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CHALLENGES AND OPPORTUNITIES OF ELECTRIC DRIVEN CENTRIFUGAL COMPRESSORS IN THE OIL AND GAS INDUSTRY

Andrea Cortinovis
ABB Corporate Research
andrea.cortinovis@ch.abb.com
Baden-Dättwil, Switzerland

Thomas Besselmann
ABB Corporate Research
thomas.besselmann@ch.abb.com
Baden-Dättwil, Switzerland

Mehmet Mercangöz
ABB Corporate Research
mehmet.mercangoez@ch.abb.com
Baden-Dättwil, Switzerland

ABSTRACT

Applications of electric variable speed centrifugal compressors in the oil and gas industry are expected to grow due to the consequential benefits of using these systems such as increased efficiency at part load operation, reduced maintenance effort, and reduced local greenhouse gas emissions. Electric driven centrifugal compressors also play an enabling role for subsea compression. This paper investigates operational challenges and opportunities presented by electrical driven centrifugal compressors from a control systems point of view. In this regard, the role of the variable frequency drive and how advanced control techniques can enhance the performance of the variable frequency drive for gas compressor applications is presented. A similar analysis is also provided from a process control perspective for the compressor. Throughout the article, the results are illustrated with simulation studies and data from both a compressor test rig and from actual field installations.

INTRODUCTION

Electric motor drivers are appearing again as a serious contender to thermal engines as prime movers. Applications in motor vehicles is the most notable one but there are other examples such as those in the maritime industry and extraordinarily in an aerospace case with a solar powered aircraft that has recently encircled the earth. Similar to all these cases in terms of a fraction of the total installed base large electric driven centrifugal compressors can be considered small in the oil and gas industry despite significant advantages in efficiency and maintenance. The relatively constant efficiency of the electric motor and drive over a wide operating range in comparison to a gas turbine driver enhances the efficiency and the flexibility of the overall system. A more common arrangement is to use an electric drive as a secondary mover to support the gas turbine in operating points unfavorable to the gas turbine.

Electric drivers also simplify maintenance. For example, the electric motor drives do not need a combustion air system and the associated filters and are also not subject to fouling or erosion. The downtime of the overall system can thus be reduced by employing electric drives. Additional benefits can be cited as: (i) absence or a reduction of local emission of green house gases or other pollutants such as CO_2 and NO_x, (ii) reduced noise, (iii) lower capital investment for grid connected plants, and (iv) enabling of subsea compressor applications.

Other challenges however are present with electric driven compressors. One reason why gas turbines are not even considered to be an option as prime movers in other industries is the lack of dynamic performance in comparison with electric drives. With electric drives, the drive torque can be varied much quicker than with gas turbines. In the electric drive there is almost no energy stored and the provided electric power can be changed in the range of milliseconds. Typically, with electric motor drivers the drive shaft inertia is also lower than with gas turbines. However, what is an advantage for many industrial applications turns out to be a disadvantage for electric driven centrifugal compressors in the case of grid disturbances. Having no thermal inertia and no internal energy storage combined with a lower mechanical inertia, the loss of grid power results in a rapid decline of rotor speed.

The situation gets worse if the grid voltage drops under a certain threshold, typically around 80% of nominal voltage. Maintaining the operation of variables-speed drives under these circumstances is a challenging task, and the industry-wide solution is to interrupt operation of the variable-speed drive until the grid voltage has recovered. In other words within milliseconds, no more drive torque is provided to the compressors. A loss of torque due to the voltage dip pushes the centrifugal compressors towards surge conditions in a matter of hundreds of milliseconds. Here the anti-surge control systems come into play and they have the responsibility to protect the compressor from entering surge under very demanding dynamic requirements.

From another point of view, when the grid voltage is stable but this time when the gas compression process faces a prompt risk of surge due to an upstream or downstream disturbance, the electrical drive is not utilized despite its potential to provide changes to torque ad speed in a matter of milliseconds.

In this article, we will explain how we can face these challenges of electric driven compressors and turn them into an advantage with state of the art automatic control techniques such as model predictive control.

The paper will include three sub parts focusing on (i) the control of the electric motor drive, (ii) predictive anti-surge control during voltage dips, and (iii) direct utilization of drive torque for anti-surge control via multivariable methods. The results will be illustrated using field data, data from experimental test rigs, and based on computer simulations.

