Simulation of shaft vibrations due to interaction between turbine-generator train and power electronic converters at the Visund oil platform

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Abstract

The Norwegian company Norsk Hydro AS has frequently experienced severe vibration problems within the power generator trains at some of their oil platforms in the North Sea. Initially, these problems were believed to have a pure mechanical nature. The generator shaft was therefore modified to increase its inherent damping, but this did only partly solve the problem. The focus was eventually directed to possible sources for the problems within the electrical power grid, especially two 7 MW variable speed drives (VSD) that serve as compressor drives. These drives are designed as current source converters (CSC), which feed synchronous motors.

In order to clarify whether the vibration problems were caused by interaction between the VSDs and the generator train it was decided to carry out a detailed analysis using the simulation tool PSCAD/EMTDC. The simulated system includes a fully detailed model of the two 7 MW compressor drives and the turbine-generator train, as well as other relevant parts of the electrical system.

The simulation results show that the VSDs can cause excessive vibration levels by two different phenomena: Interharmonics and negative damping. It is verified that the redesigned shaft gives a lower vibration level, and that the resulting vibration level becomes reduced in the presence of passive electrical loads. The results and the simulation model will be subject to further analysis in order to find permanent corrective actions to the problems, e.g. by means of dedicated power electronic devices.

1 Introduction

It is well known that power electronic converters may interfere with generators and other components in a power grid, and many publications have been presented about the subject, e.g. [1]-[3]. Problems due to interference tend to occur in power grids involving components with poorly damped natural frequencies, such as shaft and gear systems of turbine-generator trains.

At Visund, two different types of vibration problems within the turbine-generator train have been experienced. One has a transient character, and has been found to coincide with certain operating speeds of the compressor drives. The other phenomenon has only occurred a few times, but is more serious because it leads to power shutdown of the platform. It is observed as a slowly increasing vibration that develops over some time (a few minutes) to inadmissible levels, finally tripping the generator.

Early measurements have clarified that torsional and lateral vibrations occur at the lowest natural frequency of the rotating system of the turbine-generator train. Further, the node of that vibration is located to a special shaft, a so-called quill-shaft integrated with the gear between the turbine and the generator. Rotor dynamic analysis has shown that the torsional damping at the lowest natural frequency is extremely low. It is mainly determined by lateral damping within the gear transmission, transferred to torsional damping via torsional-lateral coupling. A complicating factor is also that the damping is extremely load dependent, and about 60 times higher at 10% load compared to100% load.

Initially it was assumed that the vibration phenomenon had a pure mechanical origin, independent of the dynamics of the power grid. Therefore, the quill-shaft was redesigned in order to give a higher damping, mainly by increasing its diameter from 218 mm to 240 mm. This modification reduced the vibration level, but it still remained unacceptably high.

Later on, possible interaction with the power grid came into focus as transient vibrations were found to occur at motor frequencies (compressor side) that would cause interharmonic frequencies to coincide with the lowest natural frequency of the generator shaft.

Norsk Hydro asked SINTEF Energy Research to carry out a simulation study in order to clarify whether the experienced vibration problems were caused by interaction with devices in the electric network. If such interaction could be documented, further simulations should investigate alternative countermeasures. Supportive calculations were carried out by Colding Consult ApS, and extensive data sets for the various components in the system were provided by the manufacturers and Norsk Hydro.

This paper shows the main results from the simulation study. First is given a brief description of the various interaction phenomena, followed by an overview of the modelling approach of the system. The presence of the various interaction phenomena is then assessed from the frequency domain spectrum of the simulated torsional vibration, as function of time. The simulations are done with different operating conditions.

2 Survey of interaction phenomena

At least two instability mechanisms may occur in power grids containing a generator train and power electronic converter loads. One is linked to interharmonics between the line side and the motor side of a CSC-type motor drive with thyristor rectifier and thyristor inverter. The other is linked to converters in general that is configured for running in constant power control mode (i.e. constant speed mode). This may result in a negative resistive (damping) characteristic as seen from the line side. Results from analysis of both these phenomena are presented in this paper.

