# Increasing plant availability through enhanced under voltage ride through characteristics of variable frequency drive system driven compressors


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| Vijay Ganesan | Andy Rudolph | Terje Knutsen | Erling Lunde | Andreas Meyer | Jeremy Andrews |
|---|---|---|---|---|---|
| Innomotics | Innomotics | Equinor | Equinor | Innomotics | Innomotics |
| Nuremberg | Nuremberg | Oslo | Trondheim | Nuremberg | Manchester |
| Germany | Germany | Norway | Norway | Germany | UK |

***Abstract*** – Process availability depends on the ability of compressors to withstand line disturbances when driven through e-motors connected to grid.

This paper focuses primarily on compressors driven by VFD systems that are powered from the public grid.

Line disturbances can result in under voltages at the drive input in different forms (1, 2 & 3-phase), amplitudes and durations.

The ability of the process to withstand any line disturbances depends on both the compressor and drive system characteristics.

The output torque provided by the drive system is affected by characteristics of input voltage disturbances and ride through capability of the drive.

The operating point (speed, load torque) of the compressor, the inertia and the available residual torque from drive system determines the time to surge of the compressor.

This paper explains enhancement of drive system ride-through characteristics through optimized drive control system.

Following topics are covered as part of this paper,

- *Line/grid disturbances – possible line disturbances including real time waveforms.*
- *Conventional vs novel enhanced under voltage ride though characteristics of a LCI (Load Commutated Inverter) drive.*
- *Compressor characteristics and calculating time to surge – the criteria for tripping the compressor system.*
- *Value of developed enhanced ride-through control through system simulations incorporating real measured line disturbances.*
- *Implementation in a real plant and results through measurements.*

*Index Terms* — eLVRT enhanced Low Voltage Ride Through Variable Frequency Drive VFD, Load Commutated Inverter (LCI)

## I. INTRODUCTION

In December 2022 Equinor and the Snøhvit Unit and license partners, Petoro AS, TotalEnergies EP Norge AS, Vår Energi Norge AS and Wintershall DEA Norge AS decided to electrify the Hammerfest LNG Plant (HLNG). HLNG represents one of the largest single sources of CO2 emissions in Norway and the plant has a long production perspective. Electrification will reduce the CO2 emissions from the plant with app 850 000 tons per year. Electrification means to replace the existing five gas turbines installed, with a system based on power import and thus reducing the overall CO2 footprint.

The existing powerplant is mainly supplying 3 large variable speed driven compressors. The type of frequency converter controlling the compressor-motor is a Load Commutated Inverter, LCI, delivered, with largest rating of 65 MW.

A regularity report made by the Norwegian TSO (Transmission System Operator) indicated that the expected availability of the compressor-system would drop significantly when connected to the power lines after full electrification with the existing state-of-the-art strategy protecting the converter from damage during voltage dips. The red curve in Figure 1 are disturbances in the national grid that are defined as a voltage dip or an overvoltage which is indicative for what can be expected also in the future. The root cause is in most causes severe weather, mostly heavy wind, and lightning.

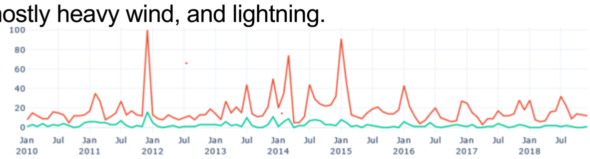



*Figure 1: incidents of faults (red) or disconnections (green) per month for power lines 220-420 kV*

Voltage disturbance statistic was based on a 10-year period for high voltage (HV) power lines. To move the electrification project further, it was mandatory to improve their ride through strategy of the variable speed drive system in use to withstand deeper voltage disturbances with reduced risk for tripping. The converter normally receives a trip-signal from the compressor-surge controller when the compressor crosses the surge trip line.

The consequence of surge on a centrifugal compressor is normally limited when an incidental **single surge cycle occurs** (caused by sudden loss of driving torque), however repetitive or continuous surging is an unwanted situation as this could result in damage to mechanical parts in the complete compressor train, excessive internal temperatures and a breakdown of the shaft sealing system. The observable consequences of surge are pressure and flow fluctuations, axial displacements, increased vibration, and increased outlet temperatures. See Figure 2 and Figure 3 below for illustration.

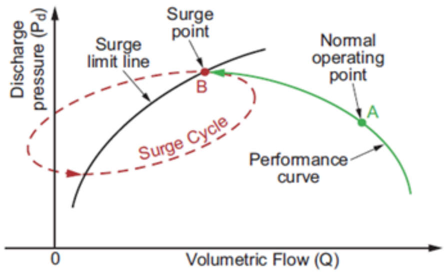



*Figure 2: Compressor operation curve*

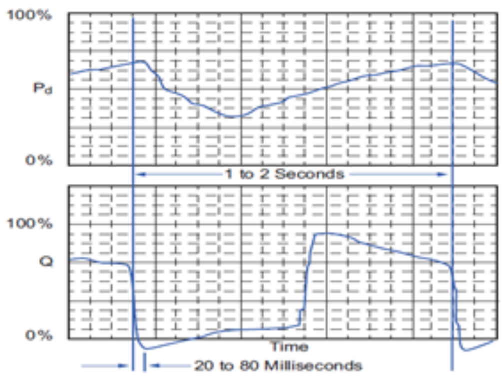



*Figure 3: Pressure and flow fluctuations when crossing the surge point shown in Figure 2 (sudden loss of driving torque)*

As a result, Equinor and Innomotics jointly developed an enhanced process ride through strategy and implemented this successfully in a plant. This paper explains the novel enhanced ride though characteristics of the complete drive system including the driven compressor.

