A model based approach to optimize controls of a large LCI VSD for minimal grid-side sub-synchronous torsional interaction

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Pieder Jörg
ABB MV Drives
Austrasse
Switzerland

Adrian Tresch
ABB MV Drives
Austrasse
Switzerland

Martin Bruha
ABB MV Drives
Austrasse
Switzerland

Abstract - Local power generation units in an industrial grid have a certain risk for interacting with power electronics loads (drives, VAR compensators, grid interties), especially if these are of comparable power. Interaction is most prone to happen at the lowest torsional natural frequencies of the power generation equipment. The paper reports, how the level of such sub-synchronous torsional interaction (SSTI) is affected by the dynamics of the controls of a large VSD.
Unlike other factors, namely the mechanical properties of the generator and the grid impedances, the damping effect of the VSD's control system can be adjusted to some extend via parameterization. A linear model based approach is reported and demonstrated with a 20MW drive installation, which allows optimizing sub-synchronous torsional damping while maintaining the necessary dynamic response to load- and reference-changes in the VSD system. In the proposed approach, only the critical frequencies of the generator and the driven equipment have to be known, while grid data and influence of other loads needs is segregated from the optimization.

Index Terms — Variable Speed Drives, LCI, Sub-Synchronous Torsional Interaction, Interharmonics, Electro-Mechanical Interaction, Closed-Loop Stability.

I. INTRODUCTION

Two very similar phenomena have been discussed in literature separately, mainly because they have been observed in different fields of application. On one hand, when planning for variable speed drive (VSD) powered turbo machinery, the chemical, oil and gas industry knows it has to deal with the excitation of rotating mechanical systems (loads) by harmonic and inter-harmonic torque pulsations, which are created as "by-product" of the electric frequency conversion.

On the other hand, when high voltage DC (HVDC) power transmission is installed close to power generation, similar electro-mechanical interactions are observed between the rotating mechanical system of the generator and the adjacent HVDC inverter substation. The phenomenon is called sub-synchronous torsional interaction (SSTI) in power transmission and distribution, as instability normally shows at the lowest (and thus sub-synchronous) torsional natural frequency of the generator.

The power electronics circuit of an LCI-type (load commutated inverter) VSD and the power conversion from AC to DC and back to AC of a classic HVDC link are based on the same topology, the simplest representative of which is shown in Fig. 1.

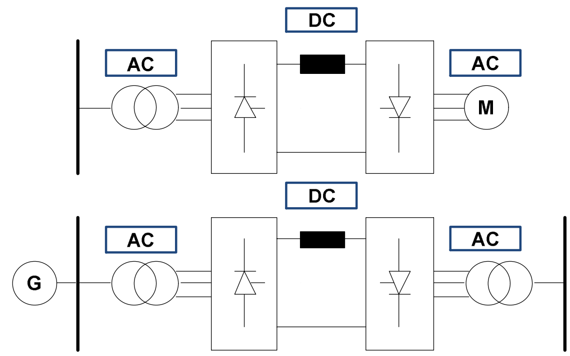

Fig. 1: Simplest circuits representing an LCI based VSD (above) and a classic HVDC link with local power generation (below), showing their similarity.

The similarity is obvious and so it is for the described electro-mechanical interaction: torsional interaction with driven rotating equipment in case of VSD and torsional interaction with the generating rotating equipment. However the approach in engineering is historically very different. For VSDs, pulsating torques are calculated analytically for the feed-forward controlled converter/motor system. This torque is applied for torsional analysis purposes to the respective motor mass in a mechanical train model [1].

For HVDC installations, a damping contribution per torsional natural frequency of the feed-forward controlled inverter is analytically derived and then compared to the natural mechanical and electrical damping of the generators and the local loads to grid [2]

The importance of closing the control loop, with the speed resp. motor position feedback for quantification of harmonic and inter-harmonic impact, has only recently been highlighted for electric motor drives [3-6] , while for HVDC, some control contribution was factored into the damping coefficients, however without making them dependent on input, e.g. frequency dependent grid impedance behavior.