CONTROL OF THE ELECTRIC DRIVE

Control of electric drive systems is a topic that was, and is, covered broadly in the literature, see for instance [1], [2] and the references therein. There exist a number of different electric drive families (voltage source converters, current source converters or cycloconverters to name a few), to power different motors (e.g. synchronous machines, asynchronous machines, DC machines), and for which different control strategies have been developed (e.g. v/f control, space vector control, and various formulations of predictive control). However, in the following we will focus on the most common type of electric drive system apparent in the oil and gas industry: load commutated inverter-fed synchronous machines.

Figure 1 shows a schematic of a variable-speed drive (VSD) system comprising an input transformer and a load-commutated inverter (LCI) powering a synchronous machine. Despite its name load-commutated inverter, the LCI is actually an AC-DC-AC converter composed of a line-commutated rectifier, an inductive DC link, and the name-giving load commutated inverter. Both the line-commutated rectifier and load-commutated inverter are composed of one or more six-pulse thyristor bridges, connecting the phases to the upper or lower potential of the DC link. A thyristor bridge can act as inverter or rectifier, depending on the selected firing angle. In the following, we will follow the common notation to denote the line-side converter as rectifier and the machine-side converter as inverter.

This type of variable-speed drive system is suitable for high-power applications ranging from a few megawatts to over a hundred megawatts, [3]. The advantages and disadvantages of load-commutated inverters for high power systems with respect to voltage source converters are discussed in [4]. In summary, the LCI convinces by its efficiency, power density, reliability and cost-effectiveness.

The main development of the LCI took place in the 1970s and 1980s and numerous industrial applications since then have demonstrated the maturity and reliability of this setup, [5].

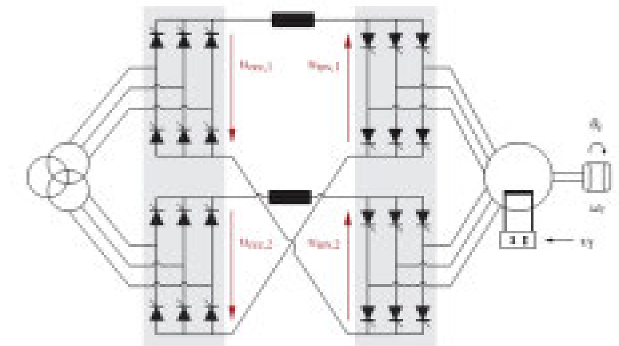

Figure 1: Variable-speed drive system composed of line-commutated rectifier, inductive DC link, load commutated inverter and synchronous machine.

The control inputs to manipulate the operation of the LCI are the excitation of the synchronous machine and the firing angles of the line-commutated rectifier and of the load-commutated inverter. Typically, a decentralized SISO approach is employed to control an LCI, i.e. a different control task is assigned to each control input. More specifically, the excitation is varied to control the machine voltage, the firing angle of the inverter is set to determine the power factor of the machine and the firing angle of the rectifier is used to control the DC link current, and ultimately the drive torque. On top of the DC link current controller a speed controller is placed in a cascaded fashion. For a more detailed description of a typical control system for this type of VSD system, see e.g. [6].

As was mentioned in the introduction, with the classic control scheme voltage dips and other grid disturbance may result in a temporary loss of the drive torque, when a so-called zero-torque ride-through procedure is carried out, [7]. In order to prevent compressors from diverging into surge, the availability of as much drive torque as possible is crucial.

Recently a novel control system for load-commutated inverter-fed synchronous machines was published, [8], [9], [10]. This new control system is based on model predictive control (MPC) and it varies the rectifier and inverter angles simultaneously without pre-assigning tasks to them. The coordination of the firing angles implies the potential for a better disturbance rejection. In particular, in the case of a grid disturbance, the classic control scheme would vary only the rectifier angle, whereas the MPC adjusts both firing angles.

After verifying the successful operation of the MPC control system on an industrial-scale pilot plant, [8], the novel MPC controller was commissioned in two out of six LCIs, each powering a 41.2 MW compressor in a key facility for the natural gas export of Norway. The ability of the MPC-controlled LCIs to provide partial torque during voltage dips was verified in winter 2015/2016, and was reported in [11]. In one such case measurements from the drive system were available as shown in Figure 2. In the figure, the black line belongs to an LCI with conventional control, whereas the dark and the light grey lines refer to two LCIs controlled with the new MPC solution. The ability of the MPC solution to provide partial torque can be seen in the recording. However, the operation is interrupted with the anti-surge trip sequence kicking-in since this sequence is not designed to consider partial torque.

