a dilemma that the connecting load can cause problems and reduction in the power deliver reliability other places in the power system.

2.2 *The Norwegian power system authority*

The Norwegian authority has evaluated the possibility to replace all turbines and generators that supply electric power offshore with electric power from land. Power from land will reduce the CO2 and NOx from offshore but realizations will be extremely expensive. The authority recommendation is not to replace existing installations, but to produce and transport the gas and oil to land where the process units will be driven by CO2 neutral generators. An alternative possibility is use of cables to carry the electric power to the offshore installations. Since transport of power and cleaning of CO2 require energy, a great challenge is to find the level of efficiency balance concerning choice of systems solution. As long as the offshore installations are within a reasonable distance from the mainland the economy favors use of cables.

New cables and transformer stations require a consequence analysis. This document includes among other elements a program plan that will include description of the consequences and the actions to mitigate negative impact in the power system. These include power systems studies to show the impact on the power grid such as load flows, short-circuit, studies, transient stability, harmonic analysis, switching transients and regularity studies among the most common.

2.3 *The oil and gas operators*

When planning a connection of oil and gas installations to the onshore power system the oil and gas operator may experience that the grid owner is not necessarily positive to this request The onshore power grid owner may explain and argue that the offshore oil and gas installation connection will or may cause several problems for the onshore power system, and that several power system upgrades must be done before the oil and gas installation can be connected. Furthermore, the onshore power grid owner may inform that the cost for the necessary power system upgrades may partly be invoiced the oil and gas company.

Common practice in the offshore industry is to have available power supply capacity necessary for the installations and some amount for reserve or backup in the form of local generators. The offshore industry is using the same concept also for supply from land. It is then often experienced that the land to offshore connection affects the power system such that required amount of power may not be available during periods of the year. Furthermore, the quality of service is different from having dedicated generators and may contribute to deterioration of the power supply availability.

The consequence analysis required by the power system authority is meant to discover these problems and establish a plan to find satisfactorily solutions for all involved parts.

A central analysis challenge is the power delivery reliability. In the subsequent sections is a quite new method for analysis of this challenge presented. The method is realized in the computer program named PROMAPS which is a central part of the analysis tools used to create solutions of the presented problems.

3 BASIC RELIABILITY METHODS

3.1 *Development history*

As responsible for electrical power supply in TSO BKK ,Yngve Aabø experienced the need for new reliability calculation tools. This need results in a master thesis proposal which was carried out by Arne Brufladt Svendsen (Svendsen, 2002). As thesis advisor Tørris Digernes discovered a method suitable for building large Markov / Kolmogorov models. A central clue in this calculation was the Kronecker matrix operators, (Sasty 1999). The method was tested by Arne Brufladt Svendsen in his thesis and found to be very efficient for reliability analysis of power systems. Since then various projects have been carried out to make the method more efficient and complete. In 2004 Tørris Digernes MathConsult received a grant from Inovasjon Norge to develop a complete theory and a program for reliability analysis of power systems. Later the same year a co-operation project including Landsnet, Troll Power and Tørris Digernes MathConsult was established. This project focused on developing efficient methods for reliability analysis of the Icelandic power transmission system. Also this project was partly financed by Inovasjon Norge. These projects resulted in a computer program called PROMAPS (Probability Methods Applied to Power Systems).

Recently a company named Promaps AS is founded as owner and responsible for the program PROMAPS and a co-operation agreement with Troll Power and Tørris Digernes MathConsult are established.

Much of the theoretical development has been inspired by the excellent textbook of Endrenyi (1978). The method concerning building of large Markov / Kolmogorov models based on unit models is presented in the comprehensive textbook of Rausand & Høyland (2004) with reference to the master thesis carried out by Svendsen (2002).

3.2 *Calculation principle*

A typical calculation sequence in PROMAPS includes the following main functions:

1. Calculation of branch reliabilities
2. Selection of relevant reliability states
3. Calculation of maximum power transmission capacity
4. Calculation of expected power shortage
5. Calculation of reliability data concerning delivery probability, mean visiting duration and visiting frequency for functioning and failed reliability states.
6. Post calculation of various auxiliary variables including economical data.

Important functions in this calculation sequence are further described in the following.