This paper deals with a field case where sub-synchronous torsional interaction occurred between power generation equipment and a large VSD, partly in combination (and supported) by torsional interaction with the driven equipment, in this case a complex turbo-compressor train.

II. FIELD CASE DESCRIPTION

A. System Description

The system under study is a large LNG production facility with local power generation and a predominant power electronic load, given by 3 large 20MW LCI drives

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(Fig. 2) and power generation consisting of up to 4 gas-turbine generators (GTGs) of about 40MVA each, with roughly 180MVA short-circuit capacity (SCC) per GTG unit. Particular is the presence of local power generation equipment close to the VSD, as the generator and its prime-mover (here the gas-turbines) are equally sensitive equipment from a torsional standpoint. There is no connection to another supply grid.

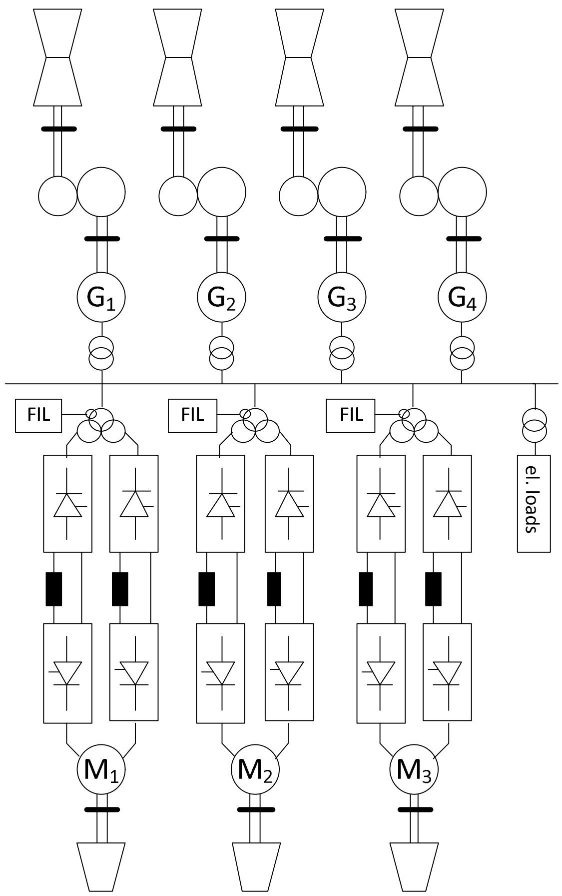

Fig. 2: The system under study, with the 3 large compressor drives as the dominant load and the 4 gas turbine driven generators.

The system has various critical frequencies, as all the three compressor trains and all the four generators do have relatively weakly damped low frequency torsional modes. The dominant modal frequencies are given in Table I

TABLE I
Dominant torsional natural frequencies of the plant

Equipment Designation	1^{st} TNF	2^{nd} TNF
GTG (4 identical)	9.5Hz	29.7Hz
1^{st} compressor	9.5Hz	18.6Hz
2^{nd} compressor	9.83Hz	23.46Hz
3^{rd} compressor	14.9Hz	21.8Hz

It can be seen, that the frequencies are very close to each other. A particularity of the plant is the coincidence of the first mode of compressor train #1 with the first mode of the GTGs.

B. SSTI Risk Assessment

The interaction between an HVDC converter and a machine is assessed by means of the unit interaction factor (UIF), a method presently not used outside the power generation and transmission community. The factor is evaluated for one VSD at the time. For this VSD, one-by-one, each power system configuration is considered, while always one unit ("the last unit to come online") is checked for interaction risk with that VSD. If the UIF_i of one VSD against the i:th generation unit, with i-1 other generation units running already, is higher than 0.1, then there will be a risk of SSTI [7]. These assessment calculations are always made prior to an HVDC project in a so called screening study . If this study shows that there is no risk of adverse interaction, no further SSTI detailed study will be made.

