ELECTRIFICATION AND IMMUNITY AGAINST VOLTAGE DIPS: A CASE STUDY

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Abstract - In the pursuit of net-zero emissions from industrial processes, several strategies have been conceived and subsequently realized. Electrification of previously steam- or gas-driven equipment sits in the forefront as an option to not only mitigate emissions, but also to improve energy efficiency. This includes electrification of low-power auxiliary equipment to that of high-power, critical systems. On the other hand, voltage dip disturbances in the electrical supply can disrupt the operation of such recently-electrified equipment and consequently affect process availability. Hence, this paper studies the consequences of a voltage dip on electrified equipment and explains the requirements for possessing a restart philosophy for a plant. Finally, the brownfield evaluation of the restart philosophy for two plants and their ride-through behaviour during an actual dip event are presented as a study case.

Index Terms — Voltage Dips, Electrification, Ride-through capability, Variable Speed Drives, Voltage Dip Immunity, Process Immunity, Brownfield Implementation.

I. INTRODUCTION

On 1st Sept 2019, the Dutch government enforced the Climate Act 2019, by laying down emission reduction targets for the years of 2030 (49%) and 2050 (95%) for all sectors that engage in carbon emissions. This includes the oil & gas sector, where, in the pursuit of such net-zero emissions from industrial processes, several strategies are being conceived and subsequently realized. Of these strategies, electrification sits in the forefront as a solution to realize a cleaner energy profile by replacing a lesser-sustainable energy source with electricity. The main reason for this preference towards electrification is the significant reduction observed in CO_2 emissions for every MW consumed.

On a small scale, electrification could be a replacement for steam-powered, process and winterizing tracing, and on a large scale, for steam- or gas-driven compressors and pumps. Moreover, the higher efficiency of electrical equipment when compared to its steam- or gas-driven counterparts, makes a compelling case for this transition. This is better explained in [1], wherein the overall efficiency of an electrically-driven compressor was strictly estimated at 51%. This was compared with its steam counterpart through a liberal estimate of 45%, consequently implying a 6% improvement on electrification. However, from a cost perspective, efficiency only plays a part after the grid connection point, implying a massive efficiency improvement to 92%. Moreover, with the increasing trend in renewable generation, and also with the introduction of Power Purchase Agreements (PPA), the operation of electrified equipment can also be made carbon-neutral.

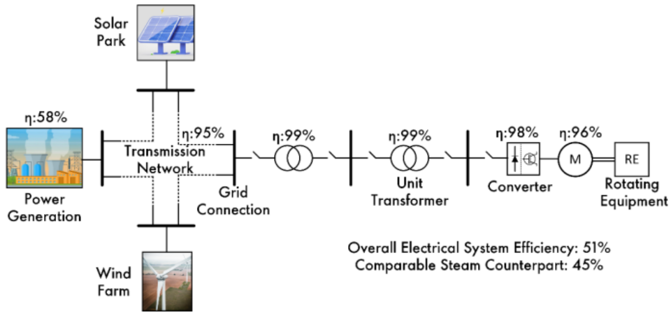

Fig. 1 The efficiency chain of an electrified system

On the contrary, electrified process equipment are challenged by a plethora of electrical grid disturbances. The taxonomy of these disturbances is explained by Kundur in [2]. Accordingly, these are divided into small disturbances which mainly comprise small variations in the load, and the large ones that involve earth faults, phase-phase faults, start-up of a large motor and so on. It can be agreed that, irrespective of the type, often the outcome of a grid disturbance is a voltage dip, i.e., a sudden drop in voltage for a duration of a few milliseconds to a few seconds, followed by a recovery to a stable voltage point.

By looking from a power system's perspective, it is evident that decarbonization is taking shape in the form of Renewable Energy Sources (RES) replacing conventional power generation. However, as explained in [3], increasing penetration of RES in the generation mix leads to a reduction in system strength with a smaller short-circuit-ratio. Consequently, a weaker power system results in poorer fault resilience with fault-induced voltage dips taking longer to recover, suggesting increased vulnerability.

