ELECTRIFYING LARGE CRITICAL COMPRESSOR APPLICATIONS REDUNDANT VSD SYSTEMS INSTEAD OF MECHANICAL DRIVERS A CASE STUDY IN SUCCESSFUL IMPLEMENTATION

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Abstract – Traditional high-power compressor applications have in the past relied on steam or gas turbines as primary drivers. In response to the growing emphasis on clean energy initiatives, the industry is shifting towards electric motors as an alternative to turbine drivers.

When speed control and therefore variable speed drives (VSD) are required, their reliability becomes an important topic. As the risk of unplanned process interruptions is to be mitigated, hot redundancy concepts have been developed.

This case study focuses on the application of such a VSD redundancy concept, for the Reactor Effluent (REC) and Heat Pump Compressor (HPC) within a large-scale propane dehydrogenation (PDH) plant process. The selection of VSD technology was driven by specific process requirements, including the need for minimal switchover time. This paper details the journey towards a successful handover to production, highlighting the considerations, challenges, and outcomes of implementing redundant VSD systems in lieu of mechanical drivers for large critical compressor applications.

Index Terms – Variable Speed Drive, VSD System, Availability, Reliability, Redundancy, High Power Application, VSI, LCI.

I. INTRODUCTION

A. Impact of large VSD into current industrial applications and design

Variable speed drives (VSD's) have a long-standing presence in the market, demonstrating a solid history of success, in critical high-power scenarios. The growing adoption of VSD systems (VSDS) in industrial high-power contexts, stems from a blend of factors including efficiency, cost-effectiveness, control capabilities, and environmental considerations. Here's a breakdown:

1. Electrical drivers surpass gas or steam turbines in both efficiency and cost-effectiveness.
2. Electrical drivers provide superior control and flexibility, enabling precise load management and output precision, which is crucial in industries such as chemical manufacturing where process control is paramount.
3. Embracing electric drivers facilitates the decarbonization of value chains, aligning with the carbon neutrality goals set out by nations and corporations alike.

VSD's offer cost-effective solutions with reduced capital expenditure (CAPEX) and maintenance expenses, coupled with enhanced availability stemming from their lower mean time to repair (MTTR) value. Additionally, electrical drivers typically have shorter delivery times compared to their mechanical counterparts. However, it's crucial to emphasize the necessity of a reliable power supply network for VSD's, unlike mechanical drivers. Moreover, when designing the shaft train, considerations must be made to determine the shaft end size of the compressor and coupling:

- Pulsating torques during operation, which may require an active damping function, or requiring dead bands to avoid torsional excitation frequencies.
- Pulsating torques in the event of a two- and three-phase short-circuit on the electrical motor.
- Gearbox integration, as adjustments to the electrical motor's speed may be necessary to match the compressor's speed.

Maintenance procedures and the necessary skillset of personnel on site can vary and necessitate development and training. There may be an increased reliance on the vendor of the electrical equipment.

B. Requirements of critical compressor applications

1) *General:* Besides ensuring personnel safety, the paramount requirement is to prevent any process interruptions between planned shutdowns. The potential production loss from a main compressor failure in the PDH process, or an ethylene cracker service could exceed one million US dollars per day. The resilience of the process to disturbances from a main compressor varies, contingent upon several factors including:

- Mass moment of inertia
- Load profile
- Compressor characteristics (preventing surge)
- Operation points
- Specific process requirements

The permissible disturbance translates into an allowable speed drop and subsequently an acceptable gap in torque to be supplied by the electrical motor.

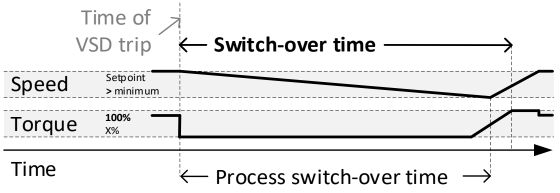

Fig. 1 Switchover time after VSD failure

From a process standpoint, the switchover time can be interpreted as the duration between the VSD trip and the motor ceasing to decelerate further. Given the marginal disparity and the ability to eliminate the dependency on the load profile, the switchover time is defined as the interval between the VSD trip, and the attainment of 100% motor torque as shown in Fig. 1.

Below are some examples electrical VSD system vendors face for the switchover time:

- PDH:
  - Torque gap < 500 ms
  - Torque gap < 1 sec
- Cracker
  - Torque gap < 300 ms
  - Back to speed setpoint < 5 sec

A thorough understanding of the process is essential to accurately establish its limits, with a particular focus on avoiding potential compressor surges. In one project example, despite the process permitting a torque gap of 300 ms, preventing compressor surge proved challenging, prompting the need for additional optimization efforts. In another project, the requirement was for the shortest possible torque gap, leading to the selection of an electrical drive vendor that guaranteed the smallest gap. Notably, neither the compressor vendor nor the process owner was able to specify the maximum allowable torque gap. Consequently, they selected a solution devoid of any torque gap, albeit at the risk of a complete trip in the event of a major failure of one of the VSD's.

2) PDH process and compressor setup: A modern PDH plant utilizing UOP's Oleflex™ process consists of two process compressors, the Reactor Effluent Compressor (REC) and the Heat Pump Compressor (HPC).

The REC is a large volume, high power, multi section compressor very similar to a crack gas compressor seen in ethylene steam crackers. Very large diameter compressors are required to handle the large suction volumes. Consisting of typically a double flow first section and a single section second compressor body. Drive configurations vary, from single large motor (the focus of this case study), separate motors with or without VSD or steam turbine drives. From a process operation point of view variable speed is important for capacity control.

The HPC is lower power handling a higher mole weight gas, consisting of a single multi section compressor. Providing heat and motive suction for the C3 splitter the heat pump compressor enables the efficient operation of the propylene product from the un-dehydrogenated propane. Variable speed for this compressor enables both process control and ease of startup in pressurized conditions.

3) Compressor coasting and maximum torque gap: A summary of the physical properties of the two trains is presented in the table below.

