POWER LOSS RIDE-THROUGH IN A VARIABLE SPEED DRIVE SYSTEM

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Abstract - Voltage dips or power interruptions in the grid cause huge problems for the users. The ride-through behavior of frequency converters can be a very good solution to bridge the gap. But how does the whole drive system react in case of power loss? The kinetic energy recovery is only successful when all the important elements in the chain fit together. This paper reconsiders the topic on a power drive system level and gives practical information to the users, based on the experience of a drive manufacturer.

Index Terms — Grid disturbance, voltage sag, variable speed drive control, power-loss ride-through, industrial power systems, sub-synchronous torsional interaction.

I. INTRODUCTION

Plant operators depend on reliability of their process controls and of the respective drivers. A failure in the system can be very expensive. The general practice is to introduce redundancy for critical parts of the system and choose safety factors during the design phase. This additional effort makes the whole system robust to component failures. But yet a short voltage dip in the power supply can bring it down within a second. The variable speed drives as one of the largest controlled electrical devices in a plant are of special concern, when it comes to power loss and how to behave under such a condition.

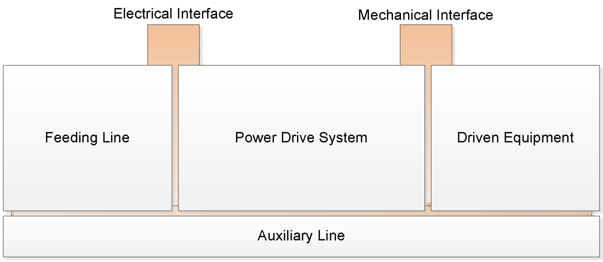

Fig. 1 Variable speed drive system and its interfaces

The whole installation can be split into three parts: feeding line, power drive system (PDS) and driven equipment, which are all supported by electrically powered auxiliaries (Fig. 1). Important for the system integrator are the two interfaces, the electrical and the mechanical. The performance at these points is crucial for the whole design, under regular, but also under exceptional boundary conditions. Interesting enough, hardly any performance requirements are stipulated during ride-through at the interfaces themselves. On the one hand, because the borderline between what can realistically be claimed and what is technically unfeasible is hard to tell during planning phase, on the other hand because it is application dependent, possibly drive-type dependent and interdisciplinary. Writing performance requirements around the electric interface touches the areas of power systems engineering, automation and control, as well as power electronics; defining requirements around the mechanical interface involves motor control, torsional dynamics and process control issues.

Nevertheless, project requirements in process industries normally talk about a minimum power loss period that has to be "survived" after the network has dropped under a certain level in RMS voltage. A typical requirement would be to stay operational for 4s at less than 85% of nominal voltage. Coming from the semiconductor manufacturing industry, it's also common to define the required time as function of undervoltage level [11]). As will be shown in the paragraph II of this paper, these requirements leae the supplier of large PDS in a grey-zone with respect to what "operational" means, since there is no commercially viable energy storage technology to bridge even outages of few cycles. The implicit minimum expectation in industry is:

- no trip signal raised
- drive reapplies referenced torque without delay

This definition has the advantage of being simple and generally valid, at least at first glance. Conditions can be defined quantitatively or even contractually between the variable speed drive (VSD) manufacturer and the process designer of the end-user. It is generally interpreted as such, that the VSD is providing full torque and following speed reference above the defined grid RMS voltage level and that it is producing no torque while riding-through the power dip. The minimum expectation versus a large PDS is based on experience with the behavior of large electric motors, connected directly on the supply line (DOL motors). As however will be shown in paragraph III, the DOL motor's behavior during a power outage is quite complex, e.g. for small asymmetric undervoltage, it is still providing torque, but with untypical torque harmonics.

In reality, the criteria under which network disturbance level the VSD would physically need to stop following torque and – if applicable – speed reference is much more complex. Depending on VSD technology (thyristor based LCI, voltage source inverter type) there are different electrical limits reached at different stages, inside the power electronic circuit as well as with respect to the interaction of the VSD with the power grid. As a consequence, transition into ride-through (with torque off and frozen speed controller) could very often be deferred as compared to the simple definition. This will be discussed in paragraph IV.

In process industries, the expected behavior of the VSD during the grid disturbance is hardly ever described. "Riding through" usually implies zero-torque at the motor shaft during that time interval. Advanced control strategies with modern power electronics may offer some torque or

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even full torque under grid-disturbance, however typically traded against another “evil” like untypical grid or torque harmonics. Relaxing some criteria and limits during transients opens new possibilities. In the following, we will use these definitions:

- *Zero torque ride-through:* no or negligible torque applied to load, VSD remains connected to line, with no or negligible current flow (“classic” ride-through).
- *Full torque ride-through:* full torque applied to load, but VSD is deliberately operated outside spec for defined criteria or limits.
- *Reduced torque ride-through:* reduced torque applied to load, VSD may deliberately be operated outside spec for defined criteria or limits.

The engineers designing variable speed wind-power generation (essentially VSDs with opposite power flow) have walked that road to some extent, under the grid-owner’s expectation to keep generators generating when the grid needs support most. However in this case, the VSDs must not make things worse in the grid, and as a consequence a variety of national grid codes has appeared over the last decade, defining how operation under a degraded grid has to be, depending on the actual or on the statistically most likely root-cause, and on the nature of the disturbance at the point of common coupling PCC [5]. We will discuss operation and the potential consequences under degraded conditions at the electrical interface (i.e. at the VSD’s PCC) with examples. The paragraph IV and the summary in Fig. 9, may be seen as a catalogue of things to be checked for full-torque ride-through.

