Turbine Replacement with Electrical Drivers -- Evaluating Options

Paper No. PCIC Europe EUR24_09

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Abstract -
The transition of steam and gas turbines to electric motor drivers provides viable options to address existing and future regulations on CO2 emission savings as well as providing lower operating expenses. The replacement of the turbines can take place in existing (so-called "brownfield" replacements) inland as well as offshore based facilities. With the existing plant layout of a brownfield installation, all possible electrical driver configurations may not be possible, such as geared solutions.

This paper will give an overview of the today's existing technical solutions for electrical drivers and especially focusing on the challenging topics to be considered with a turbine replacement. Since application requirements are different from case to case, the optimum solutions will vary based on technical and economical criteria, including the specific location details of the application. The paper will provide help to plan the scope of work on the compressor or pump train, the selection of the best solution based on technological criteria plus the impact of each train solution option on different areas such as Capital Expense, Operating Expense, Environment / Health & Safety, Reliability and Serviceability. Furthermore, interface-handling is described, like rotor-dynamic topics and foundation interaction.

Finally, an important consideration is the required planning/preparation time for a brownfield turbine replacement. The time slot for the regular plant shut down is fixed based on five to eight year schedules, it is important to start the preparation in time to be able to meet the envisaged turnaround schedule with the best solution.

Index Terms — Carbon Footprint reduction, Efficiency Increase, Turbine Replacement, Project Planning.

I. INTRODUCTION

This paper builds on a previous paper [1] that presented high speed (HS) solutions for turbine replacements with a focus on technology and another PCIC paper [8], where CO2 Emission Reduction in Chemical and Petrochemical Plants by Steam and Gas Turbine Replacement projects were discussed.

This paper is now focusing on turbine replacement projects specifically, based on best technology. Additionally, the usual challenging topics are discussed, including interfacing with the existing plant environment, related to current environmental and sustainability issues, carbon footprint reductions and finally how to meet the required reliability level, to be comparable with the highly reliable steam and gas turbines to be exchanged. For the larger applications (e.g. cracker services) reliability topics are even more important based on the huge impact of these installations. Ultimately important for a smooth project execution is the timely consideration of the necessary adaptation of the auxiliary equipment (e.g lubrication oil provisions, air provisions for electrical equipment in hazardous area and the applied cooling provisions of the motor and VFD).

The Paris Climate Accords adopted in 2015 and more recently the follow-up sessions like the COP28 in Dubai have led to many new and upcoming regulations in different regions around the world related to CO2 reduction. Countries, carbon energy producing companies, carbon refiners, carbon using manufacturers and major suppliers to the petroleum and chemical market have all had to make adjustments. Terms like "net carbon neutral", "green energy" and "sustainability" are now commonplace in stockholder meetings and reports. In recent years specifically, the 'carbon' awareness has further grown. Regions typically located in areas with a dark grey electricity production (mainly coal fired), are facing the global challenges and realizing that, although with current energy mix, steam- and/or gas turbine replacement is not affordable, the energy mix will change to 'greener' rates in near future. With this knowledge in mind, combined with a typical turbine replacement project lead time, it ultimately make sense to begin considering these electrification projects right now, also in areas with a high CO2 emission rate.

II. Project timeline and Planning

A. *Brownfield Turbine Replacement*

Nowadays for many greenfield applications an electrical drive train is considered from the beginning (instead of the traditional turbine driven drive trains), the so-called 'green-field turbine replacement projects', however a real brownfield turbine replacement project differs significantly to a greenfield project, since the boundary conditions are given (including eventually an elevated table foundation, Fig.1) and the new electrical drive train need to be adapted accordingly, and need to be integrated into a working plant. Especially the startup schedule is of ultimate importance, since there is only very limited time available for demolition, installation and commissioning. Although there is a significant difference in a replacement project of a gas-turbine and a steam turbine, there are some topics that need to be addressed in either case.

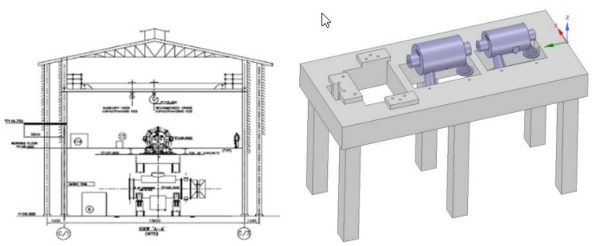


Fig.1 Typical Steam turbine layout on elevated table foundation

There are three different levels of replacement scope:

1) The ST is exchanged with an electrical driver, the compressor with a new compressor.
2) The ST is exchanged with an electrical driver and the existing compressor refurbished.
3) The ST is exchanged with an electrical drive and the compressor stay unchanged.

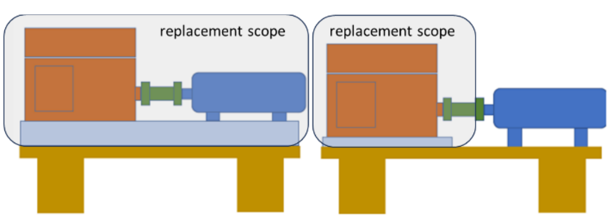


Fig. 2 Replacement scope sketch case 1~3

As for case one, the compressor OEM is involved, and the scope of work and responsibilities are very similar to new plants. The difference is, that the new compressor train need to fit within the existing foundation. This can be achieved by mounting a ready skid (purple), bearing the new compressor (blue) and driver (orange) on the existing foundation (Fig. 2)

For the interfaces between driver and compressor the compressor OEM take care as usual. Since complete removal of compressor train, including adaptation of the process piping is an even more challenging job, this might end-up with time-constraints in many cases.

In case two, the service group of the OEM is involved, and here the scope of work and responsibilities are very similar to new plants. The adjustment to the existing foundation needs to be done only for the motor (orange). The intermediate based plate (purple) might be the scope of the electric drive vendor, the responsibility for the foundation is with the compressor OEM.

The major difference for all involved parties is case three, as here the compressor OEM who usually cares about the coupling and the string analysis is not involved. This scope must be now assigned to one of the remaining parties, the End user, the EPC or the electrical driver vendor. As all of them are not specialized in such a task maybe the involvement of a third party, e.g., an engineering office, specialized in such analysis and coupling selections, might be the best choice. It might be (for different reasons) that not all required information for such studies are available. In such case, this topic may need to be covered by so called 'reverse engineering'.

With an electrical drive train, not only the 1x and 2x excitation must be considered. Additional torsional excitation are the short circuit excitations in case of a two or three phase short circuit as well as the VFD related torsional excitations.

The torsional analysis for the new string must be done. For the details of the calculation refer to API 684 recommended practice [2] and PCIC-2019-30 paper on torsional analysis of electric driven compressor trains [3].