TABLE I
PHYSICAL PROPERTIES OF REC AND HPC TRAINS

	P(sh)	n(M)	n(C)	LxWxH	M	I
	MW	rpm	rpm	m	t	kg·m^2
HPC	19.5	1500	4328	12.5x4.7x4	131	3287
REC	30.5	1500	4600	20x4.7x5	320	13617

P(sh)	Motor shaft power rating
n(M)	Motor nominal speed
n(C)	Compressor nominal speed
LxWxH	Compressor train dimensions Length x width x height
M	Total mass of the string
I	Mass moment of inertia of the string

Loss of torque from the motor can have significant repercussions on the operation of a compressor system, potentially leading to process upsets or even causing the compressor to trip offline if torque is not promptly restored. While the impact of torque loss and the subsequent slowing of the compressor can be assessed through dynamic simulation, certain factors, such as the momentary interruption of Variable Speed Drive (VSD) operation, may not be adequately addressed due to their short time scales, which fall below the resolution of the anti-surge controller.

The inertia of the compressor train plays a crucial role in mitigating the effects of torque loss. Acting as a flywheel, the compressor's inertia stores kinetic energy proportional to its speed and moment of inertia. This stored energy is gradually "consumed" by the compressor as it continues to perform gas work within the process and experiences standard parasitic losses from system components such as bearings, seals, and gears.

During the initial moments of torque loss, the consumed gas power outweighs the parasitic losses, highlighting the importance of inertia in maintaining system stability. However, the specific consequences of torque loss and the subsequent utilization of stored kinetic energy can vary depending on factors such as the type of process being controlled and the characteristics of the compressor system.

The comparison between the REC string and the HPC in terms of their inertia and speed drop upon loss of torque provides valuable insights into their respective behaviors. The REC string, characterized by significantly higher inertia relative to its gas power, exhibits a much lower drop in speed upon loss of torque. Specifically at 500 milliseconds following the loss of torque, the REC string maintains approximately 96% of its nominal speed. In contrast, the HPC, with considerably lower inertia relative to its power, experiences a faster drop in speed. By the same timeframe, the HPC's speed decreases to around 90%.

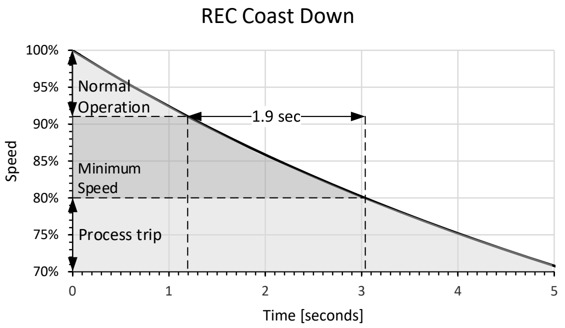

Fig. 2 Relevant part of REC service coast down

A total loss of torque lasting more than 1 second would cause the speed of the HPC to fall below its minimum operating speed range, typically set at 80%. In such cases, the compressor control system is designed to initiate a system trip as a protective measure. However, if torque is restored promptly and the operating speed remains within the normal operating range, a trip would not be triggered.

Flow disturbances resulting from the drop in speed may prompt the anti-surge system to take action by opening the anti-surge valve. Once torque is restored and flow is stabilized, the compressor can return to its set point, ensuring continuous operation.

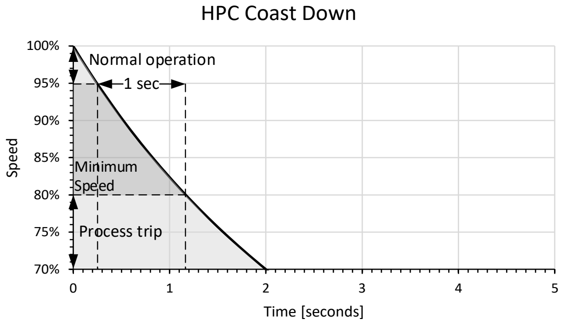

Fig. 3 Relevant part of HPC service coast down

C. Availability and redundancy

An analysis of VSD systems through a "Failure Mode Effects Analysis" reveals that single points of failure are inevitable. Specifically, examination of the VSD itself unveils over 100 potential single points of failure within such a system. VSD vendors offer various redundancy options to eliminate single points of failure, including:

- Implementing redundancy in components such as coolant circulation pumps, sensors, heat exchangers, filters, deionizers, and pressure safety valves for water-cooled units. It's worth noting that the majority of VSD's with a capacity of 10MW or higher for continuous operation utilize liquid cooling.
- Incorporating redundant control interfaces.
- Utilizing redundant uninterruptible power supplies (UPS) for control systems.
- Installing redundant auxiliary power supplies.

However, certain redundancy options are specific to particular VSD topologies. For instance, an "n+1" redundancy option for power semiconductors is viable only for load commutated converter (LCI) technology and may not be suitable for topologies employing other high voltage components. Introducing redundancy in such topologies can increase failure rates due to added complexity. For example, implementing a "1+1" redundancy for power electronics in LCI configurations decreases the mean time between failure (MTBF) figures; this is due to the need for double the quantity of thyristor firing equipment. Nevertheless, redundancy in thyristor-based semiconductors remains independent, as failed components short-circuit and do not require additional equipment for bypass.

Similarly, redundancy in power cell configurations is applicable only to topologies utilizing power cells. Implementing a "1+1" redundancy in such cases may also reduce MTBF figures due to increased complexity and the need for additional equipment, such as cell bypass mechanisms, to ensure uninterrupted operation. Additionally, redundancy achieved by adding an extra power cell using LV-IGBTs is not entirely independent, as it requires supplementary equipment. LV-IGBTs fail open and necessitate bypassing. Power cell redundancy cannot be rebuilt without a shutdown.

As emphasized in [1] and discussed further in [2], a VSD intended to operate for extended periods without shutdown, whether scheduled or unscheduled, necessitates redundancy at the macro level, such as a complete VSD or redundant converter.