A voltage dip observed in the electrical installation feeding a plant can impact operation of equipment. This is of great relevance to equipment switched through an electrically-latched contactor, wherein, such contactors drop out on loss of the coil voltage during a dip. Thus, dips can lead to equipment stoppages where the impact can range from being a nuisance to affecting plant availability, especially when the plant restart is procedurally complex and long. Given such exposure to dips, which is expected to increase with the increasing penetration of RES, there is necessity to emphasize the dip ride-through capability of any newly, electrified equipment to prevent unnecessary plant downtime. The design requirements for this capability are mainly dictated by the process that the equipment serves, and particularly, the immunity of the process to disturbances. On the other hand, the ride-through capability of an equipment is limited by the design of the electrical distribution system feeding it. Moreover, as mentioned, the strength of the connected grid must also be taken into account to appropriately compose an immunity strategy.

Thus, there is an established need to discuss the electrification theme through the lens of dip immunity. This paper makes an attempt to do so by introducing the nature of a voltage dip in Section II, explaining in detail the expectations for a process restart philosophy in Section III, and finally, demonstrating case studies from the South of the Netherlands, with two different responses to a voltage dip.

II. NATURE OF A VOLTAGE DIP

A. EN 50160

To understand the nature of a voltage dip, it is necessary to recognize what constitutes one. The European Norm of EN 50160 helps in standardizing the definition of a voltage dip as a "*temporary reduction of the rms-voltage at a point in the electrical supply system below a specific start threshold*" [4]. Accordingly, this threshold is recommended at 90% of nominal value. The standard also provides a means for categorization of voltage dips as in Table 1, using purely, two main characteristics of a dip – its duration, and its lowest residual rms-value. However, when categorizing dips, it must be noted that the category of the voltage dip at the fault source will vary from that seen at a distant section of the grid. This is explained in detail in the following sub-section.

B. Dip Characteristics

This sub-section takes inspiration from Bollen in [5], to explain what characterizes a voltage dip. The most common cause of dips are electrical faults in the grid, and can be observed in a single phase, two phases, or all three, depending on the type of the fault. Such dips are generally governed by two factors - their magnitude and their duration.

TABLE I
DIP CATEGORIZATION

Residual voltage v (%)	Duration t (sec)				
	0.01≤ t ≤ 0.2	0.2 < t ≤ 0.5	0.5 < t ≤ 1	1 < t ≤ 5	5 < t ≤ 60
90 > v ≥ 80	A1	A2	A3	A4	A5
80 > v ≥ 70	B1	B2	B3	B4	B5
70 > v ≥ 40	C1	C2	C3	C4	C5
40 > v ≥ 5	D1	D2	D3	D4	D5
5 > v	X1	X2	X3	X4	X5

Magnitude: To determine the magnitude during a dip, the following different methodologies can be employed to aggregate samples over the time-domain [5]:

1) *Using Root-Mean-Square (RMS)*
2) *Using fundamental component*
3) *Using peak voltage*

Aggregation over RMS works sufficiently only when sample-lengths are an integral multiple of half-cycle length. The second method of using the fundamental bears similar results as the first one. The third method using the absolute peak value is better in capturing post-fault overshoots than the other two. But these methods, give result to aggregated values over time, rather than one single value for the magnitude. Due to the simplicity of the latter, standards like the EN50160, and common industry practices, have adopted the lowest residual voltage as the single value representation for magnitude.

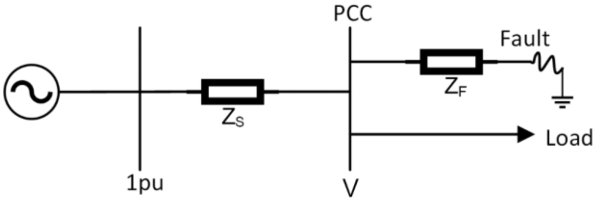

Fig. 2 Voltage divider model for conventional transmission systems [5]