3.3 *Basic reliability theory*

3.3.1 *Markov / Kolmogorov models*

The Markov / Kolmogorov model is a general method to describe the probability that a system is in a reliability state defined by the vector $\boldsymbol{\xi}$. The model has the following form (Endrenyi 1978).

$$\dot{\mathbf{p}} = \mathbf{A}\mathbf{p} \tag{3.1}$$

where **p** is the probability vector describing the probability to stay in the reliability states ξ, $\dot{\mathbf{p}}$ is the rate of change of **p** [1/year] and **A** is the transition rate matrix [1/year]. An additional requirement to the model is that $\sum \mathbf{p} = \mathbf{1}$. Dynamic solution of this differential equation requires a starting value for the probability vector **p**. However, the stationary solution is independent of the starting value.

Two important variables concerning reliability analysis in addition to the probability are the mean visiting duration and visiting frequency for the different reliability states. These variables are defined by (Endrenyi 1978):

$$\boldsymbol{\theta} = -diag\left(\mathbf{A}\right)^{-1} \tag{3.2}$$

$$\mathbf{v} = diag\left(\boldsymbol{\theta}\right)^{-1}\mathbf{p} \tag{3.3}$$

where $\boldsymbol{\theta}$ is the mean visiting duration vector [year] and $\mathbf{v}$ is the visiting frequency vector [1/year]. The mean visiting duration is the time spent in a reliability state at a visit and the visiting frequency is the number of visits in a reliability state each year.

3.3.2 *Model composition*

Assume a system consisting of two independent components with the component reliability models

$$\dot{\mathbf{p}}_\alpha = \mathbf{A}_\alpha \mathbf{p}_\alpha; \quad \dot{\mathbf{p}}_\beta = \mathbf{A}_\beta \mathbf{p}_\beta \tag{3.4}$$

Assume further that the system probability is given by combining the component reliability states. This probability can be expressed as $\mathbf{p}_s = \mathbf{p}_\alpha \otimes \mathbf{p}_\beta$ where $\otimes$ is the Kronecker product (Sasty 1999 p. 99). Time derivation of this expression gives further $\dot{\mathbf{p}}_s = \dot{\mathbf{p}}_\alpha \otimes \mathbf{p}_\beta + \mathbf{p}_\alpha \otimes \dot{\mathbf{p}}_\beta$. Inserting the component equations in this relation and rearranging using the Kronecker relations gives finally the composite reliability model

$$\dot{\mathbf{p}}_s = \mathbf{A}_s \mathbf{p}_s \tag{3.5}$$

$$\mathbf{A}_s = \mathbf{A}_\alpha \otimes \mathbf{I}_\beta + \mathbf{I}_\alpha \otimes \mathbf{A}_\beta \tag{3.6}$$

where $\mathbf{A}_s$ is the composite transition rate matrix, $\mathbf{I}_\alpha$ and $\mathbf{I}_\beta$ are identity matrixes with dimensions corresponding to the probability vectors. Note that equation (3.5) is in standard Markov / Kolmogorov form. Mean visiting durations and visiting frequencies are therefore also available from the transition rate matrix $\mathbf{A}_s$ for the composite system model. This principle can be used recursively to compose large dimensional models based on simple unit models.

3.4 *Model aggregation*

High dimension probability vectors are difficult to interpret. More insight is obtained by aggregating the probability vector. Typical aggregated reliability states are {Functioning system, Failed system}. Aggregation of a probability vector can be defined by

$$\mathbf{p}_a = \mathbf{D}\mathbf{p}_s \tag{3.7}$$

where $\mathbf{p}_a$ is the aggregated probability vector, $\mathbf{p}_s$ is the un-aggregated system probability vector and **D** is the aggregation matrix. An additional requirement is $\sum \mathbf{p}_a = 1$. This requirement is satisfied if the column sums of **D** are 1. Also an aggregated transition rate matrix can be calculated according to a function of the type

$$\mathbf{A}_a = \mathbf{f}_a\left(\mathbf{D}, \mathbf{A}_s, \mathbf{p}_s\right) \tag{3.8}$$

It is possible to show that the aggregated variables satisfy the standard Markov / Kolmogorov equation

$$\dot{\mathbf{p}}_a = \mathbf{A}_a \mathbf{p}_a \tag{3.9}$$

The matrix $\mathbf{A}_a$ contains therefore the necessary information to calculate the aggregated mean visiting durations and visiting frequencies.