D. Solutions for redundant electrical drives

1) Definition: A fully redundant drive system is designed to ensure uninterrupted operation even in the event of component failure, maintaining delivery at 100% of the nominal process demand for which the system is sized. Moreover, faulty components can be replaced, and preventive maintenance activities carried out without the need to halt the process. Redundancy can be restored after maintenance or repair.

Comparing with mechanical drivers, it is possible and feasible to have redundancy on the boiler part of the steam turbine setup, but redundancy options for a gas turbine are limited.

Detailed discussions regarding redundancy concepts at the motor level, such as employing dual stator windings both able for operation at full power, are omitted due to their complexity and limited practical benefits given the high reliability typically associated with the electrical motor. Similarly, the discussion does not extend to employing two separate motors, each designed to operate at full power on the same shaft train.

To ensure redundancy at a macro level and mitigate the risk of process interruption due to a VSD failure, there are two primary approaches. Both methods can be employed to meet the "Redundant Power Channels" requirement as specified by UOP see [9]. For this project, a deviation has not been accepted due to economic reasons.

2) Parallel operation – no zero-torque gap: Here a minimum of two VSD's are driving one motor simultaneously. The remaining one VSD, or the remaining two or more VSD's can compensate for the failed VSD by increasing the current. It is either 2x 100% or 3x 50% or 4x 33% and so on. Examples are shown in Fig. 4 and Fig. 5

There are two major advantages of this solution:

- The motor torque would only drop by the capacity of one VSD for a normal failure scenario.
- Smaller single VSD rating required. For high power, larger than the capability of a single VSD, this could be a cost-effective approach avoiding double VSD's to cover 100% motor power.

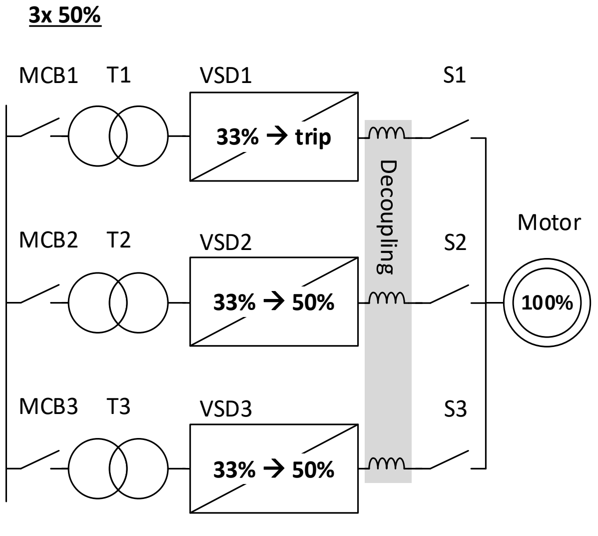

Fig. 4 Overview of redundancy arrangement with coupled VSD's 3x 50%

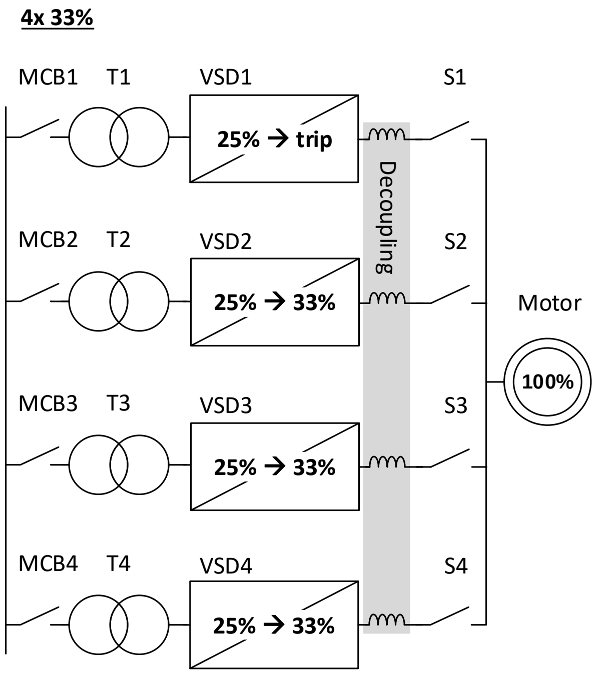

Fig. 5 Overview of redundancy arrangement with coupled VSD's 3x 33%

Main disadvantages:

- A major failure of one VSD (e.g. output short-circuit) would lead to disturbances tripping the other VSD's, losing any chance to save the process.

Further, ground fault monitoring and motor protection is to be solved separately. Decoupling reactors are required at the output of VSD's, as indicated in Fig. 4 and 5.

3) Isolated redundancy – zero-torque during switchover: Here "n+1" redundancy is used. One VSD is redundant in a hot-standby state, which means its main circuit breaker (MCB) is closed and the VSD is ready to go. In such arrangements the spare VSD can be the backup for more than one VSD as shown in Fig. 6.

The redundant VSD usually requires a dedicated input transformer due to the risk of disturbances on the input side caused by the failing VSD, which may lead to a trip of the redundant VSD. Here an external control, which can be hard-wired using relay logic is required. For example, the right switches must be opened/closed, and the right reference be considered by the standby VSD. The switchgear used can be interlocked, so that it is not possible to have both breakers of one motor closed and keep the switchover-time at a minimum, not waiting for feedback.

The major advantage is:

- The hot-standby VSD is decoupled and will not be affected by any failure of the running VSD.

Main disadvantages:

- The motor torque drops to zero during a switchover event. The process needs to be studied to confirm feasibility.
- 100% motor power is to be covered by one VSD system.

For a project with one motor only, the VSD power to be installed is 200% for a decoupled solution, whereas a 3x 50% solution would require 150%. But considering only the main power path four circuit breakers (in- and output) are needed for a decoupled system and six for a 3x 50% setup. When serving two or more motors the advantage is gone, as shown in TABLE II.