2.1 Interharmonics between motor side and line side

Fig.1 illustrates the main power components of a 12-pulse CSC motor drive system consisting of a line side thyristor rectifier and a motor side thyristor inverter. The motor is a synchronous motor capable of delivering reactive power for the inverter commutation.

This configuration results in transfer of harmonics via the DC-link between each of the two AC-sides, thus giving a direct coupling between the two AC-sides in terms of harmonics. When operated as a variable speed drive, the resulting harmonics observed at the line side depend on the motor speed. The theory behind harmonic transfer through converters is well documented in several publications, e.g. in [1], [2] and [3].

For the actual compressor drive VSD with 12-pulse converters we were especially concerned about the harmonics of order 6 times and 12 times the difference frequency between the two AC-sides ($6*f_{slip}$, $12*f_{slip}$), which could give low frequency non-integer component of significant value that could interfere with the problematic natural frequency of the generator train.

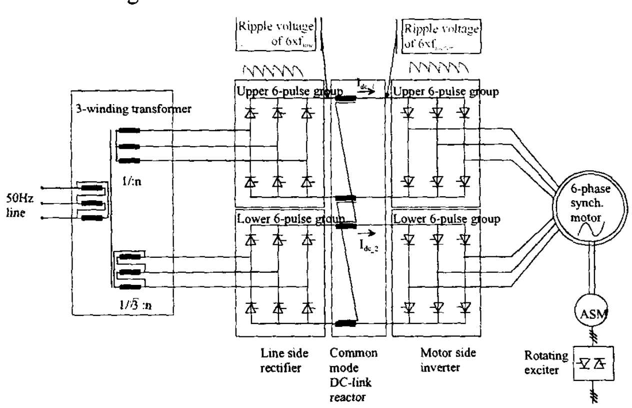

Figure 1: 12-pulse CSC motor drive system.

2.2 Negative damping from converter control

Frequency converters such as VSDs behave as active devices in the power grid. By its control system the VSD will try to compensate for disturbances in the line side, so that the influence on the load side is as small as possible. For instance, if a voltage drop occurs on the line side, a VSD configured for maintaining a specific operating point of the load will try to maintain the speed and thereby the power consumption by adjusting the control angles for the thyristor valves. This dynamic behaviour of the VSD is prevailing within the control limits of the VSD, for a CSC normally set by minimum and maximum control angles of the line side rectifier. As seen from the line side, the "constant power" behaviour of the VSD can be represented by a negative resistive characteristic, i.e. a negative damping behaviour. The presence of such components in the network represents an inherent risk for network instability, especially if there are natural frequencies with low damping in the network within a frequency range where the VSD control system is active.

3 Modelling the power grid

The simulation object is the power grid at the oil platform Visund, which is the platform that has experienced the most severe vibration problems. The platform power grid is a complex system containing a large number of drives and directly-coupled motor loads and filters at the main bus bar (11 kV), and an underlying 660 V supply system. Therefore, an important initial task was to create a reduced and simplified model suitable of numerical simulation, while still making sure that the model gives a sufficiently accurate representation of the phenomena to be investigated.

A block diagram illustrating the reduced model for simulations in PSCAD/EMTDC is shown in Fig. 2. A fully detailed dynamic model is used for each of the two main turbine-generator trains and the two compressor drives. The model also includes the harmonic filters and an equivalent passive resistive load representing the underlying 690 V system. At a later stage, some additional simulations incorporating a 5.5 MW water injection pump were carried out to check for damping effects of this component. Typical and assumed worst-case load scenarios, subject to analysis, were converted from a complete installation representation to the reduced model representation.

Most of the simulations consider the situation of a single generator feeding a single compressor drive (filters included). The reason for this restriction is firstly complexity/computing time, secondly that both instability mechanisms mentioned in section 2 can be revealed by looking at this configuration. However, if interaction between generators, or between drives is the subject of investigation, then duplication of components is required. For some simulations the modelled system is expanded with two generators, or two compressor drives.