## II. Electrical Drive System and Ride Through Definition

### A. Electrical Drive system with compressor train

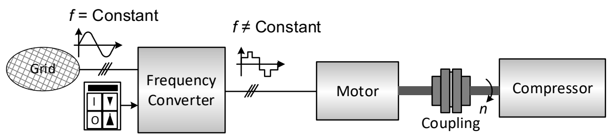



*Figure 4: Simplified electrical drive system with VFD*

Figure 4 shows a simplified representation of an electrical drive system with compressor as load machine. The operational principle of this drive system is,

- *Compressor controls process parameter – Head and Flow through its operating speed resulting in a load torque.*
- *Electrical motor drives the compressor with its electrical torque to control its speed.*
- *The motor and hence compressor speed is controlled by adjusting the voltage supply through a frequency converter.*
- *The drive (VFD) converts the constant grid voltage amplitude and frequency into variable voltage and frequency supply.*

### B. Variable frequency drive (VFD)

A VFD is the heart of an adjustable speed drive system. Power Drives System as its name suggests varies the input voltage frequency and amplitude to a motor to adjust its speed. Different Medium Voltage (MV) drives are available in market. An overview of available topologies can be found in [1].

In this paper LCI MV drive has been considered. A LCI drive (Figure 5) consists of rectifier (line side converter) and an inverter (motor side converter).

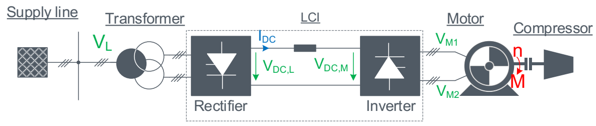



*Figure 5: Simplified LCI drive schematic*

LCI is a thyristor-based drive. The stationary operation of an LCI drive is explained below:

The LCI drive is designed to operate at a constant motor side firing angle ($\alpha_M$) to obtain optimum motor active power. With this, DC link voltage $V_{DC,M}$ is proportional to motor terminal voltage $V_M$. For an externally excited synchronous motor, its terminal voltage is proportional to its speed $n_M$.

$$V_{DC,M} \sim V_M \sim n_M$$

The torque of the synchronous motor (with constant flux) is proportional to its current $I_M$. With an LCI drive the motor current is proportional to the DC link current $I_{DC}$.

$$M_{Elec} \sim I_M \sim I_{DC}$$

The DC link current $I_{DC}$ is controlled by adjusting the line side DC link voltage $V_{DC,L}$. The line side DC link voltage is controlled through the firing angle of rectifier $\alpha_L$ and hence is proportional to $\cos(\alpha_L)$ with line voltage being constant.

$$V_{DC,L} \sim cos(\alpha_L) \cdot V_L$$

The firing angle $\alpha_L$ is also used to regulate the DC link voltage ($V_{DC,L}$) in case of fluctuations in input line voltage $V_L$. More information about the operation principal can be found in the literature like [2].

### C. Drive system operating states

Two different operating states can be defined based on the grid condition.

Stationary: at rated or specific design operating points

- *Grid: $V_{linerated}$ in kV, $f_{Linerated}$ 50 / 60 Hz ⇒ + Tolerance ($\pm \Delta V$; $\Delta f$ in %)*
- *VFD – LCI : $I_{outrated}$ A, $f_{outrated}$ Hz*
- *Motor(Syn) – up to $M_{rated}$, $N_{rated}$ in rpm*
- *Compressor – Head in kJ/kg; volume flow in $m^3/s$*

Each drive system components are designed for continuous operation within the specified range. Also, dynamic changes inside the stationary voltage tolerances are possible.

Transient:

The input line voltage can experience very short duration fluctuations which may exceed the defined tolerance. In this case the drive system tries to ride through these transient disturbances without causing any damage to any of its components.

If the voltage goes below or above the tolerance for a short period, then the drive system is into a ride through condition.

### D. Ride through

Ability of a component or a system to ride through any predefined disturbances. The disturbances are transient in nature.

Drive line under voltage ride through (conventional ride through) ⇒ **drive should not trip** in case of transient grid disturbances. Trip is defined by opening of input circuit breaker. Prior to that the inverter stops pulsing.
Depending on the grid disturbance drive can reduce its output or even provide zero torque by blocking thyristor switching pulses to withstand the disturbance. In doing so, drive can avoid any over currents which may damage the thyristors during line voltage recovery.
Process ride through ⇒ **Process should not trip** in case of transient grid disturbances.
Drive should provide maximum possible output depending on the process requirement. An overall ride through logic keeps the process running as long as possible but also trips the drive before the process runs into critical conditions.

### *E. Transient grid disturbances*

A VFD, depending on their type, measures the input grid/line voltage. events in public grid where the drive system is connected to. Type and location of fault in the grid may influence the instantaneous voltage amplitudes at drive input. Hence understanding the possible anomalies in input voltage is important to develop a robust process ride through system.

## III. Overview of Grid, Disturbances and its Effect on Drive Input Voltage

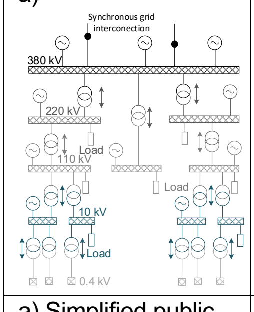
Figure 6 shows two major possibilities to provide electricity to a plant.