Regardless of who does the analysis, the steps are the same. Details can be found in [8]. Note, while the gear box solution can possibly provide a lower initial cost, the high-speed gearless solution provides a smaller footprint and weight, plus:

- Higher system efficiency
- Variable speed control
- Elimination of gearbox
- Elimination of 1 coupling
- Smaller footprint & weight
- Reduced lube oil requirements
- Reduced maintenance requirements regarding motor and gear

All of these topics finally results in lower operating costs.

B. *Turbine replacement: Typical scope to be considered*

A turbine replacement project in general, and a steam turbine replacement project specifically, is a complex task, requiring a wide variety of topics to be considered (Fig.3), such as:

- Steam balance of plant: This is quite often a complicated study, involving all available steam streams on site, considering aged (and thus less efficient) components etc.
- (Local) Electricity generation: As part of the Steam Balance of Plant study, (local) electricity generation needs to be considered
- Grid connection
- Electrical Drive System topics
- Torsional Drive Train evaluation
- Mechanical integrity regarding the new drive train set-up and decisions required accordingly regarding the choice of equipment (direct drive

solution, geared solution or even mechanical drive solution)

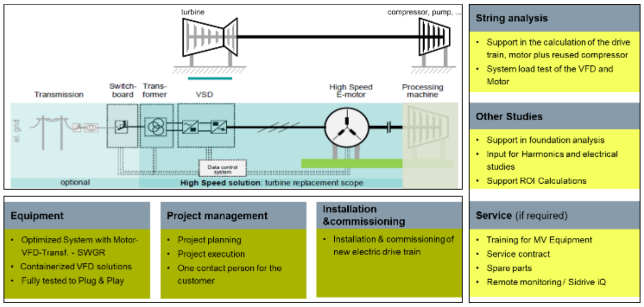


Fig.3 typical project scope for VFD equipment

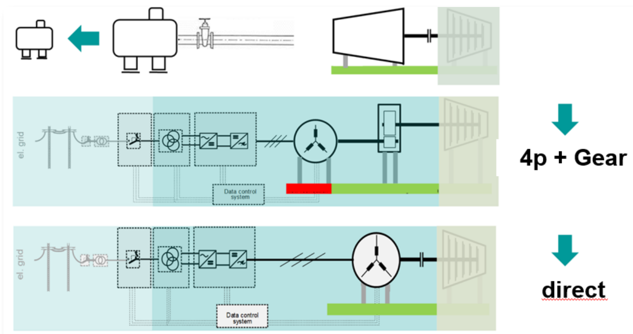


Fig.4 Turbine replacement, alternatives

An example for a typical turbine exchange with a conventional 4-pole motor and the base complications accordingly is shown in Fig.4. Applying a conventional motor, the foundation analysis and the calculations/measurement accordingly is getting complication due to the both radial and axial offset compared to the previous direct drive gas (or steam) turbine. Such offset causes an asymmetrical weight distribution on the existing foundation or table-top (Fig.5). The green marked path is a typical foundation area, in this case the footprint of the previous applied gas-turbine. As earlier indicated, steam turbines are (much) more compact compared to gas-turbines. But it is obvious that in both cases (gas and steam turbine replacement), the foundation is a very critical topic.

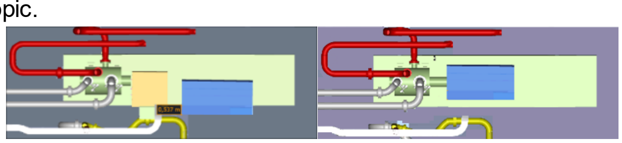


Fig.5 foundation topics with 4-pole conventional motor

Furthermore, replacing a drive train component with same speed and speed-range allows for relative easy rotor-dynamic verifications. Applying drive train component with different speed might cause complications: structural influence based on lower excitation frequency than the original setup, which might result in mechanical resonances in the interfacing components like foundation.

C. Project planning

A potential replacement project is a complicated task, requiring planning well in advance. It usually starts with first investigation and feasibility, resulting in decisive outcome regarding revised steam balance of plant, clear overview of availability of electricity and the associated grid conditions, future operation flexibility and overall plant efficiency figures, compressor upgrade requirements etc. Finally, this phase is concluded by rough technology selection, avoiding a wide variety of possible solutions that need to be investigated in next project phases. This feasibility phase is typically concluded either in-house by the company, or eventually with the support of an EPC company. Quite often the support of technology providers is required in order to be able to take the right technological decisions and finally come to the technically and economically most suitable solution.

High speed direct drive equipment is typically engineered-to-order equipment, resulting in a longer delivery time than conventional 4-pole motors. Thus, early project planning becomes even more important (Fig.6).

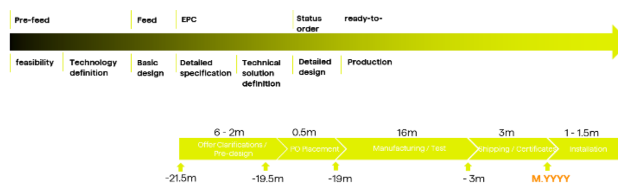


Fig.6 rough project schedule for a turbine replacement project

The typical lead time for a replacement project is 2 – 2.5 years. In case a feasibility study and/or technology definition need to be addressed too, the lead time can be easily extended to 2,5 – 3 years.

In cases where additional system testing is required (motor, VFD, eventually in back-to-back arrangement), additional months may be required in the schedule.

III. Project considerations

A. Capex versus Opex

There might be no direct advantage on CAPEX (capital expenditures) by using high speed motors. If a 4-pole + gear solution is technically available and possible to use, this offering may have the lowest CAPEX.

The strength of high speed motor solutions comes along with considerations on OPEX (operation expenditures) savings over the system lifetime based on improved overall efficiency and elimination of maintenance costs.

When only a high-speed solution is technically possible, which is quite often the case when space is the limiting factor for a turbine replacement, the final investment decision (FID) must be taken into consideration. The financial calculation for the FID is usually based on the CAPEX to exchange the turbine, the OPEX savings, as well as the earnings of the existing process for the plant. The earnings play a significant role in the FID for the return-on-investment calculation and are based on a successful installation and start-up and then continuous operation over 6 to 8 years, without unplanned shutdowns. Delays or unplanned shut down jeopardize the return on investment situation and might lead to unplanned losses.

High-speed systems for turbine replacement may be selected based on reliability, availability and the security to be installed and commissioned within the planned down time of the plant.

Applying high speed motors with massive shaft technology provides a further benefit regarding OPEX savings due to the elimination of cost-intensive balancing procedure during the lifetime of the motors.

B. Carbon footprint and efficiency increase

A traditional drive train contains several components, each with its own and specific losses and thus efficiency. Typically, the stated efficiency is directly related to the (nominal) operating point. Focusing on the nominal operating point, the following table (Fig.7) provides an overview of the different drive trains (high speed versus low speed) and their efficiencies. The picture below represents the efficiency of the evaluated motors and required gear. The VFD and transformer are not incorporated in this picture. Although the power factor of a high speed motor may be lower than that of a conventional 4-pole motor, this normally would not effect efficiency evaluation of the VFD/Transformer.