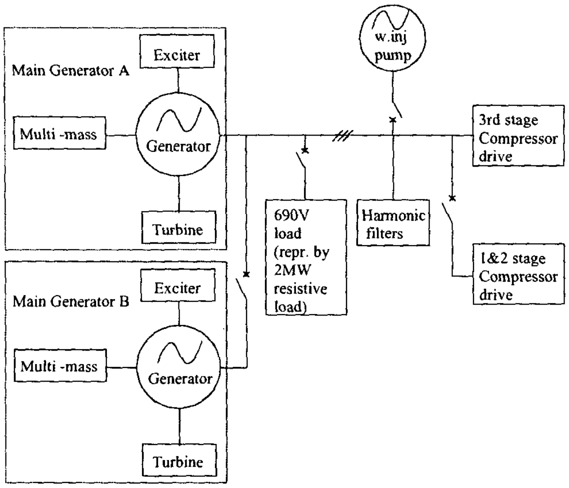

Figure 2: Block diagram of simulated system in PSCAD/EMTDC.

4 Modelling the turbine-generator train

Fig. 3 shows a block-diagram of the generator train including the synchronous generator (SM), the shaft (multi-mass), the turbine with governor, and the exciter. Also shown are the filters.

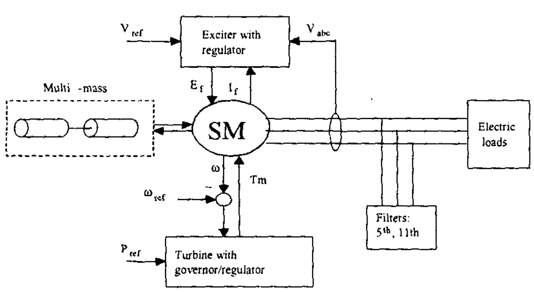

Figure 3: Block diagram of the generator train with governor and exciter.

Data for the components was obtained from the manufacturers. Detailed dynamic representations are used for the exciter and the governor, including the control loops. The power reference (P_{ref}) of the governor control was set to zero in the simulations, due to lack of information. This, however, is not believed to affect the conclusions in this paper.

Measurements have shown that the vibrations occur across the reduction gear as an oscillation between two masses. Therefore, a two-mass representation with damping is used for the turbine-generator shaft, with parameters calculated by the Colding Consult. The model is defined by two inertias, a spring constant, and a damping coefficient. A fixed value for the damping coefficient was used, corresponding to a low load situation. It is believed that this shaft model will give a fairly accurate representation of the shaft dynamics around the lowest natural frequency of concern, while the shaft dynamics above that frequency are not taken into account.

The model incorporates a fixed conversion of lateral mode damping to torsional damping, which is a simplification compared to a true model of the dynamic coupling between the two modes. There might be some uncertainty involved with this simplification. This was to a certain degree taken into consideration by doing some sensitivity analysis by varying the damping coefficient.

5 Modelling the compressor drive VSDs

5.1 Converter system overview

The power circuit of the converter system (Siemens SIMOVERT S) is the same as explained in section 2.1, with reference made to Fig 1. The control system is very similar to what is common for this type of synchronous motor drives, and is principally and briefly as follows:

- The line side rectifiers, consisting of the two 6-pulse groups, are controlled by individual current control loops. The DC-link currents are measured indirectly. I.e. they are deduced from measured phase currents on the valve sides of the converter transformer. The outputs from the current loop error amplifiers are linearized by an arcus cosine function, and transferred to gate signals synchronized to the line side phase voltages.
- The current control loops get their references from the output of an outer speed control loop. The speed is measured indirectly. I.e. it is deduced from measured machine voltages and currents.
- The motor side inverter has to be synchronized to the motor side phase voltages, and the gate signals are controlled in such a way that the extinction angles of the thyristors are kept within safe limits.
- The converter applies calculated flux from measured machine voltages and currents as feedback to the excitation controller.

5.2 Data support

The simulation model in PSCAD/EMTDC of the drive system, all the way from the converter transformer on the line side to the motor torque in the load end, is based on information from the manufacturer. More precisely, dynamic data for the following power circuits and control electronics was adapted to the simulation model:

- Converter transformer
- Line side rectifier
- Motor side inverter

- Synchronous motor and load
- Line-side rectifier control
- Current transducer model
- Current error amplifier
- Linearization of firing angle
- Current set point sampler
- Speed error amplifier, ramp-up limiter and filtering of actual value
- Motor-side inverter control
- Modelling of firing angle control
- Modelling of excitation

The modelling of the line side harmonic filters is based on information from Norsk Hydro.