If during a grid disturbance, partial power is of any use for the process, compared to zero in classic ride-through, then this could be implemented for certain classes of network disturbances in form of a reduced-torque ride-through strategy. This possible reduced-torque ride-through, very similar to the behavior of a DOL motor, is discussed in paragraph V-B.

A further point, which is neglected by the common definition of the ride-through criteria is the transition from ride-through back to normal operation, especially for zero-torque ride-through. Many drive trains are elastic and fast torque steps are not allowed from torsional perspective, hence anything but a slow transition requires at least the knowledge about the mechanical properties of the driven equipment. Since this information is not always available, a softly ramped transition is implemented by default and precious time is lost before full power is again released to the process. Unfortunately, coordination between the VSD and the overriding controller is very often not studied for such a slow transient, leading to oscillations and possibly tripping of the process during that ramp-up phase. Paragraph V-C describes possible ways how to improve performance and reduce time lost during the transition phase.

Ultimately, the PDS, the process control system with sensors and actuators and the auxiliary systems (cooling, synchronous motor field exciter, etc.) are all supplied by electricity, usually from the same grid. Whatever options for full-torque or partial-torque ride-through shall be exploited, the auxiliary systems need to support that as well, as will be outlined in paragraph VI.

II. ENERGY IN THE DRIVE SYSTEM

During a network disturbance the energy flow to the process is interrupted or at least limited. There is energy stored in the installation and it will be consumed by the process’ load if the energy from the grid doesn’t come back. One can spot the energy storage at two places; the VSD and the rotating masses of the process.

It might be helpful to calculate the energy-to-power ratio (E/P). Where E is the total energy and P the process power. E/P is a time, namely the time during which P can be consumed until the energy is zero. In reality P changes with speed so this is not an accurate calculation but an indication.

A VSD stores its energy in the dc-link. This energy can be considered as very small compared to the power required by the process. Its only purpose is to decouple the input and output side of the VSD. A practical example: For a driven power of 5 MW a motor of 6 MVA is used. In this case the stored energy in the VSD is around 30 kWs. The resulting energy-to-power ratio is 6ms.This gives a rough feeling of the order of magnitude of the stored energy in the dc-link.

The rotating masses of the process have a certain kinetic energy. If no power is provided from the grid the rotational speed will slow down. How much depends on the total inertia of the whole drive system and the load characteristic of the process. The kinetic energy stored in the system is equal to

$$E_{kin} = \frac{1}{2} * J_{tot} * \omega^2 \qquad (1)$$

where

J_{tot} Total inertia of the rotating masses

ω Angular velocity of the shaft

During a total power loss the required process energy will be taken from E_{kin}. E.g.: When during a voltage dip 10% of the energy has been consumed from the rotating masses, the new speed is $\sqrt{0.9}\,pu \approx 95\%$.

Calculating the energy-to-power ratio for a real motor (14MW, 1494rpm, 915kgm^2) gives, applying (1) and E/P, 800ms. If the process of the end user has a lot of inertia this can be a figure with the magnitude of seconds. Compared with the dc-link, which has energy stored in the magnitude of milliseconds, one can see a factor of thousand between. From the process side the rotating masses have a big influence on the ride-through behavior of the whole PDS.

III. BEHAVIOR OF DOL MOTORS

Before analyzing the behavior of VSDs, the study of the direct online (DOL) driven motors gives us some basic ideas of the problematic. The active element in this setup is only the motor starter breaker. Usually a motor protection relay is used which opens the breaker under faulty grid conditions. Also a ride-through is possible where the breaker stays closed during a voltage dip. Dips down to zero are frequently called blackout, whereas partial dips (e.g. to 60% on one phase only) are called brownout.

A common practice is the automated re-acceleration of the critical motors in a plant as described in [1] and [2]. The drawback is the high reactive power consumption which prolongs the dip additionally and avoids the fast recovery of the voltage (see [3]). Synchronous generators can support the network with introduction of reactive power. Intelligent excitation systems will take care of that.

A. *Brownout Ride-Through*

An electrical motor which is connected directly to grid always follows its frequency. The flux in the motor is rotating with network frequency (or a fraction of it when having several poles). This speed is followed even during a brownout. In order to keep the speed of the process, the same shaft power is needed. This implies that the current has to increase to a level that the power is the same as before, as shown in table I.

TABLE I
DOL MOTOR VALUES DURING BROWNOUT

	Initial State	Brownout
Voltage	100 %	80 %
Current	100 %	125 % (1/0.8)
Speed	100 %	100 %
Motor flux	100 %	80 %
Torque	100 %	100 %

The increased current leads to a temperature rise in the components. How long and if the drive system can survive a certain brownout depends mainly on the motor design. The protection relay has to trip the breaker if the motor is operated outside the specified range, at least as long as lifecycle cost (due to accelerated ageing) is more important than continuing the process.

B. *Blackout Ride-Through*

The influence on the torque and current of a short power loss (100ms on a 2 MW induction motor) was simulated. Figure 2 and 3 show the results at the interfaces. Even if the speed just drops a few percent the mechanical and electrical stress can be tremendous. Depending on the system this is not acceptable and the breaker has to trip before the voltage comes back.

