APPLYING VARIABLE SPEED DRIVES WITH STATIC FREQUENCY CONVERTERS TO TURBOMACHINERY

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ABSTRACT

Today, the variable speed drive with AC motor and static frequency converter is an outstanding solution to control the speed of turbomachines in the power range up to 100 MW and more. A wide selection of variable speed drives, both mechanical and electrical, is available. These systems are listed and discussed. The aspects that are essential for their application are dealt with. A further issue is the integration of the variable speed drive into its application environment. From the itemized electrical variable speed drive's interfaces, two are treated in more detail, namely the interface to the power supply system and the one to the mechanical system (shaft train). Some practical cases concerning design and operation characteristics of the mechanical system are subject to reflection.

INTRODUCTION

In recent years, more than 65 percent of the total electrical energy produced has been used to drive rotating machines of one kind or another. A considerable part of it is spent on driving turbomachinery.

Outdated methods for flow control that are based on fixed speed waste large amounts of energy, e.g., throttling, and generally also lead to poor process control. In this respect, control methods based on variable speed are substantially better. The electrical variable speed drives with AC motor and static frequency converter all have a very high efficiency and also far superior control features.

Static frequency converter technology has today reached a level which permits the design and manufacturing of very reliable variable speed drives for all kinds of applications and in particular for turbomachinery. They are available for high power and high speed and are applied in an ever increasing number.

DIFFERENT DRIVE SYSTEMS (GENERAL)

When planning a drive application, a multitude of drive solutions generally has to be evaluated in the light of a variety of drive tasks. On the one hand, the wide range of drive system alternatives offers the advantage that the system best suited to a particular application or drive problem may be chosen. On the other hand, the decision-making process becomes more complicated and selecting the right drive, as an optimum between drive-system features and application-related requirements, can become a complex undertaking, especially when high performance and high drive power are involved.

A number of selections have to be made before arriving at the best solution. It is opportune to insert a screening-step prior to evaluating the drive options. Selection should be made concerning: Adjustable speed or fixed speed? If adjustable speed, which kind? Electric, mechanical, or hydraulic speed control? If electric, which type of motor? AC or DC motor? And if electric with AC motor, which drive system?

An outline of drive systems available for any motion process is shown in Figures 1 and 2. The figures also provide some hints for drive system selection.

Variable Speed Vs *Fixed Speed*

For large drives, there are two practicable ways to control a flow (that is to transfer air, gas, liquid, etc.). These are based on constant or adjustable speed. Following are the main reasons why we should use adjustable speed.

• Substantial energy savings: In many industrial processes and also in utility applications, most of the machines such as

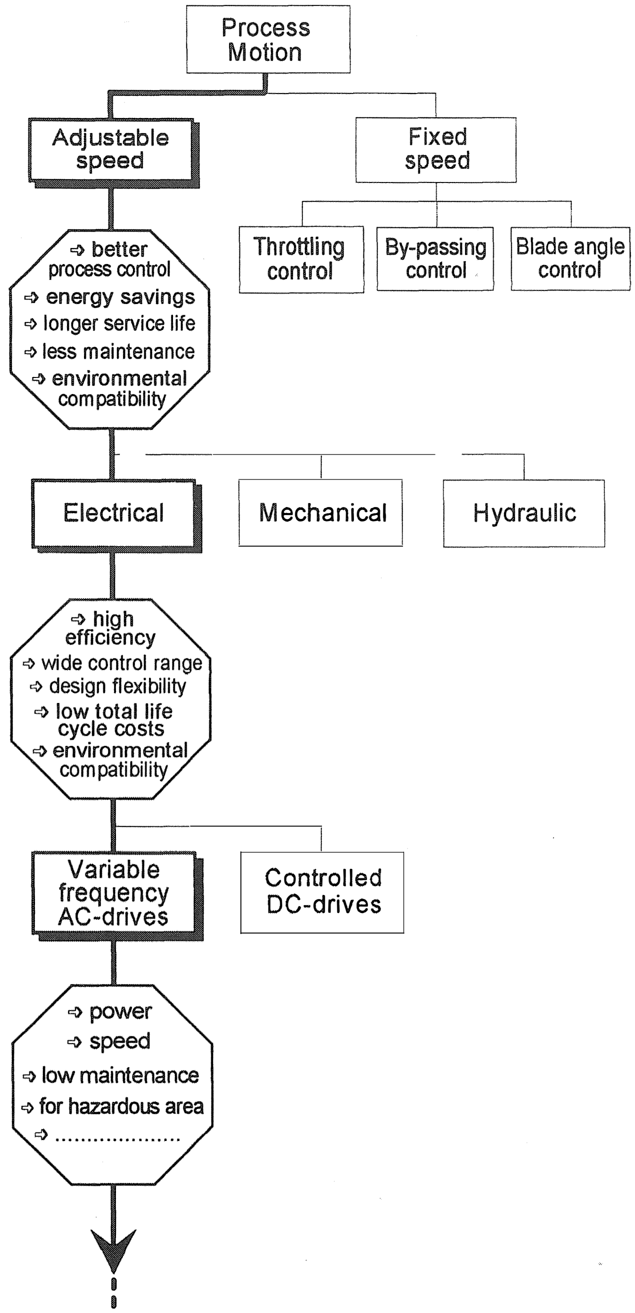

Figure 1. Drive Systems Guide.

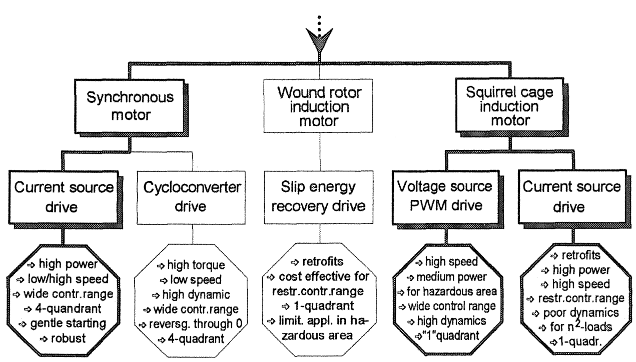

Figure 2. Drive Systems Guide (continued).

compressors, fans, blowers, pumps, etc., present a load torque to the drive system, which decreases with the square of the reduction of shaft speed. Running these machines at fixed maximum speed and controlling the process variables, such as flowrate or pressure, by mechanical means, e.g., impeding the flow with throttling valves or bypass valves, has a poor efficiency and leads to vast energy losses at operating points below equipment capacity. The energy losses can be substantially reduced if the speed of the machines is controlled according to process requirements leading to drastically lower operating costs.

• Improved process control: Adjustable speed offers the possibility to gain better control over any process. A better and smoother process control can be achieved through continuously matching the process output to demand, by means of accurate and fast control of the drive's speed (but also its torque and acceleration). Fluctuations in process output variables are avoided or at least reduced, and process stability can be improved. In many cases variable speed also enables an extended range of process regulation.

• Extended equipment life and less maintenance: The use of variable speed permits decreasing of existent vibration, which leads to reduced wear on the mechanical parts. The results are less blade/impeller erosion and corrosion, extended seal and valve life and extended bearing life. As a consequence, frequency and cost of maintenance are reduced.

• Further advantages of adjustable speed are: Less environmental impact, e.g., reduced air emission, reduced noise level, etc.

Electrical Vs Mechanical and Hydraulic Speed Control

Variable speed control can, in principle, be achieved in several ways. The most important methods in use are:

• Electric drives, motors with power electronic converters

• Mechanical drives, prime movers as gas turbines or steam turbines

• Hydraulic speed control, using electric, fixed speed motor together with a hydraulic torque converter.

The investment costs of an electric VSD, i.e., of all drive equipment with site cost for building, erection and commissioning, are lower than those of a gas turbine, respectively about equal to those of the hydraulic speed control option. Their better efficiency and low maintenance contribute essentially to large savings in operation and life cycle cost.