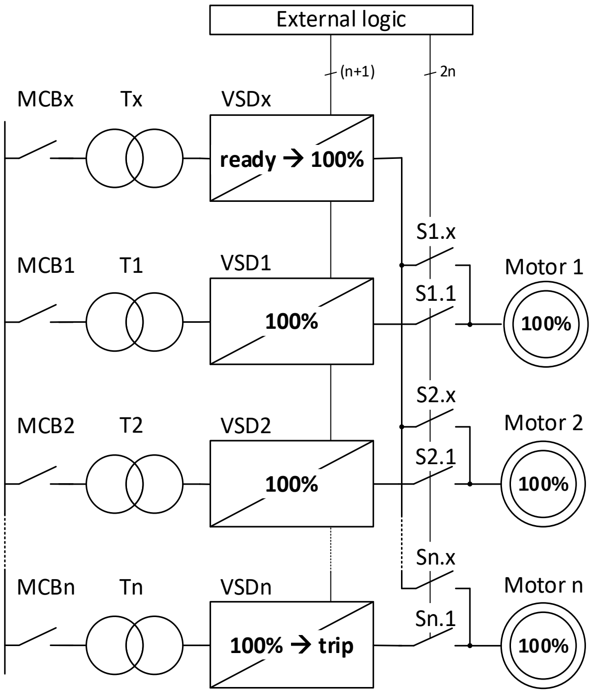

Fig. 6 Overview of an isolated redundancy arrangement

TABLE II
OVERVIEW OF NUMBER OF MAIN EQUIPMENT FOR REDUNDANT VSD SYSTEMS

	3x 50% coupled - no zero-torque gap		
# motors	# T+VSD	T+VSD pwr	# CB
1	3	150%	6
2	6	300%	12
3	9	450%	18

	4x 33% coupled - no zero-torque gap		
# motors	# T+VSD	T+VSD pwr	# CB
1	4	132%	8
2	8	264%	16
3	12	396%	24

	n + 100% Decoupled – zero-torque gap		
# motors	# T+VSD	T+VSD pwr	# CB
1	2	200%	4
2	3	300%	7
3	4	400%	10

# motors	Number of motors (e.g. number of compressor services)
# T+VSD	Number of transformer and VSD Combinations
T+VSD pwr	Total required transformer and VSD Power related to the motor power
# CB	Number of circuit breakers required (in- and output breaker)

E. *Different VSD technologies (VSI/LCI)*

Various technologies are available for high-power Variable Speed Drive (VSD) applications, as outlined in [2], [4], and [5]. Previous examples, such as those referenced in [6] and [7], have discussed the different variants of VSI solutions. However, neither VSI nor LCI technologies can be conclusively deemed superior to the other for high-power applications in general. The proven simplicity of the LCI topology typically results in the highest reliability, while VSI-based VSD's offer greater flexibility in terms of system integration.

When adhering to the "Isolated Redundancy" concept, the LCI topology demonstrates superiority due to its ability to isolate system components, such as "x" and "1" as illustrated in Fig. 6, through thyristors in a blocking state. This isolation is independent of the main circuit breaker (MCB) and output switches (S1.x and S1.1). Particularly in systems featuring a single motor, as depicted in Fig. 7 with S1.x and S1.1 closed, and benefiting from inherent line and motor voltage measurements, the LCI remains constantly aware of the motor's (and network's) statuses. Leveraging the zero-current feedback mechanism of the faulty system, control can be swiftly released, facilitating the shortest possible switchover time. Additionally, there is no need for DC-link charging, and the MCB can be switched on at any time.

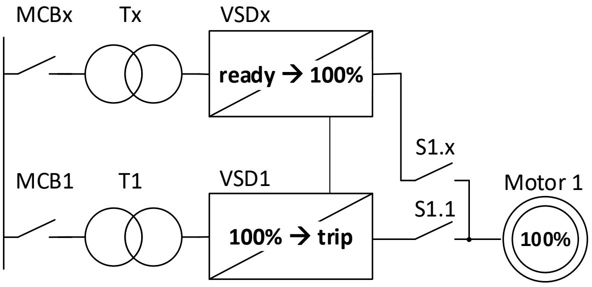

Fig. 7 Overview of an isolated redundancy arrangement with one motor and two VSD's

F. *Examples for switchover times*

Possible switchover times are depending on VSD vendor, VSD technology, communication concept with the DCS and other things, so the numbers presented in the table below should only be used as typical data.

TABLE III
OVERVIEW OF POSSIBLE SWITCHOVER TIMES FOR DIFFERENT CONCEPTS

	Parallel Operation	Isolated Redundancy	
		1 + 1	n + 1
Switchover time [ms]	100 - 200	100 - 500	200 - 500

II. DESCRIPTION OF THE INSTALLATION

A. *General VSD system setup*

In this project the approach of "Isolated Redundancy" has been selected, primarily because the process can withstand a zero-torque duration of over 500 milliseconds during switchover. The rated shaft power and speed for the two services are as follows:

- HPC: 19.5 MW @ 1500 rpm / 4328 rpm
- REC: 30.5 MW @ 1500 rpm / 4600 rpm

Both VSI and LCI technologies are available for single-VSD solutions to meet these power requirements. LCI has been selected due to its robustness and the potential to optimize switchover time as LCI allows for all output breakers to remain closed during normal operation.

Large VSD systems typically incorporate a dedicated input transformer. An intriguing aspect of this project is the utilization of two VSD's with only one transformer (T1) per motor (M1) as shown in Fig. 8. This concept is noteworthy because transformers are inherently robust and often do not necessitate redundancy measures in the first instance. However, such configurations are only viable with straightforward, external transformers.