$$V = \frac{Z_F}{Z_F + Z_S} \tag{1}$$

Bollen in [5] further provides a simplified model that showcases the factors that influence the voltage *V* near the equipment affected, as in Fig. 2. The model is an effective simplification of a conventional transmission system where the Point of Common Coupling (PCC) is the node where the load and the faulted section (three-phase fault) are both fed from. As per the voltage-divider equation (1), *V* is influenced by the source impedance Z_S and the impedance Z_F between the PCC and the fault. For systems with lower source impedance Z_S, i.e., higher short-circuit power, the voltage *V* at the terminals will not be deep. On the contrary, this substantiates deep dips when the system has lower short-circuit power. The relation between grid strength and dip magnitude is graphically represented in Fig. 3. Similarly, the impedance Z_F signifies the distance of the fault from the PCC and carries an implication that greater this distance is, the lesser the voltage *V* will fall. The presence of transformers, between the fault and the PCC also positively contributes to Z_F, and consequently improves the voltage *V*. The relation between fault distance and dip magnitude is also graphically represented in Fig. 3.

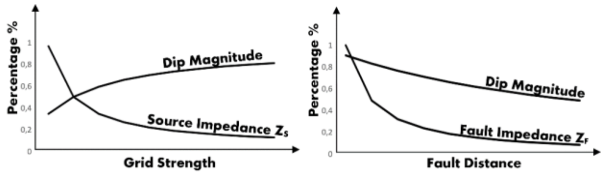

Fig. 3 Variation of dip magnitude on changes in grid strength and fault distance respectively

A drawback of this model is that it doesn't take into account the system between the PCC and the load. This system generally constitutes feeder cables, and more importantly, transformers that feed the equipment at lower voltage levels. Bollen in [5] reveals that the voltage at the equipment terminals is dependent on the type (wye/Δ) of connection of the load, and also the vector group of the feeding transformer. The latter because, a dip in one phase seen on the primary windings, can propagate to other phases on the secondary, varying both in magnitude and phase angle.

Dip Duration: The dip duration is mainly influenced by the clearing time of a fault. Subsequently, there is an indication in [5] of a fairly negative relationship between operating voltage and clearing time. This is mainly because faults in high-voltage transmission lines have shorter critical clearing times than those in distribution systems, and thus need to be cleared quicker.

Magnitude-Duration Graph: The magnitude-duration graph is an efficient method of capturing past dip events over a two-dimensional space. By overlaying the classification of Table I as shown in Fig. 4, this table offers interpretability on the most common type of dips, the deepest dip, and the shallowest one. However, it must be noted that this graph holds validity only when all dips are recorded at the same point in the grid. Additionally, the network configuration at the time of the dip can also be registered.

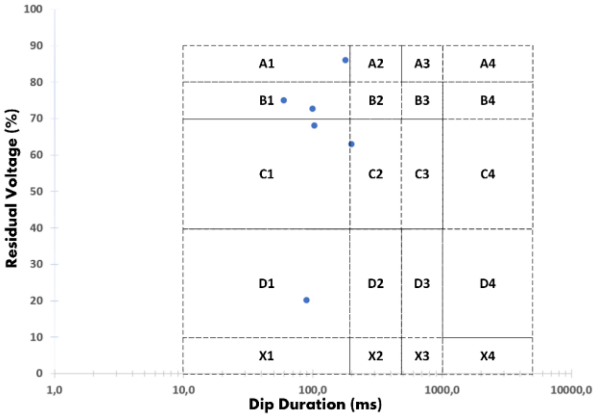

Fig. 4 EN50160 dip classification layered over an example magnitude-duration graph

C. Equipment Behaviour

The response of equipment to voltage dips can depend on the method of switching that is employed. In particular, equipment that are switched by an electrically-latched contactor can be majorly affected. Low-power equipment, such as tracing and lighting, generally do not use electrically-latched contactors, and thus their operation is not affected by dips. Similarly, equipment switched by mechanically-latched contactors do not switch-off during a dip and are subsequently able to ride through.

The block diagram in Fig. 5 can be used to explain the behaviour of a motor switched by an electrically-latched contactor through a control circuit powered by one of three phases, i.e., 1Φ AC control power supply. Such contactors operate through a coil which, when energized through a control circuit, magnetically closes the contacts of the contactor switch. The same is explained as the motor starting event in Fig. 5. However, the control circuitry only energizes the contactor on receiving a pulsed start-signal from a Distributed Control System (DCS).