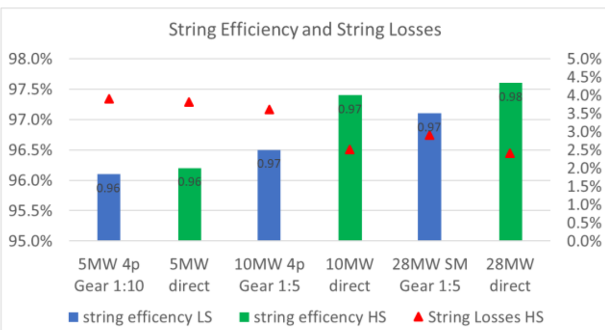


Fig.7 Efficiency comparison 4p conventional versus high speed motor

A typical requirement of a turbine is an operating speed range between 70% and 105% of the nominal speed. Deviating from the nominal operating point quite often means a decrease in efficiency.

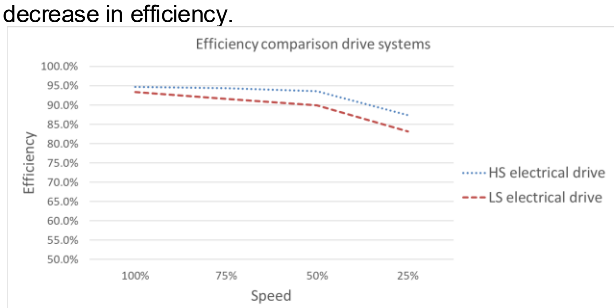


Fig.8 Efficiency comparison 4p-conventional versus high speed drive systems

Fig.8 shows the difference in efficiency values for the two drive train types over the speed range. This comparison is made for a medium power, high speed drive train. As shown in Fig.7, for real high speed applications or the real high power applications, the showed efficiency differences might be diverging.

Turbine replacement support on several fields regarding OPEX benefits: efficiency improvement and emission footprint reduction. The efficiency improvement provides a direct economic benefit. The emission reduction results in economic benefits once the emission factor (scope 2 emissions) of the electricity mix comes below a certain level (decarbonized grids), compared to the local steam production or local consumed gas CO2 emissions.

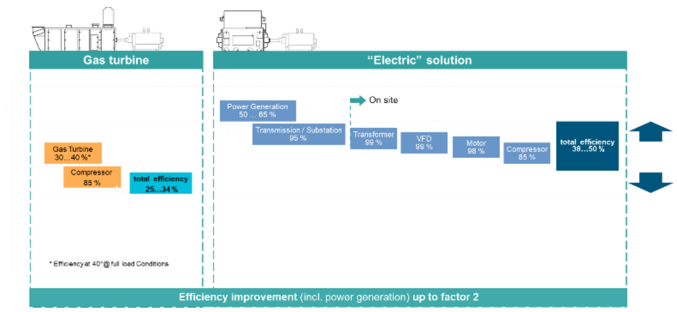


Fig.9 overall efficiency gas-turbine versus electrical drive system

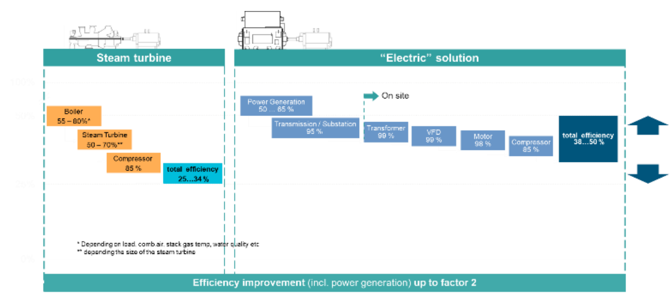


Fig.10 overall efficiency steam-turbine versus electrical drive system

As for gas turbines the emission is directly related to the function of the turbine (Fig.9), for steam turbines the emission is related to the steam production process in a boiler, either 'on-site' (direct emissions, scope 1) or off-site (indirect emissions, scope 2, Fig.10). In both cases the fuel to drive the turbine is available "anyway" and in case of the steam turbines in chemical or petrochemical plants a necessary product for the process or a byproduct of the process. Steam production is required anyway, often generated by multiple sources and/or boilers. This equipment is often very old (usually as old as the steam turbines), thus the efficiency rates are not optimal.

While the reduction of the emission footprint within the plant for this application may decrease to zero (scope 1), the energy consumed by an electrical driver must still be produced, resulting in so-called 'scope 2' emissions, and must be incorporated in the overall efficiency study, which is typically the basis for a steam or gas turbine replacement project. Nowadays, more and more renewable energy is part of a country or region energy mix, where the electricity is generated in Wind farms or Solar installations, but many regions still face an electricity mix mainly based on oil fired power stations. Based on such facts, it would even be better to run steam or gas turbines. However, in most cases such regions are committed to the general climate change measures, and the electricity mix will change rapidly in future. Since the typical turnaround schedules varies between 5 and 7 years, and the turbine replacement scheduling takes approximately 3 years or longer, it make sense to consider the future scheduled changes in the electricity mix for the next 10 years at least.

The overall drive train efficiency of a high speed, electrical driven application might come close to 95%, whereas a traditional low speed geared solution comes best case (nominal operating point) to slightly over 93% (Fig.8). Additionally, operating the compressor through the compressor operating map influences the efficiency performance of geared solution, whereas the efficiency of a VFD driven high speed motor solution is almost constant over the standard operational speed window (70 – 105%)

In general, for the real high speed applications (low power/high speed, ref to Fig.7, first two columns), efficiency-rating at nominal point might come close to each other, however with increasing power/ lower speeds, the efficiency difference is somewhere between 1% and 2%. For the large turbines replacements projects, this is a significant contribution into potential OPEX cost savings. Evaluation of the overall drive train efficiency considers following topics:

- Motor, VFD and transformer efficiency
- Additional cooling requirements for oil systems (lubrication and cooling oil)
- Cooling requirements for VFD and motor

Efficiency calculation is based on different assumed operating points over the year, not only guaranteed operating point

C. Electrical drive versus turbine: Short circuit torque

The gas or steam turbine is a mechanical piece of equipment, not bothered by any sudden significant increased forces as a result of malfunction in the system. Electrical motors however are subject to this topic. Therefore, the system design and the effects on the interfaces of those forces need to be carefully considered. If the resulting forces at the critical points are above acceptable limits, measures need to be implemented to ensure the mechanical integrity of the compressor train.

For an electrical motor, the worst case regarding the resulting forces is used to perform the calculation. Usually, this is the 2-phase short circuit case, as close to the motor as possible, e.g. 2-phase short circuit in the main terminal box (also called ‘bolted short circuit’). For this worst case, the maximum worst case Air Gap Torque will be calculated, although these worst cases are very unlikely, since there is always an impedance in the short circuit path.