- *Public grid – power supplied through transmission/distribution line up to Point of Common Coupling (PCC).*
- *Island grid – electrical power generated in the plant using fossil fuels or regenerative means. Example below shows power generation through gas turbines and generators. The plant may be yet connected to a grid for fall back emergency loads.*

In depth analysis of the possible voltage supply topologies to a plant is not in the scope of this paper.
The type of power supply to a plant has a big influence on

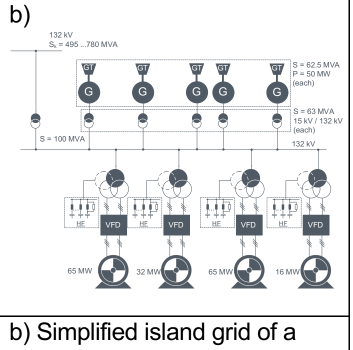
- *No. of fault incidents per year (Figure 1)*
- *Characteristic of the transient under voltage event*
- *Dynamics of voltage and frequency control and its stability*

a)




a) Simplified public grid example configuration showing different voltage levels

b)




b) Simplified island grid of a plant showing power generation through Gas Turbines and load machines

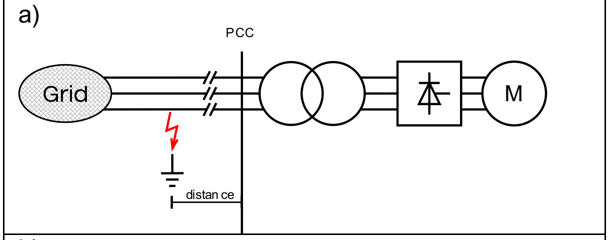
*Figure 6: Possible grid configurations*

This paper considers a compressor train driven by electric drive system with LCI based VFD connected to a public grid.

A grid fault event is very complex and can be defined through the following parameters,

- *Fault impedance $Z_{fault}$*
- *Fault type: 1-phase to ground, phase to phase, 2-phase to ground, etc.,*
- *Grid to ground impedance $Z_{ground}$*
- *Fault duration $t_{fault}$*
- *Grid Impedances depending on distance to the fault $Z_{grid1}$ and $Z_{grid2}$*

a)




b)

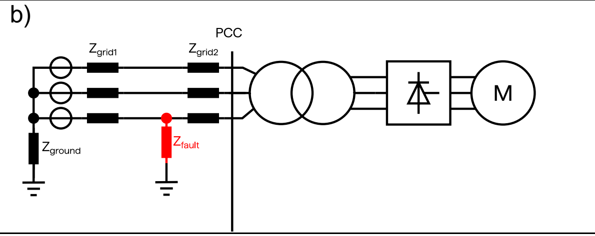



Figure 7: Simplified Grid model showing an example of one single phase to ground fault. a) simplified schematic; b) equivalent circuit diagram)

These parameters are shown in Figure 7. In reality, a grid can be assumed also as a mesh of different power sources and loads as shown in Figure 6a) and the corresponding model can become very complex.

The above parameters vary with the grid and fault scenario. This influences the drive system input voltage, represented by $V_{PCC}$. In the following sections grid faults are modeled into possible voltage waveforms. The complexity due to grid and fault types can thus be reduced to possible voltage over time at PCC $v_{pcc}(t)$. Figure 8 shows the $v_{pcc}(t)$ measured during a grid fault event.