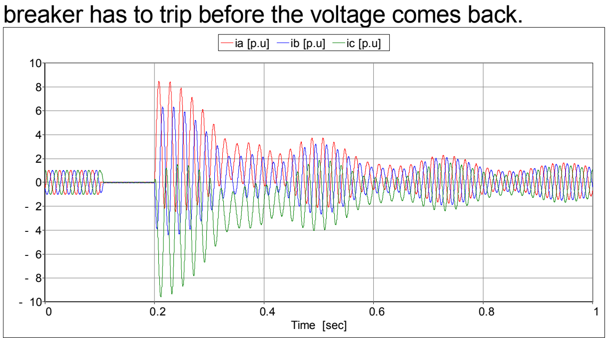

Fig. 2 Motor phase currents for a 100ms total power loss

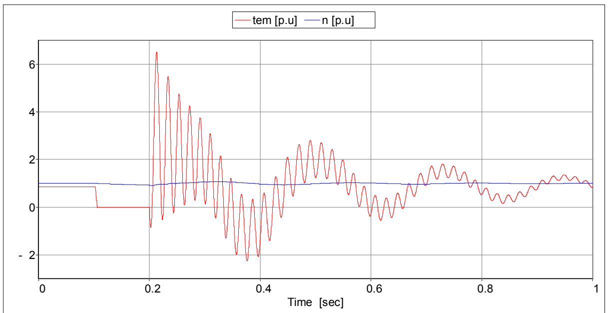

Fig. 3 Torque and speed for a 100ms total power loss

C. *Phase Loss Ride-Through*

Exactly the same simulation has been used but only one phase was lost for 100ms (Fig. 4). During this asymmetric distortion the torque oscillates at double network frequency but its average is non-zero (Fig. 5). This means that there is still energy flowing to the process and the speed decreases less than before. After clearing the distortion the torque oscillation changes back to network frequency.

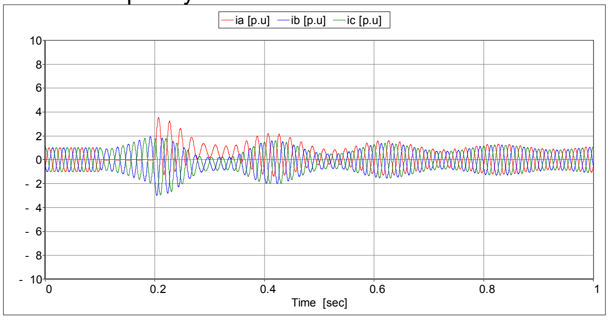

Fig. 4 Motor phase currents for a 100ms phase loss

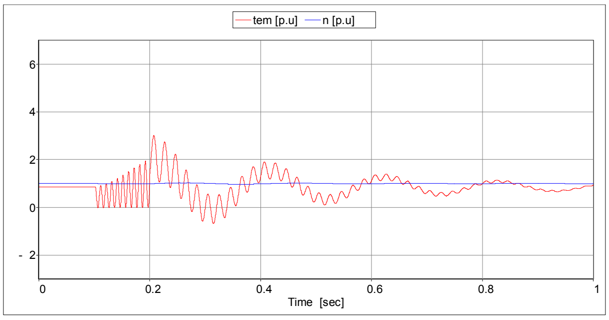

Fig. 5 Torque and speed for a 100ms phase loss

IV. ELECTRICAL INTERFACE OF A PDS

A. *When to give up on normal operation*

The control system of the PDS needs quantitative (measurable and programmable) criteria when to give up on normal operation and to go in a special ride-through procedure. Let's recall two things: hard electrical limitations (overcurrent, overvoltage) have to be respected at any time. Performance limitations (e.g. to prevent increased torque pulsations) have normally to be respected, but might be temporarily relaxed for short transients.

The common way of defining when to give up on normal operation and to initiate a classic zero-torque ride-through with a VSD is specifying an RMS voltage level, under which operation can be interrupted with a signal to the overriding control system, however without tripping the VSD. This definition makes intuitively sense, when thinking of full load operation under a symmetrical undervoltage of the grid: in order to keep full power flow, load current will have to rise inverse proportional to the voltage dip and at some point, it will reach the design limit of the electronic circuit of the VSD (see Fig. 6). Every VSD is designed for full operation with certain undervoltage, compensated by elevated input current. This designed undervoltage operation has to be differentiated against full-torque (Fig. 6, curve 4) or reduced-torque ride-through (Fig.6, curve 3), where some "soft" performance factors are neglected, compared to unrestricted performance in designed undervoltage operation. The trade-off in performances is illustrated in Fig. 6 with torque, resp. current ripple, but there could be other trade-offs.

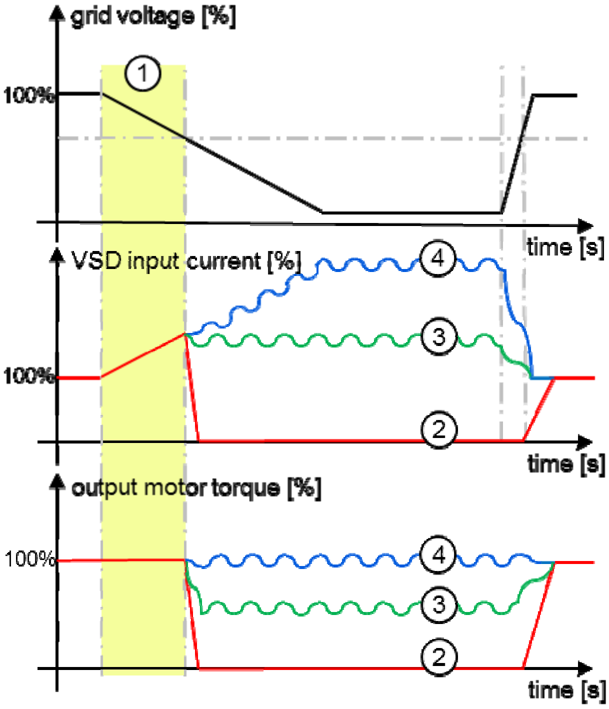

Fig. 6 Drive reaction on voltage dip with the different strategies: 1) designed undervoltage operation with no impact on performance, 2) classic zero-torque ride-through, 3) partial-torque ride-through with performance compromise, 4) full-torque ride-through with performance compromise

Upon a closer look, this definition seems less intuitive for several reasons:

1.) When a light power dip occurs under partial or low load conditions, it is equally intuitive to wonder, if deeper dips could not be survived, as the distance to the design limits for the current must be larger. This is in fact the case to some extent, however other limits have to be watched, often not directly measurable as the maximum design current.