3.5 *Creation of branch probability models*

An electrical grid is assumed to consist of branches connected in nodes. A branch may consist of generators or power import branches, transmission lines, transformers and load or export branches. In addition contain these main components normally a lot of sub components or factors that can be classified as power transmitting components, protection and reclosing components, human factors and environmental factors. A composite reliability model for each branch is build by model composition taking into account all relevant components and their probability interactions. A typical branch model may have from 1000 to 20.000 composite reliability states. These composite branch models are finally reduced by model aggregation to normally the two reliability states {Functioning, Failed}.

If the branches have the two aggregated reliability states {Functioning, Failed}, then the number of reliability states in the grid is 2^n where n is the number of branches. This number is growing very fast with the number of branches. To save computer memory and calculation time this number is reduced to relevant grid reliability states denoted Θ. The reduction is partly based on a maximum number of expected simultaneous failed branches and partly on a probability limit for the reliability states. From the reduced probability model all relevant branch reliability information can be provided with predefined accuracy.

3.6 *Calculation of maximum power delivery*

Maximum power transmission in the grid for the relevant reliability states Θ is calculated by the following maximization

$$\hat{\mathbf{P}}_i = \arg\max\left(J / \mathbf{M}_i, \mathbf{B}_i\right) \quad i \in \Theta \tag{3.10}$$

where $\hat{\mathbf{P}}_i$ is a vector containing the maximum power transmission in the grid branches, J is a cost function that is maximized subject to the electrical grid model $\mathbf{M}_i$ and the grid operation constraints $\mathbf{B}_i$. The index i designates the actual reliability states. The grid models can be of various complexity from simple linear models to comprehensive nonlinear models. However, to save calculation time simple linear models is preferred. Failed branches can be modeled by restricting the power transmission normally to zero for the actual branches or by removing the branches from the configuration matrix.

Power shortage for the various reliability states is obtained by calculating the positive difference between demanded load and maximum load.

3.7 *Power delivery shortage probability and cost*

Expected power shortage in each branch and each probability state is calculated by multiplying the power shortage for each reliability state by the belonging probability. The power shortage cost is further obtained by multiplying the expected power shortage and a defined power shortage price for each load point. A Markov/Kolmogorov model for the power delivery can be established by model aggregation. From this model is all relevant reliability data concerning power delivery available. The analysis can be performed for various load profiles. Also on line calculation of power delivery reliability is possible.

4 APPLICATION

4.1 *Regularity studies in general*

Since a power grid is in continuous change also the load delivery reliability will change continuously. The level of interconnectivity between nodes in a grid or the extent of grid meshing constitutes the transmission capacity. A highly meshed power grid has therefore a high transmission capacity. Changes in the mesh configuration or capacity levels will consequently indirectly change the power flow capacity. For example, two parallel power lines will only acts as redundant power delivery routes as long as the load levels do not exceed half of the weakest power line capacity. At the instant when this level is exceeded, the power lines will act as a series structure concerning reliability for power delivery form both power lines. To be able to evaluate a system regularity, it is important to include as much of the power grid as possible in the power deliver reliability simulation. The simulated power grid should be extended to the boundary where the grid is considered to be "strong". The 300/420 kV system in Norway is mostly considered to be strong.

The following power system factors will influence the power delivery reliability and must therefore be included in a regularity study:

- Load level
- Power flow in the branches
- Generation level and location
- Spinning reserve level and location
- System configuration
- Load priority
- Component reliability
- Branch reliability
- Maintenance interval
- Weather
- Wear and tear.

Changes in these factors may have significant affect on the grid and consequently the power delivery probability depends on both time and operation conditions. Delivery evaluations including all these factors must therefore combine calculations of probability and power flow. In meshed power system over a certain size this can only be done by a powerful simulation tool like PROMAPS or similar.

4.2 *The regularity methodology*

The regularity methodology includes a sequence having 4 main steps as shown in the following figure.