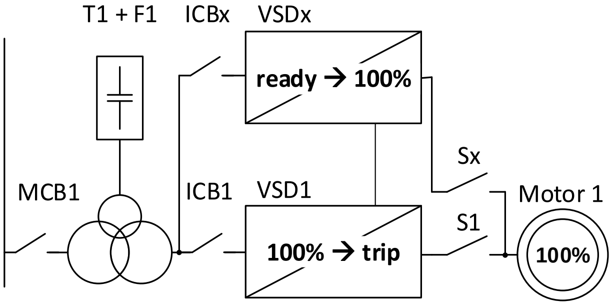

Fig. 8 Simplified overview of the project setup

For instance, employing a 24-pulse front-end with four secondary windings would entail the installation of two sets of four circuit breakers, in addition to the MCB for transformer protection. In this project, supply network power factor compensation is essential. To achieve this, a filter (F1) connected to the tertiary winding of the input transformer is utilized. This filter not only facilitates power factor compensation but also serves to filter harmonics, thereby supporting a simplified 12-pulse transformer / rectifier arrangement.

Remarkably, the VSD system is capable of functioning without the filter system, obviating the need for redundancy discussions regarding the inherently robust, passive filter system and accepting higher network supply disturbances during repair. The filter system can be reenergized, when ready without disrupting the process.

B. *VSD power hardware configuration*

Fig. 9 illustrates the Single Line Diagram of the installation. As outlined in [2], in the context of LCI systems, motors equipped with dual stator winding systems are preferred to mitigate rotor harmonic current distortion and minimize pulsating torques exerted on the driven shaft. Consequently, this configuration necessitates two output bridges per VSD, thus requiring two Output Circuit Breakers (OCB) per VSD. Additionally, for this configuration two Source Circuit Breakers (SCB) per VSD are needed to completely isolate the converters from the rest of the electrical system.

The control architecture is such that each LCI independently controls its own SCBs and OCBs, while the Input Circuit Breaker (ICB) at the transformer primary and the Filter Circuit Breaker (FCB) are only opened for transformer and filter bank protection, or in the case of both LCIs being faulty.

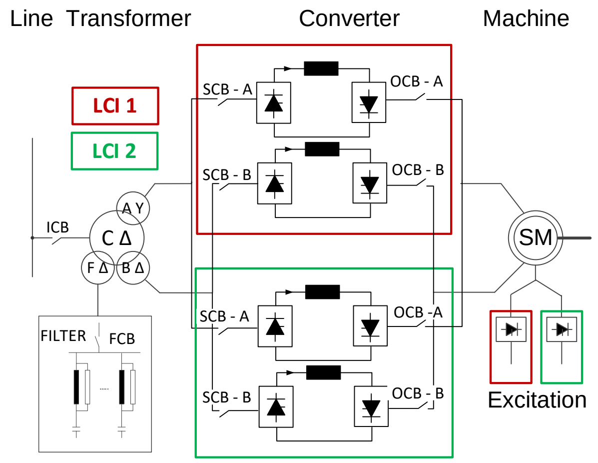

Fig. 9 Simplified Single Line Diagram of the redundant concept. Boxed in red, LCI1; in green, LCI2

The regulation of the main machine field current is achieved through brushless excitation. Each exciter per machine is powered by two excitation units, one per VSD, operating in Duty/Standby mode. These units are directly controlled by the respective LCIs. Additionally, each VSD operates its own independent water-cooling unit. This design ensures that the water circuits within the VSD's are completely physically separated.

C. *VSD control hardware configuration*

Redundancy is also implemented in the control architecture, as illustrated in Fig. 10, which depicts the configuration of the main boards and the upper-level control. Despite the complexity of the redundant LCI setup, it does not impose an increased operational burden. The upper-level control can manage the installation as if it were operating a single VSD, utilizing both I/O and fieldbus interfaces.

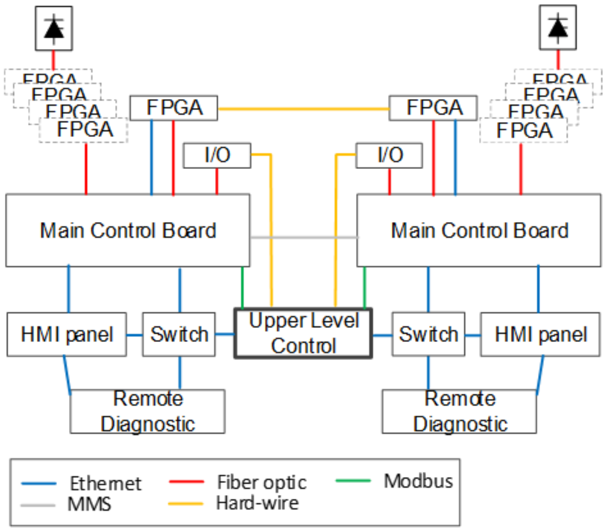

Fig. 10 Redundant control hardware architecture of the VSD system

The two main boards are interconnected via Multimedia Messaging Service (MMS) communication, supplemented by a hard-wired connection serving as a backup in case of MMS communication loss.

III. OPERATION AND OPERATIONAL STATES

A. *Circuit breaker configurations*

The setup is designed to allow the standby VSD to operate with three different breaker configurations. Each configuration balances switchover time against the level of isolation provided for the standby converter:

1) All the SCBs and OCBs of the standby converter are open, as well as the contactor of the standby excitation unit.
2) While the SCBs and OCBs of the standby VSD remain closed (closing of these breakers typically requires around a hundred milliseconds), the field contactor of the standby excitation unit remains open.
3) The SCBs, OCBs, and excitation unit contactor of the standby VSD remain closed. This configuration facilitates a faster switchover in the event of a trip in the active ("Duty") VSD.