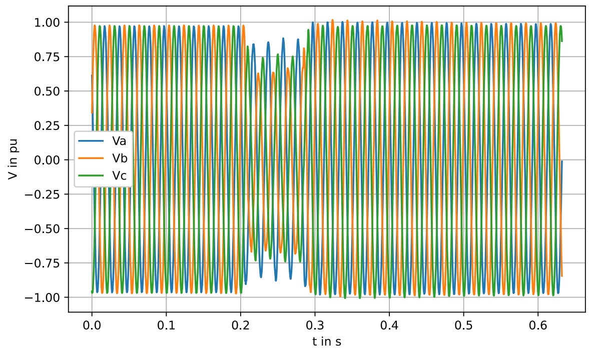



*Figure 8: Voltage measured at PCC during a grid fault event.*

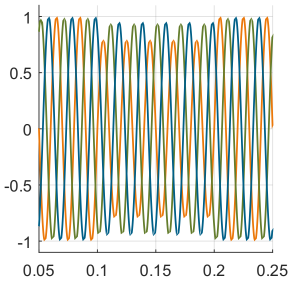
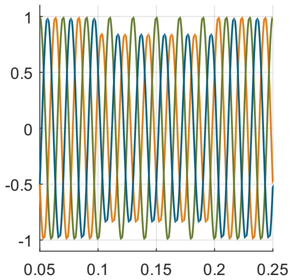
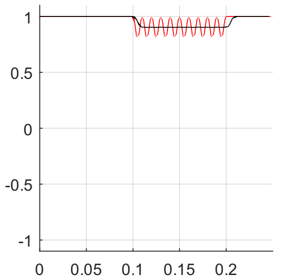
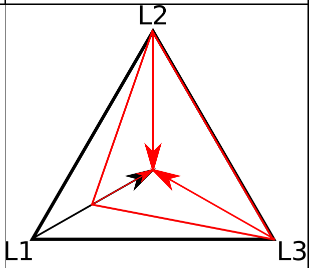
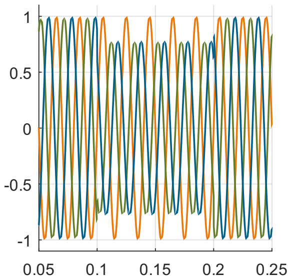
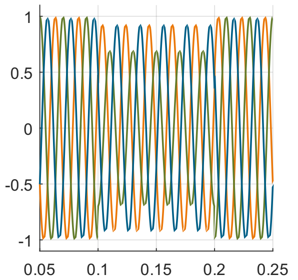
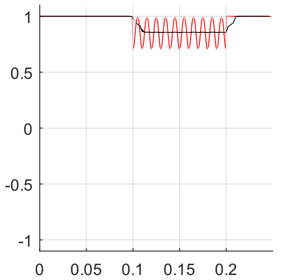
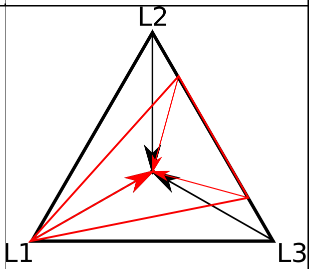
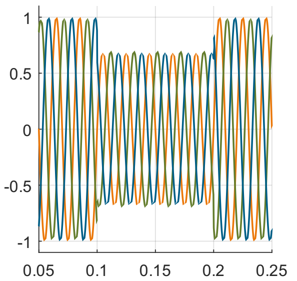
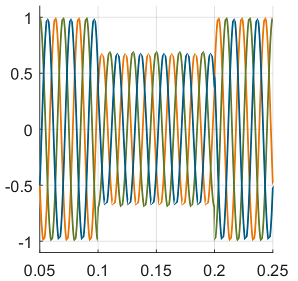
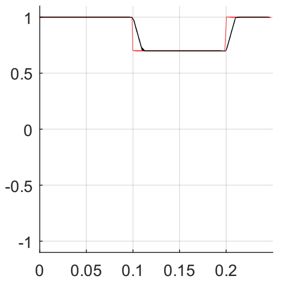
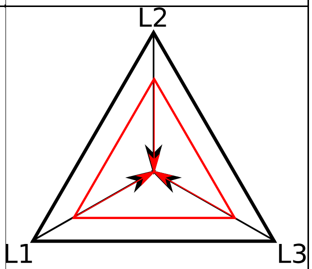
For development and validation of drive system ride through control, theoretically possible voltage waveforms at PCC have been considered. Different duration of grid faults has been considered. Typically, a medium voltage

(MV) drive is supplied by a dedicated step-down transformer without neutral point grounding at secondary side. This represents an IT grid for the drive. As a result, only positive-sequence and negative-sequence components of grid voltage are relevant for the drive behavior. The parasitic zero sequence component can be neglected.

Thus, to simulate grid faults following theoretical fault types with amplitude and duration have been defined as shown in Table 1.

- *Fault type 1 represents a simplified line-to-ground fault.*
- *Fault type 2 simplifies two-phase fault.*
- *Fault type 3 simplifies a three-phase.*

*Table 1: List of three theoretical fault cases with different voltage representations*

| | Line-to-star point voltage | Line-to-line voltage | Voltage amplitude (red); positive sequence voltage (black) | Voltage vectors |
|---|---|---|---|---|
| Fault type 1 |  |  |  |  |
| Fault type 2 |  |  |  |  |
| Fault type 3 |  |  |  |  |

With the simplification, we need only three parameters to describe a transient grid event.

- *Fault type*
- *Residual voltage amplitude in pu (per unit) of rated value*
- *Fault duration*

## IV. Development of a Novel Enhanced Ride Through Control for LCI Drive

### A. Conventional ride through behavior of a LCI drive

Figure 9 shows the conventional ride through behavior. Following areas can be identified in it.

1. *Typically, the LCI drive could operate between 110 % to 90 % of input rated voltage without derating. These limits depend on the drive dimensioning. Reducing the lower limit of 90 % will lead to higher reactive power at the rated operating point.*
2. *Between 90 % and 80 % the drive reduces its output power (torque and/or speed).*
3. *The drive blocks the switching signal to thyristors (pulse blocking) below 80 % of rated input voltage. With pulse blocking zero torque will be provided. If the voltage recovers in a certain time, then the drive reaccelerates the motor and load.*
4. *After a timeout the drive will be tripped (drive system turn-off). The time out duration can be mostly set as a parameter.*

The conventional ride through controls the dc link current only through the firing angle $\alpha_L$ of line side rectifier. The firing angle motor-side inverter $\alpha_M$ is kept constant at an optimum value and will only be adjusted to avoid any inverter commutation failures. The dynamic is limited to the dynamic of the current controller. DC-Link current can be controlled effectively only the firing angle $\alpha_L$ of line side rectifier reaches its permissible minimum value e.g. ( $\alpha_L$ =

5°).

In addition to that, in a controlled 6-pulse thyristor converter (B6C), its firing angle can only be adjusted 6 times per grid period (20 ms for 50 Hz) grid. This is due to the fact the thyristors cannot be turned OFF and need to be line / load commutated.

In case of a grid under voltage, the DC-Link voltage drops proportionally once the line side firing angle $\alpha_L$ reaches its permissible minimum value. After this limit DC-link current also dops and hence the motor torque. And when line voltage recovers and jumps back to its nominal value, the DC-link voltage cannot be regulated as firing angle $\alpha_L$ can only adjusted after next current zero crossing. This represents a dead time in controlling dc-link current which may shoot up to very high values resulting in over current trip.

This is the main reason for blocking the switching pulses once the input voltage falls below a certain precalculated value (~ 80 %).

This drive behavior of blocking pulses is preferred in weak grids like in case of island grids.

To avoid grid instabilities the control of the drive should limit is bandwidth. This is done by a slower reaction of the drive to voltage changes.

Pulse blocking shall provide zero torque to the driven machine. In this paper gas compressors are considered as load machines. With zero torque depending on the operation point of the compressor, the power drop quickly driving the compressor into surge limit. This is explained in detail in section I

This means the drive can successfully ride through a grid fault but could still trip (shutdown) the process.