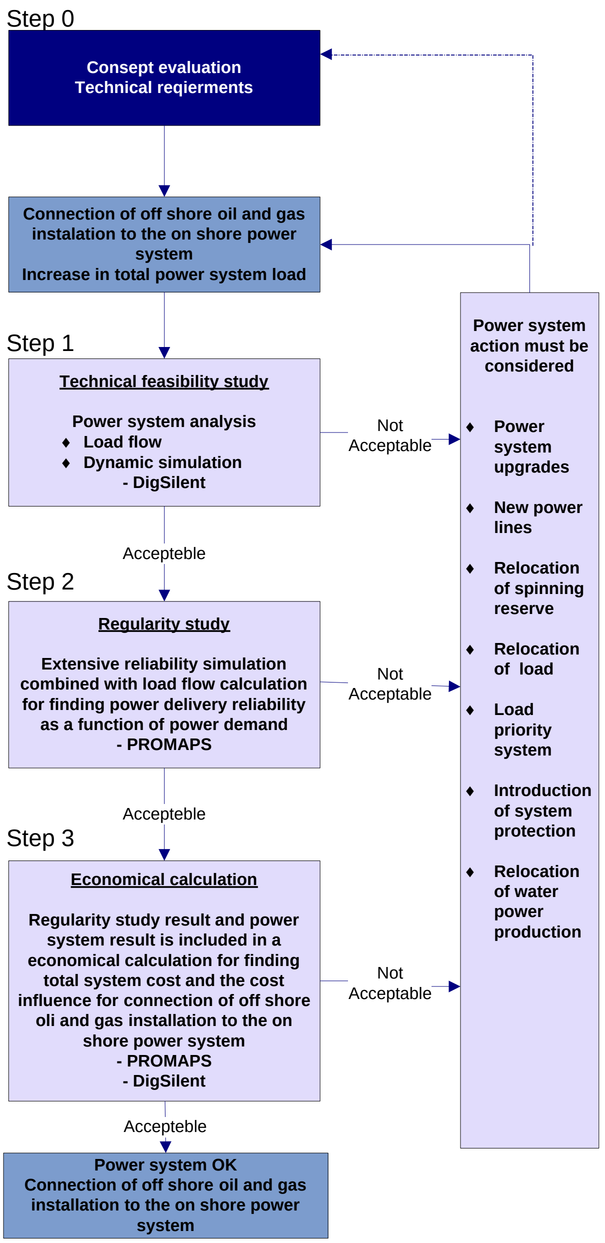

Figure 1: Regularity analysis methodology

The steps are described in the following.

Step 1: Technical feasibility study

This step includes a full load flow analysis of the power system to be connected both before and after connection of the offshore oil and gas installation. The planed load profile for the offshore oil and gas installation is included together with the onshore load profiles for the same period.

Load flow analysis: The load flow analysis calculates heavy loads for chosen time periods. The main goal for the load flow study is to investigate that the voltage is inside acceptable levels and that overload does not occur.

Dynamic analysis: This analysis simulates how the power system is affected during different fault situations in the dynamic fault range.

The simulation tool used is DigSilent PowerFactory.

Step 2: Regularity study

The main goal of this step is to investigate that the power system can handle the increase in load caused by connection of the offshore oil and gas installation to the main power system. In this step it is also checked that the systems unavailability is inside the governments suggested requirement. Furthermore the power delivery probability at the offshore oil and gas installation will be calculated together with the impact the load increase will have on the main power system. The simulation tool used for this analysis is PROMAPS.

Step 3 Economical calculations

Regularity study results and power system results are included in an economical calculation for finding the total system cost and the cost influence for the electrification of the offshore installation. The simulation tools used are PROMAPS and DigSilent PowerFactory.

5 PROJECT EXPERIENCE

5.1 *Regularity levels and complexity*

As stated earlier the power systems regularity is in continuous change do to changes in load level, production and production places, maintenance and power system faults. The regularity of a power system can be characterized by load regularity “breaking points”. The “breaking points” for a load can be illustrated by a graph that show the mean duration in functioning state or mean time to failure (MTTF) as function of demanded power as shown in figure 2.