B. *Operational States*

At any given time, the VSD's must be in one of the operational states: OFF, Duty, Standby, or Faulty. Additionally, for this specific installation, two additional states, Master and Slave, are implemented. However, it's important to note that the Master-Slave configuration does not provide any technical benefit in terms of redundancy. These operational states are detailed further in Table IV. It's essential to ensure compatibility between the operational states of the two VSD's. For instance, both VSD's cannot be in Duty, Standby, Master, or Slave simultaneously. If one VSD is in Duty, the second one coming online will automatically switch to Standby. This results in four main possible state combinations:

1) Both VSD's are OFF
2) One VSD is Duty while the other one is OFF, for example due to maintenance or due to a fault condition.
3) One VSD is Duty and the second is Standby
4) One VSD is Master and the second is Slave

Fig. 11 describes the operational states combinations for this setup. From the OFF-OFF state, one LCI (irrelevant which one is on, the setup is completely symmetrical) is sent to Duty and starts to operate. When the second VSD comes online, it automatically switches itself to Standby (breakers are managed according to the chosen breaker configuration). The situation is the one depicted in Fig. 12. In this Duty-Standby combination, the Duty VSD takes 100% of the load, controls the speed (or torque), runs all the current and voltage regulation loops as per normal operation. All the setpoints for the operating point are sent over to the Standby VSD, to allow the latter one to come online avoiding control transients. From this configuration, it is possible to transition to a Master-Slave configuration, as illustrated in Fig. 13, wherein each VSD bears 50% of the load. The Master VSD is responsible for running the speed loops and controlling voltage via the excitation unit. In the event of a trip, the faulty VSD is halted, bringing its load to zero. Subsequently, the healthy VSD transitions to the "Duty" state (if not already) and assumes 100% of the load while running all relevant control loops, as depicted in Fig. 14. Once the fault condition is resolved, the second VSD can return to operation as Standby.

TABLE IV
OPERATIONAL STATES

VSD state	**Control functions**
OFF	No control function Breakers: - SCB and OCB of the VSD are open - Field contactor open
Duty	Control functions: - Speed/Torque control - Current control - Voltage control (excitation unit control) All setpoints sent over to Standby VSD. Breakers (for configuration 3): All SCB and OCB are closed. Field contactor is closed.
Standby	Control functions: All setpoints are read from Duty VSD and ready to operate. Breakers (for configuration 3): All SCB and OCB are closed. Field contactor is closed.
Master	Control functions: - Speed/Torque control - Current control (50%) - Voltage control (excitation unit control) All setpoints sent over to Slave VSD. Breakers (for configuration 3): All SCB and OCB are closed Field contactor is closed
Slave	Control functions: - Torque controlled (Slave) - Current control (50%) - Voltage control inhibited (excitation unit in Standby) All setpoints received from Master VSD. Breakers: All SCB and OCB are closed Field contactor is closed
Faulty	VSD tripped. Breakers: All SCB and OCB are open (VSD is isolated) Field contactor is open

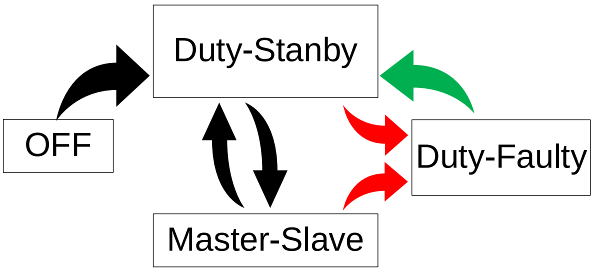

Fig. 11 Possible transitions of the redundant concept

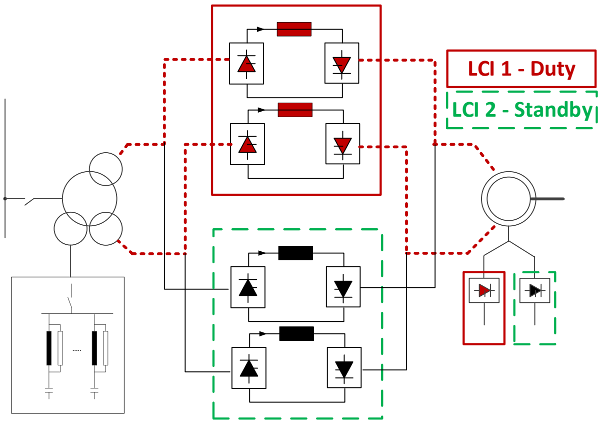

Fig. 12 Duty-Standby state: LCI1 drives 100% of the power, while LCI2 is in standby (0% of power). The power path is shown in dotted line

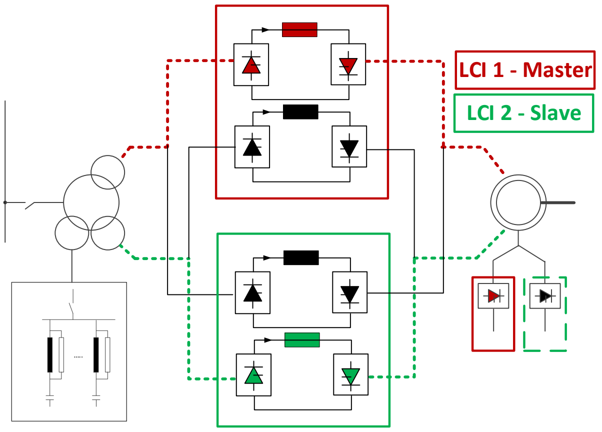

Fig. 13 Master-Slave state: 50% of power flows through LCI1 and the remaining 50% through LCI2. The power path is shown in dotted line

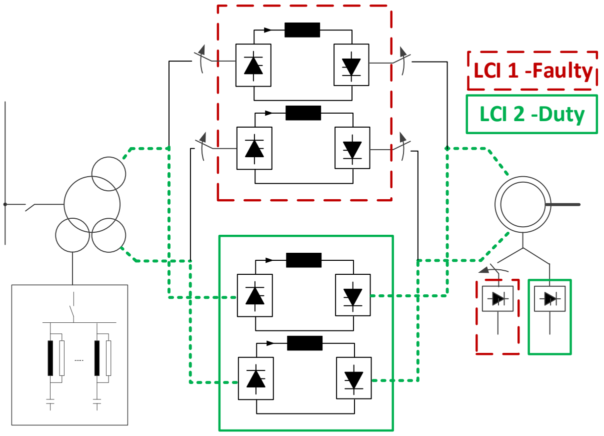

Fig. 14 LCI1 in "faulty" state, LCI2 taking over as "Duty", driving 100% of the power. The power path is shown in dotted line