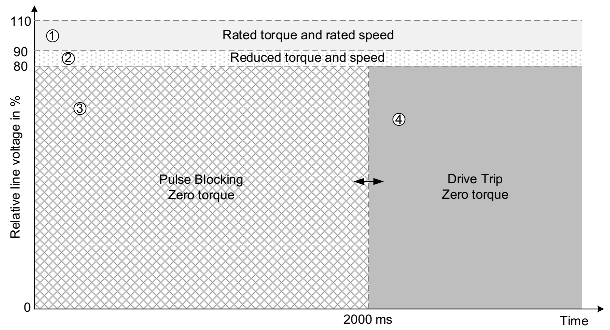



*Figure 9: Conventional ride through behavior*

*B. Enhanced Low Voltage ride through (eLVRT)*

<u>Objective of eLVRT: do not induce process trip</u>

- *Provide maximum possible torque to compressor during input grid under voltage transients (section V)*
- *Avoid any drive trips due to over current during voltage recovery.*

The control of LCI drive has been further enhanced to improve its ride through capability. This is done through two main changes.

- *Implementing a digital band stop filter at twice the grid frequency with the grid voltage measurement.*
- *Dynamic DC-link current control through motor side firing angle $\alpha_M$ : If the grid side firing angle $\alpha_L$ reaches its permissible minimum value then motor side firing angle $\alpha_M$ controls the DC-link current*

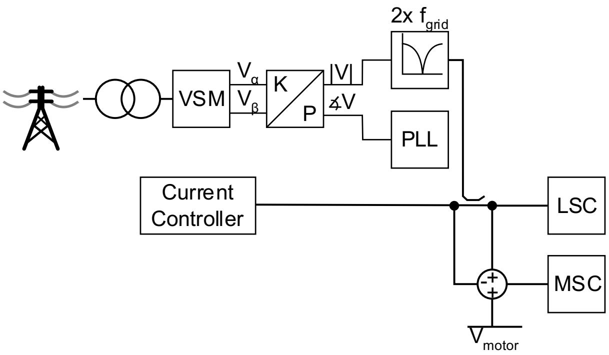



*Figure 10: Simplified control logic*

Figure 10 shows a simplified control logic. The grid voltage is measured with a voltage senses module (VSM). The VSM provides the grid voltage as αβ components these components are transformed into polar components (magnitude and phase angle). The angle is used for the PLL (Phase Locked Loop) but this is not relevant for under voltage ride through. During unsymmetrical faults twice of the grid frequency appear in the amplitude. This frequency is filtered with a notch filter.

The current controller provides a set point for the line side converter (LSC). The maximum possible voltage of the LSC is technically limited by the available grid voltage. If the set point of the current controller is less or equal to the maximum possible voltage, then the LSC can achieve the required voltage and the motor-side converter (MSC) runs with nominal firing angle that is proportional to $V_{motor}$.

A grid fault can reduce the maximum possible voltage that the LSC can achieve below the setpoint of the current controller. In this case we have a difference between the maximum voltage and the setpoint of the current controller. This remaining voltage is subtracted from the setpoint of the MSC.

The advantage of this direct feed forward to the setpoint voltages of the LSC and MSC is that the current controller does not get influenced and the reaction is very fast.

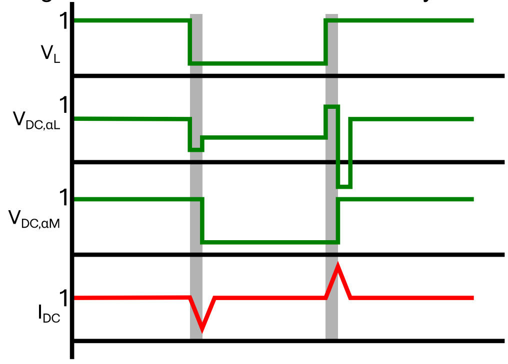



*Figure 11: Simplified behavior of the eLVRT feature*

Figure 11 show simplified the behavior of the control strategy. When the line voltage drops then immediately the voltage of the LSC ($V_{DC,\alpha N}$) drops. With the next firing signal to the LSC the line side DC voltage will be increased as much as possible if this is not possible the MSC will reduce the motor side voltage ($V_{DC,\alpha M}$) to keep the DC link current constant. For a line commutated inverter (LCI) the torque is proportional to the DC link current. But this is only valid if the motor-side firing angle is constant. If the motor-side firing angle is adjusted, then the torque is also proportional to the cos($\alpha_{MSC}$) and the torque during grid fault is reduced but there is still some torque for the process available. A rough estimation is that output torque (M) is proportional to the amplitude of grid voltage (|V|). This can be seen as line in Figure 13. The estimation is not perfect, but the real grid fault is also not ideal.

When the grid voltage recovers then also the voltage of the LSC recovers immediately, but the LSC and MSC firing angle can only be adjusted with a certain delay. During this time, the DC link current will rise and can trip the drive if the overcurrent limit is exceeded.

It is not possible to avoid the rise of the current because you do not know when the voltage recovers. That's why the drive is set into a special operation mode to handle this event. If the drive detects a voltage step of a certain level (e.g.: 10 %) then the drive disables the overcurrent protection. But to protect the drive itself it is not allowed to run without overcurrent protection. That's why at the same time the setpoint of LSC voltage is set to negative value. This forces the DC link current to zero. Additionally, the current controller is frozen.