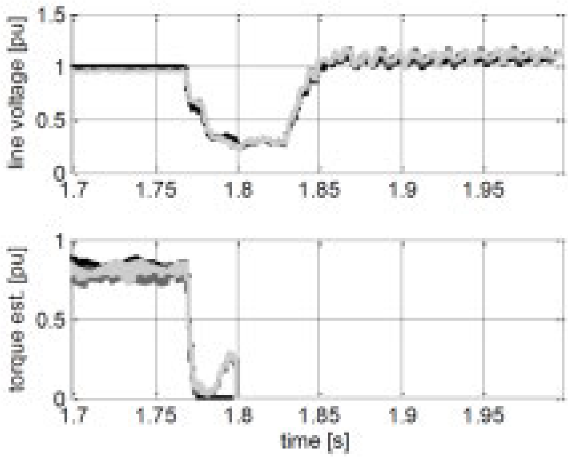

Figure 2: Estimate of the residual power during voltage dips.

SURGE AVOIDANCE DURING VOLTAGE DIPS

The possibility to ride-through and at the same time to provide partial torque with the electrical variable frequency drive is an essential part of enabling a centrifugal compression system to ride through a voltage dip, however it turns out that it is not sufficient in some cases. As depicted in Figure 3, the centrifugal compressor system consists of three tightly coupled systems: (i) the electrical system, (ii) the mechanical system and (iii) the compression system. Zero torque or partial torque during a voltage dip result in unfavorable conditions for the operating point of the compression process, which is pushed towards the surge limit. Depending on the recycling piping design and the cold recycle valve actuation speed, the anti-surge controller might not be able to react fast enough in order to protect the system against surge conditions. In these cases, an additional trip logic is implemented on the variable-speed drive, which is tripping the compressor based on a static relationship of the compressor operating point, e.g. the distance to surge. These static approaches have to be designed for worst-case conditions and are therefore over-conservative for the majority of voltage disturbances.

A novel approach presented in [12] aims at online computation of the remaining time in the safe operating range using electrical and process signals as well as using a model for predicting the evolution of the gas compression process in a relevant time window. The dynamic gas compressor model in this work was already validated with experimental data [13,14]. In this solution, the process measurements are sampled at 50ms and are used to estimate the initial conditions of the compressor model, whereas the electrical variables are sampled much faster at 5ms and used to determine the actual available torque. In this multi-rate arrangement, the slower process measurements are replaced using the model predictions when new values are not available. In the next step the compressor model equations are numerically integrated for a given prediction horizon. The resulting system trajectories are then used to check when the compression system crosses the surge line within the prediction horizon and to obtain the so-called dynamic-time-to-surge or $T2S$ value. These calculations are repeated in a moving horizon fashion at a fast sampling rate of 5ms accounting for fast dynamic torque changes, as it is the case during a voltage dip. Finally, the dynamic-time-to-surge can be used to decide whether to ride through a voltage dip or to shut down the compressor based on a threshold representing how fast the anti-surge system is able to react. For example, if the hot recycle valve has an actuation time of 300ms from receiving the opening signal to reaching 60% of flow capacity; the following logic can be used:

- If $T2S(k < 305ms$, initiate trip sequence
- If $T2S(k) \geq 305ms$, continue operation and re-evaluate T2S at the next sampling instant

