TORSIONAL INTERHARMONIC INTERACTION STUDY OF 75 MW DIRECT-DRIVEN VSDS MOTOR COMPRESSOR TRAINS FOR LNG DUTY

by

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ABSTRACT

In all-electric-driven liquefied natural gas (LNG) plants, converter-fed synchronous motors up to a power of 100 MW are being offered. During operation of compressor trains by a variable speed drive system (VSDS), integer and noninteger harmonics are generated in the converter. Intersections of integer harmonics with relevant torsional natural frequencies of the system can generally be avoided within the operating-speed range. The intersections of the noninteger excitation frequencies with torsional natural frequencies within the operating-speed range cannot be eliminated if the train is designed to operate below and above a motor supply frequency of approximate grid frequency. The generated harmonic torque excitation may have an essential impact on the torsional behavior and the reliability of the entire train and ultimately the reliability of the whole LNG plant.

Due to this fact a traditional torsional analysis as specified in API 617, Seventh Edition (2002), is an obligatory task. This analysis normally considers the VSDS train operating as an individual mechanical train, including motor, coupling, and compressor, even if it is installed in a multiunit plant. As a further simplification, the torsional model does not include the full electrical/mechanical interaction.

To ensure reliable operation of a 75 MW refrigerant-compressor train in an LNG plant, the effect of the full coupled electrical and mechanical VSDS train, including the electrical grid had to be investigated. In addition, with respect to torsional oscillations, two or more identical trains in parallel operation have been investigated in detail to determine the interaction.

This paper details multiple issues associated with the electrical and mechanical interaction and additionally the interaction of two or more identical trains in parallel operation with respect to torsional oscillations during converter operation. The paper also provides a comparative overview of the torsional design with regard to results of the individual mechanical system, without electrical/mechanical interaction, and the results of the full coupled electrical-mechanical model.

The detailed analytical investigation of the behavior of the torsional system has been carried out to demonstrate the integrity of such kind of projected plant configurations for LNG duty.

INTRODUCTION

The oil and gas industry is moving toward mega-plant sizes especially with regard to liquefied natural gas (LNG) plants. For these applications large single-shaft radial compressors driven by gas turbines and/or large electrical synchronous motors are required.

Converter-fed synchronous motors combined with radial turbocompressors up to a power of 100 MW are being offered for all-electric-driven LNG plants. The typical train configuration is direct-driven and/or driven through an intermediate speed-increasing gear. This paper focuses on the motor-driven application without an intermediate gear.

Most variable speed drive systems (VSDSs) rectify alternating line current (AC) of 50 Hz or 60 Hz, to direct current (DC), and invert the DC to variable-frequency AC current. The AC-DC-AC conversion adds torsional excitation frequencies to the system. Integer and noninteger harmonics generated in the converter cause torque oscillations in the motor-air gap. Especially in the case of VSDS of type load-commutated inverter (LCI), interharmonics cannot be disregarded. Excitation of torsional vibrations occurs at relatively low running speeds for integer harmonic distortion. Coincidence of torsional natural frequencies and integer harmonics occurs during start-up for a short period of time due to acceleration. Several start-up simulations demonstrate that the occurring peak torques are at low levels. Resonance condition of integer harmonics with relevant torsional natural frequencies within the operating-speed range can generally be avoided due to the fact that the excitation frequencies are rapidly increased with speed, whereas the intersections of the noninteger excitation frequencies and the torsional natural frequencies of the rotating equipment cannot be eliminated if the train is designed to operate below and above a motor-supply frequency of approximate grid frequency. The noninteger harmonics, also called *interharmonics*, are created by differences of line- and motor-supply frequencies with an order number of 6, 12, 18, 24, … . Usually, the magnitude of excitation decreases with increasing order number.

In principle, generated harmonic torque oscillations may have an essential impact on the torsional vibration behavior of the entire train. Consequently the driver and compressor manufacturers must carry out detailed analyses to examine the operational condition of the rotating equipment. Therefore, close collaboration of driver and compressor manufacturer in designing and engineering of such a VSDS-driven train is essential, as also stated by Hudson (1992).

First of all, fatigue in the torque-transmitting elements has to be avoided. This may be caused by torsional excitation. Furthermore, in systems including intermediate gears, lateral vibrations of the pinion and bull-gear rotors could also occur. Due to the fact that torsional and lateral vibrations are coupled via the gear mesh, excitations have to be examined to avoid higher lateral amplitudes and/or to avoid clattering in gears in addition to possible fatigue problems. The compressor trains considered in this paper are of directly driven type as already mentioned.

A traditional torsional analysis as specified in API 617, Seventh Edition (2002), was carried out as a first step. On the assumption that there is no interaction between different trains, this analysis determines the torsional natural frequencies and mode shapes of the whole torsional system of one single train. The air-gap torque caused by short-circuit conditions of the motor was simulated and the resulting transient torques were analyzed. It goes without saying that the components have to be capable of transferring this kind of transient condition. Additionally the response of the mechanical system caused by the excitation mechanisms of the VSDS was analyzed in detail. The generated steady-state motor air-gap torques, as an external excitation, are transferred across the main mass of the motor into the mechanical system. Therefore, the response in the train elements is mainly determined by the excitation magnitude and the amplification of the mechanical torsional system. The results have to be evaluated with regard to components torque capabilities for continuous operation.

The second step was investigation into the electrical and mechanical interaction of two or more VSDS connected to the grid with respect to torsional oscillations. Whereas the traditional torsional analysis considers the air-gap torque as an external steady-state torque, the interharmonic interaction study takes into account the fully-coupled mechanical and electrical model including the electrical main grid. At first speed ramping is simulated with one VSDS to establish the reference cases. This means that speeds with higher torsional responses need to be determined for further investigation. The selected speed points with significant amplitudes were simulated in steady-state operation. In the following step the interaction of two identical trains coupled via the electrical main grid were investigated. The first VSDS ran within the resonance as predicted whereas the second VSDS train was ramped up. The results are presented in a matrix of responses of two trains depending on operating speeds of each individual system to demonstrate the occurring interaction.

To enable a clear understanding of the interaction of various systems, the general configuration of the projected LNG plant was reduced to a configuration of two identical compressor trains. It is well understood that more than two systems will exhibit smaller coupling effects between the individual shafts due to phase-averaging effects. Nonetheless, the occurring torque responses in the train were calculated for one, two, and finally for three VSDS-driven LNG trains operating in parallel.

GENERAL MECHANICAL OPERATING BEHAVIOR OF A VSDS

Working Principle of a Synchronous Motor

The air-gap torque is essentially generated by the air-gap flux and the stator current of the motor. The star-point of the motor is typically isolated in drive applications. Hence it is preferable to use space-vector representation since only two motor currents are linearly independent. Thus the air-gap torque is given by the imaginary part of the product of stator current and air-gap flux corresponding to a cross-product calculation. Deviations between air-gap torque and load torque cause variations in the motor speed depending on the inertia of the mechanical system. The usual d/q-axis (d-axis = direct axis, q-axis = quadrature axis) representation is obtained by a transformation from a static coordinate system to a coordinate system rotating with the fundamental electrical frequency thus obtaining constant components for currents and voltages.