Due to the similarity of power electronics topology, the risk for sub-synchronous torsional interaction between VSD and power generation, or even between compressor train and power generation (through the VSD) is proposed to be evaluated by using the same factor. The factor for one VSD and the i:th unit coming online is defined as follows:

$$UIF_i = \frac{MW_{VSD}}{MVA_i}\left(1 - \frac{SC_i}{SC_{tot}}\right)^2$$

where:

- UIF_i Unit interaction factor of i:th generation unit
- MW_{VSD} MW rating of the VSD
- MVA_i MVA rating of the i:th generator machine
- SC_i Short circuit capacity at the VSD supply bus excluding the i:th generation unit
- SC_{tot} Short circuit capacity at the VSD supply bus including the i:th generation unit

After the experience with the here presented system, we recommend evaluating the UIF per train for each project, as if the train would run solo i.e. MW_{VSD} equals the power of one unit. This is typically only the case during the commissioning, but also this operation needs to be ensured.

The unit interaction factors (UIF) for one VSD running is evaluated and given in Table II for different number of GTGs in operation.

TABLE II
UIF per individual GTG and 20MVA drive load

#GTG in operation	UIF of one GTG unit
2	0.125 (→ SSTI risk)
3	0.056
4	0.031

For the case where 2 GTGs are running, the qualitative evaluation shows a risk for sub-synchronous torsional interaction, a risk which materialized in field during the commissioning phase of the plant, when the respective operating conditions were met.

The evaluation of the UIF is clearly only an indicator for SSTI-risk. In practice we have observed SSTI also for the configuration of 3 GTG running with 1 VSD as load, and with very little additional loads (typical for commissioning phase).

The numbers that go into the UIF also clearly neglect the fact, that the VSD is an active load, i.e. that the control circuits with their settings for controlling e.g. thyristor firing, intermediate DC current or electric motor speed do affect the torsional stability for equipment connected to either side of the converter system.

C. Measured Sub-Synchronous Torsional Interaction

During one of the first start-up attempts of the train #2, we found the DC link current of the VSD and, as consequence, the air-gap torques of both load motor and generators, to behave as shown in the waterfall diagram in Fig. 3. The diagram shows the frequency content of the DC-link current over time. The DC-link current is a very good representative of air-gap torque. From left to right, the compressor train accelerates from 1200rpm (20Hz electrical) to 3600rpm (60Hz). The acceleration ramp lasts about 500s, which is shown on the x-axis.

The spectra are plotted in logarithmic scale, in order to reveal all the signal content The diagonal lines are interharmonic torque pulsations of the LCI. They are changing as a function of speed. The horizontal lines are speed independent pulsations, such as the torsional natural frequencies or integer harmonics of the grid frequency. The interharmonics of the LCI go to zero at several speeds, e.g. for 12* line frequency - 12*motor frequency this can be seen around 420s, where a motor frequency of 50Hz (3000rpm) is reached.

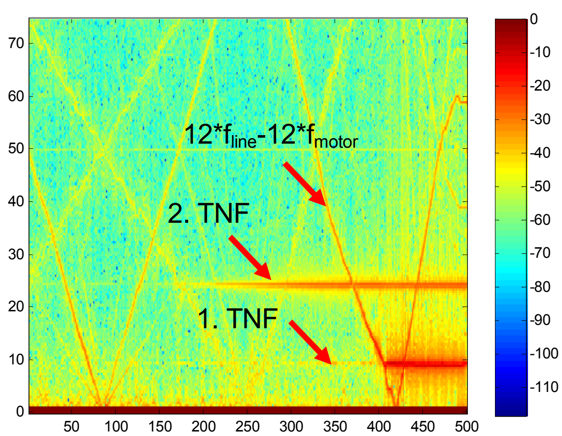

Fig. 3: Waterfall diagram of VSD DC-link current of a start-up of compressor train #2 (y: frequency [Hz], x: time [s], color-map: logarithmic intensity of frequency component). DC current is representative for air-gap torque for both motor and generator.

Around 400s into the measurement, the same inter-harmonic is crossing a torsional natural frequency around 9.5Hz. The TNF is excited and then latches into an instability. Further analysis revealed it was the first TNF of the GTGs and in consequence, lateral vibrations in the GTG's gearbox were already approaching trip limits.