If the DC link current reaches zero than the overcurrent protection is activated again and the LSC setpoint is set from the current controller and the current controller is unfrozen. This leads to a fast-raising DC link current.

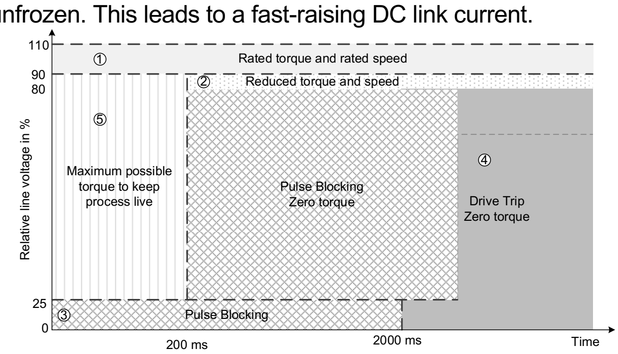



*Figure 12: Operating rang during grid faults.*

With this feature the operating range of the converter is increased (Figure 12).

## V. Validation through system simulations

The development of this feature is done in multiple steps. The first loop is done by the software development team and the second loop is done in a software in the loop (SIL) simulation. The firmware of the drive is compiled into a DLL and load in a system simulator (Ansys Twinbuilder) that contains the converter model, motor with a simplified load model and a grid model. More about SIL can be found here [3].

The grid model contains all three grid fault types (Table 1) within 9 voltage steps. The load model represents four different operating points. In total the software is tested against 3 x 9 x 4 = 108 test cases. Also, this feature is tested against 25 real measured grid events like Figure 8. This leads with four operating points to additional 100 test cases. After multiple iterations the result in Figure 13 is reached.

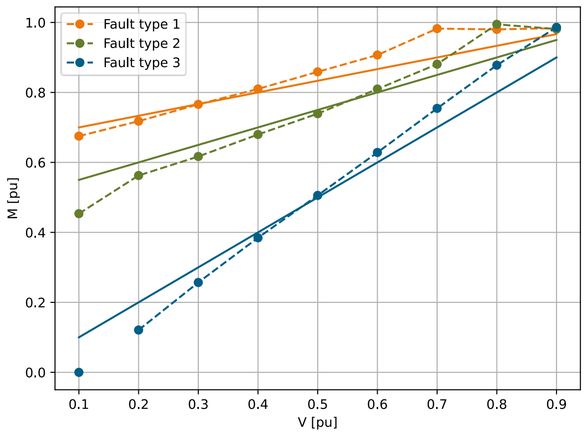



*Figure 13: Available torque for different voltage dips*

This figure shows the available torque after this improvement. With this feature, the drive can provide torque also below 80 % grid voltage. For the connected process only, the available torque is relevant. The graph is useless for the process simulation, but with this graph, the process simulation and a statistic of grid faults the availability of the process or production loss can be estimated.

The drive ride through has been significantly improved. But if the delivered torque is less than the current process status is needed, then this state can only be handled for a certain time until the process reaches a critical state. This critical state can damage equipment and should be avoided. A certain time before the process runs into a critical state it must be shut down.

The results from this development project had to demonstrate a plan with high likelihood of success to secure the electrification project and to convince our partners for LNG plant to move forward. Several partner meetings were held and this ride through challenge was one of the main topics discussed. Without a high likelihood of success, the electrification project could not move forward.

In 2019/20 a regularity study with the Norwegian TSO for the new 420 kV power line was enabled, which should due to grid models and statistics estimate the power reliability at site for various load scenarios in the region; estimated disconnections per year including duration of power outage and remaining residual voltage at different types of fault (number of impacted phases) as a function of distance from site and with expected frequency of such incidents per year. This regularity study was very helpful to quantify the expected compressor trips and power disconnection that could be expected per year in conjunction with possible remaining torque that could be provided as a function of remaining voltage at various load scenarios for impacted electrical phases at site.

Further in 2020/21 Equinor outsourced a dynamic study with company Kongsberg Digital to estimate and verify success of defined torque losses (caused by voltage dips) with various durations of torque losses. One of the challenges is the compressor train, which consists of 3 variable speed drives feeding each compressor. There are 2 compressor-stages, each with a capacity of 65 MW, along with surge controllers. Additionally, there is a single stage compressor with a capacity of 32 MW and an anti-surge controller. These 5 compressor stages were impacting each other and if one surge controller is in surge the entire compressor train must be tripped (no LNG production possible). The purpose of this study was to register Time to Surge (T2S), register Time in Surge (TiS), checking potential instabilities between compressors stages, quantify process disturbances, hence avoiding process trips.

## VI. PILOT STUDY

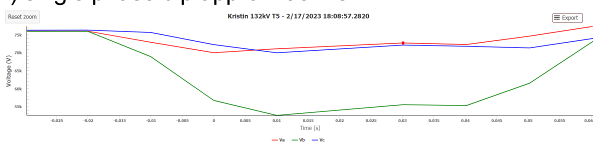
A great challenge for the electrification in addition to simulations was to find a pilot for implementing the Improved ride through software. A 40 MW sales gas compressor driven by the same variable speed drive system at a different location in Norway was facing the same challenge; several trips due to voltage dips happened every year. Innomotics had tried different methods to improve the ride through with the existing Software without success. It was later decided that this sales gas compressor was the perfect candidate for piloting and was initiated in 2019.

When the piloting for improved ride through was approved some additional study simulations for the sales gas compressor system was required:

A dynamic simulation study with Aspen Hysys Dynamics$^{TM}$ with focus on voltage dips was completed in March 2021

Further a simulation study with Vysus Group was completed December 2020 with evaluation of coupling torque loading from voltage dip events. Two examples are shown in Figure 14.