The apparent power of the motor is determined by magnitude and angle both of motor terminal voltage and (back) electromotive force (emf) acting on an impedance. The active power is mainly determined by the angle between space-vector of terminal voltage and space-vector of electromotive force (emf) (polar wheel-angle) whereas the reactive power is mainly determined by the magnitudes of terminal voltage and emf.

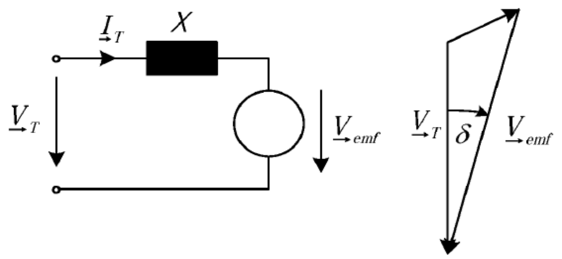


Figure 1. Equivalent Circuit and Space Vector Diagram of Synchronous Machine.

where:

$\underline{V}_T$ = Terminal voltage
$\underline{I}_T$ = Terminal current
$\underline{V}_{emf}$ = Electromotive force
X = Synchronous reactance

Working Principle of the LCI

The VSDS is composed of rectifier, DC-link, inverter, and a converter transformer on the line side. Sometimes the filter circuits are directly connected to the converter transformer via an additional winding.

In applications where the synchronous machine is operated by a VSDS of type LCI the excitation unit will be controlled to generate constant nominal flux in the air gap. The magnitude of the current is controlled by the rectifier DC-voltage via the rectifier firing-angle with reference to the phase of the line voltage to achieve the speed reference value.

The firing angle of the inverter is kept at a constant value with reference to the phase position of the rotor. Hence the air-gap torque is directly controlled by the current magnitude since the air-gap flux is at nominal value and the angle between air-gap flux and stator current is constant.

Operating Behavior of the VSDS

In the high-power range two six-pulse thyristor bridges are connected via a three-winding transformer to the line voltage thus exhibiting 12-pulse characteristic in its total line current. The motor will be equipped with two three-phase systems displaced electrically by 30 degrees, exhibiting again 12-pulse characteristic. Each three-phase system of the motor is connected via one six-pulse bridge to its DC-reactor, which is again connected via one six-pulse bridge to one of the converter transformer windings. The decoupling between motor voltage and line voltage is only partial due to the finite inductance of both DC-reactors. Thus disturbances depending on line and/or motor frequency are transmitted from motor to line side and vice versa. Thus interharmonic frequencies, given by arbitrary integral linear combinations of $6 \bullet F_S$ (system/line frequency) and $6 \bullet F_M$ (electrical supply frequency from converter to motor), can be observed in the active power at any location of the fully coupled system consisting of grid, converter, and motor.

Occurrence of the Integer and Noninteger Harmonic Excitation Torques

The stator current is composed of interharmonics characterized by frequencies $6 \bullet \kappa \bullet F_S + (6 \bullet \lambda + 1) \bullet F_M$ during steady-state operation; κ and λ are an arbitrary positive or negative integer. The transformation into the rotating coordinate system results in frequencies of $6 \bullet \kappa \bullet F_S + 6 \bullet \lambda \bullet F_M$. The air-gap torque is the product of air-gap flux and stator current. The flux is mainly given by a constant quantity in the rotating coordinate system, thus the air-gap torque is composed of the same frequencies as the stator current.

Since only the subsynchronous first mode of the compressor shaft can really be excited via the motor, harmonics can be excluded as a possible source of excitation during steady-state operation (from the definition integer multiples of fundamental). But interharmonics may equal the resonance frequency of the first shaft mode depending both on the frequencies F_S and F_M and on the coefficients κ and λ. It is known from Fourier analysis that the envelope of the magnitudes of the Fourier coefficients decreases as the inverse of the frequency. Thus the biggest magnitudes for interharmonics of the air-gap torque are to be expected for low order linear combinations of F_S and F_M.

Figure 2 shows an example of the spectrum of the active power of the motor during ramping through the operating speed range.

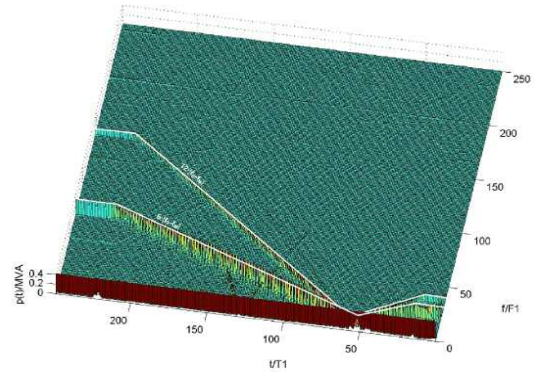


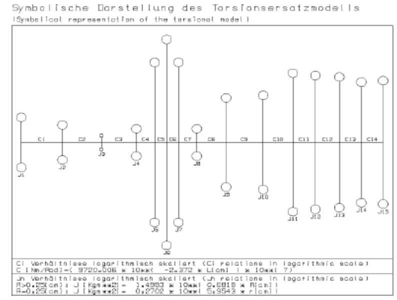
Figure 2. Spectrum of Active Power of 86 MVA VSDS During Ramping.

TRADITIONAL TORSIONAL ANALYSIS IN ACCORDANCE WITH API 617

Torsional Model

The torsional model of the LNG train under consideration consists of an eight-mass model for the driver, a two-mass model for the coupling, and a five-mass model for the compressor. The details of the individual models used for motor, coupling, and compressor depend on the models provided by the corresponding manufacturers. These models often consist of concentrated-mass moment of inertias and massless torsional springs. Figure 3 represents the torsional model, the mass moment of inertias, and the torsional stiffnesses of the elements.

Symbolische Darstellung des Torsionsersatzmodells
(Symbolical representation of the torsional model)



Konzentrierte Parameter
(Concentrated Parameter)

NG	NB	NE	JN Kg*m**2
1	1	1	7.0000
2	1	2	4.0000
3	1	3	0.4000
4	1	4	3.0000
5	1	5	406.0000
6	1	6	2220.0000
7	1	7	406.0000
8	1	8	3.0000
9	1	9	29.5500
	2	1	
10	2	2	35.7933
	3	1	
11	3	2	183.2631
12	3	3	152.8475
13	3	4	136.7187
14	3	5	94.4109
15	3	6	104.6464

Verteilte Parameter
(Distributed Parameter)

IG	NB	IE	CI Nm/Rad	JI Kg*m**2
1	1	1	0.792 *10⁷	
2	1	2	1.249 *10⁷	
3	1	3	3.206 *10⁷	
4	1	4	144.573 *10⁷	
5	1	5	633.092 *10⁷	
6	1	6	633.092 *10⁷	
7	1	7	144.573 *10⁷	
8	1	8	11.504 *10⁷	
9	2	1	2.000 *10⁷	
10	3	1	10.598 *10⁷	
11	3	2	56.701 *10⁷	
12	3	3	39.514 *10⁷	
13	3	4	60.301 *10⁷	
14	3	5	66.816 *10⁷	

Figure 3. Torsional Model and Model Data.

The torsional natural frequencies and the mode shapes of the described model are presented in Table 1 and Figures 4, 5, and 6.

Table 1. Torsional Natural Frequencies.