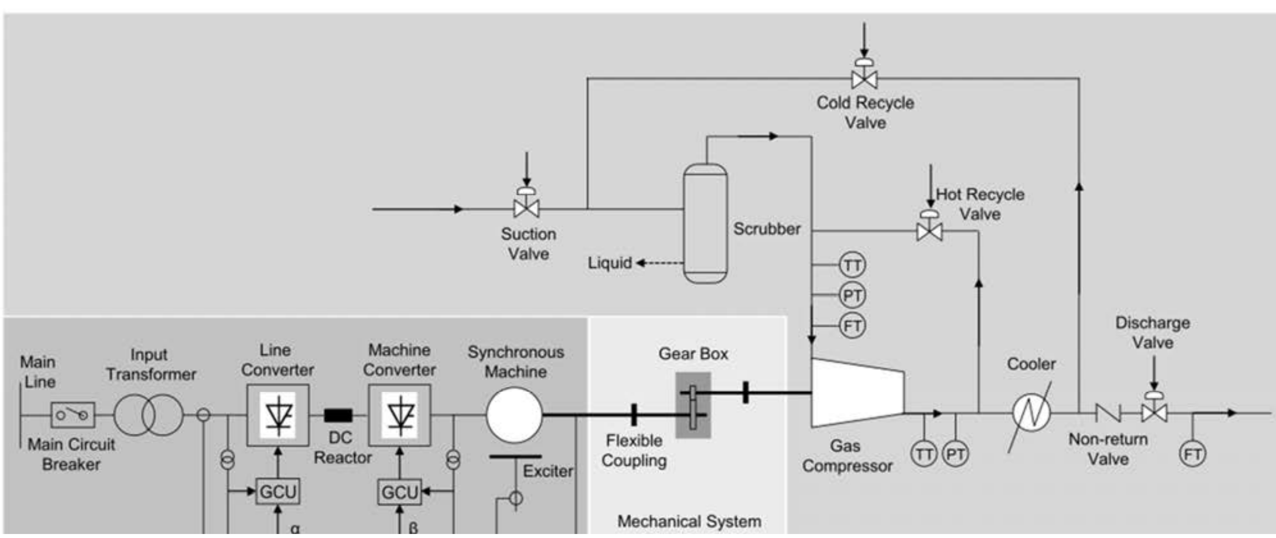

Figure 3: The electrical and the mechanical subsystems in an electrical compression process

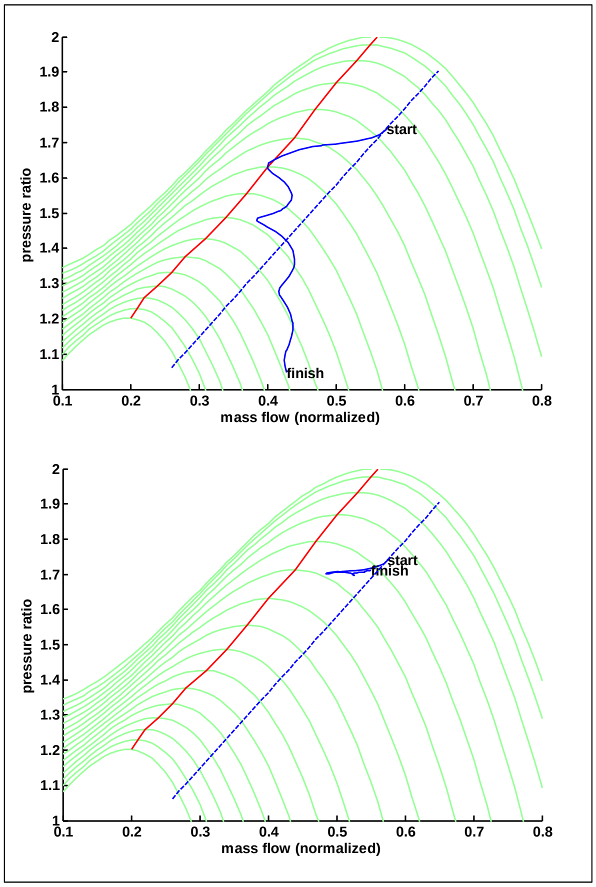

Figure 4: Simulated trajectories of the compressor operating point during a voltage dip

In order to illustrate the dynamic-time-to-surge concept two cases are shown in Figure 4. These cases also illustrate how important it is to receive partial torque from the electrical drive during a voltage dip, in order to ride-through the complete system.

In the top plot in Figure 4 the operation of a compressor is simulated for several seconds starting with a voltage dip lasting for 300ms, during which the electric drive is not able to provide any torque at all. The dynamic-time-to-surge computations predict that the compressor would enter into the surge area and thus initiate the opening of the hot recycle valve starting a shut down. In the lower plot, the electric drive is able to provide 30% of the initial torque throughout the voltage dip. In this case, the dynamic-time –to-surge computations do not reach the critical threshold until the end of the voltage dip and, with the drive torque returning to the initial value, the compressor re-accelerates back towards the original operating point.

TORQUE ASSISTED ANTI-SURGE CONTROL

The challenges faced by electric driven centrifugal gas compressors and how these challenges can be faced using state of the art automatic control techniques has been covered in the previous sections. As mentioned before, the ability to dynamically change the torque applied to a system is used as an advantage by many industrial operations, for example in the metals industry. On the other hand, the drivers for centrifugal compressors are preferred to be decoupled from dynamic tasks. As explained in the previous sections, the anti-surge control task is indeed a very dynamic and very demanding critical control problem and the utilization of the electrical drive as an actuator in providing anti-surge protection can be a potential asset.

The torsional balance of a driveshaft is a linear system. This means the addition or removal of torque impact the system in the same way only in different directions and more specifically with the same angular acceleration magnitude. The voltage dips today already expose the compressor driveshaft to a removal of drive torque within a matter of milliseconds, which is proven tolerable. Controlled changes of drive torque of smaller magnitudes and over longer time windows such as every 50ms, the typical sampling rate for anti-surge control, can be considered acceptable for a torsional considerations.