The second TNF of the train #2 can also be distinguished. It is visible in this logarithmic plot as soon as some load is transferred through the VSD. The excitation level is however within acceptable limits.

At this point, a model based approach was chosen to understand the role of the converter and its controller to reject sub-synchronous voltage due to GTG torsional oscillations and to decouple the load mechanical system and the GTG mechanical system from each other.

III. MODEL BASED APPROACH

A. Modeling of the LCI current control loop

In search for a simplified model, which is good enough to capture the effects encountered during commissioning of the plant, it was decided to focus on the current control loop and to think of the voltage fluctuations due to torsional oscillations on generator and motor as disturbances to that circuit.

Fig. 4 shows a block diagram from which we will derive the transfer functions of the current control loop. Both inverters are producing a DC-voltage out of their respective AC voltages. The motor side AC voltage, and thus also the DC voltage, are by principle controlled so that the voltage is proportional to the motor stator frequency. Theoretically, the rectifier would always be running at the same operating point, which is only slowly adapted in practice for system performance optimization. The line side AC voltage is turned into a variable DC-voltage which has to drive the desired current through the DC-link inductor against the rectified motor voltage.

AC voltage deviations from pure fundamental voltage, e.g. due to harmonic distortion by other equipment (line sie) or induced by torsional oscillations of the electric motor (load side), are entering into the DC link through the respective inverter: Frequencies other than the inverter operating frequency are passing unchanged into the DC voltages (Udc1 resp. Udc2 in Fig. 4) and are driving corresponding AC currents of the same frequency in the DC-link inductor. This can for example be seen in the spectra in Fig. 3, where the excitation of the torsional natural frequencies is becoming visible at the identical frequencies in the DC-link.

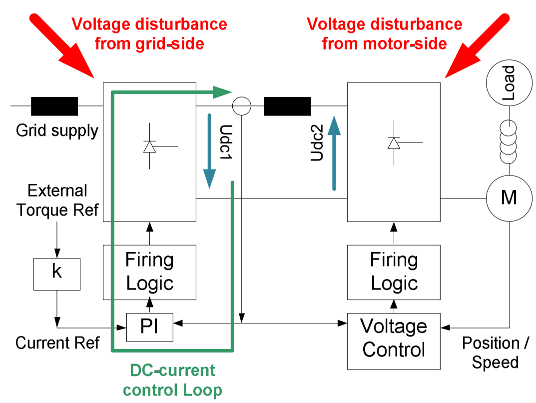

Fig. 4: Schematic diagram of current control loop of an LCI, where the mechanical oscillations of both grid and motor-load are modeled as voltage disturbance.

Fig. 5 shows a block diagram of the current control loop, which directly can be transformed into a transfer function. For small signal analysis, this linear model needs not to include the motor side, as it represents a constant DC voltage inside the loop.

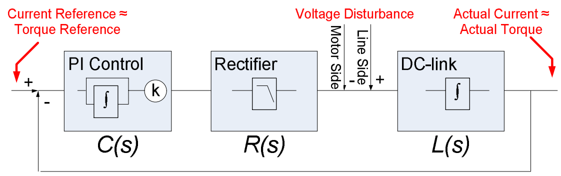

Fig. 5: Block diagram of the current control loop for torsional stability study purposes.

The current controller is of classic PI type. The control part of the model is formulated in p.u., with scaling by nominal current I_{nom} at the input:

$$C(s) = \frac{1}{I_{nom}} \cdot k_P \left(\frac{T_i s + 1}{T_i s} \right)$$

The rectifier is modeled as first order delay and scaled with the nominal rectifier DC voltage U_{DC1nom}. The delay of a 12-pulse rectifier is assumed to be maximum 1/12 of the period and minimum zero. The mean-delay is T_U thus the line frequency period T divided by 24.

$$R(s) = \frac{1}{1 + sT_U} \cdot U_{DC1nom}$$

where

$T_U = T/24$ average delay time based on line frequency period T

The DC-link is modeled as an ideal inductor.

$$L(s) = sL_{DC}$$

The disturbances in the AC line voltage and motor voltage are fed with correct sign as AC disturbances to the DC-voltage that drives the current in the DC-link inductor. The two noise sources are applying voltage to the DC-link inductor with opposite sign. The same voltage disturbance on both side would consequently be cancelled and not impact the current regulation, which is typical for common mode voltages. However – when referring back to the full schematic in Fig. 4 – it will exchange energy through the DC-link without affecting the DC-current.