Type	f1/Hz	f1/rpm	f2/Hz	f2/rpm	f3/Hz	f3/rpm	f4/Hz	f4/rpm
Compr. Train	25,15	1509	115,32	6919	183,55	11013	293,7	17622

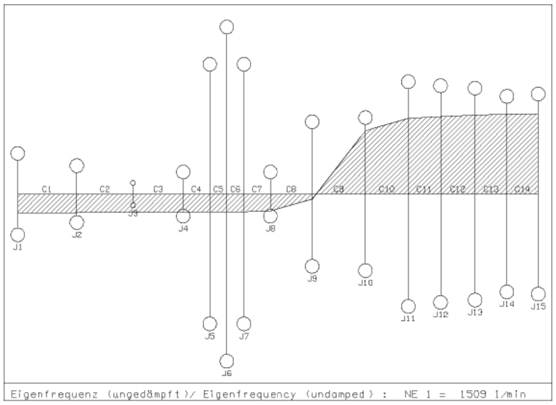


Figure 4. First Torsional Mode Shape at 1509 RPM.

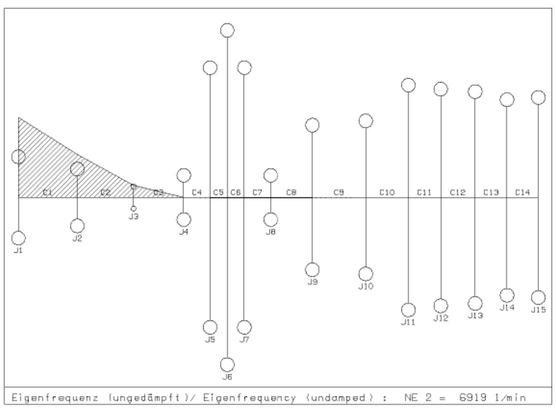


Figure 5. Second Torsional Mode Shape at 6919 RPM.

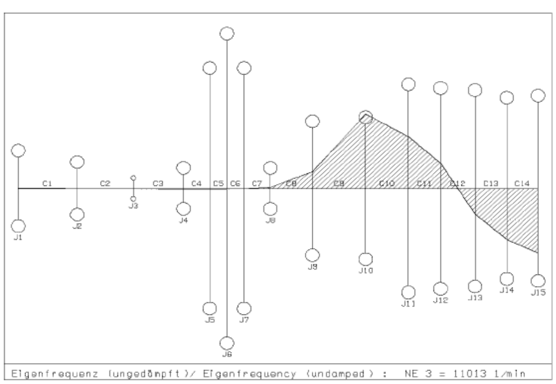


Figure 6. Third Torsional Mode Shape at 11,013 RPM.

It is well reflected in the authors' experience that the fundamental torsional natural frequency is normally of primary importance regarding torsional excitation generated in the motor-air gap. During resonance, this vibration mode is capable of facilitating large amplifications of dynamic torque that may result in catastrophic failure of one or more drive components, whereas the amplification of higher-order natural frequencies is on much lower levels. Nonetheless, torsional eigenvalues of higher orders are also considered in detail in the design.

Strategy of the Harmonic Excitation Analysis

Due to the fact that the intersections of noninteger excitations and torsional natural frequencies cannot be avoided, it is essential to evaluate the response of the torsional system during operation within the specified operating-speed range of the compressor. For the specific train under investigation a modal damping of 1 percent is reflected in the authors experience and is therefore the basis of this analysis. Notwithstanding, the effect of modal damping will be analyzed in the sensitivity study within this publication.

1. In the first step it is of paramount importance that the torque-transmitting elements of the train are specified to transmit the static torque including service factor for continuous operation. Additionally, the train elements must be designed adequately to transmit the torque ripples during continuous operation and transient torques in short-circuit conditions. Therefore, the train components have to be specified for:

• Maximum continuous torque including service factor (quasistatic condition) for continuous operation.

• Maximum continuous torque and superimposed permanent oscillating torque of ± half of maximum torque for an infinite number of load cycles.

• Maximum continuous torque and superimposed a transient-dynamic torque for a finite number of load cycles depending on probability of load-case occurrence.

2. In the second step based on the torsional model as already described, a harmonic excitation generated in the air gap is transferred across the main mass of the motor into the train. The response in the torque-transmitting elements is divided by the excitation torque in order to get the amplification factor (AF). Therefore, the AF is defined as the ratio of response torque to excitation torque. The result of the analysis is therefore the amplification of the system versus rotating speed. This is presented in Figure 7 and in Table 2.

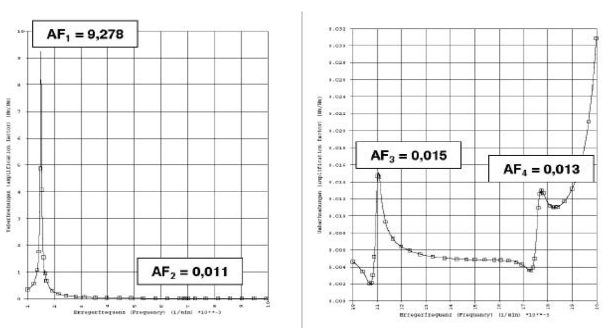


Figure 7. Results of the Harmonic-Excitation Analysis.

Table 2. Summary of the Results of the Harmonic-Excitation Analysis.

Order	Torsional natural frequency [rpm]	Amplification factor [-]
1	1509	9.278
2	6919	0.011
3	11013	0.015
4	17622	0.013

3. In the third step a Campbell diagram (Figure 8) has been drawn. The torsional natural frequencies are shown as horizontal red lines. The blue lines represent the excitation lines of the integer and noninteger harmonics of the inverter. The intersections of the natural frequencies with the excitation lines within the operating-

speed range are marked with circles. The intersections with highest excitation magnitude of the individual torsional frequencies are highlighted with bigger circles.

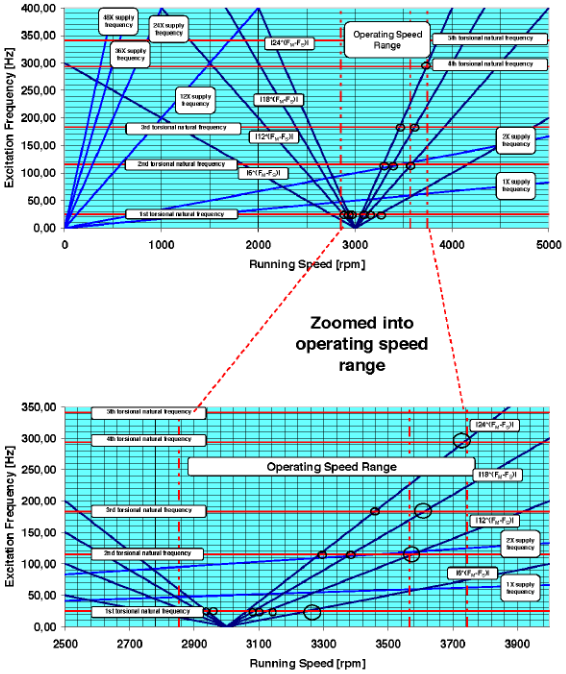


Figure 8. Campbell Diagram.