During a dip event, the voltage of the 1Φ control power supply may fall below the threshold value required to keep the contactor magnetically latched. In such a case, the contactor switch opens, and after the voltage recovers, remains open until a new start pulse is received.

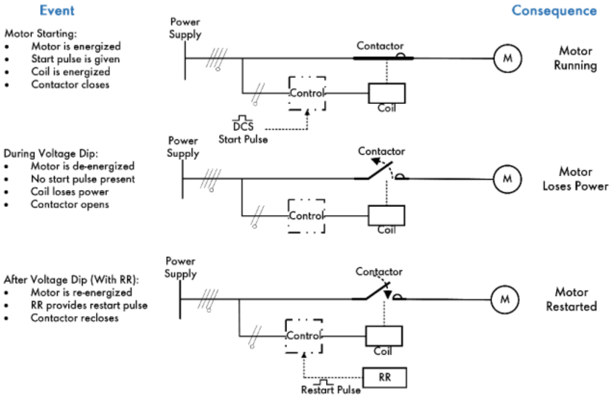

Fig. 5 A block diagram explaining the behaviour of a motor fed by an electrically-latched contactor.

To ensure a quick and automatic restart immediately after recovery, a Restarting Relay (RR) is introduced into the control circuitry. An RR is capable of detecting a dip event, and upon recovery, is able to provide a start pulse similar to that of the DCS. Hence, the contactor is again magnetically latched-in, and the motor is restarted.

Variable Speed Drive Systems: To enable variability of the process, Low Voltage (LV) and Medium Voltage (MV) motors driven by variable speed drive (VSD) systems are utilized. These systems are highly sensitive to voltage dips and as a consequence are made more robust [6]. In particular, a kinetic buffer or a similar support technique is used to assist the drive during a dip event by utilizing the inertia stored in the motor's rotor to maintain a stable DC link voltage. Consequently, the extent of this ride-through capability is influenced by the rotor's designed mass and load-type.

III. DIP RIDE-THROUGH EXPECTATIONS

As stated before, voltage dips have a direct impact on the operation of crucial equipment and in turn on plant availability. A plant shutdown due to a dip can be prevented by ensuring critical equipment is able to ride-through. This can be achieved by employing a restart philosophy. One ingredient for restart philosophy is determined by the needs of the industrial process to ensure stable, effective operation during a dip event. Often, industrial processes are an amalgam of multiple systems that contain sub-systems or equipment wherein multiple process-related parameters are controlled. In [7], this understanding is used to develop the concept of Process Immunity Time (PIT) to form the groundwork for a general restart philosophy.

By summarizing PIT in [7], we can obtain it as the maximum allowable time the process can withstand the idling of an equipment, with a possibility of a process recovery on restart of that equipment. This is better explained in Fig. 6 which shows the behaviour of a process parameter (pressure, level, temperature, flow, etc.) during a dip event. Given a dip event initiated at T_1, the parameter starts to deviate from its operating point P_{OPT} after a delay time ΔT. If the equipment is restarted and brought back to its pre-dip operating status on or before the time T_2, then the process is able to recover. On the contrary, if the equipment is unable to restart as above, the process is no longer able to return to its pre-dip state, and subsequently collapses. This time interval T_2-T_1 that is inherent to an equipment participating in the process is the PIT of that equipment. Thus, the precursor to developing a restart philosophy is to identify the critical equipment, that is necessary to be restarted after a dip event in order to ensure process continuity and stability. It is worth mentioning that the process cannot be protected against voltage dips longer than the PIT of identified critical equipment. In other words, the shortest PIT in the process determines the longest voltage dip the process can withstand.