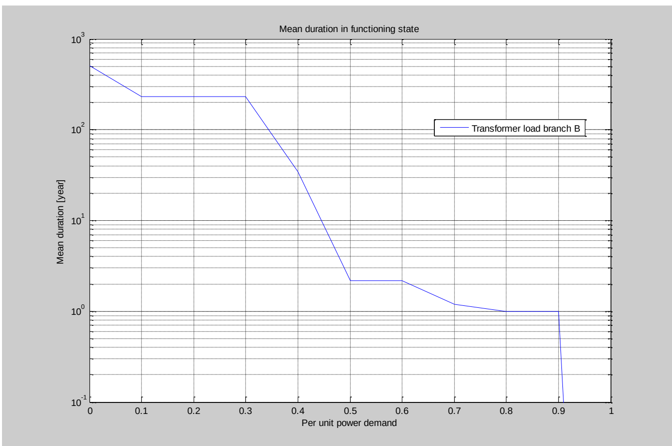

Figure 2: Mean time to failure as a function of demanded power

The previous figure shows a typical power delivery situation for a load point in a power system. The different "breaking" point on the curve illustrates different capacity levels being reached in the meshed network behind the current load point. For example: from 0.1(10%) to 0.3(30%) load demand the regularity level in MTTF for this load point represents the maximum regularity. This means that the meshed power system behind the load point has full redundancy. The power system behind this load point represents production, spinning reserve, transmission lines/cables and transformers.

At 0,3(30%) the first "breaking" point is encountered. A typical reason may be that the capacity of one of two parallel transmission lines is exceeded. One of the power lines is then not able to handle a fault on the other. The parallel power lines will in this situation acts as a serial structure. The next breaking point is encountered at 60% load demand. This situation can be caused by lack of spinning reserve in the system. If the system loses a production unit or a power plant in this situation, the spinning reserve is not large enough to serve the power demand.

This illustration is quite easy to follow in a small network. However if the power system is large with for instance over 150 internal branches and over 50 load branches and the grid is highly meshed, the picture is quite different concerning evaluation of the power systems regularity. In addition the load priority and frequency protection in the system connects all load branches, meaning that if there is a fault or a combination of fault, the load priority will cut the loads with the lowest priority.This will result in different regularity level as function of demand for all load branches depending on the fault location. To even more complicate the situation the load flow, production level and spinning reserve is also continuously changing. These facts results in very complex calculations and in even more complex evaluation of the results.

5.2 *Connection of large offshore loads to the onshore power system - an example*

An offshore power system was evaluated for connection to the 132 kV on shore power system at the cost of Norway. The actual power system was modeled with 150 branches. The border point in the analysis was at the strong 300 kV system. An expected yearly load profile was available. The power system model was highly meshed

The first step for all regularity studies like this is to create a base case representing the current power system with summer and winter conditions as a minimum. When the model can recreate the past and existing situations with regards to power flow, power losses, registered unavailability and CENSE-cost, the simulation of increased load due to connection of the offshore oil and gas load installation can be preformed.

For this particular case the power system seemed to be acceptable after the power flow and dynamical analysis was preformed. However, after the regularity simulation was preformed for the base case, the results verified that there already was problems with the power system regularity level at the winter load situation. This result indicated that the power system already experienced periods where the regularity level was not acceptable. However, if the period with maximum load is short, the regularity breaking point level that is not acceptable is also short and will not significant affect the average regularity level.

The important information from the base case is however that the system already has a regularity problem for a period of time in the current situation. This means that if a new load is connected to the power system, the reduction in the overall power system regularity due to the load increase is only partly caused by the new load. The problem was already in the system. However, the new load will probably make the system to stay for a longer time at the low regularity level.

If the TSO argues that the new load in the system creates a drop in the regularity level for the power system, it is important to show and document that the problem in the power system was already there. The introduction of the new load increases only the time the system is in the problem state. If the TSO argues that the owner of the new load must participate in the investment concerning power system upgrades necessary to achieve an acceptable regularity level, the fact that the system already experienced this problem must be taken into consideration regarding sharing of the cost.

5.3 *Evaluation of different power system upgrades to achieve acceptable regularity level*

When evaluating different power system action and upgrades there are several possibilities to investigate. First of all there are probably several power system upgrades which the TSO already have evaluated long time before the new load came into consideration. The TSO power system upgrades may not solve the current problem, but may be a part of a long term power system upgrades. The TSO may use the new load as an excuse to front their investment strategy and use the new load as a cause for doing the upgrades. Power system upgrades is usually associated with bad publicity. A publicity the, TSO do not want to be directed towards them self. Hence the new load may be used as a motivation for this investment process. Therefore it is of the upper most importance that the power system upgrades are the right ones.

The next step in the regularity investigation is to simulate the power system created in the base case with the new load connected and with expected loads in the existing power system representing the year the new load is connected. Furthermore, if the new load is to be connected several years in the future, the new power system state before and after the load connection must be investigated. The different TSO proposed power system upgrades must also be taken into account in the simulations .

The results for this particular simulation case are shown in the following figure.