Depending on practical implementation (e.g. for different VSD vendors), additional blocks such as current feedback filters etc. will have to be added.

If we want to study stability of the current controller with respect to reference, but also with respect to noise/disturbance, we can now plot the bode diagram of the open loop. The diagram in Fig. 6 is taken for one of the 20MVA VSD in the system of study. These are dual channel 6p LCI, with – per channel – nominal DC-link current of 2062A. nominal rectifier DC-voltage of 5103V and a DC-link inductance of 7.5mH. The current controller is set according the symmetric optimum. This means the kp and the Ti is chosen such that the 0dB crossing is near the maximum phase and in the middle of that section of the gain, which falls at -20dB. This tuning principle results in a *kp* of 0.1 and a *Ti* of 200ms. Setting the controller according symmetric optimum would be the typical parameterization for such a VSD and established the base-line for the following experiments.

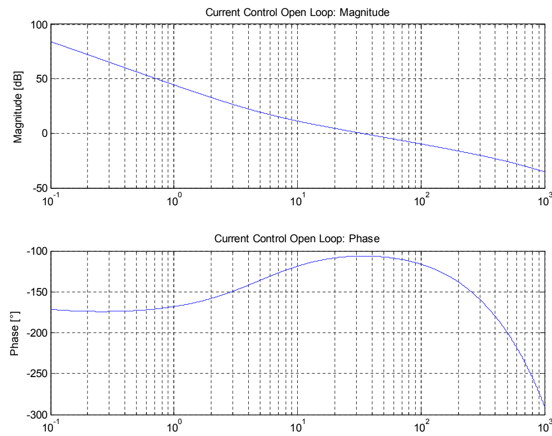

Fig. 6: Open loop bode diagram of the current control loop in Fig. 5 with controller settings according symmetric optimum (*kp*=0.1, *Ti*=0.2), x-axis labeled in rad.

One can nicely distinguish the following areas in the magnitude plot. At the low frequency end, the curve drops at 40dB/decade due to the DC-link and the I-part of the PI-current-controller acting together. Then, starting from around 1Hz, the curve is falling with 20dB per decade only. This is the effect of the DC-link inductor. At higher frequencies, the first order delay of the rectifier starts to come into the picture. In addition, there is a second order low pass filter in the current measurement in this particular VSD, which will reduce gain and add phase above 500Hz. However with this setting, the filter is not entering the topic of interest of this paper.

The closed loop transfer functions of the control system for the reference and for the disturbances are very similar and do have the same denominator. This means, that for stability, the diagram in Fig. 6 is valid to study both cases.

$$\frac{C(s) \cdot R(s) \cdot L(s)}{1 + C(s) \cdot R(s) \cdot L(s)}$$ reference to output

$$\frac{L(s)}{1 + C(s) \cdot R(s) \cdot L(s)}$$ disturbance to output

B. Experimental data

There were two things out of the first experimental start-up in Fig. 3 that needed an explanation:

1) Why is the current controller not countering the oscillation at 9.5Hz in the DC-link current?
2) The 1st TNF of GTG and the 1st TNF of train #2 are very close: Is there a combined electro-mechanical interaction with two mechanical systems involved?

In order to answer the first, we turn to the bode diagram in Fig. 6. With 9.83Hz, the first torsional natural frequency of the compressor train #2 is above the 0dB point of the open loop control characteristic. Furthermore, the transfer function from disturbance to DC-link current can be plotted for various controller gains now. When looking at Fig. 7, it can be seen, that for a kp of 0.1, a voltage disturbance applied to the DC-link inductor will be amplified and have a relatively larger current as consequence. At a torsional natural frequency, this current will again excite the generator (or the motor) further and lead to more voltage disturbance. Or in other words: The control system of the VSD has a negative contribution to the damping of the torsional natural frequencies and risk for SSTI/closed loop torsional interaction is high.