2.) The voltage at the point of connect is not independent of the load of the VSD itself. This becomes most obvious at the moment when the VSD is going into zero-torque ride-through and voltage is increasing back to acceptable values immediately, since the load is off now. In cases where the VSD comprises filter banks and capacitors for reactive power compensation, the voltage may even rise above nominal level due to local overcompensation, even though the fault that originally led to the undervoltage is not cleared yet. For symmetric undervoltage dips, the maximum converter input current would actually be a much better criterion to determine, if a zero-torque ride-through should to be initiated.

3.) In practice, most power dips will be asymmetric, as their typical root causes are phase to neutral shorts (tree falling on overhead line, insulation breakdown resulting in earth fault), phase to phase shorts (overhead lines touching under strong side winds) or inrush events (transformer magnetization, DOL motor start, etc.). Again intuitively, one would expect the same design restriction on maximum current as for symmetric dips to limit operation. However when looking into the grid behavior under such a fault, depending on fault location and transformer configurations between fault and VSD, other design limits may be reached earlier than the maximum design current. Which limits will be reached, depends on the chosen control strategies. Fig. 9 in the following section lists the most important limits.

4.) Another possible motivation to go into a classic zero-torque ride-through is not the dip itself but the recovery of the voltage. If the voltage comes back fast, both the voltage source inverter, as well as the current source inverter topology may have problems. The DC capacitor bank of a voltage source inverter forms a resonance together with grid- and transformer impedance, which is excited by the returning voltage; the reactor current of a line commutated current source inverter may overshoot if the voltage recovery happens just after one thyristor has fired. Then it takes relatively long before the next commutation can take place, and reduce the current again. The overshooting of the dc-link can partly be handled by overdesigning VSDs. Alternatively special control strategies are necessary to prepare the converter for the voltage recovery, one of them is to reduce power to gain current-margin on a thyristor controlled LCI, i.e. partial-torque ride-through.

5.) Another limitation is linked with the electric motor: when the input voltage is lower than the terminal voltage of the motor. For all drive topologies with controlled or un-controlled rectifiers at the input (i.e. not active front-ends AFE), it becomes challenging to rotate flux in the motor, as they create the motor stator voltage directly out of the line voltage. Thus the flux in the motor has to be reduced, which for synchronous motors happens only slowly over the rotor's field exciter or by loading the motor with inductive reactive power with the converter. Depending on inverter topology, the VSD can reduce the stator flux directly and very fast before the rotor flux is able to react, thus enabling full torque during short dips.

Taking the simple relationship (2) between flux and voltage (stator resistance can be neglected at nominal speed) one can see why the flux has to be reduced during a voltage dip.

$$\overrightarrow{\Psi_s} \approx \int \overrightarrow{u_s} * dt \qquad (2)$$

where

$\overrightarrow{\Psi_s}$	Stator flux vector
$\overrightarrow{u_s}$	Stator voltage vector

The graphical interpretation of (2) is given in Fig. 7 and shows that for a circular movement of the flux, the voltage is equal to the tangential velocity.

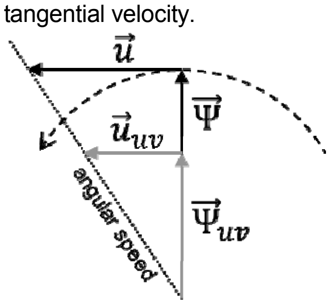

Fig. 7 The tangential velocity of the flux is given by the available voltage. For undervoltage u_{uv}, also flux needs to be reduced to continue rotating the rotor (and flux) at a given motor speed.

The angular velocity is given by the motor speed, and if motor speed shall be kept constant during a voltage dip; but if the necessary tangential speed can't be reached with the available voltage, then the flux needs to be reduced. Reducing flux on the other hand will again reduce torque and speed might drop anyway, if the torque producing part of the current is not increased at the same time. And increasing current limited by the current that already flows to reduce the flux.

Understanding these limits and linking them to the grid topology and to potential grid disturbances is of major importance when trying to continue operating under low load condition. It may even be necessary to quantify the expected limits for each load point a priori, so that output power could be reduced actively in those cases where partial operation is beneficial for a process to mitigate the impact of a power dip, i.e. when thanks to advanced process control, advantage can be taken from reduced power, rather than having to accept a period of zero power (see section V-B).

B. *Full Torque Ride-Through*

1) *Drawing Parallels with Power Systems Experience:* As mentioned in the introduction, variable speed wind power generators are required by most national grid codes to continue operation also under severe grid disturbances, very much like every fixed speed synchronous generator (e.g. hydro generator) would do. Thanks to the IEC norm 61400-21, which describes how to measure performance under grid disturbance, the various grid codes have a quite common way of defining, which grid disturbances have to be tolerated. These represent at the same time also the most frequent disturbances. According our experience, they also correspond to the most likely disturbances at industrial plants. The focus is on both symmetrical and asymmetrical voltage drops. The disturbances are described in terms of depth and duration. The same profiles in depth over time are assumed to happen both on all the three phases as well as on a single or two phases. The phase angle, at which the event is starting, is usually not discussed. Under asymmetric conditions, the phases of the 3-phase supply-grid will change phase relationship and not be shifted by 120deg against each other anymore. This is usually also not discussed, but is self-understood to some extent, as it depends on the specific installation with its transformer configurations.