IV. RESULTS

A. *Switchover "Duty-Standby" to "Faulty-Duty"*

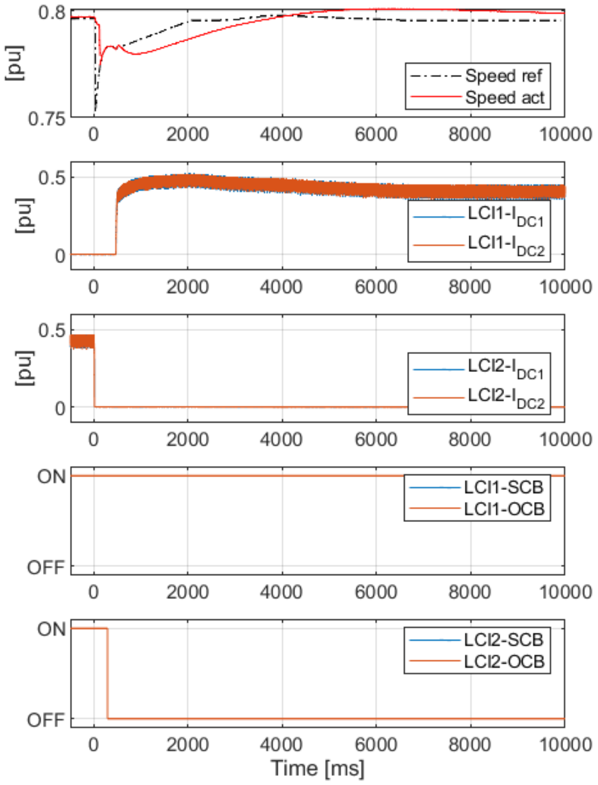

Fig. 15 REC – Switchover from Standby (LCI1) - Duty (LCI2) to Duty (LCI1) - Faulty (LCI2)

The redundancy concept was effectively integrated into the REC and HPC compressor applications with a nominal power of 30.5 MW and 19.5 MW respectively. Numerous switchover tests were conducted successfully. However, during the commissioning phase of this project, only partial load testing was feasible, allowing for approximately 80% of rated speed and 50% of nominal torque to be applied for the REC service.

A switchover from "Duty-Standby" to "Faulty-Duty" configuration is illustrated in Fig. 15 and Fig. 16. The trip occurs at time 0. Prior to the trip, LCI 2 is in the "Duty" state, while LCI 1 is in "Standby". It can be observed that the OCBs of the Standby VSD are in closed position, consistent with the breaker configuration described in Chapter III.A., which is configuration 3. The SCBs, OCBs, and excitation field contactor remain closed during Standby operation. When LCI 2 trips at time t=0, its current is immediately brought to zero, and the SCBs and OCBs open shortly thereafter. LCI 1 transitions to the Duty state and assumes control over speed/torque, as well as current and voltage regulation.

When LCI 2 comes to a halt, the speed begins to decrease. It's important to note that the "Speed act" signal in Fig. 15 represents an estimated value, and during the transition, this signal may experience slight disturbances. However, the lowest point is reached when the DC current of LCI 1 is increased and torque is reapplied, enabling the motor to accelerate once more. In this instance, it takes approximately 4 seconds for the speed to recover.

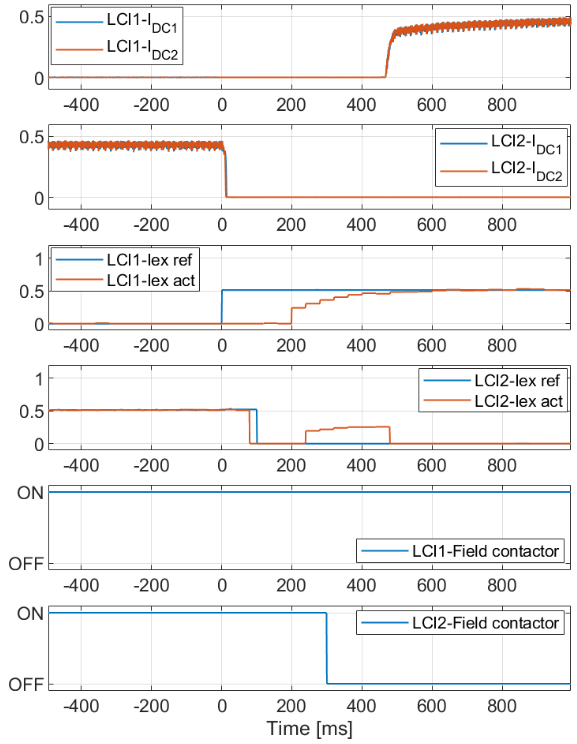

Fig. 16 REC – Switchover from Standby (LCI1) - Duty (LCI2) to Duty (LCI1) - Faulty (LCI2); enlarged view.

The duration of this recovery period naturally varies based upon several factors:

- Operating conditions
- Machine and load inertias
- Acceleration ramp time settings
- Margin of driving torque over the load torque.

Hence, it's more pertinent to consider the torque gap, which directly correlates with the DC link current for LCI and signifies the switchover time. Upon examination of Fig. 16, it's evident that the DC current of LCI 1 begins to increase approximately 450 milliseconds after the trip occurrence. In this project, the worst-case scenario for losing the process was determined to be approximately one second. Therefore, a switchover time of around 500 milliseconds was deemed adequate, requiring no further optimization.

Notably, Fig. 16 also demonstrates that the DC current of the drive transitioning to Duty, along with the excitation current, are controlled smoothly without transients to the correct setpoint. This is accomplished by exchanging setpoint information via the MMS communication link.

B. *Switchover "Duty-Standby" when communication fails*

This section demonstrates the switchover from Standby to Duty when MMS communication is unavailable, for example, due to damage. Fig. 17 and Fig. 18 display the most significant signals.