With a phase shift close to 90 degrees, the torque produced by this current has also the worst possible phase-relationship, as air-gap torque of the generator (or the motor) will be following motor mass speed by 90 degrees as well, thus optimally "pumping" the torsional resonance like this.

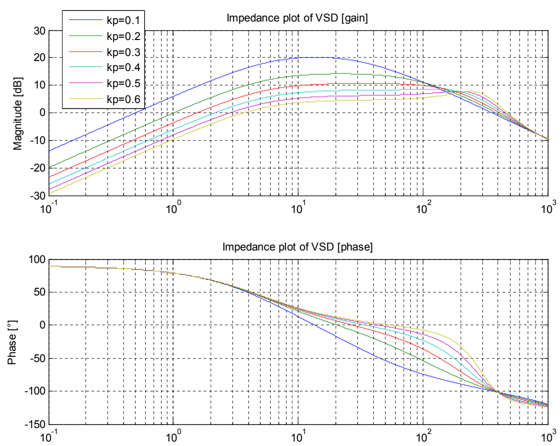

Fig. 7: Transfer function from a voltage disturbance to the actual DC-link current, plotted for different gains of the current controller and scaled to p.u..

With the previously described model, a series of experimental load tests with the different kp settings as in Fig. 7 were planned and – due to availability – executed on train #1. In these tests, load is varied in steps, while speed is always close to 100%. With the island grid of the system under study, both train #1 and train #2 showed the same behavior, which was to be expected as all VSDs were identical. With base-line settings for the current controllers, the first TNF of the GTGs was undamped to an extent that was not tolerable. Both trains and the GTGs have their first TNFs very close to each other, for train #1 and GTGs they are even identical to the first digit after the comma. Consequently, the train #1 took also part much stronger in the SSTI of the VSD with the generators.

Fig. 8 shows the waterfall plots of the DC-link current, which largely corresponds also to air-gap torque of the electric motor. For values smaller than kp=0.2 the measurement sequence could not be completed, since torsional oscillation turned out to be too large for increased load currents. The series of full measurements was only possible starting from kp=0.2. With increasing kp, the frequency, at which the undamping is the strongest and gives most rise for torsional instability, is shifted from the 1st TNF (kp=0.1 or smaller) to the 2nd TNF (kp=0.3) and finally above both TNFs (kp=0.6). The same effect is observed on both sides, at the GTGs as well as at the compressor trains.