Basically, this is a ‘theoretical’ value, not having any effect on the interface points of the electric motor, in this case being the compressor shaft end.

Referring to Fig.11, for the different damping coefficients between the air gap and the first important point (coupling hub of the compressor), the calculated torque values appearing at the compressor coupling hub are much lower compared to the maximum worst case air gap torque (Fig.12).

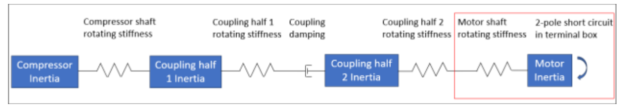


Fig.11 Torsional Vibration System

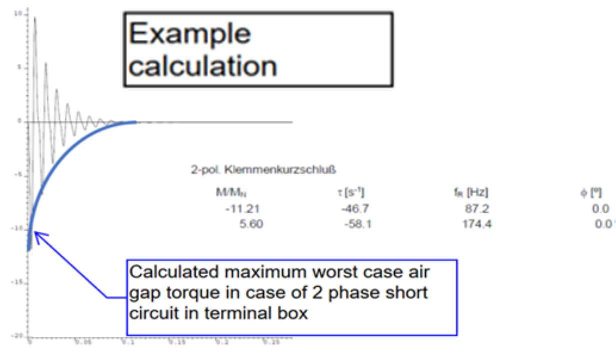


Fig.12 Example graph for transient 2p-SC- torque

Based on experience, the remaining SC-torque at the compressor coupling hub (coupling half 1) is reduced to less then 50%.

In case this torque is still too much for the overall string integrity, the coupling design can be changed in such a way that the transmitted torque transients are kept within the acceptable limits. This can be done by several different parameters, e.g. coupling length, coupling diameter, coupling material. In the ultimate case that the string integrity can not be ensured by adapting the coupling design, alternatively a ‘shear-coupling’ may be applied. This coupling type ensures that any torque exceeding the compressor capabilities is not transmitted, but ultimately stopped by the coupling.

Optimizing motor design in order to lower the maximum short circuit torque value is also an option, however the effect is only very limited, and this will affect the general properties of the motor like reduction of efficiency. This in turn affects the total OPEX, which is not beneficial for the overall project.

D. VFD induced torque pulsations

Since the new equipment (motor, VFD and transformer) will be connected to already existing and aged components (compressor and eventually re-use of the coupling), special care must be given to the interfaces. Main mechanical interface of the motor to the compressor is the coupling. The coupling is transmitting the torque from the motor shaft to the compressor. Usually, driving the motor with a VFD (LCI or VSI) causes relatively high harmonic content in the output. Basically, this harmonic content is resulting in harmonic oscillations on the output side, especially in the produced torque. If not mitigated, these output torque pulsations can seriously damage the coupling, or in worst case the compressor internals. One way to reduce the output harmonics is to implement output filtering. This will reduce the pulsating torque in certain extent, but mostly not within very low levels. However, adding output filtering will impact the overall drive train efficiency.

Another alternative to influence positively the output torque pulsation, is to apply the multi-level topology (Fig.13).

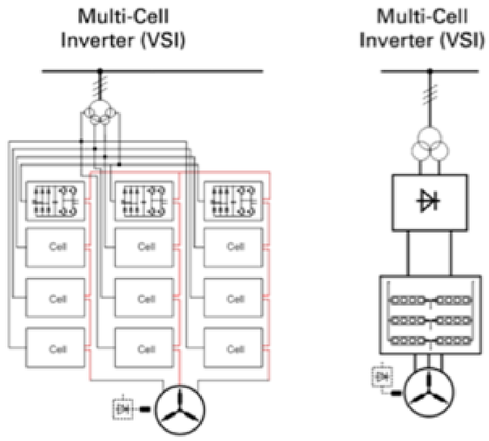


Fig.13 VFD topology with multi-cell layout

This topology provide almost sinusoidal output voltage without adding any output filtering (Fig.14).

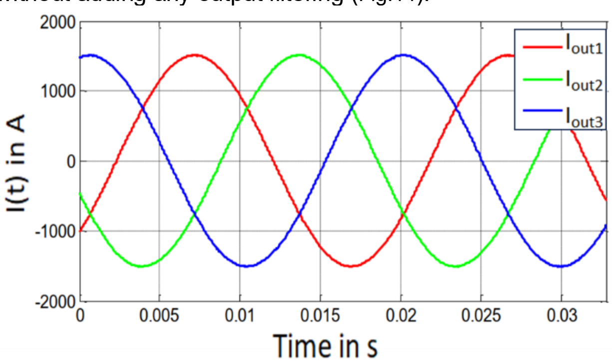
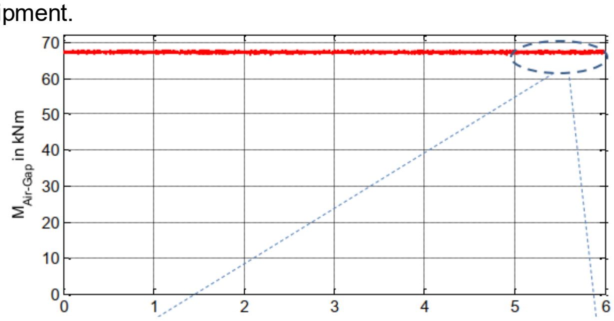


Fig.14 12MW motor current operated at M2C VFD in nominal operating point

This behavior results ultimately in low (or actually no) output torque pulsation (output torque ripple stays well below the 1%, Fig.15), which ensures highest de-risking of the installed equipment.



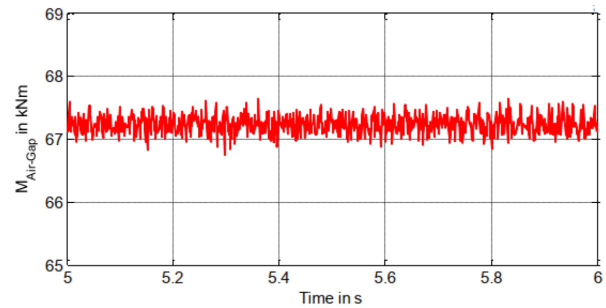


Fig.15 Zoom of torque pulsation at the operating point according fig.13

E. Compressor name plate power versus actual power

Turbine replacement projects are often replacing turbines that have run for 30-50 years. Just considering name plate ratings for the steam turbines and/or gas turbines quite often provide the wrong basis: in the 40 previous years, it might be that (process) optimizations and/or other activities influences the actual power requirements of the compressor. Therefore, it is quite normal that the actual power consumption over the year must be evaluated, in order to investigate the actual power requirement under different operating conditions and different ambient conditions. Such measurements need to be investigated, compared to the original compressor datasheets and incorporated in the final motor requirements. This avoid time consuming iterations of design processes.