Whereas the economic advantages of the electric VSD option are generally at the fore, one should not forget further benefits resulting from several of its superior features. High reliability of the electric equipment and short time to repair of the modular designed static frequency converters (SFCs) guarantee the required high drive availability. The potentiality of the electric VSD system for wide speed control range, superior control accuracy and dynamic response makes provision for better process control and thus for increased production quality. The electric VSDs permit quick soft start as opposed to the gas turbine and will not impair the supply system as is the case when starting the motor of the hydraulic control option direct on line. Environmental issues, such as total lack of air emissions and substantially reduced noise level, are further advantages of the electric solution. Last but not least, it is also the design flexibility of the SFC of the VSD that has brought the electric option in a favorite position. Modular design provides more flexibility in the placement of the SFC, leading to good utilization of the available installation space. The SFC does not require space close to the motor contrary to the gas turbine, the steam turbine and the hydraulic torque converter. It can be located in a separate switchgear room, or if necessary, even outdoors in a containerized walk-in cabinet.

AC Vs *DC*

The electric VSD version may be implemented with:

- Voltage controlled DC motors or
- Frequency controlled AC motors

The incentives to use AC motors for variable-speed drives are not only that these motors are simpler, more rugged and less subject to wear and tear but also the fact that they can be operated at considerably higher speeds, voltages, and powers than DC motors.

The size and power of DC machines–up to several MW depending on speed range–are subject to certain technological limitations. The mandatory commutator and brushes restrict the armature voltage and current along with the speed. The commutator is the main cause of stoppages for maintenance. It is also the commutator that makes complicated encapsulation necessary if the motor is to be used in hazardous area. Moreover, the power-size/weight ratio of an AC motor is superior to that of a DC motor and the same is generally true for the power-size/price ratio.

Adjustable-speed AC drives have not primarily replaced adjustable-speed DC drives in applications traditionally dominated by the latter, but rather they are being used where modern AC drive technology offers opportunities which previously could not be realized, or could only be realized with great difficulty using DC motors.

The major technical reasons for choosing adjustable speed AC drives are:

- Requirements for high drive power and/or high drive speed
- Applications where ambient conditions or special circumstances either put the DC motor at a disadvantage or exclude its use entirely.

After this short comparison and discussion of the major drive systems basically suitable to high power turbomachinery application, it seems as if all considerations made so far favor the electric variable speed AC drive option.

One attribute of these drives, namely the physical property of their static frequency converters to generate harmonics, needs special consideration. This is given in INTEGRATION OF THE LARGE AC DRIVE INTO ITS APPLICATION ENVIRONMENT (INTERFACES).

VARIABLE SPEED LARGE AC DRIVES (LAD)

The various drive systems for speed control of AC motors are based on static frequency converter (SFC) equipment. The fundamental function of the converter is to transform the AC power from the power system of fixed frequency and voltage to AC power of adjustable frequency and voltage to control the torque and speed of the AC motor (Figure 3).

Compared to variable-speed DC drives, of which finally only one standardized converter configuration for control has prevailed, LADs may be designed and built according to one of several different systems (Figure 2). All are based on the combination of a suitable AC machine, namely a synchronous or an induction motor with one of the available SFC types.

Experience has shown that there are several drive systems basically suited for most applications. The SFC key configurations currently used for medium to high power turbomachinery applications are shown in Figure 3. The corresponding LADs are:

- Synchronous Motor/Current Source Converter (LCI for short)

The LCI drive system (load commutated inverter) is based on a current-source-inverter (CSI) of the DC-link type and is for use with a synchronous motor.

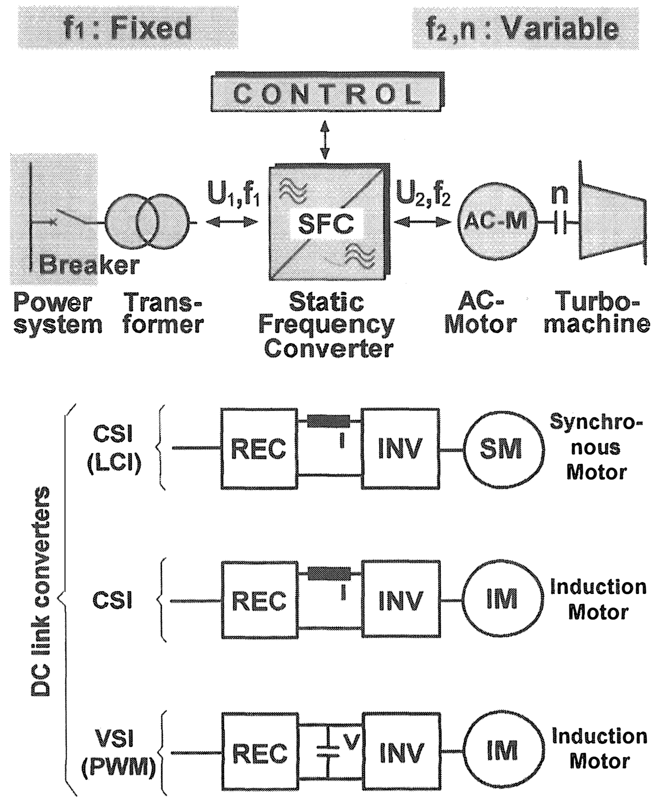

Figure 3. Key VSD Systems for Large Turbomachinery.

- Induction Motor/Current Source Converter (CSI for short)

The CSI drive system is based on a current-source-inverter (CSI) of the DC-link type and is for use with a cage induction motor.

- Induction Motor/Voltage Source Converter (PWM for short)

The PWM drive system (pulse width modulated) is based on a voltage-source-inverter (VSI) of the DC-link type and is for use with a cage induction motor.

As the concept and functions of these drive systems are well known [1], this presentation is restricted to a summarized presentation of those features that are essential to the turbomachinery application. Subsequently, in the section following this one, special emphasis will be put on aspects that are of importance when integrating the LADs into their application environment.

The typical power and speed limits for the variable speed drive systems considered are plotted in Figure 4. The limits are primarily determined by physical constraints in the motor and by the motor design. The SFC of the current source type, an example of which is shown in Figure 5, places practically no restrictions on the maximum design power. Variable speed synchronous motors with unit power exceeding 40 MW, for operation up to about 4000 rpm, have been built to drive natural gas transmission compressors. Motors with even higher power of up to 100 MW and more are being manufactured for special applications, e.g., fan drives for wind tunnel facilities.

Commonly, the power rating of the cage induction motor for variable speed application seldom exceeds seven to twelve MW. Whereas, the lower values are more applicable with the PWM converter, the upper limit is valid with the CSI converter type. Maximum speed is about 7000 rpm. If even higher speed is required, motors must be built using nonstandard material and unconventional design.

Motor and converter voltage are chosen in such a way that the entire drive system is designed to its economic optimum. For

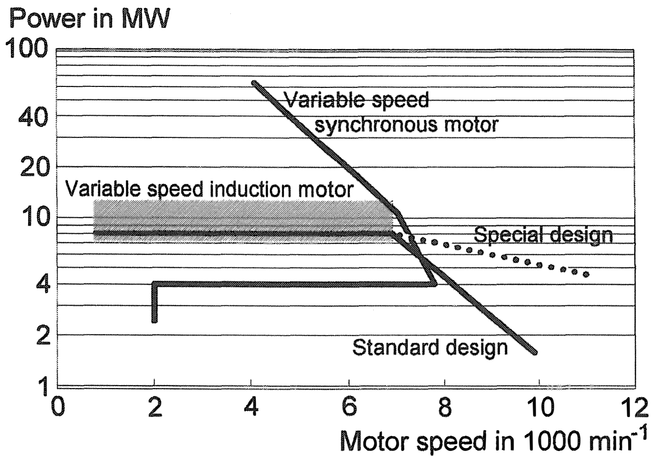

Figure 4. Typical Power and Speed Limits of Large VSD Systems.