Definition of Integer and Noninteger Harmonics

Based on a conservative assumption, the excitation magnitude of the steady-state harmonics has been determined by the manufacturer of the converter. The results are summarized in Figure 9. The given magnitude is related to the rated torque of the driver. It is obvious that the lower the order of the integer or noninteger harmonics the higher the excitation amplitude. Whereas an excitation profile versus driver speed can be expected for the integer harmonics, the noninteger harmonics are at this stage expected to have a constant magnitude. Expected excitation magnitude of the noninteger harmonics according to Figure 5:

- $|6*(F_M - F_S)|$ => Approximately 2 percent of motor-rated torque
- $|12*(F_M - F_S)|$ => Approximately 1 percent of motor-rated torque
- $|18*(F_M - F_S)|$ => Less than 1 percent of motor-rated torque
- $|24*(F_M - F_S)|$ => Less than 1 percent of motor-rated torque

where:
F_M = Motor supply frequency
F_S = System/line frequency

Three-Phase Synchronous Motor with Solid Cylindrical Rotor

P_N = 75100. kW M_N = 202,9 kNm N_N = 3534. rpm F_{MN} = 58,9Hz F_N = 50.Hz

Air Gap Pulsation during Current Source Converter Operation
Reference base for the pulsation torque mP is the fundamental torque M in the actual operating point. The per-unit-value of the speed n are related to the nominal speed NN of the motor.

Integer Harmonic Torque Pulsation during Start-Up and Normal Operation

$m_p(t) = 1 + \Sigma m_{p\mu} * \cos(2\pi * \mu * F_{MN} * n * t - \Phi_\mu * \pi/180)$ [p.u.]

	order no. μ		12		24		36		48	
	pulsation torque		amlitude	phase	amlitude	phase	amlitude	phase	amlitude	phase
	n [p.u.]	F_M [Hz]	m_p [p.u.]	Φ [°]	m_p [p.u.]	Φ [°]	m_p [p.u.]	Φ [°]	m_p [p.u.]	Φ [°]
forced commutation range	0.02	1.18	0.098	13.3	0.082	13.8	0.071	16.4	0.069	19.0
	0.04	2.36	0.181	13.6	0.126	19.1	0.072	20.8	0.031	5.5
	0.06	3.53	0.249	16.3	0.114	21.0	0.034	-16.3	0.023	-55.1
	0.08	4.71	0.291	19.2	0.069	5.5	0.033	-55.6	0.004	62.1
	0.10	5.89	0.300	21.3	0.054	-40.3	0.009	-23.0	0.005	20.7
natural commutation range	0.10	5.89	0.080	128.8	0.027	177.3	0.008	-144.8	0.002	168.9
	0.20	11.78	0.079	130.8	0.027	-176.5	0.008	-135.3	0.002	179.6
	0.40	23.66	0.078	132.6	0.026	-172.9	0.008	-130.2	0.002	-174.6
	0.60	35.34	0.078	133.2	0.026	-171.7	0.008	-128.6	0.002	-172.7
	0.80	47.12	0.078	133.4	0.026	-171.1	0.007	-127.6	0.002	-171.7
	1.00	58.90	0.078	133.6	0.026	-170.7	0.007	-127.1	0.002	-171.1

Integer harmonics

Non-Integer Harmonic Torque Pulsation due to Ripple Content of DC Link Current

$m_p(t) = 1 + \Sigma m_\mu * \sin(2\pi * F_\mu * t)$ [p.u.]

order no. μ	6	12	18	24
frequency Fm [Hz]	pulsation torque amplitude m_μ			
$\mu*(F_{MN}*n-F_N)$	0.02	0.01	< 0.01	< 0.01
$\mu*F_N$	-	0.05	-	0.02

Non-Integer harmonics

Figure 9. Definition of Integer and Noninteger Harmonics.

4. The given amplification factors of the individual torsional natural frequencies have to be multiplied by the torque amplitude of the corresponding excitation frequency from the inverter-motor system. The result is maximum steady-state oscillating torques within the train elements during operation at the corresponding operating speed in condition of torsional resonance.

Summary of the Results of Stationary Excitation of the Inverter and Mechanical Evaluation

The relevant resonance conditions of the first, second, third, and fourth torsional natural frequency within the operating-speed range are highlighted with a bigger circle in the Campbell diagram (Figure 8). The resonances, marked by a smaller circle, are clearly of lower amplitude and therefore less harmful in terms of fatigue.

At a motor speed of 3252 rpm, the first critical speed of 1509 rpm (25.15 Hz) with a corresponding AF of 9.278 will be excited by an excitation magnitude of 2 percent of the rated motor torque of the noninteger harmonic line $|6*(F_M - F_S)|$. Therefore, the maximum response in the train elements is a dynamic torque of *18.56 percent* (2 percent*9.278) of the rated torque. Torsional natural frequencies of higher orders (i.e., second and higher order) cannot be excited due to low amplification factor.

Although the train elements are capable of transferring the maximum continuous torque and superimposed permanent torque oscillation of ± half of the maximum torque for an infinite number of load cycles, the compressor manufacturer allows only an oscillating torque of up to 25 percent of the motor-rated torque. Thus it is permissible to use half of the allowable dynamic torque capability to achieve reliable operation of the LNG train. All occurring peak torques are less than the torque capabilities of the elements. Based on these results, the above defined design criteria of the manufacturer are fulfilled and a fatigue failure is not expected (Table 3). This means that the shear stresses are all on an allowable level and no individual stress and/or fatigue analysis is required.

Table 3. Summary of the Results of Stationary Excitation of Inverter.

Motor Type	SynchronousMotor
Pair of Poles [-]	1
Type of DC-Link	12-pulse Frequency converter with current link
Slip	1
Netfrequency [Hz]	50

	Order n_e	1	2	3	4
	Eigenfrequency [1/rpm]	1509	6919	11013	17622
	n_{Mot} [1/rpm]	3252	3577	3612	3734
	T_{Mmax}/T_{rated} [%][1])	2,00%	1,00%	1,00%	1,00%
Coupling Motor - STC-SH	AF[2])	9,278	0,011	0,015	0,013
	$T_{osz max}$ [%][3])	18,56%	0,01%	0,02%	0,01%
	check (o.k. < 25%) [4])	o.k.	o.k.	o.k.	o.k.

[1]) stationary maximum excitation (caused by the inverter)
[2]) amplification-factor (result of the harmonic analysis)
[3]) oscillating torque (excitation * amplification)
[4]) train components are capable of 1,5 times of rated torque at continuous operation

FULL COUPLED ELECTRICAL AND MECHANICAL INTERHARMONIC INTERACTION STUDY

Simulation Model of the Electrical and Mechanical System

- Model of the synchronous machine—The model of the synchronous machine consists of a representation of Park's equation in d- and q-axis (Figure 10).

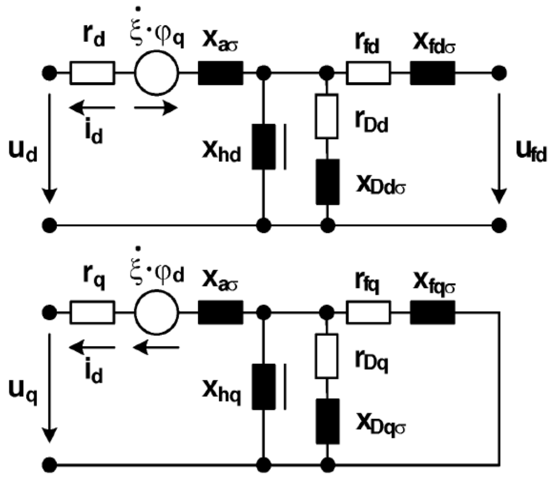


Figure 10. Equivalent Circuit of the Synchronous Machine.