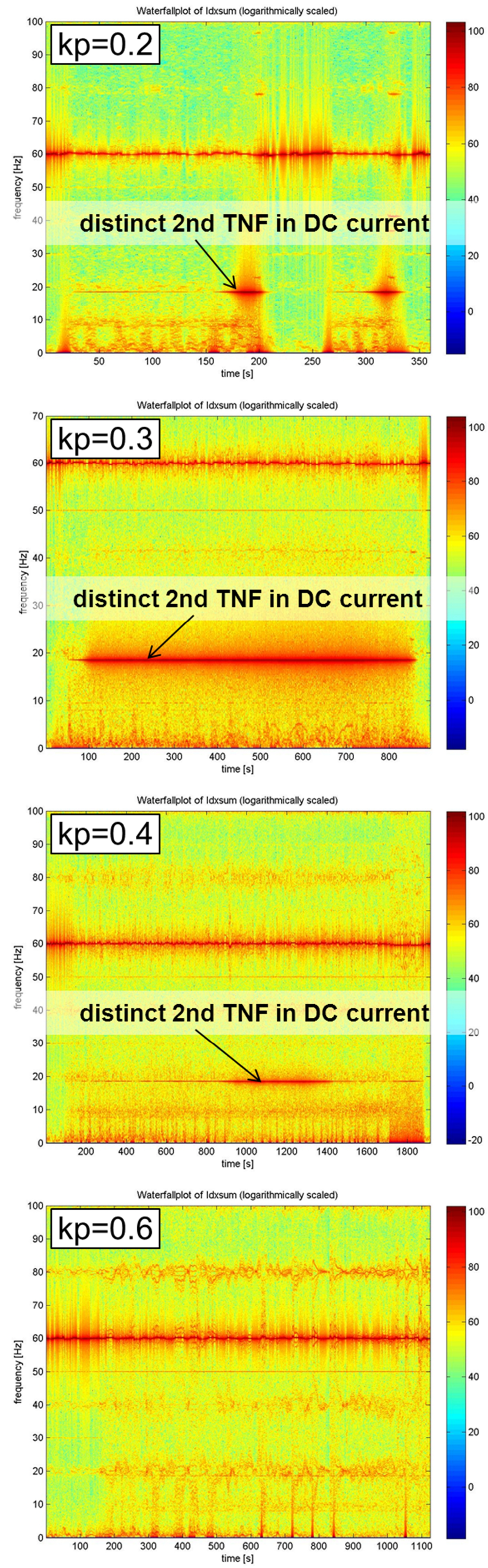

Fig. 8: Waterfall plots of DC-link current under various loads at steady speed for different current controller gains. DC-link current largely corresponds to electric motor air-gap torque.

Any kp>0.2 is already sufficient not to excite the GTGs 1st TNF, however due to the presence of the 2nd TNFs of the compressor trains, the gain needs to be increased further. Note that the equally strong 60Hz component corresponds to the electric motor frequency, is purely electrical and is of no concern to the mechanical performance.

The second topic for further experimental scrutiny was the impact of having torsional natural frequencies lying very close to each other. As mentioned earlier, identical frequencies, in perfect counter-phase, could actually cancel their impact on the DC-link, but they would still be exchanging energy through the VSD. The amount of energy (voltage-disturbance times DC-link current, over time) even scales linearly with the DC-link current. But in this case, there would be no possibility to counter-act them with the current controller. From the experience with the plant however, it seems that this case is in practice probably not occurring.

Nevertheless it could be observed, that the amplitude of the resonance limit cycle, be it under line side SSTI or be it under compressor side electro-mechanical torsion interaction, is changing nearly linearly with the load, which means with the power transfer through the VSD. The simplified model approach doesn't reflect this, as fundamental frequency and torsional natural frequencies should be independent of each other in a linear system. To illustrate, the time-series of the load test with kp=0.2 (cf. Fig. 8) is given in Fig. 9. The load peaks correspond with the highest excitation of the 2nd TNF, even though there is no direct excitation of it as function of a converter harmonic or an interharmonic, which would be scaling with load current.

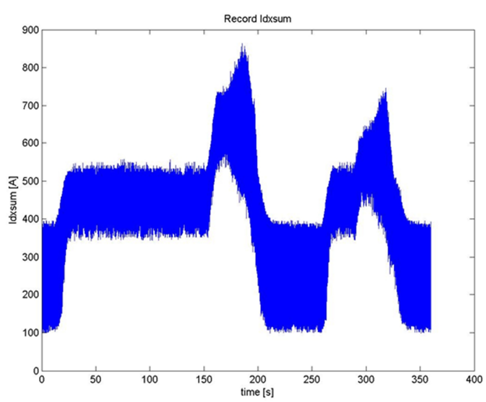

Fig. 9: Time series of the load applied during experiment with kp=0.2. Excitation of the 2nd TNF scales with the fundamental power.

C. Discussion of found parameter settings

Increasing the gain of the current controller means also moving away from the symmetric optimum. As long as only a simple PI is used, there is only this one degree of freedom in order to optimize disturbance behavior. Any change will also affect reference tracking behavior. Higher proportional gains particularly mean higher 0dB crossing frequencies with lower phase-margins. The controller follows the reference quicker, but also with overshooting. In addition, there are other resonances in the system, which also need to be avoided, both of electrical and. mechanical nature (e.g. filter banks, higher torsional natural frequencies, …). The 0dB of the current-control loop might get close to one of these.