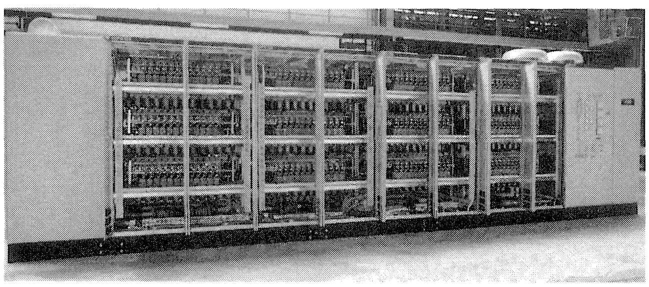

Figure 5. Water-cooled, LCI-type Current Source Converter, 41 MW, 0 ... 60 Hz. (Supply for synchronous motor, 0 ... 3600 rpm, for variable speed driving a natural gas compressor).

turbomachinery applications of the power class considered, this generally means "higher voltage for higher power" so that medium voltage drives (MVD) prevail. Variable speed synchronous motor drives for voltages up to 10 kV have become standard practice, but special solutions for higher voltages have also been designed. Variable speed cage induction motor drives with PWM voltage source inverters are presently built with voltages up to about 3.3 kV. For higher motor voltages, step up transformers at the SFC output are put to use. However, induction motor drives with current source inverters are built for higher motor voltages up to about 6.9 kV.

The selection of the best suited VSD system depends mainly on the application. Apart from obvious premises related to quality aspects such as proven, highly reliable solutions, the VSD systems for high power turbomachinery applications should fulfill the following requirements:

- Present a wide range of power ratings, leaving the option for an overall economic rating.
- Offer a wide range of speed ratings, in order to be rather free to choose rated speed for process optimization also from an economical point of view.
- Have an adequate speed control range.
- Have the fully controlled soft start capability.
- Be "network friendly" with regard to reactive power and harmonics.
- Be within acceptable levels of electromagnetic torque pulsations.
- Permit operation in hazardous areas.

It is obvious that the drive system should also satisfy general requests as low prime costs including equipment, engineering, civil works, erection and commissioning, and low operating costs (high overall efficiency, reduced maintenance, environmental issues, etc.), all playing a part in the economic drive evaluation.

The characteristics and attributes of all three key LAD systems put forth (Figure 3) are largely consistent with the requirements for application to high power turbomachinery.

The synchronous motor VSD is best suited to very high power, single-motor applications and also in conjunction with high speed requirements. The LCI type of SFC places practically no restrictions on the maximum design power. The motor is fully self controlled and hunting or loss of synchronism is ruled out. Regenerative braking can be achieved without including any additional equipment in the SFC.

In the power range up to about 12 MW the cage induction motor VSDs gain momentum and tend to replace the synchronous motor VSDs. Main impetus is the ongoing development of turn-off power semiconductor devices (GTO thyristors). At present the voltage source converters and the current source converters are competing for predominance. The current stage of development of both types of converters makes use of PWM GTO-thyristor inverter technology. The purpose of it is to improve voltage and current waveforms and to reduce harmonic effects.

The voltage source PWM type is a highly efficient drive with extremely low consumption of reactive power throughout the whole speed and load range. It has outstanding dynamic performance and can be controlled down to zero speed while maintaining a smooth torque, a characteristic which, as a matter of fact, is not so much of importance in turbomachine applications.

The CSI type of SFC for the induction motor displays quite a limited speed/load operation field which is, however, very well suited to the typical squared torque-speed characteristics as they occur in turbomachine applications.

The different converter configurations of all three LAD systems are clearly defined and well established. Today suppliers offer standardized equipment, which is more and more superseding application and even project specific configurations. This standardized equipment is based on modular mechanical and electrical designs. Sufficient modularity permits a high degree of pre-fabrication and component standardization but still has the intrinsic flexibility to comply with special applications and with customer requirements. Focused on technical and economical benefits, standardization of designs and of equipment not only leads to improved quality and increased availability of these VSDs but also cuts down the engineering effort required, altogether resulting in reduced total cost, in an expeditious schedule and in less risks.

INTEGRATION OF THE LARGE AC DRIVE INTO ITS APPLICATION ENVIRONMENT (INTERFACES)

The main components of the drive system are the motor, the converter with its controls and, if needed, the transformer. An outline of the drive system integrated into its application environment is shown in Figure 6. Already at an early stage of any project, this integration calls for careful treatment of the drive interfacing.

In LAD applications it is not recommended that an entrepreneur purchases and puts together components such as a motor, a converter, a transformer and switching equipment to solve his specific drive task. It is more expedient that he procures the complete drive system, including system engineering and commissioning, from a single authoritative supplier. Apart from the basic drive design, the drive system engineer has to take into consideration the aspects related to the integration of the drive into its application environment. SFC technology has evolved to an extent where it is now possible to build very reliable, high power VSDs. To support this advanced technology in its correct application, it is

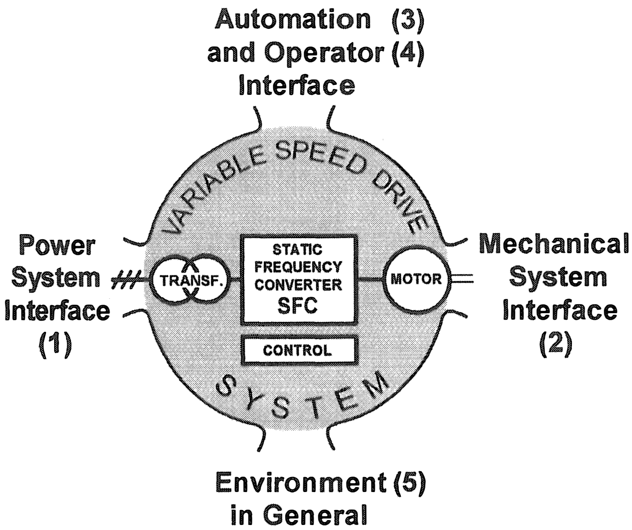

Figure 6. Integration of the Drive into its Application Environment.

absolutely essential that the manufacturer and supplier work closely together with the customer/enduser right from the planning phase.

The major interfaces of the drive to its application environment are between:

1. Drive and power system
2. Motor and mechanical system
3. Drive control and control room/automation
4. Drive control and operator (local).

Interfaces (1) and especially (2) are subject of further examination and discussion, but first a few comments on (3) and (4) along with on environment in general are given.

At interface (3) the integration of the drive controls is looked upon at the plant level (control room, automation). From the point of view of plant control, the drive is generally regarded as an ancillary function. Data exchange should be restricted to signals necessary to accommodate functions to the safe application of the various operating modes. The communication with, for example, the control room can be designed with analogue and binary input/output modules, using conventional wiring. However, today digital solutions dominate and, therefore, the drive should provide communication interfaces for serial data exchange. As communication standards are only just firming up, the bus interface (hardware and protocols) should be such that it conforms with those types most commonly used and offers the customer a high degree of flexibility to accommodate changes.

At the operator (local) interface (4), there is a demand for easy-to-use, powerful operator panels, presenting all information in plain language. They feature parameter access and handling, along with extended diagnostic capabilities. They facilitate rapid troubleshooting and contribute to high availability in case of a malfunction.

Some words to environment in general. Aspects such as installation restrictions, conveyance of the cooling media and of electric power, have to be evaluated. Here modular design of the LADs provides more flexibility in the placement of the drive, leading to good utilization of the available installation space. Also aspects as–demands on safety class, a well designed earthing system, and proper shielding of components–are prerequisites if problems, resulting from insufficient electromagnetic compatibility, are to be avoided.

Drive ⇔ Power System Interface

Both the influence of power system disturbances on the drive system behavior and the impact the SFC can have on the power system generally need careful analysis. Power system disturbances can affect the voltages at the SFC's input in terms of voltage transients, undervoltage, voltage dips and voltage loss, frequency deviation and harmonic distortion. The SFC has to be robust enough to largely withstand these disturbances and the drive system as a whole has to be examined in this respect. For certain disturbances, a ride-through capability is required.