Such exercise is usually done in the feasibility phase, allowing for the right decision making before going into the detailed phase. In this phase, a decision might be made whether the compressor remains unchanged, the compressor requires an overhaul or eventually the compressor requires a complete exchange (as discussed also in previous chapter). Those decisions significantly influence the required CAPEX and might positively contribute to the operational benefits after enhancement of the plant capacity according the latest requirements.

F. Auxiliaries

The main equipment for a turbine replacement project like motor, ASD and transformer are often the primary focus of the initial investigation and detailed engineering. While this equipment may be the most important equipment upon which the final decision (FID) will be made, to meet the (typical) short turnaround schedule, it is as important not to neglect the required auxiliaries. The auxiliary provisions need to be evaluated, added and/or adapted to the new situation.

1) Lubrication Oil provision

Lubrication oil is mostly available on the site for compressor and turbine lubrication. Usually, it can be adapted to the high speed motor bearings, however, it is important to understand the oil system properties well in advance.

The typical lubrication oil usage of (steam) turbines is higher than the requirements of the 2 bearings for a high speed motor, resulting in an overcapacity of the installed oil skid. Thus, it is important to calculate the required oil consumption of motor and compressor and install provisions to regulate the oil flow to the bearings of both the motor and compressor.

In case of turbine replacement with a conventional 4-pole motor with gearbox, the total oil consumption might exceed the available oil skid capacity, requiring in-time modification of the lubrication oil system.

2) Cooling requirements

a) Motor:

With a turbine replacement project, it is important to consider the cooling requirements as a priority in the early stage of the project. A turbine does not need additional high cooling requirements, but an electrical motor (whether high speed or low speed) requires much more cooling. Thus, exchanging the turbine with an electric motor require significantly changed cooling provisions. Since the turbine did not need cooling water requirements, quite often no water provisions are available. Looking for air cooled motors is therefore a good alternative, however cooling air does have a few disadvantages:

- Cooling provisions for an air cooled motor do have significantly increased dimensions compared to an air cooled motor
- The increased dimensions and the cooling air requirements may result in a significant weight increase.
- The efficiency of an air cooled motor is normally lower compared to a water cooled motor
- Eventual redundancy measures result in even further enlarged dimensions and weight

Both dimensions and weight are critical for (steam) turbine replacements. This is especially the case for relative small power ratings below 5-7MW. Turbines in this power-range are very compact and light weight, therefore every saving in weight and dimensions is beneficial for the existing foundation suitability. Therefore the water cooling option is always the favorable option. Nevertheless, if not available and foundation properties allow for increased dimensions and weight, besides the water-cooling IC86W, most standard available cooling concepts can be selected, like IC666, IC616 or IC37 (Fig.16).

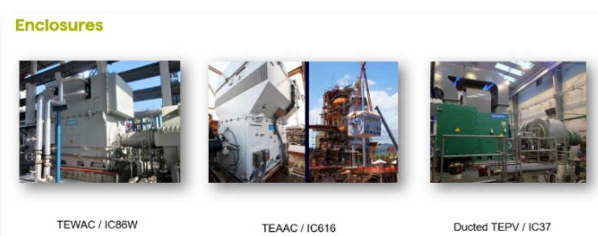


Fig.16 Different possible cooling types for High Speed motors

b) VFD:

VFDs are available in both air cooled and water cooled alternatives, although for higher power rating water cooled VFD's may need to be used. The water-cooled VFD's do have an internal de-ionized closed loop water circuit. The water is via a water-to-water heat exchanger cooled to an external cooling water loop. This external cooling water system (including eventual glycol content) can be designed flexible to the site requirements:

- Plant cooling water system
- Dedicated VFD cooling water system, eventually with fin-fan coolers
- Combined VFD and motor cooling water system

G. *Manufacturing capabilities and balancing*

Rotor balance and overspeed testing are vital for high-speed motors. The balancing will be done according to the ISO standards [5] [6]. API 541 [7] refers also to this standard. In any case, in the balancing machine the residual unbalance will be checked at the rated speed points.

The overspeed test will be done according to the relevant project specification and vary between 10% and 20% overspeed. As some power@speed combinations are particularly challenging, sometimes a lower overspeed is agreed between the parties. Reduction in overspeed for specific applications is not always advised. One of the reasons for this overspeed test is based on laminated rotor-designs with many different and interconnected materials. With the overspeed test, it is ensured that the complete rotor is 'settled', ensuring best possible quality when it leaves the factory. This topic is valid for many of the high speed rotors too as shown in Fig.22, however for the massive shaft technology (Fig.17), there is nothing to 'settle', since the rotor is one solid piece of equipment. Based on that knowledge, lowering the 'overspeed' can be established without compromising any of the required quality or (long term) reliability design goals of the high speed motor.

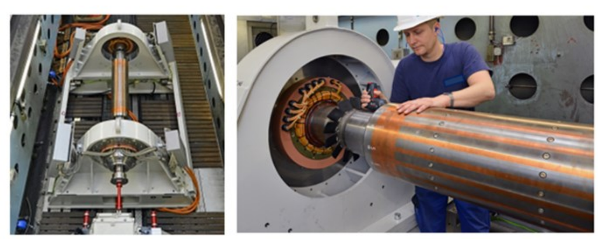


Fig.17 high speed motor rotor, massive shaft design (in balancing bunker, here with Active Magnetic Bearings

In the factory balancing machine the required low residual unbalance to fulfill the vibration requirements can be achieved.

For a massive shaft with no moving parts, also the handling after balancing, the vibrations and impacts on the shaft and motor during assembly, transport and installation will not change the residual unbalance situation. The vibration results achieved in the customer FAT will be kept.

This is crucial for the Turbine replacement market as the short installation and commissioning window does not allow additional time for field balancing of the rotor.

Besides the ensured short and defined installation and commissioning time in case of high speed motor with massive shaft, the residual unbalance and the rotor dynamic situation because of the residual unbalance remain unchanged over the lifetime of the machine. This behavior is not only a theoretical representation, but is proven:

- Unchanged residual unbalance by design
- Complete massive shaft installed base did not require any rebalancing during or after commissioning
- With more then 5 million cumulative operating hours and motors for almost 20 years continuous operation, no single need for rebalancing
- Based on field feedback, identical motors on Active Magnetic Bearing technology can be commissioned without any need of tuning, thanks the ultimate high reproduction and manufacturing capabilities for this kind of motors

The challenges with high-speed rotors include high centrifugal forces, large friction losses, and requirements for low residual unbalance as shown in Fig.18. All parameters must be met for continued operation and long-term reliability.
Both the rotor material and connections must be properly designed to withstand high stresses caused by the centrifugal force. Additionally, the expansion of material at high temperatures as the rotor heats up during operation must be carefully addressed. It is to ensure that the rotor's vibrations stay within the acceptable limits as required by IEC60014 or API 541.