1) single phase dip approx. 90 ms




2) 2-phase dip approx. 90 ms

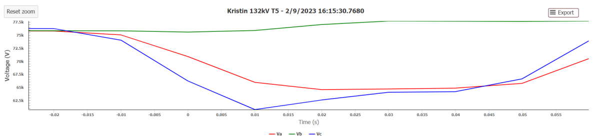



*Figure 14: Some power dip examples*

Novel control features

Two important requirements led to two separate solutions:

The compressor system, drive, motor, compressor, should be robust to transient disturbances from the grid. This is solved with the new eLVRT control functionality (ref. section B) which will continue to deliver the available power during various disturbance scenarios – until not possible any longer.

The compressor should at all times be protected from harmful oscillations, i.e., compressor surge that can cause mechanical damage to internals (bearings, seals, etc.). In some situations, this can only be avoided by a compressor shutdown (a trip). The conditions for this are determined by a separate Surge Protection Logic.

## VII. SURGE PROTECTION LOGIC

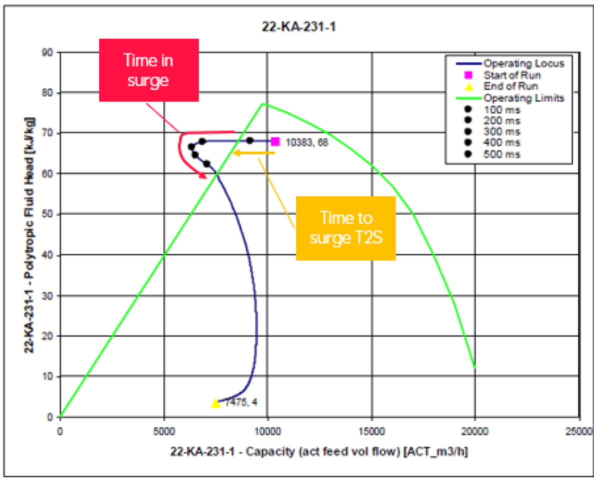



*Figure 15: Compressor transient responses. Trip, Time-to-surge and Time-in-surge.*

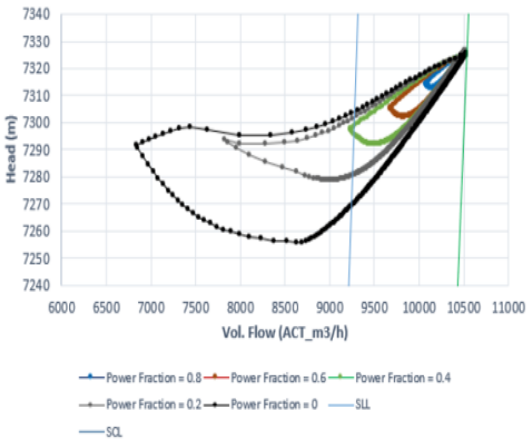



*Figure 16: Compressor transient responses. 200 ms voltage dip, for variable residual power (0, 0.2, 0.4, 0.6, 0.8). Aspen Hysys Dynamics simulation study.*

From the compressor side, a main risk is running into surge. Surge can originate from loss of power, or sudden reduction of gas through-flow. Both will cause the operating point to move to the left, and potentially cross the Surge Limit Line (SLL). Figure 15 illustrates the concepts of:

Time-to-Surge (T2S): We need to estimate this when an event occurs, such as a trip. T2S tells us how long it will take to reach the surge region, and during this time system should initiate appropriate action to avoid the surge situation.

Time-in-Surge (TiS): Depending on the robustness of the machine, it can tolerate a short time-in-surge – or none at all. This is very hard to measure, estimate, or simulate.

Figure 16 shows a case where 80 % or 60 % residual power will avoid running into surge, 40 % power will touch the surge limit line, while below 40 % the compressor will spend some time-in-surge. This depends a lot on the initial operating point, if we move this to the right it will less likely run into surge.

A simulation study was carried out to map out the conditions where the compressor is at risk of running into surge. Especially, the aim was to identify the operational limits from which the compressor would avoid surge if tripped. This is identified at the Safe Trip Line (STL) and is illustrated in Figure 17.

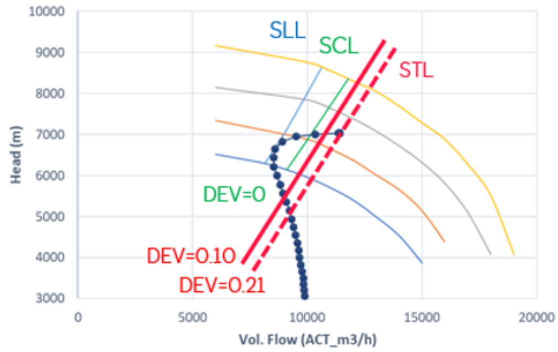



*Figure 17: Compressor map and Safe Trip Line. STL = 0.21 was found from the simulation study, while a less conservative limit at STL=0.10 was found during commissioning.*

## VIII. TECHNOLOGY QUALIFICATION

To validate this feature in a full test setup is very expensive. The eLVRT feature and time to surge calculations is "only" a control component, that's why it has been tested in a separate hardware in the loop (HIL) setup. This setup contains all hardware control components without the power electronic parts and mechanical components.

The solutions were qualified for first use (Technical Readiness Level 4 – TRL4) based on modelling and simulation studies and hardware-in-the-loop testing at Innomotics test facility. First use testing will be performed at one of Equinor's onshore gas export facilities and after a sufficient amount of experience gathering it aim to be proven technology (TRL7) later this year.