The reactions of the drive on the power system are caused mainly by consumption of lagging reactive power for control of the converter and by injection of current harmonics into it. Both reactions are typical features of the current and of the voltage source converter types, whereas for the latter the effects are much less dominant. The reactive power requirement principally means an additional load on the supply. The power factor, i.e., the ratio of the active power to the apparent power, of current source converters is typically 0.85 to 0.92 at rated speed and rated load and declines with reduced speed. With quadratic torque-speed characteristic, which is the load in turbomachine applications, the maximum reactive power consumption is at rated speed and load even though the power factor declines at reduced speed.

Harmonic Generation

Variable speed large AC drives act as nonlinear loads on the connected power system. The static power conversion equipment put to use distorts the current waveform compared to the pure sine wave shape. This distortion can be expressed as a sum of harmonic waveforms. From the standpoint of harmonic generation, the current source converter and the voltage source converter are both of the DC-link type. They may, in first approximation, be considered as harmonic current sources injecting the currents into the power system. The generated harmonics are known and can be sorted according to the following categories.

• Characteristic integer (i) harmonic currents with typical frequencies

$$f_{S(i)} = (a \times p_S \pm 1) \times f_S \qquad (1)$$

are integer multiples of the fundamental frequency f_S of the supply system. [p_S = 6,12, ... is the pulse number of the rectifier configuration, a = 1,2,3 ... ordinal number and ($a \times p_S \pm 1$) the harmonic order]. Ideally looked at, the per unit magnitude of these harmonic currents is equal to the inverse of the harmonic order. It follows that only the lower order harmonics are of any significance for harmonic effects.

• Characteristic noninteger (n) harmonic currents. In all DC-link type converters, the output section ("inverter") is not completely isolated from the input section ("rectifier"). The energy storage capacity of the inductor, respectively of the condenser bank in the DC-link, is limited, which results in a DC ripple. The effect of this is the generation of harmonic currents with noninteger frequency multiples, caused by interference from the constant supply frequency f_S with the speed dependent motor frequency f_M, which are injected into the supply system.

The frequencies of these noninteger harmonics can be represented by

$$f_{S\,(n)} = (a \times p_S \pm 1) \times f_S \pm b \times p_M \times f_M \qquad (2)$$

[p_M = 6,12, ... is the pulse number of the inverter configuration and b = 1,2,3 ... ordinal number]. These interharmonic sidebands are typically small in magnitude, provided that the dimensioning of the DC-link storage elements is sufficient and are, under normal circumstances, uncritical. But as their frequencies vary with drive speed (n proportional to f_M) they should be checked regarding their effect on the supply system.

• Noncharacteristic harmonics, which are not specific to the perfected design objective, can originate from imperfections, such as imbalance, whether in the power supply system (unbalanced voltage amplitudes and phase relations) or in the drive system (components, control, asymmetry in the firing angles). Noncharacteristic integer along with noninteger harmonics may develop. Since such harmonics are not deliberate they occur, if at all, only in small magnitudes and can usually be ignored. However, in critical applications they should be considered presuming appropriate values gained from experience.

System Reaction

Attention should be paid to the matter of harmonic injection. The current harmonics injected into the power system cause voltage drops across the power system reactance and lead to distorted voltages (voltage harmonics and notching), at the point of common coupling (PCC). This could cause interference with other equipment in the plant. In applications with weak power systems having low fault levels, these effects could become troublesome.

The amount of harmonics that may be tolerated to preserve the quality of the power system at the PCC is specified in the IEEE Standard 519-1992. This standard recommends acceptable levels in terms of current harmonics, voltage distortion and telephone interference. In most VSD applications, with supply systems having sufficient fault level, standard drive equipment can comply with these limits without any special measures. However, attention has to be paid to applications with very high drive power, especially when supplied by relatively weak power systems. In such cases, and even more if resonant conditions can be expected, a harmonic study of currents and voltages at the start of the project is recommended in order to avoid problems rather than having to cure them later on.

Remedies

Reducing the harmonic reaction of the VSD on the supply can be achieved in one of three ways. One basic method is the use of "network friendly" SFC configurations. The design of the rectifier for 12-pulse operation, cancelling the more dominant 5th and 7th harmonics, is a good way to reduce the harmonic impact on the power system. For higher drive powers this has become a standard solution. A PWM-controlled voltage source converter on the supply side of the SFC, practically loading the supply system with sinusoidal currents and a power factor of one, could become an ideal solution in the future.

Another obvious way is to increase the fault level at the PCC. A practical method for such an increase is to move the PCC to a higher voltage system. The limits of system harmonic voltage levels can so be better adhered to.

A third method, more of a remedial solution, is the addition of harmonic filters at the PCC, i.e., several absorbing LC shunt filters tuned to the frequencies of those harmonics which are to be kept away from the supply (Figure 7). As the filters are capacitive at 60 Hz, their use provides a certain degree of power factor correction as additional benefit.

However, attention has to be paid in case of any resonant condition in the power system. The power source impedance coupled with the filters represents in general a parallel resonance at lower frequencies which could be excited at corresponding drive speeds. This situation becomes quite complicated if the frequency-dependency of the power source impedance enters into the game. In such a case a thorough system analysis is necessary. Efficient computer programs for network analysis and harmonic filter calculation are available.

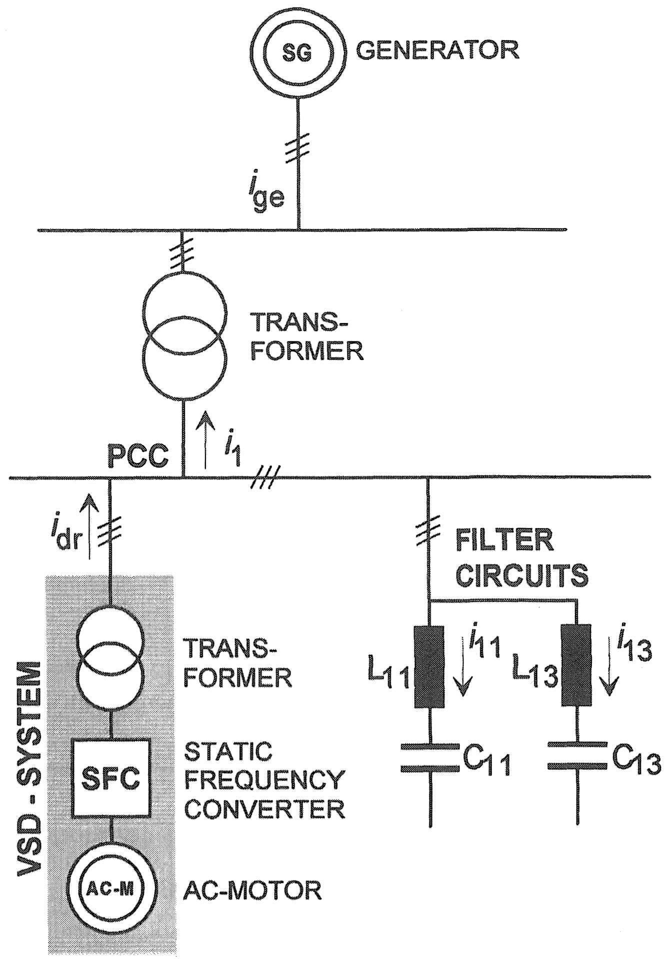

Figure 7. Arrangement of VSD with Filter Circuits at Point of Common Coupling.

Drive ⇔ Mechanical System Interface

At this interface special attention has to be paid to the following items:

• The electromagnetic torque of the motor and the torque of the load machine

• The response of the whole shaft train to the electromagnetic torque of the motor and that of the load machine (torsional analysis)

• The rotordynamic properties of the whole shaft train (lateral critical speeds, unbalance response, complex eigenvalues)

• The design restrictions, if specified, concerning the selection of the coupling type and its mounting on the shaft

• The requirements relating to the foundation of the motor.

Harmonic Generation

The electromagnetic torque harmonics of the motor basically have similar properties as the current harmonics described in the previous section. The harmonic categories are listed hereafter, irrespective of their technical significance.