5.3 Summary of approximations and uncertainties

In some areas the converter model is probably unnecessarily detailed as regards the problems under investigation. In other areas some approximations were necessary because of either missing information, or model limitations in PSCAD/EMTDC. However, the approximations are assumed to have only a small affect on the studied converter interaction problems. The approximations of most concern are:

- Dynamics for the synchronization of control angles for the rectifier and inverter.
- The dynamics of the load-torque characteristics
- The dynamics of the excitation controller

6 Simulation of interharmonics

In order to examine the hypothesis of interaction between the generator train and interharmonics from the VSDs as described in section 2, simulations were carried out for different power grid situations:

1) One VSD is accelerated so that the interharmonic components produced at the line side momentarily coincide with the natural frequency of the generator train.
2) One VSD is operated in stationary condition at speeds that coincide with the natural frequency of the generator train.
3) Repetition of tests 1) and 2) when there are loads in addition to the VSD.
4) Effect of two-generator operation.

All simulations were carried out using the modified (240 mm) quill-shaft.

An example from the simulations is shown in Fig. 4. This is obtained from an operating situation where the motor is ramped up from 45 Hz to 55 Hz, thus passing through the frequency points where the critical shaft frequency coincide with $6*f_{slip}$ and $12*f_{slip}$, as explained in chapter 2.1

Description of plots in Fig. 4 (from top):

No1: The generator frequency and the motor frequency. The motor is initiated with a speed corresponding to 45 Hz, in order to avoid the long simulation time involved with starting from standstill. When connecting the VSD at t=5 sec), the motor frequency initially drops because of the lag within the VSD speed control loop.

No2: The calculated values for $6 \cdot f_{slip}$ and $12 \cdot f_{slip}$. According to the theory, torque oscillations could appear when these quantities become equal to the natural shaft frequency (14.36 Hz), which is shown with the horizontal line.

No3: The electrical air gap torque (T_e) and mechanical torque (T_m)

No4: The torsional torque (T_{12}) at the node between the two masses. It is seen that large oscillations are excited in T_{12} each time 6·fslip and $12 \cdot f_{slip}$ pass through 14.36 Hz (see No 2). However, the second time $6 \cdot f_{slip}$ passes through 14.36 Hz (t=32.5 sec) the oscillation decays instead of increasing. This could be a result of the excitating oscillation being in opposite phase with the already present oscillation. The peak value of the oscillation is 0.125 p.u. of the nominal generator torque.

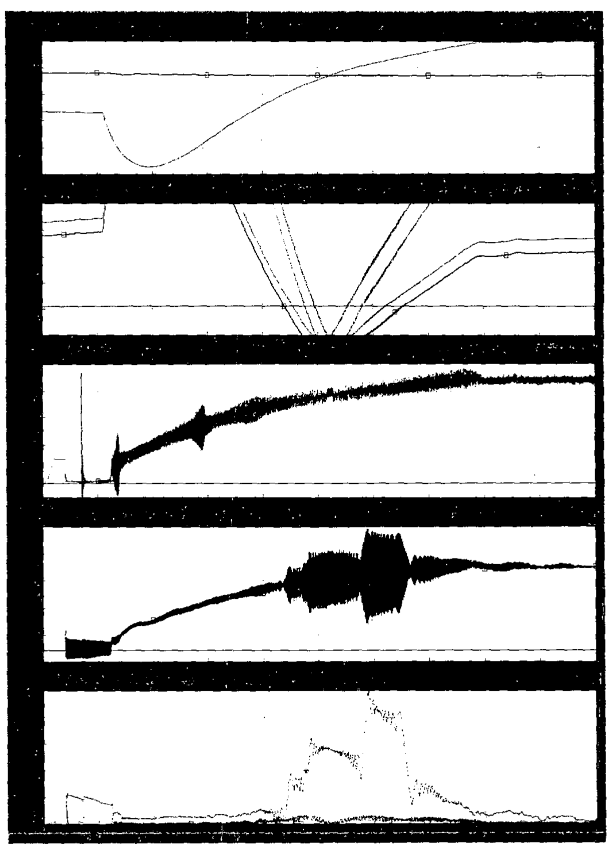

Figure 4: Ramping up motor from 45 Hz to 55 Hz

No5: The rms-value of the 14.36 Hz oscillation component, for T_e, and T_{12}. It is clearly seen that the torque oscillation is strongly present in T_{12}, and weakly present in T_e.