The successful activation of eLVRT is shown in Figure 18 and Figure 19. The voltage dip was a 1-phase, 90 ms, 39% residual voltage.

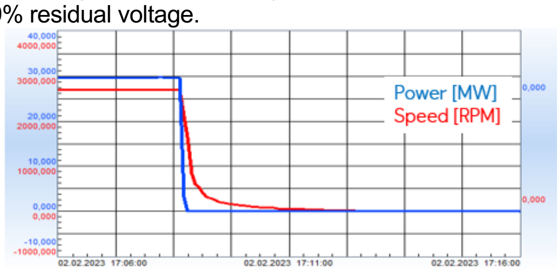



*Figure 18:Voltage dip scenarios typical trip prior to commissioning*

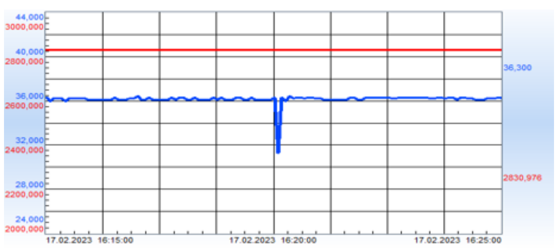


*Figure 19: Voltage dip scenario ride-through with with eLVRT.*

The Surge Protection Logic calculates an estimate of the time to reach the STL (T2STL), with the actual motor power provided by the drive (eLVRT). If the actual remaining time to surge trip reaches zero, the drive will trip. In Figure 20, the initial operating point was at a safe distance and T2STL started at 760 ms and the dip recovered after less than 100 ms. Another case, Figure 21, shows what happens when the operating point starts with a small margin, T2STL = 30 ms, and the drive is forced to trip when the remaining T2STL reaches 0.

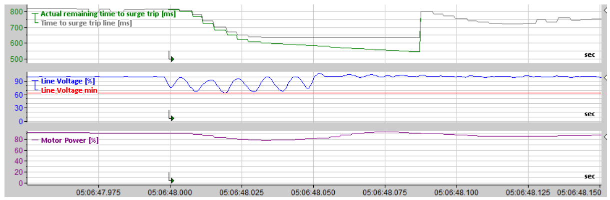


*Figure 20: {2-phase, 60 ms, 64 %} voltage dip, starting at safe distance to the STL and ride-through is achieved.*

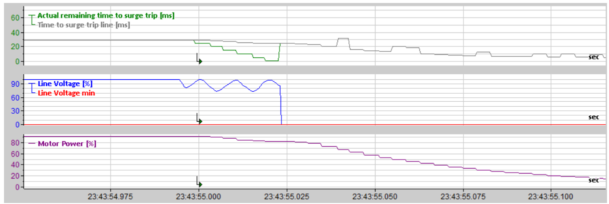


*Figure 21: {2-phase, 60 ms, 74 %} voltage dip, starting with 30 ms time to STL, hence, the drive trips.*

## IX. CONCLUSIONS

This paper describes the challenges to with public grid connection of a critical process on an example of an LCI drive. It shows steps from conventional drive ride through to achieve process ride through. This requires an improved drive ride through so that the drive is able to provide torque during gird fault events. The second step is to simulate that feature and use these results as input for process simulations to develop a trip logic. Both functions are tested on a HIL setup and after passed this test it is installed on a real process.

The result in the real world looks very promising. The drive survived serval grid events and the whole process rides through this grid fault.

To develop a process ride through functionality it is important to have a close cooperation between the component manufacture and the end user.

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## II. VITA

**Vijay Anantham Ganesan** is technical consultant in the field of medium-voltage drive systems for the Oil and Gas

industry at Innomotics, Process Industries and Drives in Nuremberg, Germany. He received his M.Sc. degree in electrical power engineering from RWTH Aachen University, Germany in 2005.
vijay.ganesan@innomotics.com

**Andy Rudolph** is an engineer at Innomotics in Nürnberg. He improved the SIL simulation of medium-voltage drive systems. He received his Diploma degree (Electrical Engineering) from TU Chemnitz in 2011.
andy.rudolph@innomotics.com

**Terje Knutsen** received his M.Sc. degree in Electrical engineering from the Norwegian Institute of Technology and Science (former NTH) in Trondheim, Norway, in 1985. He has held various positions within Siemens in Norway and Germany before he joined Equinor (Statoil) January 2013 where he is currently working as a Specialist Electrical Engineer within the Technology Digitalization and Innovation unit with various topics for Variable Speed Drives.
tekn@equinor.com

**Erling Lunde** is a lead researcher in Equinor's business area Technology, Digital and Innovation. He received a Dr.Ing. degree in cybernetics and robotics from the Norwegian Institute of Technology and Science (former NTH) in Trondheim, Norway, in 1991. He worked as a consultant in automation technology for various industries until joining Statoil (now Equinor) in 2011.
elunde@equinor.com

**Andreas Meyer** received his M.Eng degree in electrical engineering from TH Nürnberg in 2019. He is an engineer at Innomotics in Nürnberg working on Hardware in the Loop (HiL) systems and on system simulation of medium-voltage converters.
meyer.andreas@innomotics.com

**Jeremy Andrews** graduated from Sussex University, UK with an honors degree in Engineering. He has worked with medium voltage drive systems in the oil & gas industry for 30 years and is currently employed at Innomotics (a Siemens Business) as global business development and strategic account management head. He has been a member of PCIC Energy Europe for over 10 years and is currently sitting in the committee as Secretary, Executive Committee Vice-Chair. Jeremy.andrews@innomotics.com