• Characteristic integer (i) harmonic torques, with typical frequencies:

$$f_{T(i)} = c \times p_M \times f_M \qquad (3)$$

are integer multiples $c \times p_M$ of the fundamental electrical frequency f_M of the motor (at speed n). [$p_M = 6, 12, ...$ is the pulse number of the inverter configuration and $c = 1,2,3 ...$ the ordinal number].

The amplitudes of some of these components can, in worst cases, amount to about 0.20 of the rated torque for the LCI and to about 0.40 for the PWM. Usually, they are about 0.10 of the rated torque.

• Characteristic noninteger (n) harmonic torques. They are also caused by interference as explained in *Drive ⇔ Power System Interface.* Their frequencies can be represented by

$$f_{T(n)} = c \times p_M \times f_M \pm d \times p_S \times f_S \quad (4)$$

[$p_S = 6, 12, ...$ is the pulse number of the rectifier configuration $d = \pm 1, \pm 2, \pm 3, ...$ integers and f_S the fundamental frequency of the supply system].

The amplitudes of some of these components can, in worst cases, amount to about 0.10 of the rated torque. Usually they are about 0.03 of the rated torque.

• Noncharacteristic harmonic torques, which are not specific to the perfected design objective, can originate from imperfections as explained in section *Drive ⇔ P•wer System Interface.* Noncharacteristic integer along with noninteger harmonics may develop. The amplitudes of these harmonics are generally small and, therefore, usually not considered in the torsional analysis.

• In addition to the torque harmonics mentioned so far, the PWM drive system also generates characteristic harmonic torques originating from the PWM inverter switching frequency (modulation). The PWM strategy is, among others, to reduce low frequency torque pulsations at the expense of high frequency torques. The corresponding pulsations generally occur well above the first five mechanical resonances of the shaft train. In the lower frequency range, the amplitudes of these types of harmonics are small and, therefore, usually not considered in the torsional analysis.

• Another characteristic of the PWM drive system is the occurrence of torque transients due to pulse pattern switchover. Here discontinuities must be considered in the average torque and also in the characteristic integer harmonic torques, each time the drive passes through a pattern switchover speed. With a well tuned control, the shaft torques excited by this phenomenon remain below the level of those excited by characteristic harmonics and switchover is also relatively infrequent.

• In the case of LCI systems, a transient due to pulse operating mode occurs at the beginning of runup (up to about five percent of maximum speed). In this operating mode the torque is intermittent. The magnitude of the first pulse must be higher than the breakaway torque. This means that in applications with turbomachines (torque proportional to the square of the speed) it can be kept low.

For torsional analysis, all torque components with frequencies up to 100 Hz which have amplitudes not less than 0.01 of the rated motor torque should be considered. Components with frequencies above 100 Hz are considered only if their amplitudes are higher than 0.03 ... 0.05 of the rated torque.

System Response

The response calculations for the shaft train have to cover the whole speed range including all relevant operational modes. For a VSD these are: The steady-state operation (control range), the runup and electrical disturbances. In addition, all excitation torques produced by the load machine have to be considered. They must be specified by the responsible manufacturer.

• In most cases, the examination of the steady-state operation of a variable speed drive can be limited to its performance when running at some of the lowest resonance points [2]. An example of a frequency map for an LCI drive is shown in Figure 8. For a shaft train built with couplings using steel components only, the response calculations should be made with a conservative internal damping value, i.e., D = 0.005. Only elastomeric couplings have considerably higher damping values. Usually, the highest transmissibility ratio appears under resonance conditions with the first torsional natural frequency. In most cases, the highest shaft torque occurs at the resonance of a noninteger component with the first natural frequency of the shaft train (one of points C, D or E, F in Figure 8). In steady-state operation the stresses occurring within the shaft, couplings and rotors should never exceed the fatigue limit of the material.

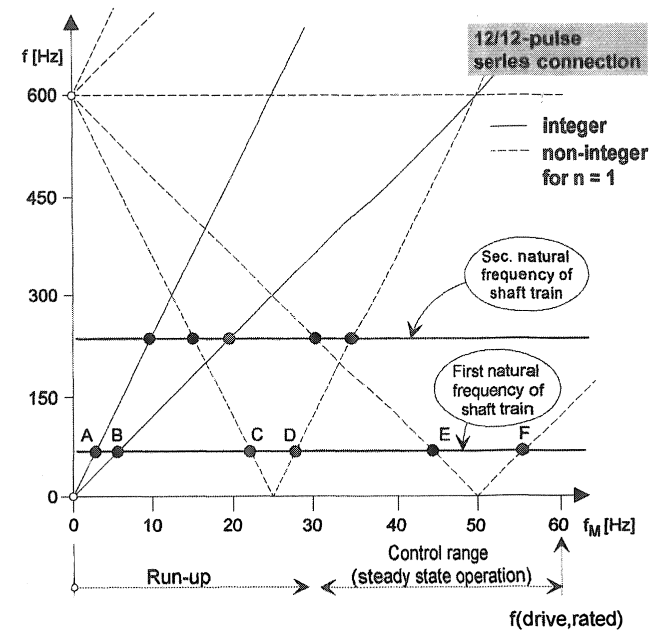

Figure 8. Frequency Map of an LCI Drive (f = exciting resp. natural frequency, f_M = motor supply frequency).

• Runup of a VSD is an operational mode that does not normally determine the shaft dimensions. Nevertheless, it is highly advisable to perform a torsional analysis for this mode also. All three of the drive types under consideration produce the same/similar excitation during runup as in steady state operation. The only exception occurs with the LCI (see the final point section *H•rmonic Torque Generation*). The corresponding shaft train stresses, especially when running through the first torsional natural frequency (points A and B in Figure 8), are considerably lower than those occurring during the direct-online start of the motor. The design rules for fixed-speed motors with direct-online starting allow the sizing for this kind of operation to be done according to the fatigue strength for a limited number of load cycles. For larger motors, 5000 down to 1000, runups are acceptable values, depending on application. In any case, the stresses in the shaft train of a VSD during runup will be considerably lower than those of a comparable fixed speed motor when starting directly online.

• Further points requiring consideration are the electrical disturbances. Most electrical machine manufacturers take the line-to-line terminal short-circuit as the worst case disturbance. This short-circuit is highly unlikely. The magnitude of the electromagnetic short-circuit torque is higher than that of any other electrical disturbance, be it in the frequency converter or in the power system.

The shaft can, therefore, be sized without any additional safety margin. An essential prerequisite is that the torsional stress in the critical shaft section does not exceed the torsional yield point of the shaft material. In those cases where the stress cannot be kept below this limit by acceptable changes to shaft train dimensions (coupling) and/or material quality, the application of a shaft-torque limiting device is acceptable. This may consist of shear pins, slipping of a shrink-fit connection, etc.

Remedial Measures

The basic measure is the use of "shaft train friendly" SFC configurations. The design of the inverter for 12-pulse operation, for instance, leads to the cancelling of the more dominant sixth, eighteenth, etc., harmonics, which corresponds to a reduction of the harmonic impact on the shaft train.

Additional measures to reduce torsional oscillations of the shaft train are:

- Avoiding any torque amplification at and around critical shaft train resonance via control (speed control loop).
- "Electromechanical damping" of the mechanical system. An example is given in case study *LCI for ID-Fan.*
- Avoiding critical operation at and around mechanical resonance speed by a narrow automatically actuated "blocking speed window."
- Shifting the first torsional natural frequency out of the operating control range. An example is given in case study *PWM for Recycle Gas Compressor.*

CASE STUDIES

The case studies reported here are the only known disturbances for which the authors' company had to organize a special task force. All other VSDs delivered, representing more than 1000 MW of installed power, were put into service by our commissioning personnel without any difficulty.