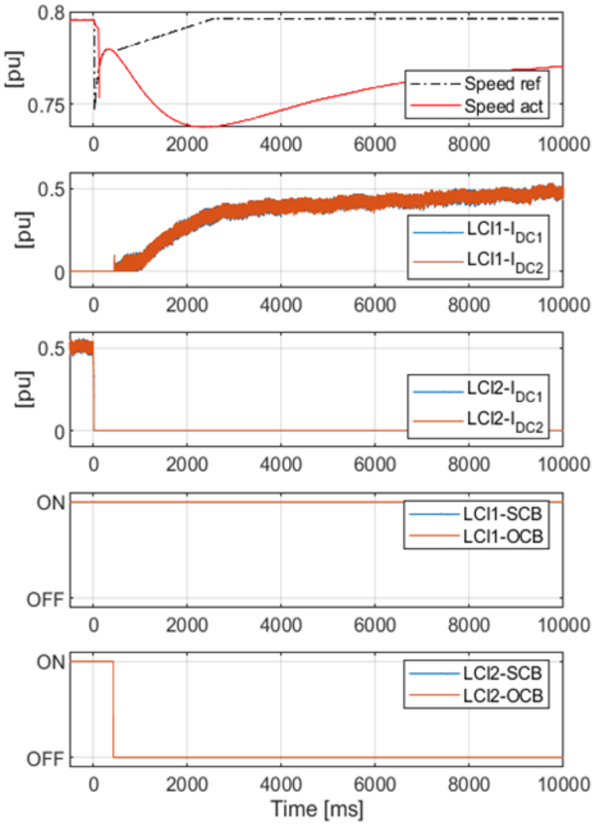

Fig. 17 REC – Switchover with communication failure: from Standby (LCI1) - Duty (LCI2) to Duty (LCI1) - Faulty (LCI2)

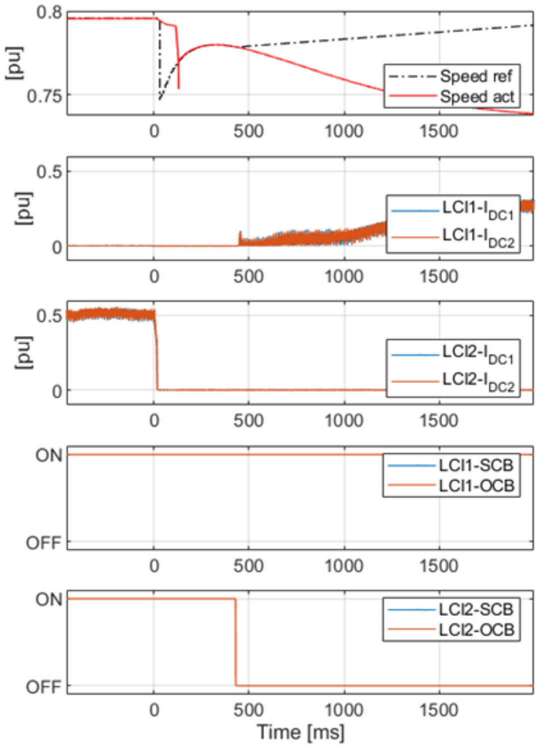

Fig. 18 REC – Switchover with communication failure: from Standby (LCI1) - Duty (LCI2) to Duty (LCI1) - Faulty (LCI2); Enlarged view

In this scenario prior to the trip, LCI 1 is in Standby while LCI 2 is in the Duty state. The switchover principle remains the same as in the previous section: Following the trip, the Standby drive transitions to Duty and assumes control over speed, current, and voltage.

However, in this case, with MMS communication unavailable, the Standby controller does not receive operating point information, or setpoint references. Consequently, the DC current reference ramps up slowly from zero, while the machine is excited to restore nominal flux. This leads to a longer torque gap, causing the speed to drop further and remain below the preset reference for a longer duration.

The behavior is here illustrated only for explanation purposes and the dynamics of the controller could vastly be optimized for this case as well.

V. CONCLUSIONS

The successful commissioning of the project has demonstrated the feasibility of achieving very short switchover times in real-world process environments. It corroborates the tests in a laboratory environment as outlined in [3].

The robustness of the process exceeded expectations, with the owner accepting a switchover time of 400 milliseconds not pursuing obvious options for further optimization, underscoring the prioritization of system readiness for production.

Balancing the robustness of standard VSD product supply with the risks associated with highly engineered solutions remains a challenge in such projects. Our recommendation to integrate logic specific to the project or process into the overriding control system, whether through hard-wired relay logic or within the distributed control system (DCS), aims to alleviate long-term maintenance and troubleshooting concerns.

System testing methodologies, including combined, string, and full-load testing, were not conducted as they were deemed unnecessary and of limited value. Instead, testing on a digital twin proved instrumental in preparing for a successful commissioning process, as discussed further in [8]. Real-time simulation provided an efficient platform for refining the switchover logic embedded within the project-specific part of the VSD firmware. Issues could be replicated and investigated within a controlled lab environment, facilitating highly efficient troubleshooting.

The commissioning phase involved testing various operation schemes, such as the seamless recovery of tripped VSD's for rebuilding hot redundancy after maintenance or repair, as well as interrupting and reestablishing communication links between VSD's. Noteworthy is the adoption of identical firmware across all VSD's, reflecting best practice standards for maintenance and troubleshooting.

Moving forward, upcoming projects will strive for advancements in system behavior, with a particular focus on optimizing switchover times to bolster process stability. Furthermore, delving deeper into integrating logic from VSD suppliers into control systems holds promise for enhancing system maintainability.

In conclusion, the successful commissioning of this project underscores the importance of rigorous testing, robust design principles and collaboration between stakeholders to achieve optimal performance in industrial process environments. By leveraging the lessons learned from this endeavor, future projects can aspire to even greater levels of reliability and operational excellence.

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VII. VITA

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