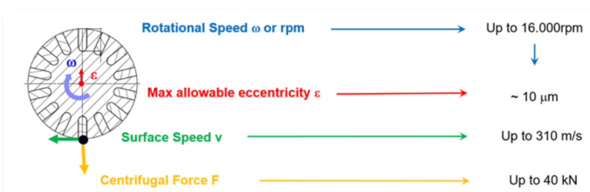


Fig.18 High speed rotor challenges

The vibration is mainly caused by the residual unbalance and can be expressed in the unbalance Grade such as G1 or G2, in the residual unbalance itself in g/mm or in the eccentricity of the axis of rotation towards the axis of gravity.
To understand the extremely low level of the allowed residual unbalance, eccentricity is a good parameter to measure. For a high-speed rotor the allowable level of eccentricity is within the range of 10µm, which is a fraction of the thickness of a human hair. To achieve this machining the rotor must be completed with a high degree of precision and after balancing no movement of any part in the rotor is permitted, even in the order of magnitude of micrometers.
If rotor parts are loosen over time the residual unbalance will change, mostly increase. As a result, rotor vibration increases and may reach the shutdown level in the worst case.
The friction losses are the primary losses of the rotor. Friction losses can be reduced by machining a smooth rotor surface which allows for increased cooling flow by not creating unnecessary turbulence.
For rotor dynamic calculations, a Campbell diagram is developed, and unbalance responses are calculated as shown in Fig.19. Based on the dynamic calculations sleeve bearings in either lobe or tilt pad design are considered.

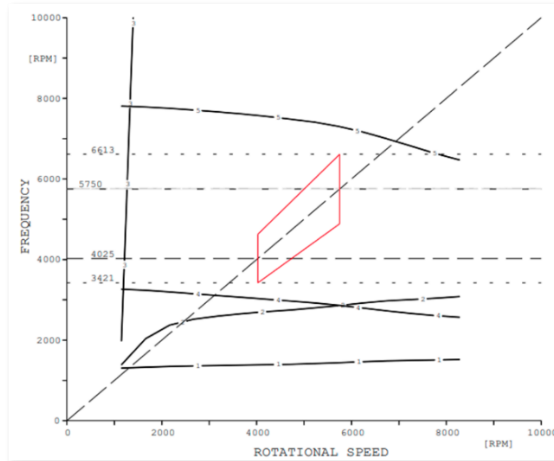


Fig.19 Example of a Campbell Diagram for a 35MW@5750rpm High Speed Motor on sleeve bearings

The speed range is usually 70% to 105% of the driven equipment speed and vibration limits are either according to IEC60014 or API 541. At least two balancing planes near the active part are required and optional balancing planes near the bearings that are accessible when the motor is assembled for possible trim balancing may prove beneficial.

H. Digitalization, digital support

Customers around the globe are realizing the topic of 'digitalization' need to be covered, however they are suspicious and still curious about how to implement and what are the customer benefits. In the past, digitalization was implemented for separate drive train components in the best case. Nowadays digitalization will have a holistic approach, covering all drive train components, including motor, VFD, Cooling unit, transformer and if required other related equipment. Including some additional data-sources regarding motor, such as real time bearing measurements and eventually an online PD monitoring system can provide operators real benefits on major topics, like reliability, availability and other OPEX related improvements.
Once drive trains are fully digitalized, it is possible to implement the full benefits, in accordance with the plant digitalization strategy. Benefits may include the following:

- Automatic reporting periodically regarding general drive system status
- KPI reporting, extendable for only 1 compressor train up to complete customer installed base
- Automatic threshold recognition and responses
- Condition based maintenance like cleaning requirements
- Optimization of drive train performance by analyzing and combining process- and drive train data
- Further optimization of the reliability and availability by pro-active response
- Remote assistance options, both proactive and, eventually, reactive

I. Reliability and Availability

The translation of the principle of “Reliability” into engineered features means to design single parts made from a limited number of pieces and to incorporate into fail safe products utilizing proven manufacturing concepts wherever it is possible.

The practical guide to design is first to identify the main and common causes which lead to a shutdown of the motor, then to identify the reason behind these causes and to design the components to avoid the identified reasons.

For high-speed motor applications main and common reasons for shutdown are vibrations exceeding the allowable limits, problems in cooling of the bearings, instabilities in the closed loop system of the active magnetic bearing system (AMB, if applicable), noise and other disturbances on the sensors of the AMB system. These reasons can occur in the final testing of the machine in the manufacturers’ test bed and delay delivery and project schedules. They can also occur after a certain operating time when components change their behavior.

A high-speed motor is necessarily driven by a VFD since the required frequency is above grid frequency. Generally, the VFD with it’s active control and semiconductor components is subject to potential failure, and should be investigated regarding reliability as stringently as the motor.

The third component necessarily required in a high speed drive train is the dedicated VFD transformer. Generally, transformers are considered and has been proven to be highly reliable equipment for many years, contributing to a maximized overall drive train reliability.

Engineered products such as high-speed motors and VFDs do also need preventive maintenance and service. The products will age and have failures even with a design following the principle of “Reliability”. The downtime for maintenance and repair must be as short as possible and the necessary work should be able to be performed on site, with the motor mounted on the foundation. This leads to the principle of “Availability” (Fig.20)

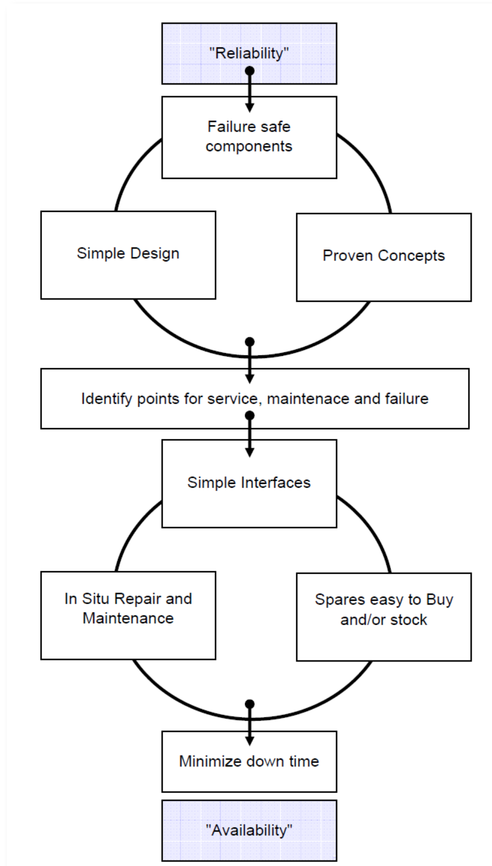


Fig.20 Principle of “Reliability” and “Availability” and connection to design process

J. SERVICE NEEDS AND SERVICEABILITY

High speed motors, and specifically motors with massive rotor technology’ do not require as much service as known for standard asynchronous motors. The service intervals for such items as accessory checks, bearing shell inspections and eventual PD-measurements can be aligned to the regular shutdowns intervals (5-7 years) or eventually implemented as automatic ‘online’ measurements. Adding ‘remote services’ by means of digitalization approach allows for a further optimized maintenance, also referred to as ‘predictive’ maintenance. Especially typical ‘degrading’ elements such as de-ionizers, coolers in converter cooling unit and motors and eventual oil systems can be automatically supervised and reminded for required exchange (during operation) if required or change-over in case spare equipment is installed. Including eventual required redundancy measures in VFD and motor allows for many years of uninterrupted operation, in full alignment with the regular maintenance intervals of the assets.