LCI for ID-Fan

In 1993, the existing two induction motors driving the two ID-fans in a 1000 MW conventional steam power plant were replaced by two variable speed LCI drives. The arrangement of this system is shown in Figure 9. It comprises a double-flow centrifugal fan connected to an LCI-fed, eight-pole 5481 kW synchronous motor by a resilient (elastomeric block) coupling. The operating range of this drive is between 270 and 890 rpm, i.e., 18.0 to 59.3 Hz supply frequency. The torsional analysis showed the following shaft loads:

Runup	0 to 890 rpm	52 ± 80 kNm
Steady-state operation	270 to 890 rpm	58 ± 6 kNm
Short circuit (Figure 10)	270 to 600 rpm	58 ± 8000 to 256 kNm
	600 to 890 rpm	58 ± 256 kNm

During steady-state operation and also during runup, the stresses occurring in all shaft elements are below the allowed limits. In case of the very improbable terminal line-to-line short circuit (Figure 10) in the operating range from 270 to 600 rpm, according to motor supply frequency between 18.0 and 40.0 Hz motor supply frequency, the von Mises stress can reach and even considerably exceed the material yield strength of the shaft parts. At the time the above calculations were made, modifications to the shaft train were no longer possible (existing foundation, fixed delivery date, etc.). The only practicable solution to the problem was the modification of the coupling to incorporate shear pins, recommended and supplied by the coupling manufacturer. The design of the shear pins was for an alternating torque of 256 kNm. The maximum allowed alternating shaft torque of 450 kNm for the weakest shaft element guarantees an adequate safety margin.

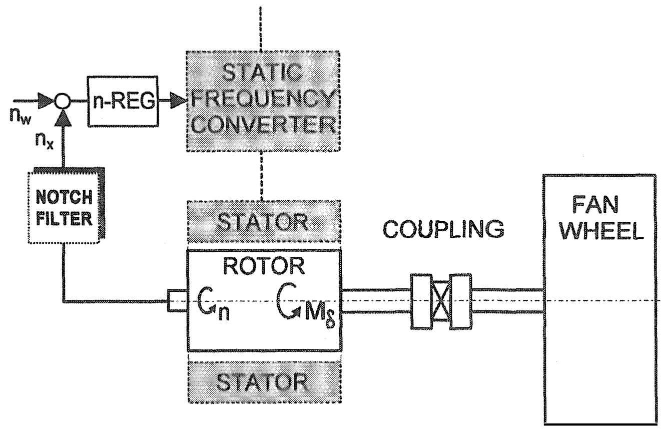

Figure 9. Block Diagram of an ID-fan Drive, 5481 kW, 0 ... 890 rpm. Notch Filter in the Speed Control Loop tuned to First Natural Frequency of the Shaft Train.

After about 200 days in operation the shear pins failed on one drive unit and about 40 days later the same occurred with the other one. During this time the fans had been in continuous operation.

The metallurgical examination report on the broken pins stated: " ... , these fractures initiated at the shear neck radius and propagated due to cyclic metal fatigue, ..." The events which caused the fractures obviously produced stresses that exceeded the fatigue (endurance) limit of the pin material. This indicated that the disturbing effects occurred only occasionally, perhaps during runup or other special operating conditions, e.g., speed change.

The currents measured in the DC-link indicating the electromagnetic torque pulsations, showed that the speed controller had a high noise sensitivity. The addition of a notch filter in the speed measuring channel is depicted in Figure 9. The filter is tuned to the first natural frequency of the shaft train. This resulted in the reduction of the system response by about 50 percent. Unfortunately, this change did not bring a sufficient decrease in the shaft torques. The shear pins continued to break.

A thorough examination of the coupling concept and the quality of the machining, especially that of the shear pins and their fixation in the coupling flanges (Figure 11), showed that the shear pins were poorly designed and also not machined finely enough. Bending moments due to misalignment were transmitted directly to the shear pins. During operation, the holes in the coupling flanges were deformed by knocking action. As a result the pins were no longer tightly held and, therefore, additionally stressed. Shear pin rupture was the consequence. The collars on both sides of the pin notch retained the pins within the flange. During further rotation, the protruding pin stubs repeatedly struck one another, producing axial impact forces that damaged the guide bearing and the bracket. It was found that the sharp notch (small radius) on the pin had been badly manufactured, having small dents and sharp corners from which cracks initiated. Note that couplings using shear pins are working satisfactorily in many rolling mills [3].

The final solution, which has now been in operation for more than two years, was to replace the shear pins by normal coupling bolts. This was possible because further electrical studies showed that, in the speed range between 90 and 490 rpm, a reduction of the air gap flux was permissible. In this way the short-circuit excitation torques were considerably reduced (Figure 10). The corresponding response shaft torque no longer caused overstresses to any part of the shaft.

LCI for Ethylene Compressor

In 1986, the steam turbine driving the ethylene compressor in a petrochemical plant was replaced by an LCI drive. The block

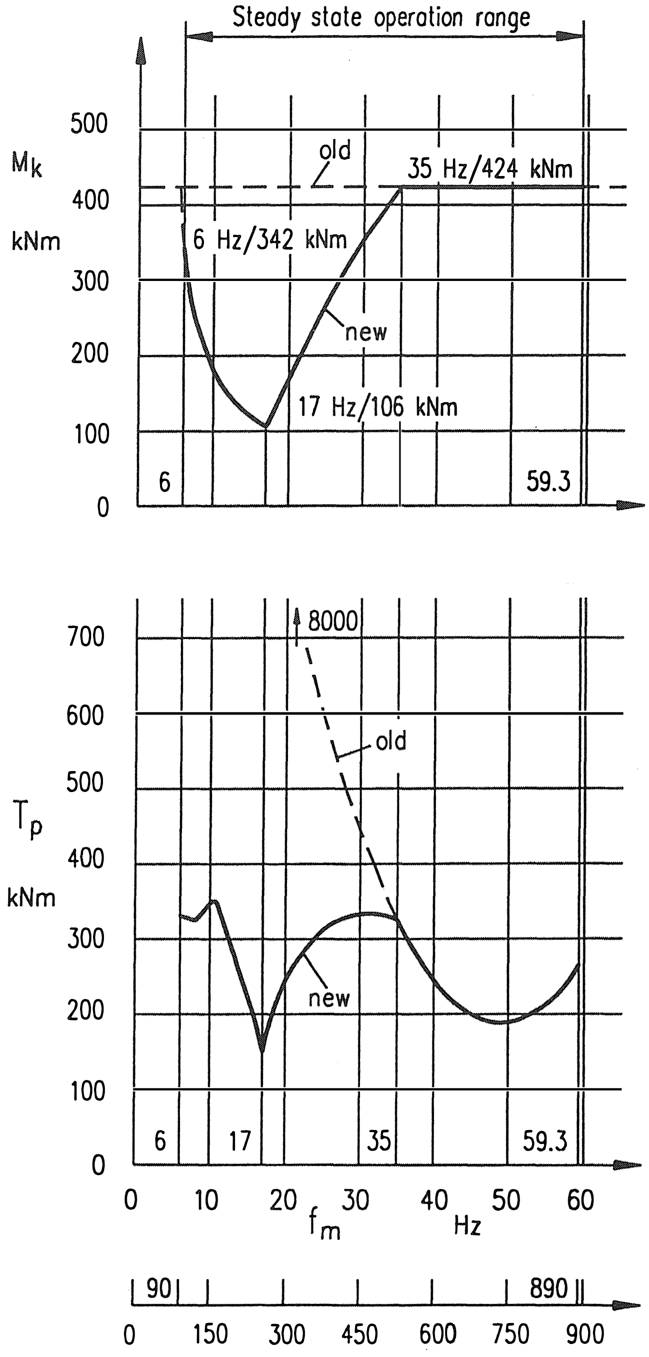

Figure 10. Peak Values for Electromagnetic Torque (upper diagram) and Shaft Torque (lower diagram) for a Line-to-line Terminal Short-circuit.

diagram of the shaft train for the upgraded drive is shown in Figure 12. The 13400 kW synchronous motor with a solid pole rotor, fed by an LCI converter, has an operating range between 5700 and 6400 rpm, i.e., 95.0 to 106.7 Hz supply frequency. The motor was connected to the low-pressure compressor via a membrane twin coupling with a long (≈1500 mm), slender, floating spacer shaft. This torsionally soft shaft was necessary to enable the motor to be anchored on the existing steam turbine foundation. The first torsional natural frequency of the shaft train was 11 Hz. The

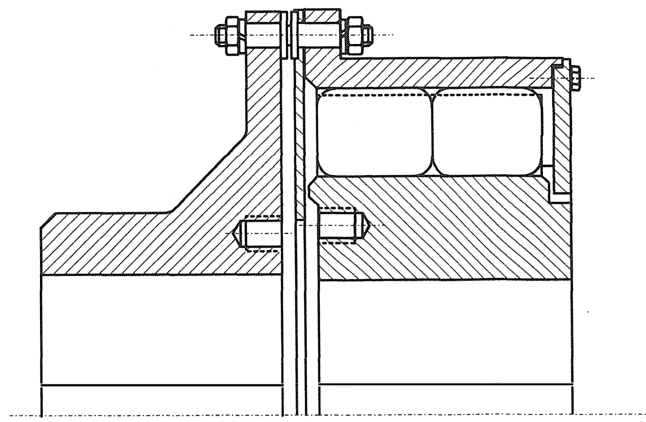

Figure 11. Longitudinal Section of the Resilient Coupling with Shear Pins.