Fig. 8 shows an overview over what representative grid codes require to be handled. The x-axis shows the duration of the dip and the y-axis indicates the corresponding worst-case depth. In other words, long dips down to zero voltage are so unlikely, that they are excluded. The longer the dip, the less deep it is expected to be.

The grid-codes do even go further and describe what the generators, especially the VSD based systems, have to do during the dip. The focus is clearly on supporting the grid. In view of the other process loads and the VSD auxiliaries connected on the same grid, this philosophy also would make sense for industrial drives, only that VSDs of voltage source inverter type usually have passive front-ends (diode rectifiers), which much restricts possibilities. The classic no-torque ride-through known in process industry is also foreseen in power generation, however needs agreement with the system operator and usually is limited to times <1.5s.

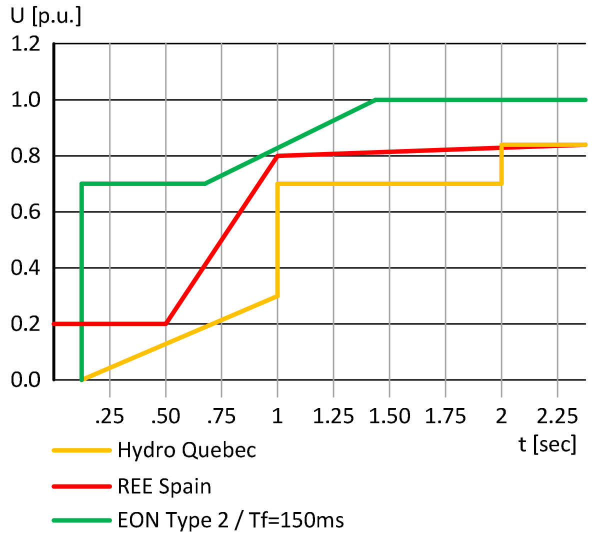

Fig. 8 Typical dip depth and duration requirements for wind power generators, above the curve, the generators have to support the grid with capacitive reactive power!

Restoration of pre-dip power is usually also required within a given time. The UK grid code e.g. specifies restoration of active power to 90% of pre-conditions within 500ms for short dips (<140ms), or within 1s for longer dips after the grid returned to 90%.

It has to be noted, that these requirements come from a grid operator perspective. They are characterized by two guiding ideas: first, the classes of grid disturbances of concern shall be well described and cover the most likely events; second, the stability of the grid has high priority and must be supported. Both ideas should also be followed in process industries, latest when power electronic (VSD) loads start to become predominant, compared to other loads. Only describing the classes of disturbances gives electric equipment designers a realistic chance to evaluate bottlenecks and to develop strategies for full-load or partial-load ride-through. And with all the other electric equipment important for the process (auxiliaries, controls), keeping the grid within tolerances must be prioritized in order to prevent secondary faults, which may also bring down the process.

2) *Challenges and Opportunities for Full Torque Ride-through:* Short asymmetric voltage dips of duration and depth as shown in Fig. 8 are the most common grid disturbances also in industrial plants. When only one or two phases are dipping, then still enough energy can be drawn from the grid to provide the desired torque with the electric motor, however the deeper the dip, the more the system will resemble a single-phase supplied load, where power flow is pulsing with 100Hz. Despite the relatively small DC-link storage, this is a pulsation that still can be smoothened with the DC-link and with the rotational inertia of the load. When trying to implement full torque ride-through strategies for this class of disturbances, several criteria have to be watched, which still may require a zero-torque ride-through at some point. Beyond the obvious maximum continuous designed current of each phase, we foresee at least the categories and issues listed in Fig. 9, that need to be checked. Several issues are even site-dependent and will require at least some routine check-ups before full-

torque ride-through can be applied to a specific project. Others are more general and may be resolved by overdesigning or adapting the VSD for the specific application. The list only includes issues with the VSD main-circuit and neglects auxiliaries, which will be discussed in paragraph VI.

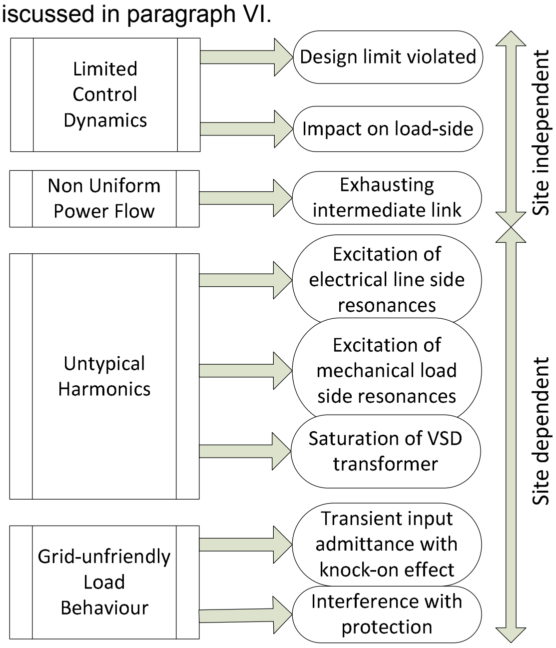

Fig. 9 Categories of challenges that may need to be addressed before riding through with full torque

In order to determine which compromises have to be expected in performance, the two basic classes of grid-side power electronics circuits need to be distinguished:

- controlled or uncontrolled rectifier bridge (diode rectifier front-end of voltage source inverters, thyristor-controlled rectifier of an LCI)
- voltage source inverter with an active front-end

a) *Limited Control Dynamics*: The first challenge lies in the fact that both voltage as well as phase of the line can rapidly change during asymmetric dips. This puts the PDS control designer into a dilemma: the reference tracking behavior for current (resp. torque) under nominal operation, constrained by a cost effective size of DC-reactor or DC-capacitor, is optimal with time-constants in the range of a cycle (15-20ms), while the recovery of the grid happens faster than this. Adapting the controller to follow the grid voltage disturbances makes the reference tracking “nervous”, i.e. the torque will tend to overshoot, when operating points are changed. It would also become more susceptible to other noise coming from grid. For all that noise, the converter will look like a negative resistance from the grid side, i.e. current will rise when voltage drops. Experience with the large LNG plant reported in [9] show, that increasing current controller gains by a factor of 3 (thus including roughly another half decade of harmonics into the bandwidth of the current controller of the PDS) increases grid voltage THD by roughly one percentage point; i.e. harmonics between 5Hz (normal bandwidth) and 35Hz (increased bandwidth) are also actively rejected, but the PDS looks like a negative resistor to the grid.

When tuned normally (i.e. slower), the current controller will show transient errors at the beginning and at the end of a grid disturbance. Transient control errors resulting from grid voltage changes usually lead to errors in current control, and for sure in one of the two transients of the grid-disturbance in overcurrent. Under high loads, such a overcurrent together with the high fundamental current may reach trip limits. In addition, for LCIs with their current controlled rectifiers, torque errors as function of transient current errors may be applied to the driven load. These transients may be cyclic (at least few cycles) and need to be studied if critical to the load.

Transient control errors resulting from phase changes also lead to errors in current, but in LCIs also to untypical harmonics in the current and thus in the load torque. Single and double grid frequency torque pulsations have to be expected during transients. The uncontrolled diode rectifier is the most robust solution in terms of transient errors due to control.

b) *Non-Uniform Power Flow:* In the extreme case of an asymmetric voltage sag with one phase dropping to zero, power cannot be taken continuously from that grid anymore, but will pulse at double grid frequency. Also in less severe dips, the topology of the power electronics and the drive transformers may prevent uniform, continuous power flow. Power flow will be smoothened out of the intermediate storage (capacitor bank or DC-reactor), as long as the load is continuing to be driven with uniform, continuous power, which will lead to oscillations in voltage resp. current. The oscillations may lead to complete depletion and discontinuity on one hand, or to overload (e.g. overvoltage across DC-capacitor) on the other hand.

c) *Untypical Harmonics:* Network disturbances will contain a rich spectrum of harmonics. The frequency converters of VSDs are non-linear loads and especially the integer harmonics in the grid voltage will be transformed into other integer harmonics inside the inverter, which again will result in different current harmonic spectra in the line-side current. During regular operation, a frequency converter will only have integer harmonics of the order 6k ±1. This fact is used in design to place parasitic resonances of electric filters on the non-occurring even and triplen harmonics. During grid disturbances, any other integer harmonic can occur, and particularly even harmonics cannot be excluded. Some of them may thus excite parasitic resonances of filters during grid disturbances and their impact needs to be checked. Special attention needs to be paid to filter protection settings, as protection must not trip on grid disturbances ear-marked for full-torque ride-through.

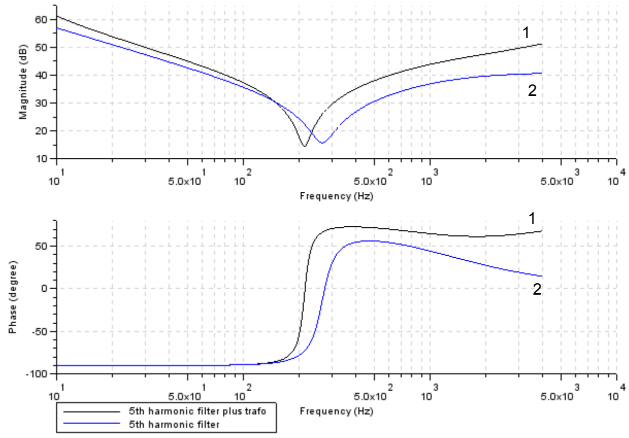

Fig. 10 The parasitic resonance of a 5th harmonic filter (2) is seen near 4th harmonic from grid (1) and may be

excited during full-torque ride-through

To illustrate a case, which would be sensitive to even harmonics, Fig. 10 shows as an example the fifth harmonic filter of a LCI drive, curve 2 as seen by the VSD at 265Hz and curve 1 as seen from the bus by another VSD, with parasitic resonance near 200Hz.

The diode rectifier and the controlled thyristor rectifier are, as a special case of transformation of harmonics into other harmonics, transforming positive sequence 2^{nd} harmonics into DC-components on the converter side of the drive transformer. This will after some time-constant lead to the well-known core-saturation of the transformer, with a detrimental impact on the adjacent loads on the same bus. As shown in [6] by Stemmler, the controlled rectifier may be instable for firing angles in inverter mode between 0..45 degrees, if a positive sequence 2^{nd} harmonic occurs over certain time under grid imbalance. Depending on reactor size, the stable range will be extended from 45 degrees downwards. As shown in the same publication, the effective reactor size as function of the physical reactor size, together with active control "virtual" inductance matters for stability.

Contrary to the reported HVDC transmission application, drive transformers have smaller saturation time constants (approximated by L_m/R_m) and may consequently already saturate during a long full-torque ride-through. On a plant electric system level, power electronics controls play an eminent role in two ways:

- For the VSD under investigation itself, whether its control scheme is capable of preventing core saturation also at small inverter firing angles.
- For other VSDs in the plant, if their complex admittance, exhibited to the grid at 2^{nd} harmonic is amplifying positive sequence voltage disturbance as function of 2^{nd} harmonic current, thus pushing transformer core saturation.