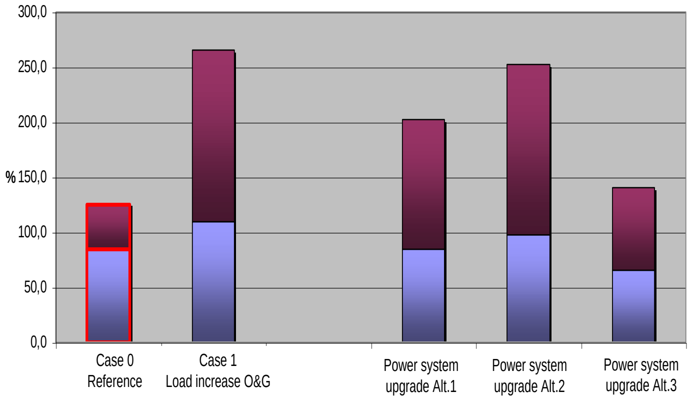

Figure 3: Evaluation of different power system upgrades

The 100% value represents the base case values at present time, while the bars represent values at the time of connection of the offshore load. The blue part of the bars represents thermal power loss and the red part represents regularity loss emerged from the expected power unavailability and the CENSE-cost.

Bar number 1 from left represents the power system before the connection of the offshore load. Bar number 2 represents the expected cost after connection of the new load. Bar number 3, 4 and 5 represents different power system upgrade proposals for correction of the reduced regularity and increased thermal power losses. The analyses results clearly show the impact on the onshore system. The cost concerning bar 1 above 100 % represents increase due to general load increase in the period from present evaluation time until connection of the offshore load. This increase alone shows that the system already is stressed even before the load is connected. This is illustrated in bar number 2. Furthermore, the power system upgrade alternatives 1 and 2, bar number 3 and 4, do not solve the power delivery problem. Alternative 2 do not solve the problem at all. Alternative 3 is clearly the best upgrade. All three alternatives include new power lines and cables with different routes. Alternative 1 and 3 represent new power lines and power cables directly connected to the new load point and are therefore reducing the regularity cost. Alternative 2 represents a power line supporting the existing power grid, which reduces the thermal power loss costs but does not have effect on the bottle necks in the system and therefore is the regularity cost almost not reduced at all.

However, the alternative most likely to be chosen is a forth alternative suggested by the offshore load company. This alternative is based on splitting the load into to two different locations at the onshore power system. By doing this almost the same properties as for the presented alternative 3 in the figure above was achieved and the planned power system upgrades that the TSO wanted to realize could be postponed.

6 DISCUSSION AND COMMENTS

This presentation has highlighted the challenges both the TSO and the oil and gas companies are faced with when connecting large loads to a onshore power system. Furthermore a methodology is presented which is applied and tested in several electrification projects in Norway. The projects results together with the difficulties concerning agreement between the partners regarding the right investment, has illustrated the need for these kinds of studies. In addition, the only way to achieve valid results for this kind of complex studies is by performing comprehensive power system and regularity analysis.

The presented method for calculating the regularity is quite new, but available experiences indicate that the method is surprisingly efficient, accurate, fast, and flexible. Large systems with high degree of details can be analyzed. A number of interesting variables can be presented; including economical data.

A load branches “breaking” point has been illustrated and the importance for identifying these for all the load branches in the system is crucial when evaluating a power systems overall regularity.

Since a power system is dynamic, variables such as power demand, power production, load flow, and short circuit levels will continuously change. The same changes also apply for the power delivery reliability results at each load branch. It is important to be aware of this fact, when operating a power system. Different action and changes in a power system will change the reliability of power delivery. Power grid operators, power system planners and the new customers to be connected to the existing power system should be aware of this and make their decisions based on the best information available.

Typical applications of the method regarding onshore power system are power system concept studies, maintenance planning, operation planning, protection strategy planning, power loss minimization and on line calculation of existing grid reliability.

Further applications of the method will be studies concerning connection of offshore oil and gas installations to the onshore power system and also offshore wind farm connection to the onshore power system.

7 "NON-ELECTRICAL" APPLICATIONS

Typical non-electrical applications are fluid flow systems including oil flow, and general material transport. Presumably also traffic and communication systems can be analyzed by this method. In these cases the power flow model is replaced by the actual system model. The principle based on unit models can also be used in general probability and reliability calculations to build extremely large models.

8 ACKNOWLEDGEMENTS

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