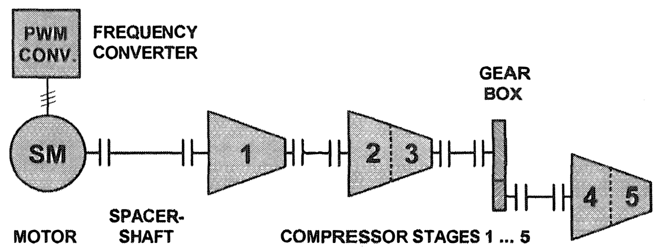

Figure 12. Block Diagram representing Shaft Train of Five-stage Compressor (power rating 13000 kW, max. speed 6400 rpm., resp., 11540 rpm).

following torque peak values between the motor and the compressor were calculated:

Runup	0 to 5700 rpm	5 ± 19 kNm
Steady state operation	5700 to 6400 rpm	20 ± 1 kNm
Short circuit	5700 to 6400 rpm	20 ± 5 kNm

The resulting torsional stresses are below the permissible limits.

The calculation results for lateral critical speeds, unbalance response and complex eigenvalues were acceptable and indicated no cause for concern. As usual at that time, the oil-film coefficients for the motor bearings were determined for mean values of bearing load, bearing clearance and oil viscosity. The operating speed range for the shaft train, comprising motor, floating spacer shaft and low-pressure compressor with one half of the gear coupling at the nondrive end, lay between the third and the fourth lateral critical speeds.

After about two weeks of test runs, the shaft failed. A thorough investigation with extensive tests using a provisional spacer shaft, led to the final solution. An auxiliary bearing was added to the floating shaft and the membrane couplings were replaced by rigid flange couplings. After this modification, only two critical speeds still lay below the operating range. The critical speed dictated by the spacer shaft was now above the operating speed range. In this case, a solution featuring the replacement of the existing four-lobe bearings of the motor by tilting-pad bearings was not considered safe enough. Since these modifications have been done, the machine has provided trouble-free continuous operation.

The investigation of this incident has shown that the calculation of complex eigenvalues should not be restricted to a model of the complete shaft train. It must also consider the possible scatter of the values for the oil-film coefficients. In such cases, the Two Limit Cases (TLC) Method [2] is applied. The calculation of the oil-film constants is performed for the following limit values of the relevant variables:

Bearing load	1.6 times static load	0.4 static load
Clearance	upper tolerance limit	lower tolerance limit
Oil viscosity	at min. temperature	at max. temperature

The studies have shown that in this case nonconservative oil-film forces have brought into action a latent instability that manifested itself through the kinematically weakest link, i.e., the floating spacer shaft. For this final dimensioning, the complex eigenvalues were calculated in the speed range 5000 to 7000 rpm. The complex eigenvalues for a speed of 5400 rpm are given in Table 1. When running through this speed the damping coefficients, i.e., the real parts of the seventh, eleventh, and seventeenth eigenvalue, become positive. Positive damping values are an indicator that with time a continuous increase in vibrations must be expected.

Table 1. List of Relevant Complex Eigenvalues.

$\lambda = \alpha \pm \iota\, \omega$ $\qquad \alpha\,[1],\ \omega\,[H\zeta]$

ASSUMPTION FOR OIL FILM CALCULATION							
LOWER LIMIT				UPPER LIMIT			
		α	ω			α	ω
1	-	28976.347	0.0	1	-	105331.823	0
2	-	24499.504	0.0	2	-	88835.242	0
3	-	23810.279	0.0	3	-	79336.756	0
4	-	20932.460	0.0	4	-	45003.147	0
5	-	3790.790	0.0	5	-	42339.098	0
6	-	2494.565	0.0	6	-	39591.327	0
				7	-	37789.209	0
				8	-	37188.461	0
				9	-	29962.824	0
				10	-	8849.825	0
				11	-	2582.858	0
				12	-	2094.032	0
7	+	**0.542**	32.11	13	-	1.878	39.69
9	-	15.125	91.92	15	-	16.256	99.54
11	+	**8.525**	121.10	17	-	4.424	126.71
13	-	4.178	125.64	19	-	33.851	148.64
15	-	34.356	143.04	21	-	0.409	188.61
17	+	**1.711**	169.94	23	-	0.268	199.28
19	-	43.336	253.97	25	-	8.682	341.61
21	-	11.507	315.28	27	-	5.357	368.27

PWM for Recycle Gas Compressor

In 1990 we received an order for a recycle gas compressor for a refinery plant. The shaft train of this 2280 kW installation comprised a four-stage, single-shaft centrifugal compressor, a high-speed membrane coupling, a single-stage spur gear, a low-speed membrane coupling and a four-pole cage induction motor fed by a pulse width modulated (PWM) inverter. The speed control range of the motor is 840 to 1575 rpm, i.e., 28.0 to 52.5 Hz supply frequency. With a gear ratio of 8.96 the compressor speed range is 7526 to 14112 rpm. In this case, the compressor manufacturer was the only one contracted to perform the torsional analysis, which was limited to the calculation of the torsional natural frequencies for a lumped 12-mass system. The first natural frequency was calculated to be 32 Hz. This was later confirmed by measurement.

On the test stand in the compressor manufacturer's factory, high lateral vibrations on the gearing low-speed shaft were detected. These vibrations were load dependent and occasionally reached unacceptable values of about 70 μm p-p in the speed range 1400 to 1600 rpm. The dominant frequency was not the rotational frequency of about 25 Hz as would be expected, but 32 Hz, i.e., the first torsional natural frequency of the shaft train. Subsequent measurements of the torsional oscillations in the shaft train confirmed the suspicion that the lateral vibrations were the result of the transmission of pulsating torques through the gears. In Figure 13, a runup from 850 to 1575 rpm is shown. The first vibration peak, at about 960 rpm, is the transient excitation of the first natural frequency by the fundamental supply frequency. The other three peaks are the consequence of a self-excited, impulse-like, stochastic occurrence. The dominant frequency in the waterfall diagram is 32 Hz. The vibration records, when running the drive at 1575 rpm with a load of 1000 kW and 2000 kW, respectively, are given in Figure 14. Here also, the first torsional natural frequency is predominantly excited in an impulse-like stochastic manner. The measured peak amplitudes vary between 1.0 and 5.3 kNm. The maximum allowed torque amplitude for this shaft train is determined by the gearing and amounts to 4.8 kNm, which is 35 percent of rated torque (13.7 kNm at 1500 rpm). Additional control tuning brought no appreciable reduction of these stochastic impulse amplitudes.