The important role of the complex admittance, resp. impedance of controlled active loads is further elaborated in the next section or in [7,8 and 9].

The untypical harmonics generated by a network disturbance into the VSD may also appear in the currents on the load side and finally as untypical torque harmonics in the electric motor air-gap. This is specially the case for LCI-type VSDs. The most likely harmonics to occur under network disturbance and full-torque ride-through however are the 1X and 2X torque pulsation, which should not pose problems to the driven load, as these frequencies may occur for mechanical reasons as well and should be accounted for, at least to some extent.

d) *Grid-Unfriendly Load Behavior:* The VSDs, especially the ones with controlled front-ends (VSI with active front-end and LCI with controlled thyristor rectifier) have to be understood as complex, time-variant impedances or admittances on the grid. Other industries, such as the electric railway traction, put very conservative criteria on this complex admittance. They typically require passivity for the VSD admittance over the whole frequency domain. Such criteria have to be fulfilled also during grid disturbances.

The VSD control strategy for full-torque ride-through could also pose a problem to the grid and its recovery from the disturbance. Simple strategies tend to load phases with undervoltage more than healthy phases, which may lead to a knock-on effect on the grid and on auxiliaries. Having a look at grid-codes for wind power generators again, grid-operators have started to require capacitive reactive power support to the unhealthy phases.

V. MECHANICAL INTERFACE OF A PDS

A. General Behavior

The VSD can provide regular operation for dips of about 20-30% depth (remaining 70-80% of voltage) then it switches usually to zero-torque ride-through. The torque will be reduced to zero or even a small negative values in order to support the dc-link with energy (for voltage source inverters). This prevents large inrush currents and voltage overshoots when the voltage comes back and also keeps the induction motors magnetized. The technique is also known as kinetic recovery and was discussed here [4]. The advantage is that the VSD doesn't have to trip and is able to re-accelerate the motor immediately after the distortions is cleared. The crucial point is that the rotational mass does not drop under the mechanical system's minimum speed or even come to a stop during the dip. This criterion is process depended and cannot be generalized.

B. Reduced Torque Ride-Through

Depending on the nature of the power dips, different supervision rules could be applied in parallel, each of which can initiate a classic ride-through reaction. The items to supervise correspond to the issues identified in the previous paragraph. For cases, where the process could profit from getting partial power, a reduced torque ride-through could be initiated in a similar fashion. The rules however would have to be carefully selected and will largely depend on the application and the plant.

The integration of partial-torque ride-through into a plant-wide control design needs to be thought through. Obviously, a compressor will approach the surge-line slower as compared to a classical zero-torque ride-through and so will buy time for the compressor performance control and the process control to adjust valve positions. Wherever the outer loop may end-up being faster than the speed controller of the VSD under partial-torque ride-through, the cascade of controls may need to be extended with dynamic resets (dynamic anti-windup).

Fig. 11 shows the full decision tree when considering all three options for riding through grid disturbances in a concrete project. The decision tree is guiding the work during project engineering, but needs to be implemented in the PDS controller for later operation as well. The topics in the rectangular blocks are defining the studies to be done during project engineering: the disturbance types need to be addressed, an impact study for trying to run full torque under those disturbances needs to be carried out, then VSD internal "ultimate limits", i.e. effects where zero-torque ride-through becomes mandatory, need to be defined and last but not least, the dependency of those criteria ("ultimate limits") on load needs to be studied.

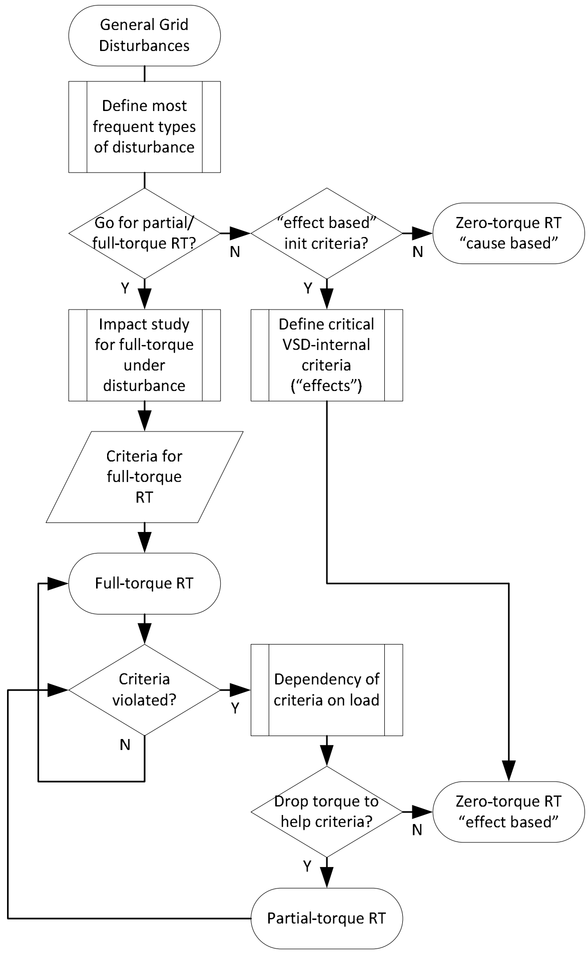

Fig. 11 Design tree for utilization of all advanced ride-through features. The quadratic sub-process blocks indicated preparatory studies to be carried out.