• Mechanical model of the LNG train—The torsional model of the compressor shaft consists of five mass elements and four coupling elements exhibiting sufficient accuracy with respect to simulation of the air-gap torque. The replication is optimized with respect to the accuracy (range of 99.6 percent) of the resonance frequencies of the first three modes (Figure 11 and Table 4).

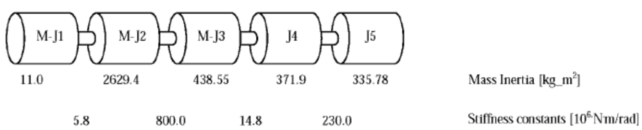


Figure 11. Torsional Model and Model Data.

Table 4. Torsional Natural Frequencies.

Type	f1/Hz	f1/rpm	f2/Hz	f2/rpm	f3/Hz	f3/rpm	f4/Hz	f4/rpm
Compr. Train	25,166	1510	115,76	6946	183	10980	233,88	14033

• Electrical model of the grid and VSDS—The electrical system is represented by a short-circuit impedance to achieve a coupling between different VSDS. The converter topology feasible for the high-power range is depicted in Figure 12 and consists of four six-pulse thyristor bridges operated in such a way that 12-pulse characteristic is achieved both for grid and motor. The DC-reactors of one VSDS are negatively coupled to reduce the constant flux portion. The necessary filter circuits might either be connected to the high-voltage bus or to a quartenary winding of the converter transformer as shown in Figure 12.

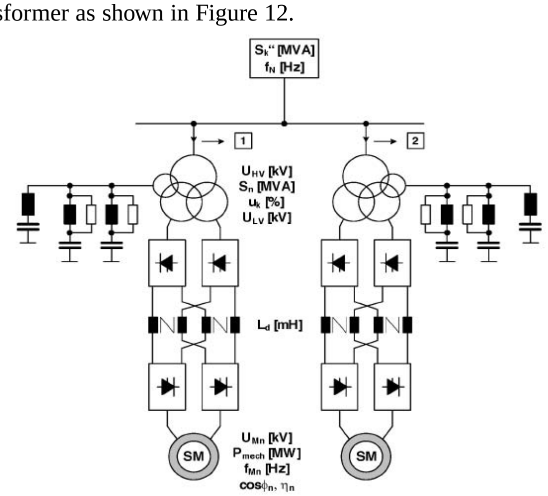


Figure 12. Electrical Model of the Grid and VSDS.

• Control scheme—The general control scheme of a VSDS comprises two subcontrols:

• Rectifier control consisting of a cascaded speed and DC-current controller structure

• Inverter control consisting of a motor model and of a cascaded flux and excitation current controller structure

The control blocks are depicted in Figure 13. The trigger-sets of the rectifier control are synchronized to the phase of the grid voltage via a phase-locked loop-controller (PLL-controller). The reference value of the DC-current controller results from the output of the speed controller. The DC-voltage of the rectifier is determined by the corresponding firing angle obtained as output value from the DC-current controller.

The trigger-set of the inverter control is synchronized to the emf of the motor, which is derived from a motor model within the control. The inverter is operated with a constant firing angle. The excitation voltage is obtained from a cascaded control structure using excitation current and motor terminal voltage and motor current as input quantities.

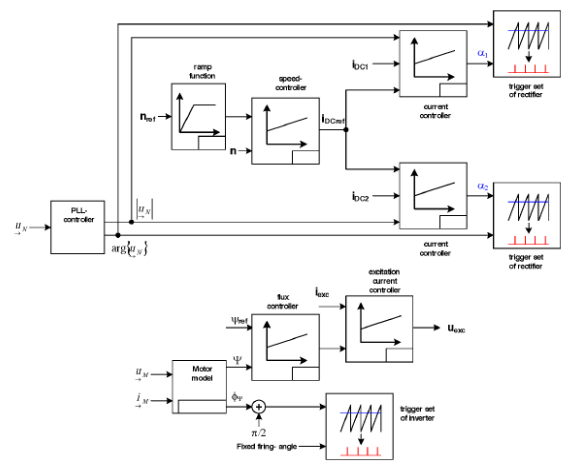


Figure 13. Control Scheme of VSDS.

Analyzing Strategy to Determine Maximum Interaction

• LNG-train in solo operation (ramping to find torsional resonances)—At first one VSDS was ramped through the complete steady-state operating range (47 Hz to 62 Hz). A slope of 4.4 rpm/s was selected to obtain a clearly visible reaction of the shaft at its resonance modes exhibiting a low modal damping (Figure 14).

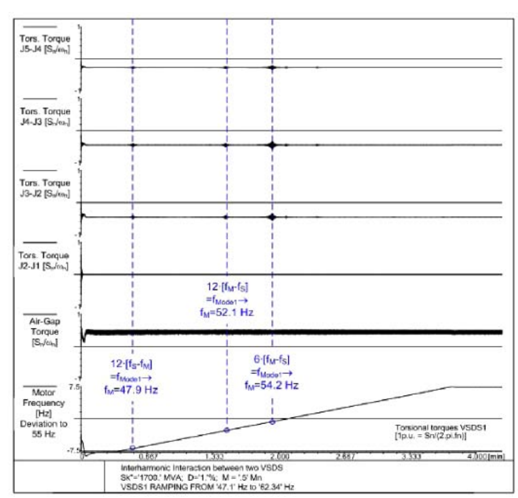


Figure 14. VSDS in Single Operation Ramped up Within Operating Speed Range.

The resonance modes were detected by the maxima of the envelope of the torsional torques acting between the mass elements of the shaft model. Further iterations establish the critical drive speeds at which full excitation of the various shaft resonance modes were achieved.

• Two LNG-trains in parallel operation—Then interaction of two VSDSs was investigated. One drive operated continuously at one of the critical drive speeds and the other drive was ramped again from 47 Hz to 62 Hz. The critical speeds of this second drive were determined again from the maxima of the envelopes of the corresponding torsional torques. Then steady-state operation for both drives was simulated where the speed set-point of the first drive is used from ramping in solo operation and the speed set-point of the second drive was taken from the ramping in parallel operation. Whereas Figure 15 presents the response in VSDS-train 1 at a constant speed of 54.201 Hz, Figure 16 presents the torque response of VSDS-train 2 during ramping. In the event of equal speeds for both drives, the difference of the two polar wheel-angles will be zero due to ideal symmetry. The effect of differences in polar wheel-angle position will be investigated for one selected case later on.

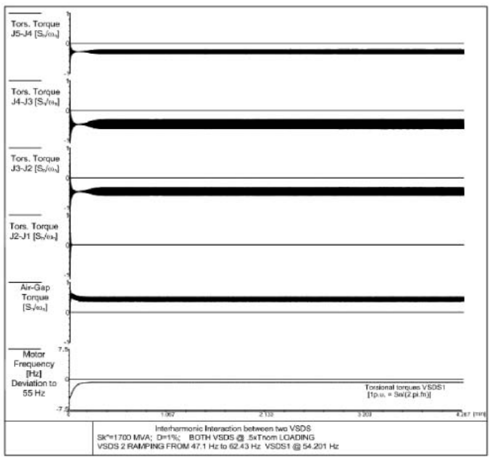


Figure 15. VSDS1 Operating at 54,201 Hz and VSDS2 Ramped up.