Fig. 5 shows the frequency spectrum in the range t=0 sec to t=35 sec for the torsional oscillation torque T_{12}. The spectrum is seen to be dominated by the 14.36 Hz oscillation component. Similarly as in the time plots, the vibration level increases strongly when passing through the critical frequencies that are indicated in the figure by $6 \cdot f_{slip}$ and $12 \cdot f_{slip}$.

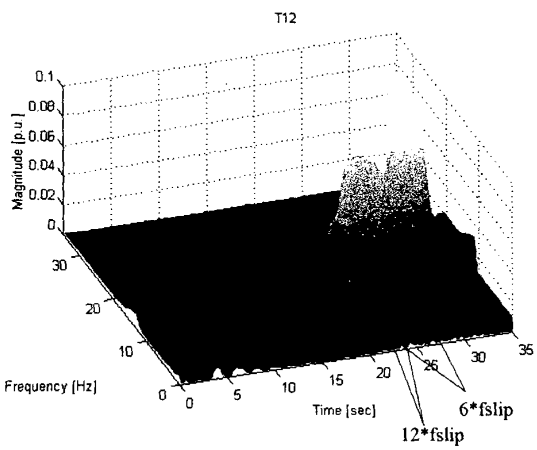

Figure 5: Frequency domain analysis of T_{12}.

A similar analysis was carried out for several state variables in the generator train, in the AC-grid, and within the converter. E.g., for the DC-link current of the VSDs, "bands" were found in the DC-link current at $6{*}f_{slip}$ and $12{*}f_{slip}$, thus verifying that the actual converter behaves like a current source at interharmonic frequencies.

7 Simulation of negative damping

In order to determine if the observed phenomenon of a slowly increasing vibration level under constant operation of the VSDs can be linked to the converter loads, systematic simulations were carried out under different load conditions. The simulations include the following:

1) One VSD fed from a single generator with original quill-shaft (218mm). No additional load.
2) Two VSDs fed from single generator with original quill-shaft (218mm). No additional load.
3) Two VSDs fed from single generator with modified quill-shaft (240 mm and 290 mm). No additional load.
4) Simulations with additional load, e.g. a 5.5 MW water injection pump.

An example from these simulations is shown in Fig. 6. This is a simulation where a single generator with the original shaft feeds two compressor drives. The motors are running at 40 Hz and 45 Hz respectively, which is outside the operating points where interharmonic interaction takes pace (to be sure that the two phenonenons are not mingled). There are no additional loads. The vibration level monitored at the critical node is seen to increase in an exponential way, demonstrating an unstable situation.

Description of plots in Fig. 6 (from top):

No1: Generator frequency and motor frequency

No2: Six times and twelve times slip frequency. (Controls that that interharmonic frequencies does nor interfere with critical frequency of 14.36 Hz during this simulation)

No3: Generator mechanical and electrical torques.

No4: Torque at the critical node of the turbine-generator train

No5: The rms-value of the 14.36 Hz oscillation components for T_{12}.