An advantage of decoupling the driver from anti-surge control is the simplification of the control problem. In a conventional installation, the compressor speed and hence the driver torque is used to control the operating point namely one of the variables among discharge pressure, suction pressure, compressor flow, and pressure ratio. This process control loop is carried out at a rate of 0.5 to 1s. The anti-surge control on the other hand is achieved via controlling the anti-surge valve with a faster control loop running at 50ms. The only way to include the driver torque in the anti-surge control is therefore to resort to multivariable techniques. Here MPC is again a proven choice.

In order to test and confirm the prospect of utilizing the driver torque as an actuator, an implementation has been carried out at a compressor test rig as shown in Figure 5. More information on the test rig can be found in [14]. The system is designed to mimic conditions at a typical gas compression plant but utilizing air as a medium and smaller scale electric drive and compressor at a nominal power rating of 15kW. The sensing and actuating capabilities are also similar to those that can be found in a typical compressor installation.

Given their critical role in compression plant safety, anti-surge control systems are validated against a number of disturbance cases. These include suction and discharge side valve closures and, as previously covered, the emergency shut down without driver torque. This latter case is not suitable to demonstrate the assistance of the drive for anti-surge control. Between the suction and discharge side valve closures, the discharge side disturbance is more severe and therefore was chosen as a case to illustrate the benefits of the proposed approach.

At this point, it is important to briefly mention the basics of anti-surge control. All centrifugal compressor plants have a description of their surge lines. Preferably, this description should come from a recent surge line testing campaign. For anti-surge control, the surge line is shifted to the right of the compressor map towards the stable zone by a certain margin.

Figure 5: Electric driven variable speed compressor test rig

This margin depends on the combined ability of the sensors, control algorithms, and the actuators in rejecting disturbances. If the sensors that track the operating point and detect surge are unreliable, if the anti-surge valves have a long time delay, or if the control algorithm is tuned in a sluggish way this margin needs to be enlarged. Compressors are meant to compress and given the shape of the compressor maps the highest compression ratio is achieved when the system is closest to the surge line, therefore a large surge margin means a loss of performance. Moreover, since the operating space of the compressor is bounded in all directions with the surge, stonewall, minimum and maximum speed limits, a large surge margin also means a loss of operating flexibility. The aim is therefore to reduce the surge margin.

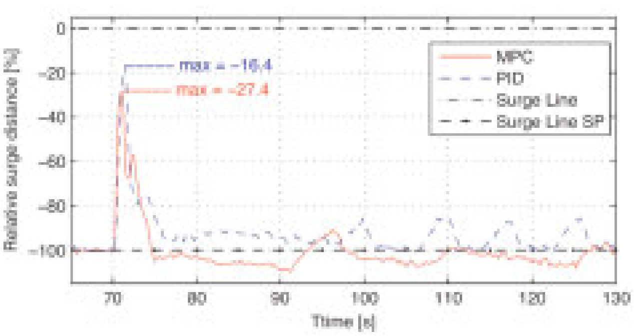

Figure 4: Simulated trajectories of the compressor operating point during a voltage dip

In Figure 6, the measurements from two identical experimental runs in the compressor test rig are shown. In these experiments, the discharge valve is suddenly closed and the system is pushed towards surge. The initial operating point is located right on the surge margin or the surge control line. In the figure -100% represents the surge control line and 0% represents the surge line. Two control solutions are compared under the same conditions. The MPC based solution uses the drive torque as an additional actuator to the anti-surge valve and the PID solution, representing the conventional approach, uses only the anti-surge valve. In short, the results indicate that the MPC solution utilizing the electric drive is able to steer the compressor away from surge with an 11% better margin compared to the traditional solution. This result implies that the MPC based and torque assisted solution can be used to shrink the surge margin, increase the performance and provide more flexibility for the compressor.

CONCLUSIONS

Electric drive solutions for centrifugal compressors offer significant advantages making them a strong competitor against gas turbines as the traditionally preferred solution. This is especially the case when electric power from the grid is available. Despite these advantages, the grid connection brings about several challenges. This article provides a summary of the authors experience in dealing with these challenges and their attempt in converting some of the challenges into new opportunities. Most of the described solutions here are only possible because of advances in automatic control technologies and because of the increased availability of computational power at embedded systems level enabling the solution of complex optimization problems in less than a millisecond. The overall experience level of the industry with electric driven compressors is low. As more systems are deployed and more field experience is collected, the authors expect to see additional technology developments taking place and taking the advantages of the electric driven systems even further.

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