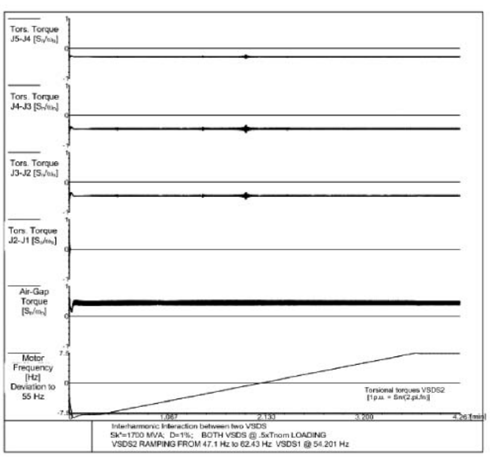


Figure 16. VSDS2 Ramped up and VSDS1 Operating at 54,201Hz.

• Effect of three VSDS in parallel operation—For one selected case three drives are operated continuously at the critical speed where the interharmonic $|6*(F_M - F_S)|$ hits the first resonance mode. These results allow a direct comparison to the results of the case with two VSDSs in parallel operation and quantify the degree of coupling via the common electrical bus. The polar wheel-angles of all motors are equal due to the ideal symmetry of the simulated system. Therefore a variation of polar wheel-angle difference is performed again for this case.

Sensitivity Study of the System

With respect to half- and fully-loaded trains, short circuit capacity (S_k”), torsional damping (modal damping D), and variation of polar wheel-angle the authors investigated the sensitivity of the coupled electrical-mechanical system.

Due to the fact that higher peak torques were observed for Mode 1 and significantly lower values for Mode 2, the results of the sensitivity study summarized in Tables 5, 6, and 7 present the peak torques of Mode 1 only.

Table 5. Summary of Results of the Sensitivity-Study Compressor Load.

	Interharmonics Interaction Study Motor (peak torque related to motor rated torque)				
	modal damping	two motors in operation			
		Train 1		Train 2	
		full load	half load	full load	half load
Sk" = 1700.MVA	1,00%	7,00%	8,60%	7,00%	8,50%

Table 6. Summary of Results of the Sensitivity-Study Short-Circuit Capacity.

	Interharmonics Interaction Study Motor (peak torque related to motor rated torque)				
	modal damping	single motor operation	two motors in operation		three motors in parallel operation
			PMR 1	PMR 2	
Sk" = 570.MVA	1,00%	8,70%	8,70%	8,70%	not available
Sk" = 1700.MVA	1,00%	8,60%	8,60%	8,60%	8,73%

Table 7. Summary of Results of the Sensitivity-Study Modal Damping.

	Interharmonics Interaction Study Motor (peak torque related to motor rated torque)				
	modal damping	single motor operation	two motors in operation		three motors in parallel operation
			PMR 1	PMR 2	
Sk" = 1700.MVA	0,20%	31,80%	31,50%	31,60%	not available
	1,00%	8,60%	8,60%	8,60%	8,73%

• Compressor load—Based on the results listed it is obvious that dynamic peak torques at half-load condition are between 20 percent and 40 percent higher in contrast to the torsional behavior of a full-load train (Table 5). Although the LNG plants will operate more or less at full-load condition, as a conservative assumption half load condition is considered in this publication for all analysis.

• Short circuit capacity (S_k”)—The effect of the variation of the short-circuit capacity of the electrical main grid of Sk” = 570 MVA and 1700 MVA is incorporated in this study. As can be seen in Table 6, the peak torques are more or less at the same level. Therefore, the influence of the short-circuit capacity is virtually negligible in a range of realistic grid condition.

• Torsional damping (modal damping D)—Whereas a 1 percent modal damping of the mechanical system for the specific train under investigation is well reflected in the authors’ experience, the variation of the modal damping of 0.2 percent should be understood as a theoretical worst-case condition (Table 7) for the purpose of a sensitivity study. As expected, the response of the torsional system is significantly higher.

• Variation of rotor angle—The steady-state operation of two or three VSDSs was simulated disregarding the relative position of the rotor. Hence the rotor angles of motors of different VSDS will be equal in the case of identical operation points for these VSDSs.

Therefore the impact of a variation of the rotor angle difference was investigated for a selected case (1700 MVA and $|6*(F_M - F_S)| = f_{Mode1}$) both for two and three VSDS. The upper plot in Figure 17 shows the rotor angle difference between VSDS 1 and VSDS 2. The rotor is adjusted stepwise every 11 seconds in steps of approximately 15 degrees by applying dipole-shaped current pulses for one second via the DC-current controller. Then steady-state conditions are kept for 10 seconds to ensure sufficient settling of transients. The response in maximum torque for both drives is depicted in the lower plot of Figure 17. The maximum value will not exceed the value obtained in the case of symmetrical conditions, approximately 8.8 percent (Figure 17).

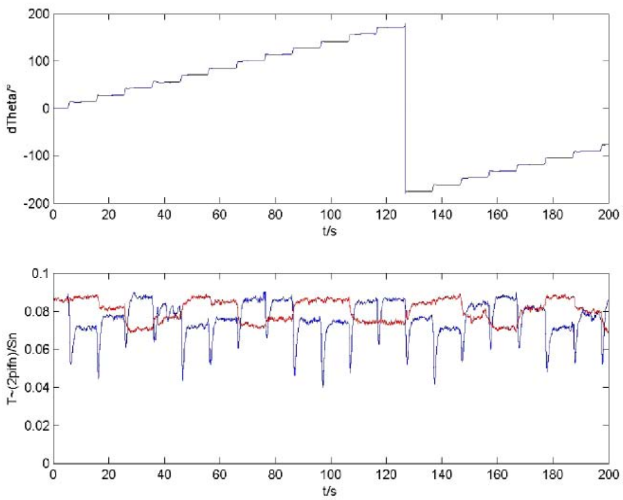


Figure 17. Torque Response for Two Trains in Parallel Operation.

In the case of three VSDS, a different result may be expected since two VSDS can operate synchronized, thus having a stronger impact on the third drive. Figure 18 contains the result of this simulation. Only one rotor-angle difference curve can be recognized in the upper plot of this figure since two drives are synchronized. The lower plot shows the maximum values for the envelopes of the torsional torques—again two curves are identical. The biggest value of almost 9.96 percent is obtained for an angle difference of approximately 15 degrees. Due to the greater impact of two VSDS on one VSDS, the range of values for the rotor angle difference, when steady state has been reached after application of each rotor angle step, is almost doubled (see blue curve in Figure 18) in contrast to the case with two VSDS (see blue curve in Figure 17).

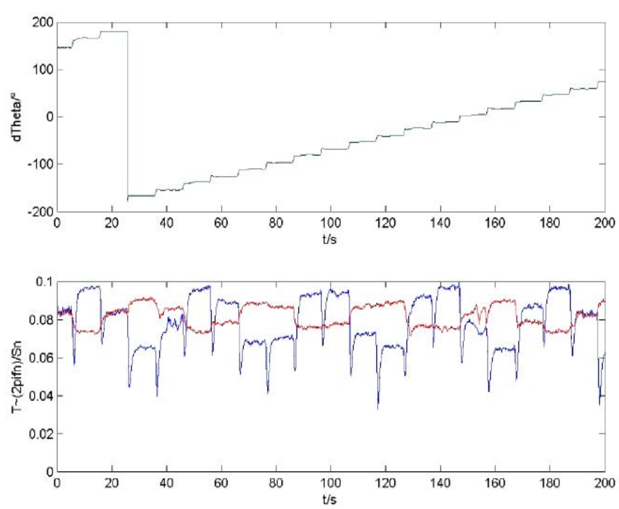


Figure 18. Torque Response for Three Trains in Parallel Operation.