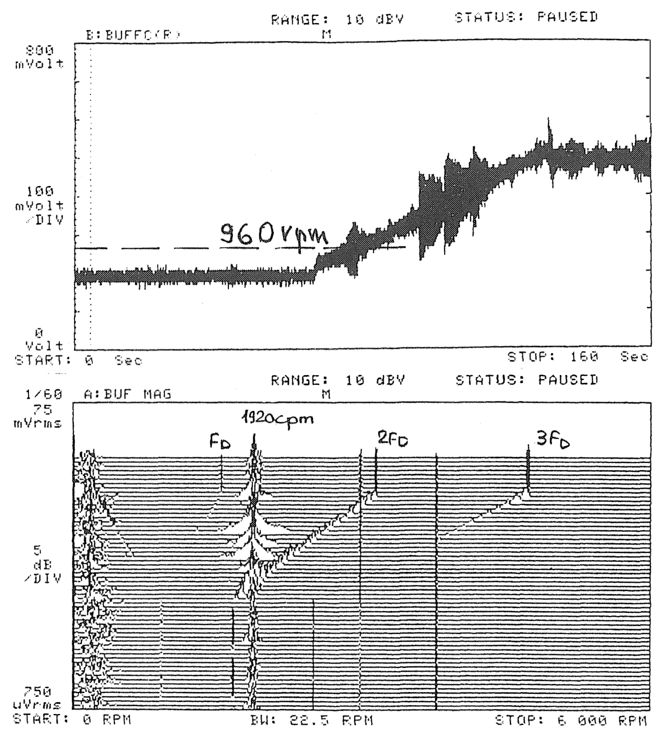

Figure 13. Shaft Torque and Waterfall Diagram for Runup from 850 rpm / 190 kW to 1575 rpm / 990 kW.

A practical solution to the problem was to displace the first natural frequency below the steady-state operating frequency range of the drive, expressed both as rotational speed in Hz (14.00 to 26.25 Hz) and as electrical frequency (28.00 to 52.50 Hz). This was realized by replacing the low-speed membrane coupling by an elastomeric tire coupling. The first torsional natural frequency was thus reduced from 32 Hz to 8 Hz. Because of the commissioning closing date, the testing of the new arrangement could not be performed in the test stand.

Onsite security regulations did not allow the installation of the shaft torque measurement system which had been used on the test stand. A "synthetic" measurement of the electromagnetic torque had to be used instead. As main input data the current and voltage in the induction machine were continuously measured. From these, the electromagnetic torque was calculated on line in a machine model. Three tests were run. Each test comprised a linear speed runup and a constant speed period followed by a linear rundown. The first test run is plotted in Figure 15. The marked regions were examined in more detail. The regions 1.1 to 1.4 correspond to changes of pulse width modulation modes. The regions 1.A and

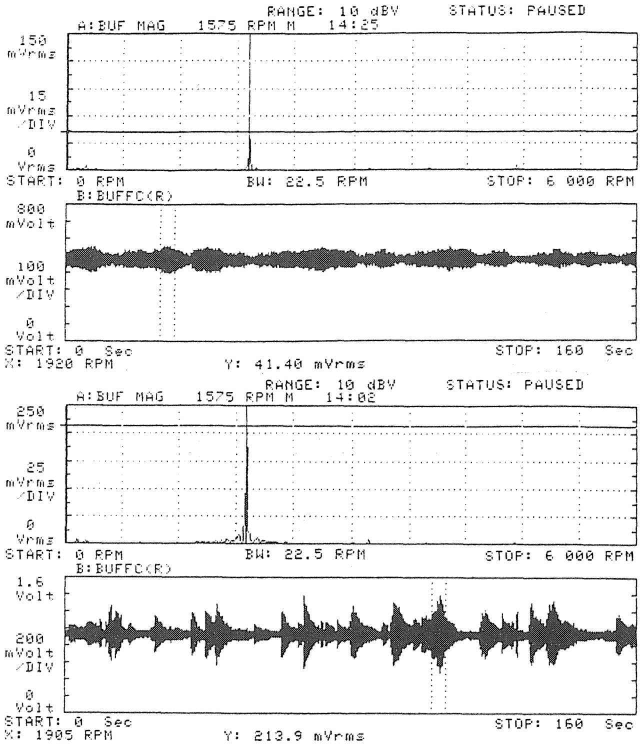

Figure 14. Record of Shaft Torque Course and Frequency Response Characteristic (in upper diagram for 1575 rpm/1000 kW and in lower diagram for 1575 rpm/2000 kW).

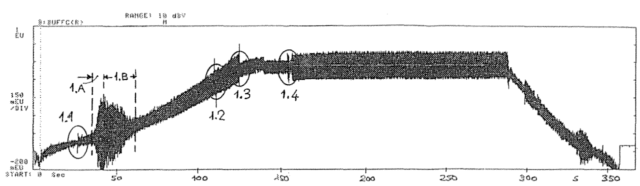

Figure 15. Electromagnetic Torque during First Test Run.

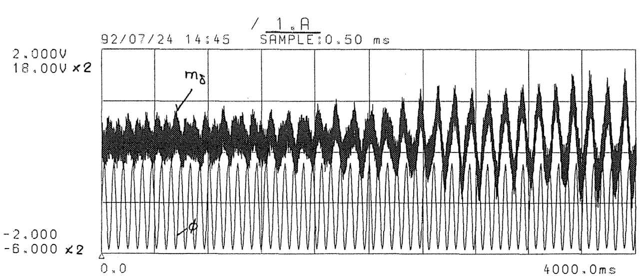

Figure 16. Electromagnetic Torque and Magnetic Flux in the Motor during Buildup of the First Torsional Natural Frequency Instability.

1.B indicate a self-excitation of the first torsional natural frequency. In Figure 16 the region 1.A is shown with a much larger time resolution. It can be seen that with increasing speed the fundamental frequency of the electromagnetic torque actually changes from about 16 to 8 Hz.

Since the installation of the elastomeric tire coupling three years ago, no further problems with the drive have been reported.

CONCLUSION

For some time now it has been undisputed that adjustable speed based process control is by far more favorable than mechanical control in conjunction with fixed speed. Substantial energy savings and improved process control are just two of many benefits.

In recent years, variable speed AC drives have gained in popularity for an increasingly widening field of applications. With power and speed ratings which far exceed those of DC drives, they have become the ideal solution for high power and high speed motion control. Variable speed drives, built with induction and synchronous motors, based on static frequency converters of the DC-link types, are the key systems currently used for medium and high power turbomachinery applications. Depending on the type of motor, they are already being built with unit ratings up to about 12 MW, respectively about 100 MW.

Compared to other adjustable speed control alternatives, the variable speed AC drives: save energy, reduce wear and tear on mechanical parts, reduce maintenance requirements, guarantee a smooth process and increase the life expectancy and reliability of the plant, even under difficult operating conditions.

Many equipment manufacturers already offer standardized static frequency converters based on modular mechanical, electrical and software designs. On the one hand, this permits a high degree of prefabrication and component standardization. This results in technical and economical benefits during all stages of the project from planning, specifying and ordering, through engineering, design and manufacturing, to testing, erection and commissioning and finally to operation and maintenance. On the other hand, the modular approach permits easy adaptation of the static frequency converter to customer specific requirements.

As variable speed AC drives are high technology systems, consideration of the interface aspects relating to their integration into the application environment should not be forgotten, especially when they are applied to high power turbomachinery. Both the influences of the environment on the drive and the impact of the drive on the environment are of importance. A total drives commitment not only comprises the drive system engineering but must also cover the electrical analysis of the power supply system and the torsional analysis of the mechanical system. With careful design, the influences of harmonic and other impacts are kept under control. The static frequency converter technology has evolved to an extent where it is now possible to build the most reliable variable speed AC drives for turbomachinery applications.

NOMENCLATURE

AC	Alternating current
CSI	Current-source-inverter
DC	Direct current
GTO-thyristor	Gate-turn-off thyristor
ID fan	Induced-draft fan
IEEE	Institute of Electrical and Electronic Engineers
LAD	Large AC drives
LCI	Load commutated inverter
LC shunt filter	Inductive capacitive shunt filter
MVD	Medium voltage drive
PCC	Point of common coupling
PWM	Pulse width modulated
SFC	Static frequency converter
VSD	Variable speed drive
VSI	Voltage-source-inverter

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