No6: DC-link current of compressor drive upper twelve-pulse group

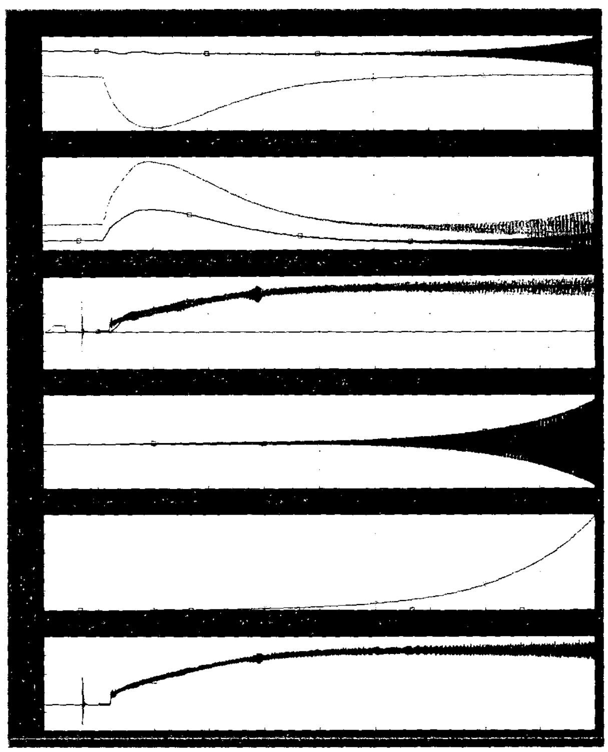

Figure 6: Two compressor drives fed from single generator – Shaft diameter 218 mm.

8 Conclusions

General conclusions

- Simulation using PSCAD/EMTDC have demonstrated that interaction can take place between the turbine-generator shaft and the converter loads in the electric network at Visund. Both the interaction mechanisms described in section 2 have been identified and demonstrated.

- The mechanical modifications of the generator train (redesign of the flexible shaft between gear and generator) were shown to give a stronger damping of the vibrations, thus verifying the experience on board Visund.
- The presence of an additional resistive load of 2.0 MW in the 11 kV network was shown to mitigate the instabilities.
- A positive damping effect was also found to result from the 5.5 MW water injection pump. In the case of the modified shafts, the unstable behaviour shown in fig. 6 was mitigated, while unstable behaviour was still possible with original shaft. The damping from the pump motor is not as effective as that of a pure resistive load with same power consumption.
- Time domain simulations using the PSCAD /EMTDC software have proved to be a highly effective approach in clarifying possible interaction phenomena in power grids with power electronic converter loads. However, successful application of this tool requires that the power electronic control loops etc are modelled with sufficient details, and that sufficient data is available from the manufacturers. In order to get full insight into the mechanisms behind the phenomena, supplementary tools like frequency domain analysis are required.

Conclusions regarding interharmonics

- It has been confirmed that excessive torsional shaft oscillations can occur due to interaction between the generator shaft lowest natural frequency and interharmonics generated by the compressor drives.
- The source of the interactions was found to be frequency components in the DC-link currents generated by the difference between the fundamental frequency of the generator (f_g) and the motor (f_m). When the motor frequency is such that $6*|f_g-f_m|$ or $12*|f_g-f_m|$ coincides with the lowest natural frequency of the generator shaft, excessive shaft oscillations result.
- When the compressor drive is allowed to run through critical operation points with its maximum slew rate, and with no additional load in the grid, then the torsional vibration level reached 0.24 p.u. peak-peak.
- If the drive is allowed to stay at critical speeds, the oscillations will reach unacceptable levels. Oscillations at the lowest natural frequency of the shaft have been simulated with amplitudes as high as 2.5 peak-peak of the nominal generator torque (at $6*f_{slip}$)). It should be emphasized that nonlinearities are expected to become important at such high oscillation levels, resulting in inaccurate simulation results.
- The simulations also indicate that the control system of the actual compressor is passive with respect to this phenomenon. This, however, is not fully investigated, and will be subject for further studies.
- The simulations also imply that neither the turbine governor nor the exciter interferes with the oscillations introduced by interharmonics.

Conclusions regarding negative damping

- Exponentially increasing generator shaft oscillations due to negative damping has been simulated for a situation where one generator powers both compressor drives. The instability depends on the inherent mechanical damping of the turbine-generator train, and the additional electric damping (resistive load) in the power grid. A positive damping effect from the 5.5 MW water injection pump has also bee demonstrated.

9 Further work for evaluation and selection of countermeasures

One sub-target for the simulations was to establish a tool for evaluating alternative or supplementary countermeasures to shaft modifications. This is planned as an activity to be continued. For the time being, the following countermeasures have been considered:

- Possible modifications of the generator exciter system and the control system of the compressor drive VSDs.
- A dedicated active DC-type filter or attenuator in the DC-link of the VSDs, tuned to the critical generator shaft frequency.
- A dedicated active AC-type filter or attenuator in the 11kV network, directly, or preferably via a transformer. A such device could also be configured to take care of other possible interaction sources in the platform power grid.

References:

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