Already the classic zero-torque ride-through could be improved by going from "cause" based initialization criteria to "effect" based initialization criteria. An example could be to wait for an over-current rather than to go into zero-torque based on grid-voltage levels, which don't pose a problem to operations per se yet. Criteria for full-torque ride-through are defined in an impact study, which essentially checks the impact of dropping performance in certain points, in order to continue full torque under disturbance. The list of criteria gives the ultimate pain threshold. For those thresholds, load dependency has to be evaluated in a second study, in order to know the derating levels to allow partial load ride-through.

C. Transition back to normal operation

At some point, the grid disturbance will disappear and the PDS has to recover from ride-through and go back to normal operation. The topic is hardly ever addressed in specifications.

There are two control loops that have to return working normally: The inner torque control loop and the outer speed control loop (if used). Both loops should be re-initialized to their present state of operation.

After full-torque ride-through, there will be no transition back to normal, as both loops have kept on working. Both after reduced-torque as well as after zero-torque ride-through, initialization is necessary.

The torque control loop should ideally be put to the actual load torque. Load might have changed over the time the grid was disturbed and needs to be identified. Special attention needs to be given to the build-up of torque at this stage. The torque increase could be made very sharp from electric perspective, but then might excite torsional resonances. Torque can be reapplied immediately, if the disturbance had lasted less than ¼ period of the dominant torsional natural frequency between motor and load. For longer disturbances, load torque has to be ramped back with slow ramps or with steeper ramps, where the reference was filtered at the critical frequencies. If the controls are tuned fast for strong disturbance rejection, then there is also the risk that those fast controllers un-damp the lower torsional modes, because the torsional resonance interacts with the control circuit, which may even result in continued torsional excitation, as reported in [10].

The speed controller needs to be re-initialized at actual speed, which may have dropped over the time of the grid-disturbance. It must only be released from anti-windup by the time the inner loop is again following the reference. The same is true for any overriding integrating controller.

VI. AUXILIARY AND CONTROL POWER

During the different grid disturbances that could happen, also the auxiliary and control power is affected when not fed from a different source. This has a non-negligible effect on the ride-through behavior of the whole drive chain. The auxiliary voltage powers small 3-phase induction motors for cooling. The effect of different failures is analog to those on the DOL motors in section III. During a brownout, the coolant flow is still given as long the frequency stays stable. But the auxiliary motors will overheat and their protection relays may trip at a certain point.

In contrast, a total auxiliary power loss implies an immediate stop of the coolant flow (usually water or air). The heat cannot be transported any longer and the heat sinks of the semiconductors keep heating up. As the coolant temperature at the power-part outlet is no longer meaningful for the self-protection, the time without auxiliary power is limited to some seconds by the drive software. The used delay before the trip depends on the thermal capacity of the heat sinks and on the actual load. If the main power fails together with the auxiliary power of course the classic zero-torque ride-through time can be quite large due to reduced losses. A redundant line from a different sub-station or bus bar can be used to increase reliability of the cooling systems. Especially in the case where auxiliary power distortions are more common than main power distortions.

The control power is not allowed to fail at any time. The control boards need the energy in order to control the VSD and also provide the protection. That's why the control line should always be backed-up by an external (from the plant) or an internal UPS.

The cooling of transformer and motor is for short interruptions of several seconds less critical than the one of the VSD. The thermal time constant could be minutes whereas the VSD has seconds. A brownout instead could also be critical to those components because the cooling fans might overheat.

Also to consider are the switchgears and main circuit breakers. They should not open during a network distortion. This might be due to control power loss or the protection might trigger. If the PDS shall survive grid disturbances, the whole factory protection and auxiliary supply concept has to be designed accordingly.

For synchronous motors also an excitation unit is needed, which is fed from the auxiliary power or with an additional transformer from the main power. As the excitation unit is an active device it reacts to network distortions and needs to do a ride-through itself if necessary. During an excitation unit ride-through no current will be driven in the rotor windings and the flux decreases with rotor time constant. With reduced flux limited torque can be produced in the motor. The rotor time constant limits the ride-through time which itself depends on the motor size.

VII. CONCLUSION

Short voltage dips down to about 70-80% remaining voltage can usually be handled without losing performance. For deeper voltage sags, it may still be possible to provide full power, but only by compromising on "soft" performance criteria, e.g. at the cost of increased harmonic pollution to the network. This temporary operation with less performance, but providing full torque to the load, is defined as "full torque ride-through". A special design of the PDS might be required to handle overshooting when the voltage comes back and in case of symmetric dips provide the additional current that is needed in order to compensate for the voltage (1/0.7 = 143% current). Dips below this threshold will be handled as zero or reduced torque ride-through. State of the art is the zero torque ride-through. The drive tries to survive the distortion without tripping and continues the operation after the voltage comes back.

Reduced-torque ride-through is very complex and requires an interdisciplinary approach. But there we see also a major opportunity for improvement in the future. Especially with compressors with their small rotational inertia, which are quickly running towards surge, already for short dips of some 200ms, a reduced torque ride-through could help to stay away from surge longer and to gain time for valves to adjust load. In order to keep on operating the PDS with partial torque, the exact limitations have to be determined in studies, e.g. in simulation, and these limits need to be defined as function of load.

Crucial is also the interaction between process controls and the PDS controls. When the PDS runs into a torque limit (e.g. due to an undervoltage) it has to communicate that in a proper way to the process control. The process control can react and prevent integrator wind-up. In a scenario with partial-torque, advanced anti-windup schemes might be necessary such as dynamic reset. These schemes will have to ensure, that the overriding controller doesn't wind-up or overshoot, when the PDS controllers are working at reduced performance.

Special attention needs also to be given to auxiliaries that need to be supplied during grid disturbances as well. Mostly UPS will be used to buffer the control circuits, whereas cooling circuits are designed in a robust way for the majority of grid disturbances.

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IX. VITA

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