Especially the topic ‘cooling’ need some attention: typically, a motor cooler element is very reliable, if the process conditions are kept (pressure, flow, temperature), the cooler will not ‘fail’. However, whether plate type heat exchangers or tube type heat exchangers, there is a possibility that these coolers will be contaminated in time. Especially with large cooling water systems, containing thousands of cubic meters of water, might be clean after commissioning, but it is usually not ensured this will remain the case after longer time of operation (5, 10 or 15 years). A contaminated RAW water system may cause an early contamination of the applied coolers, resulting in lower cooling capacity and finally might require a power limitation, or worst case result in a trip of the compressor. Thus, especially when 5 – 8 years uninterrupted operation is required, redundant coolers might need to be considered.

As the massive rotor is a 'one-piece' equipment without moving parts, special maintenance services for the rotor such as rebalancing, adjusting components and cleaning is not required. Based on the massive rotor design, degrading of the rotor-dynamic situation is avoided, ensuring running the motors without any rebalancing campaign in lifetime.

With regular inspections of the motor according to the standard service manual and operation as per the specification, an operating time up to several decades can be expected.

The areas for service such as bearings, coolers, auxiliary fans, or accessories are easy to access without removal of the motor or rotor.

IV. Technology

A. High Speed Motor

The main mechanical components of a high speed motor affected by operating at high speeds are rotor and frame. The rotor must cope with the higher centrifugal forces. The frame, as it supports the rotor, must be stiff enough to withstand excitations at frequencies higher than 60Hz. One of the possible designs is shown in Fig.21

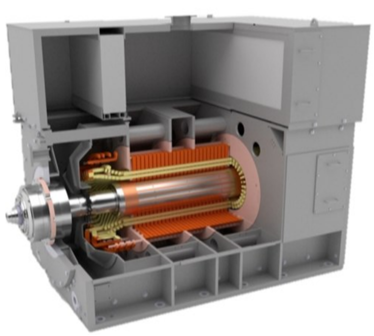


Fig.21 high speed motor with massive shaft technology

The high-speed rotor design varies among different manufacturers as shown in Fig.22. The frame is usually a welded design with fabricated steel, where Finite Element Methods (FEM) are used to determine dynamic behaviors. Currently, the following solutions are offered for high-speed rotors by different manufacturers :

- Laminated rotor with laminations shrunk on the shaft. The windings overhang and are secured by special retainer rings.
- Laminated rotor with the laminations staggered and held together with the shaft end by tie rods, the copper cage inserted and bolted.
- Permanent Excited Motors (PEM) rotors
- Large rotors with open slots (w/o copper cage) as reluctance motors.
- Large rotors, where the copper is bonded to the steel by diffusion welding and forms a single-piece rotor (herein called massive rotor).

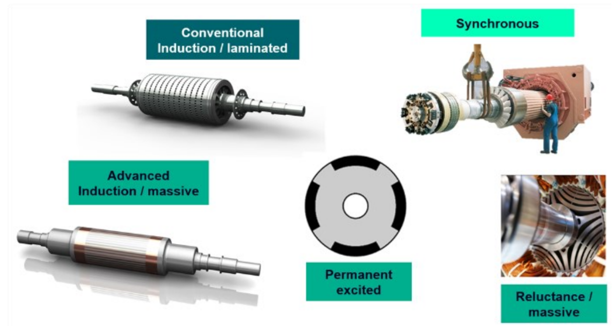


Fig.22 Different designs for high-speed rotors

The focus in this paper is on the high speed motors with massive shaft technology. A high speed motor capability chart for motors with massive shaft technology is shown in Fig.23.

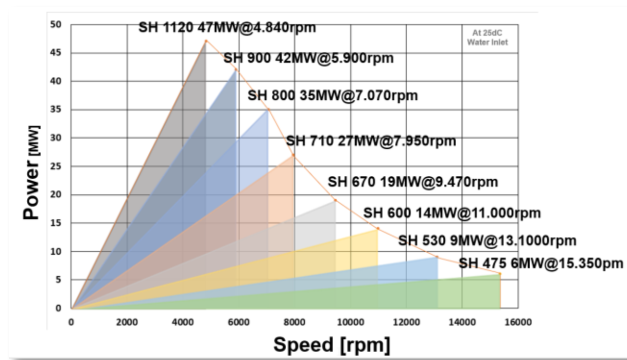


Fig.23 High Speed massive shaft technology -- capability chart

B. Variable frequency drive (VFD)

For VFD and transformers the established product lines used in the Oil & Gas industry can be used. It must be checked that the VFD is matching the motor for example regarding the insulation system, but this is not a topic only for high-speed systems but generally for VFD applications. Furthermore, specifically for high-speed systems, output frequency has to be considered and might cause some de-rating of the power electronics, in order to keep the required reliability, when going up to typical (very) high speeds like 16,000 rpm.

When replacing a Steam Turbine, the motor replaces the turbine as the driver. As discussed before, the reliability and availability level of the Steam turbine can be reached with the motor, if the motor is designed properly. Frequently applied VFD technology is depicted in Fig.24

The VFD (and possibly a transformer) is an additional component that is added to the system compared to a mechanical driver. It has to be made sure that the electrical drive components (VFD, transformer and motor) is as reliable and available as the steam turbine.

VFD reliability can be enhanced with cell bypass technology in case of multi cell technology, like M2C or H-bridge topology

(Fig.24). Additional redundant auxiliary systems, and/or semiconductor redundancy (in case of 3/5-level NPP/NPC topology).