II. CONCLUSIONS

A simple linear model of the current control loop is established, and both torsional oscillations of the load, as well as of the generators, are modeled as disturbance to that loop. The simple model allows to visualize how to choose the parameters of the current controller in case of SSTI or electro-mechanical closed-loop interaction on the load side.

Further studies will be necessary to fully understand impact of cross-coupling between load trains and generator as well as scaling with current. The simple model approach will not be able to quantify the amplitude of the resonance limit cycle; however it will help to choose the current controller such that all involved torsional natural frequencies are sufficiently damped.

III. ACKNOWLEDGEMENTS

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VI. ABREVIATIONS

LCI = load commutated inverter
LNG = liquefied natural gas
GTG = gas turbine generator
PI = proportional integral (controller)
SCC = short circuit capacity
VAR = volt-ampère reactive (reactive power/current)
VSD = variable speed drive
HVDC = High voltage DC (transmission)
SSTI = Sub-synchronous torsional interaction
TNF = Torsional natural frequency
UIF = Unit interaction factor

VII. REFERENCES

[1] API 684 Rotordynamic Tutorial: "Lateral Critical Speeds, Unbalance Response, Stability, Train Torsionals and Rotor Balancing"

[2] Padiyar K.R., "HVDC Transmission Systems", Wiley Eastern Limited, New Delhi, India, ISBN 81-224-0102-3, 1990.

[3] V. Hutten, R. Zurowski, M. Hilscher, "Torsional Interharmonic Interaction Study of 75 MW Direct-Driven VSDS Motor Compressor Trains for LNG Duty", *Proceedings of the 37th Turbomachinery Symposium.*

[4] C. Sihler, S. Schramm, J. Song-Manguelle, P. Rotondo, S. Del Puglia and E. Larsen, "Torsional Mode Damping for Electrical Driven Gas Compression Trains in Extended Variable Speed Operations", *Proceedings of the 38th Turbomachinery Symposium*

[5] S. Del Puglia, S. De Franciscis, S. Van de moortel, P. Jörg, T. Hattenbach, D. Sgrò, L. Antonelli, S. Falomi, "Torsional Interaction Optimization in a LNG Train With a Load Commutated Inverter", *Proceedings of the 8th IFToMM International Conference on Rotordynamics* 2010, Seoul, Korea

[6] P. Jörg, A. Lenzi, V. Depau, „Optimization of Transient Behavior of Complex Turbocompressor Shaft Lines", in *IEEE IAS Annual Meeting Record*, 2011, Orlando

[7] R.J. Piwko, E.V. Larsen, "HVDC System Control for Damping of Subsynchronous Oscillations" EPRI EL-2708 Research project 1425-1 Final report, October 1982.

IV. VITA

Pieder Jörg received his M.Sc degree 1995 from the Swiss Federal Institute of Technology, Zurich. He joined ABB at Corporate Research in the area of power electronics. In 2002 he joined the business unit Medium Voltage Drives as head of product development. Since 2010 he is focusing on business and technology development for demanding drives applications. He has been involved in various studies and improvement projects involving large VSD driven systems with demanding rotor dynamics. pieder.joerg@ch.abb.com

Adrian Tresch received his M. Sc. degree in electrical engineering 2003 from the Lucerne University of Applied Science. In 2006 he joined ABB Medium Voltage Drives as development engineer for control algorithms. He has been specializing in the analysis of complex shaft line systems and was involved in various studies about the interaction of variable speed drives and multiple inertia systems. In 2011 he received a diploma in technology management and business economics from the Swiss Federal Institute of Technology, Zurich. Beginning of 2013 was assigned as global service product manager of ABB drives. adrian.tresch@ch.abb.com

Martin Bruha received his M.Sc. degree in 2011 from the University of West Bohemia in Pilsen, Czech Republic. His professional interests are around modeling and closed loop simulations of Medium Voltage Drives and its interaction with multi-mass mechanical loads. Since 2011 he is working in the System Design group of ABB Medium Voltage Drives. martin.bruha@ch.abb.com