COMPARISON OF THE RESULTS OF BOTH ANALYSES

Torsional Natural Frequencies

With regard to the expected simulation time caused by the complex electrical and mechanical model the torsional model of the LNG train is reduced to five masses within the interharmonic interaction study. Nonetheless, the first three torsional natural frequencies of both models deviate less than 0.4 percent. The higher deviation of the fourth-order natural frequency base on the reduced number of masses (Tables 8 and 9). This paper demonstrates that torsional natural frequencies of higher orders cannot be excited and are therefore not relevant for this consideration.

Table 8. Torsional Natural Frequencies of Traditional Torsional Analysis.

Type	f1/Hz	f1/rpm	f2/Hz	f2/rpm	f3/Hz	f3/rpm	f4/Hz	f4/rpm
Compr. Train	25,15	1509	115,32	6919	183,55	11013	293,7	17622

Table 9. Torsional Natural Frequencies of Interharmonic Interaction Study.

Type	f1/Hz	f1/rpm	f2/Hz	f2/rpm	f3/Hz	f3/rpm	f4/Hz	f4/rpm
Compr. Train	25,166	1510	115,76	6946	183	10980	233,88	14033

Torsional Response Within the Resonance Condition

With regard to calculated peak torque level the results of the various analyses have to be compared. The key results of the analyses are summarized in Table 10. The fundamental torsional natural frequency (Mode 1) can be stimulated by the excitation torque $|6*(F_M - F_S)|$ generated in the inverter at a speed of 3252 rpm. At this speed a torsional resonance with highest peak torque occurs. This result can be seen in all analyses without exception. The results of interharmonics interaction study vary between *8.60 percent* and *9.96 percent* whereas the traditional torsional analysis predicts *18.56 percent* of motor-rated torque.

Table 10. Comparison of Analysis Results.

	Torsional Analysis (electrical and mechanical system uncoupled)		Interharmonics Interaction Study Motor		
	Excitation torque amplitude 2% *) *) base on previous figures	Excitation torque amplitude 0,93% **) **) base on results of interaction study	single motor operation	two motors in operation	three motors in parallel operation
	peak torque related to motor rated torque operating at 3252. rpm (54,2Hz)				
Mode 1 (25,15 Hz)	18,56%	8,63%	8,60%	8,60%	8,73%
	peak torque related to motor rated torque opearting at 3579. rpm (59,645Hz)				
Mode 2 (115,32 Hz)	0,01%	0,01%	0,03%	0,03%	not available

The interaction study used the determined air-gap torque amplitude of 0.93 percent of the rated torque and 2 percent within the traditional torsional analysis. Based on the interaction study, one is now in a position to recalculate the response in the mechanical system within the traditional torsional analysis. With the most accurate determined oscillating air-gap torque of 0.93 percent the expected response amplitude will only be *8.63 percent*. Therefore, the results of the various analyses are finally close together and vary only in a range of *8.60 percent* to *9.96 percent*.

Regarding Mode 2 all analyses determine a resonance condition at a motor speed of 3579 rpm. However, for this load case all analyses predict a negligible peak torque level.

SUMMARY OF THE RESULTS

During operation of compressor trains by a VSDS integer and noninteger harmonics are generated in the inverter and are converted into torsional excitations. The torsional excitation is transferred via the motor-air gap to the main mass of the motor and thereby transferred into the torsional system. Coincidences of integer harmonic excitations and relevant torsional natural frequencies within the operating speed range can, in general, be avoided. The coincidences of the noninteger excitation frequencies with torsional natural frequencies of the rotating equipment cannot be eliminated within the operating speed range if the train is designed to operate below and above a motor supply frequency of approximate grid frequency, as can be seen in the Campbell diagram (Figure 7).

Due to the fact that the generated harmonic-torque excitation may have an essential impact on the torsional vibration behavior of the entire train, it is a normal task in the turbomachinery industry to carry out a detailed torsional analysis. Therefore, to demonstrate the integrity of such projected 75 MW LNG plant configurations a detailed investigation of the behavior of the torsional system on an analytical basis is of paramount importance for realization in the near future. The results of such traditional torsional analysis are as follows:

- Torsional natural frequencies and corresponding mode shapes
- The checking of existing and required separation margins and system tuning, if necessary
- Peak-torque responses caused by transient conditions (short circuit, power interruption, power reclosing, network changeover …)
- The checking of occurring transient torques and torque capabilities of the individual components for a finite number of load cases

For VSDS only:

- The checking of coincidences of integer and/or noninteger harmonics with torsional natural frequencies are present within the operating speed range.
- Determination of mechanical amplification of the individual torsional frequency
- Calculating the torque amplitude (excitation magnitude multiplied by AF) under resonance condition
- The checking of occurring steady-state torques and torque capabilities of the individual components for continuous operation

To determine the dynamic peak torque in the torque-transmitting elements caused by inverter operation two different analyses were conducted. A traditional torsional analysis as specified in API 617, Seventh Edition (2002), was carried out. This analysis determines the torsional natural frequencies and modes shapes of the whole torsional system of one single train, under the assumption that there is no interaction between different trains. The air gap torque caused by short circuit conditions of the motor is simulated and the occurring transient torque has to be evaluated regarding torque capabilities of the train components. Additionally, the mechanical response caused by converter-torque ripple within the operating speed range was determined. The transient torques as well as the *interharmonics* of the motor are transferred across the main mass of the motor. This excitation can be understood as an external excitation without interaction to the electrical system.

In the second analysis the interaction of two or more VSDS connected to the grid with respect to torsional oscillations was investigated. Whereas the traditional torsional analysis considers the air-gap torque as an external torque, the interharmonic interaction study takes into account the coupled mechanical and electrical model including the electrical main grid.

With regard to calculated peak torque level the results of the various analyses need to be compared. The key results of the analyses are summarized in Table 10. The fundamental torsional natural frequency (Mode 1) can mainly be stimulated by the excitation torque $|6*(F_M-F_S)|$ generated in the converter at a speed of 3252 rpm. At this speed a torsional resonance with highest peak torque occurs. This result can be seen in all analyses without exception. The results of the interharmonics interaction study vary between *8.60 percent* and *9.96 percent* whereas the traditional torsional analysis predicts *18.56 percent* of motor rated torque. Based on the interaction study the response can be recalculated in the mechanical system within the traditional torsional analysis. With the more accurate oscillating air-gap torque of 0.93 percent instead of 2 percent of the rated torque the expected response amplitude will be *8.63 percent only*. It has to be pointed out that the excitation torque magnitude of 2 percent of the rated torque can be seen as a conservative approach, as is well demonstrated in these two independent analyses. However, the results of the various analyses are ultimately all close together to vary between *8.60 percent* and *9.96 percent*.