1) VFD technology: Decision for safe operation over lifetime

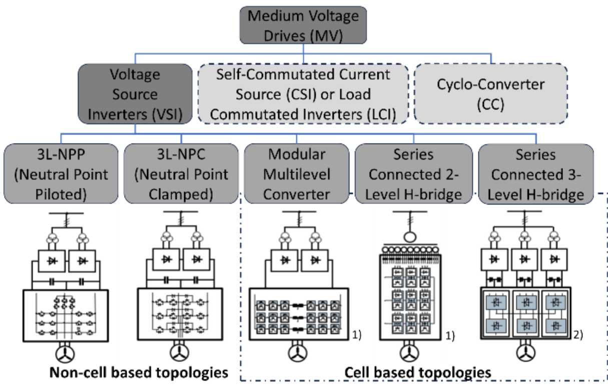


Fig.24 Available VSI topologies

Cell based topologies based on LV semiconductors do have significant benefits, compared to non-cell based technologies. In both topologies, N+1 redundancy can be added. However, in the non-cell based topologies, the typical redundancy measures are implemented by 'adding' semi-conductors into the power circuit. Such N+1 redundancy topology is only valid for the semiconductors itself. This means:

- Defective semiconductor will not be 'bypassed', but remains in power circuit.
- A large extent of VFD failures are not semiconductor related, but more often the remaining part of the VFD like DC-link or VFD inverter.

Eventually failed semiconductors remain in the power circuit, causing additional losses etc.

The cell based topologies based on LV-semiconductors however provide an 'all-inclusive' bypass, resulting in ultimate reliability, not only capturing semiconductor failure, but also any other component of the power circuit except the diode rectifier. Included components in the bypassed cell are:

- LV semiconductors
- DC-link capacitors
- IGBT control boards
- Cell power supply

V. FIELD EXAMPLES

A. Experience and real world applications

Why is a reference list important? First, to see if there is regular production of the special motors, ensuring that the knowledge at the supplier as well as the sub-suppliers is updated continuously to industry standards, regulations and customer requirements. Second, to see if returning customers exist and show satisfaction with the product, project execution and later operation. Third, for new customers to see if their requirements fit into already designed and operating high-speed motor envelopes.

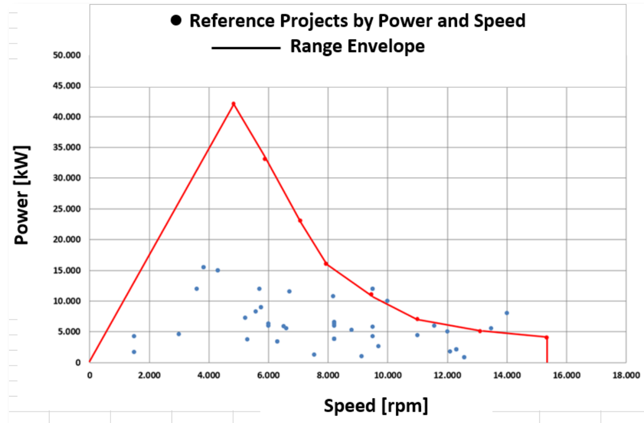


Fig.25 Reference projects vs Range Envelope

Fig.25 shows in blue dots some references by power and speed. We can see a wide range as with a current maximum power of approximately 15MW. This is because voltage source VFDs for asynchronous motors for high power are recently available with increased power acceptability, and the market demand is increasing with the requirement to investigate replacing steam and gas turbines in Oil, Gas and Petrochemical applications (onshore and offshore). Those are typically in a range from 25 MW to 35 MW, or even more.

Current requests indicate this demand up to 35MW for future gas turbine replacements, but there are no reference projects available for high-speed induction motors in the high megawatt range.

Also, for power "or" speed which fit in the envelope of references, it is unlikely that the requested power and speed will hit exactly the power and speed combination of a reference build. The existing turbine-compressor-trains in the field, installed over the past 50 years are application specific and have power and speed combinations for which existing references are not available but being addressed.

The solution here to find reference points for an application, is referred to as "cross referencing." The reference case can be built up across several independent technical fields. Those fields are:

- Power
- Speed
- Rotor dimensions
- Surface speed at rotor outer diameter
- Centrifugal force load
- Rotor dynamic and bearing parameters

For each individual technical field, a cross-reference to an existing project can be made. If a cross reference for each parameter for a high-speed motor is identified, the motor can be regarded as "referenced."

This proceeding can save time and money, as prototyping is expensive and should be done only if necessary.

VI. CONCLUSION

While the design changes and implementation challenges exist to replace the common gas turbine and steam turbine installations on new and existing installations, the push for increased operating efficiency and decreased emissions of CO2 are leading more and more to the option of electrical drivers for mechanical equipment in the Petrochemical industry.

Many elements are needed to successfully execute a turbine replacement with electrical driver. Project timing and planning is important to set the project up for success. Early parameters such as: is there enough space for a new drive train, or will the foundation meet requirements, or does the compressor need to be replaced, will impact the path of the project.

Today, more than ever before, the advanced electrical systems with field-verified motor designs with single-piece rotor cages, high availability variable speed drives with built-in redundancy and digital system control and monitoring provide the reliability demanded by these applications and also leading to operating expense reduction and lower CO2 emissions.

Even with many challenging aspects of a turbine replacement with electrical driver exist, they can be managed for a successful change to an electric drive train.

High Speed direct drive systems brings many benefits to customers, like:

- Highest reliability, enhanced VFD redundancy features
- Increased efficiency
- Minimized wear
- Simplest drive train setup
- Significant footprint benefits

VII. REFERENCES

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VIII. NOMENCLATURE AND ABBREVIATIONS

Q	Balancing Grade acc DIN ISO 1940
ω	Angular velocity
ε	Distance between geometric center and center of Gravity
VFD	Variable Frequency Drive
FAT	Factory acceptance test
FPSO	Floating Production Storage and Offloading Vessel
HIP	High Isostatic Pressure
1x 2x	one time and two times speed/frequency
OEM	Original Equipment Manufacturer
EPC	Engineering Procurement Construction
OPEX	Operational Expenditure
CAPEX	Capital Expenditure
FID	Final Investment Decision
CO2	Carbon Dioxide
LCI	Load Commutated Inverter
VSI	Voltage Source Inverter
AMB	Active Magnetic Bearing
PD	Partial Discharge
HEX	Heat Exchanger
FEM	Finite Element Methods
M2C	Modular Multilevel Converter
NPP	Neutral Point Piloted
NPC	Neutrol Point Clamp

IX. VITAE

Hartmut Walter graduated from the Technical University in Berlin in 1996 with a master's degree in engineering science. After graduation he joined Siemens Large Drives facilities in Nuremberg/Germany. Since 2018 he is working on developing solutions for turbine replacements, currently within Innomotics, a Siemens company

Bart Sauer graduated from Case Western Reserve University in 1989 with a Bachelor of Science degree in Mechanical Engineering. He has been an employee of Siemens (now Innomotics) at the ANEMA motor plant in Norwood. He has been an author on four previous IEEE papers and is currently a member of the IEEE / API 541/546/547 committee.

Gijs van Maanen graduated from The Hague University of Applied Sciences in 1995 with a bachelor's degree in electrical Drive Systems Technology. After graduation, he joined Siemens Large Drives in the Netherlands. In his current role, he is responsible for Global Project Development, key area Turbine Replacement Projects within Innomotics, a Siemens company