Regarding vibration Mode 2, all analyses of the compressor strings show a resonance condition at a motor speed of 3579 rpm. However, for this load case all analyses show a negligible peak torque level. This low dynamic torque level will not be able to cause fatigue in the mechanical system.

Within the worst-case operating condition, the calculated oscillating torques are between *8.60 percent* and *9.96 percent* based on the results of the interharmonics interaction study. The results give a clear indication that the real interaction will be at an extremely low level. In spite of conservative assumptions, the results of the uncoupled torsional analysis present a peak torque of *18.56 percent* of rated torque. Even under conservative assumptions, the occurring torques are well within the allowable level of 25 percent of rated torque. Therefore, the given design criteria are fulfilled.

Based on these results no further action is required. Nonetheless, for this project the driver-compressor manufacturer confirmed that a dynamic torsional measurement will be conducted during shop-testing of the entire train. As such, the occurring dynamic torques generated by the converter will be visible.

The relevant results for the boundary conditions short-circuit power S_k" of 1700 MVA and a modal damping of 1 percent are summarized in Tables 11 and 12. The maximum peak torque for Mode 1 (related to first torsional natural frequency) is given in Table 11 and peak torque for mode 2 (related to second torsional natural frequency) in Table 12.

Table 11. Maximum Peak Torques of Mode 1 During Operation of Both Trains.

Speed Train 1 54,2 Hz half load	Speed Train 2	54,2 Hz	47,9 Hz	59,645 Hz
	Load Train 1	8,50%	7,90%	8,60%
	Load Train 2	8,50%	5,60%	0,94%
Speed Train 1 52,1 Hz half load	Speed Train 2	54,2 Hz	47,9 Hz	59,645 Hz
	Load Train 1	5,60%	4,70%	4,50%
	Load Train 2	7,96%	4,50%	0,60%
Speed Train 1 51,4 Hz half load	Speed Train 2	54,2 Hz	52,1 Hz	59,645 Hz
	Load Train 1	0,87%	1,00%	0,60%
	Load Train 2	8,50%	4,60%	0,07%
Speed Train 1 59,645 Hz half load	Speed Train 2	54,2 Hz	52,1 Hz	59,645 Hz
	Load Train 1	0,88%	0,62%	0,03%
	Load Train 2	8,60%	4,50%	0,03%
Speed Train 1 56,43 Hz half load	Speed Train 2	54,2 Hz	47,9 Hz	59,645 Hz
	Load Train 1	1,10%	0,46%	0,12%
	Load Train 2	8,50%	3,96%	0,04%

Table 12. Maximum Peak Torques of Mode 2 During Operation of Both Trains.

Speed Train 1 54,2 Hz half load	Speed Train 2	54,2 Hz	47,9 Hz	59,645 Hz
	Load Train 1	< 0,02%	< 0,02%	< 0,02%
	Load Train 2	< 0,02%	< 0,02%	0,03%
Speed Train 1 52,1 Hz half load	Speed Train 2	54,2 Hz	47,9 Hz	59,645 Hz
	Load Train 1	< 0,02%	< 0,02%	< 0,02%
	Load Train 2	< 0,02%	< 0,02%	0,03%
Speed Train 1 51,4 Hz half load	Speed Train 2	54,2 Hz	52,1 Hz	59,645 Hz
	Load Train 1	< 0,02%	< 0,02%	< 0,02%
	Load Train 2	< 0,02%	< 0,02%	0,03%
Speed Train 1 59,645 Hz half load	Speed Train 2	54,2 Hz	52,1 Hz	59,645 Hz
	Load Train 1	0,03%	0,03%	0,03%
	Load Train 2	< 0,02%	< 0,02%	0,03%
Speed Train 1 56,43 Hz half load	Speed Train 2	54,2 Hz	47,9 Hz	59,645 Hz
	Load Train 1	< 0,02%	< 0,02%	< 0,02%
	Load Train 2	< 0,02%	< 0,02%	0,03%

The maximum excitation of the first mode occurs when at least one of the trains operates at a frequency of 54.2 Hz (operating speed 3252 rpm). The maximum occurring peak torque of the train, which operates at 54.2 Hz, is predicted to be between *7.90 percent* and *8.60 percent* of motor-rated torque. The peak torque level varies depending on the running speed of the second motor (Table 11).

The maximum excitation of the second mode can be achieved by operating at least one of the trains at 59.645 Hz (operating speed 3579 rpm). The results of the peak torque level are between *<0.02 percent* and *0.03 percent* of motor-rated torque, depending on the operating speed of the second motor (Table 12).

CONCLUSIONS

- The traditional torsional analysis as specified in API 617, Seventh Edition (2002), is an essential task.

- The train components have to be specified for different torque capabilities:

  - Maximum continuous torque including service factor (quasi-static condition) for continuous operation

  - Maximum continuous torque and superimposed permanent oscillating torque of ± half of maximum torque for an infinite number of load cycles

  - Maximum continuous torque and superimposed a transient dynamic torque for a finite number of load cycles depending on probability of load case occurrence

- Torsional natural frequencies, corresponding mode shapes and required and existing separation margin have to be checked. Transient condition (short circuit, power interruption, power reclosing, network changeover, …) should be simulated and must comply with the torque capabilities of the train components.

- For VSDS trains coincidences of integer and noninteger harmonics with torsional natural frequencies within the operating speed range have to be analyzed. Steady-state torque amplitude in resonance condition should comply with the torque capabilities of the individual components for continuous operation.

- So far all train components are designed for transmitting a torque fluctuation of ± 0.5 times of rated torque (superimposed to the static torque) and the expected torque fluctuation is less than ± 0.25 times of rated torque no additional fatigue analysis is required.

- The interaction interharmonic study of the full coupled electrical and mechanical system including the grid is the most accurate analysis method to predict the dynamic electrical and mechanical behavior.

- The observed interactions of the electrical and mechanical system of two or more VSDS are all at an acceptable level based on this analysis. This includes the results of the sensitivity study of various parameters (half- and fully-loaded trains, short circuit capacity (S_k”), torsional damping).

- Both analyses finally reached almost the same result in terms of steady-state torque amplitude. Therefore, the reduced five-mass model used in the interaction study presents a sufficiently accurate picture of the mechanical train behavior.

- The maximum excitation of the first torsional mode occurs when at least one of the trains operates at a frequency at which the fundamental torsional natural frequency can be stimulated by the excitation torque $|6*(F_M - F_S)|$ (lowest order of *interharmonics*) generated in the inverter.

- Torsional natural frequencies of higher orders typically cannot be excited by an excitation at the motor air gap due to low amplification of the mechanical system.

- Finally it can be concluded that the uncoupled torsional analysis as specified in API 617, Seventh Edition (2002), is a sufficiently analytical method to predict the torque response in the train elements caused by an inverter operation. Bear in mind that the accuracy of the results is mainly influenced by the accuracy of the expected air-gap torque.

- Ultimately, in the design of VSDS trains, close collaboration of the driver and compressor manufacturers is of vital importance.

NOMENCLATURE

AF	=	Amplification factor
D	=	Modal damping
emf	=	Electromotive force
F_M	=	Electrical frequency into the motor
F_S	=	System/line frequency
LCI	=	Load commutated inverter
LNG	=	Liquefied natural gas
SK”	=	Short-circuit capacity
VSDS	=	Variable speed drive system

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