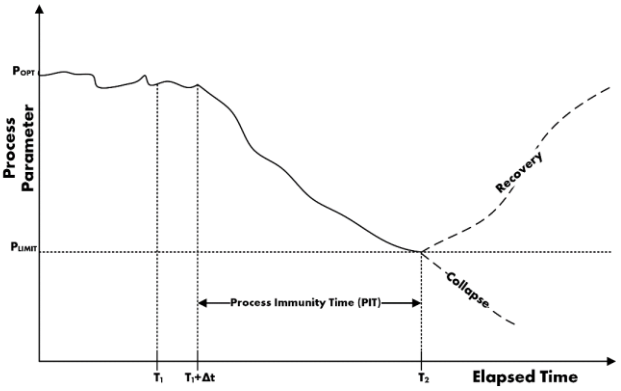

Fig. 6 The concept of Process Immunity Time (PIT)

Upon determining the critical equipment, it is necessary to investigate the restart possibility given the supply limitations of the electrical installation. For very short dips of a few milliseconds, equipment can likely be restarted simultaneously without any large current intake and overloading. However, for substantially longer dips, simultaneous restart of equipment that are fed from the same distribution board can lead to large currents which can lead to overload and the spurious activation of the associated protection device. Therefore, the restarts of such critical equipment are required to be distributed in the form of wave sequences, where the sequence is determined by the respective PITs.

Some recommendations mentioned in [7] were to replace AC coil contactors with those of DC, or to implement a controlled restart directly via the DCS. For the plants used in the topic of the case study, these methods were found to be laborious and not practical, as provisions for restarting relays (as in Fig. 5) already existed in every distribution field supplying the electrical equipment. It is also noteworthy to mention that these plants, in general, use a criticality philosophy, wherein critical equipment that require uninterrupted supply of power are by design already provided with a back-up Uninterruptible Power Supply (UPS) connection via an automatic transfer switch. This safeguards these equipment from grid disturbances including voltage dips. Such equipment can be safely excluded out of the restart philosophy.

The restarting relays with a delay function were used in the following methodology to build a plant-wide restart philosophy, pictorially represented in Fig. 7.

1) Identify the equipment required for process immunity, i.e. ride-through.
2) For these equipment determine the respective PITs through process technology.
3) For every distribution board, verify if restarting is possible. If not, repeat step 1 to re-evaluate scope.
4) Using the PITs, engineer the restarting wave sequences by adjusting the delay functions of the restarting relays.
5) Install the restarting relays in the respective distribution fields.

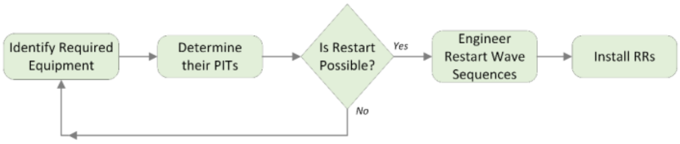

Fig. 7 The block diagram of the strategy to implement the restart philosophy

IV. CASE STUDY

The following case study discusses the implementation of the above steps and its consequence for two plants - A and B which includes a high-speed MV VSD system, when faced with a real voltage dip at 19:43h on 21st April 2023 in the transmission grid supplying the site. The Fig. 8 shows a single line diagram of the network during the time of the dip. The site relies on two incomers at 150kV and 30kV respectively. Subsequently, the two plants are fed at 6kV through multiple step-down transformers.

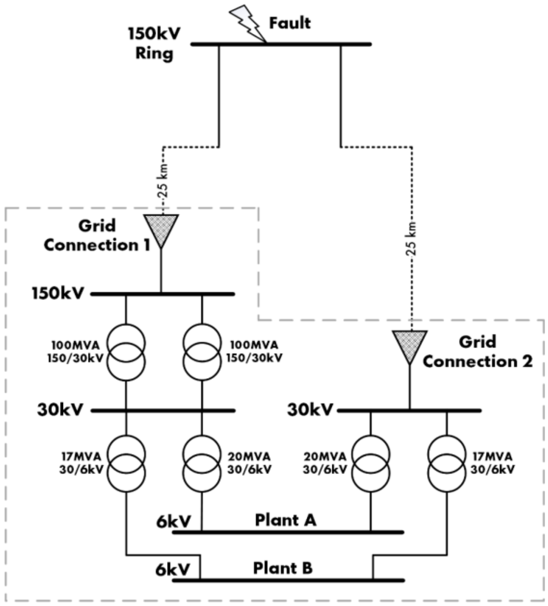

Fig. 8 The single line diagram of the site connected to the 150kV ring network

The single line in Fig. 8 also depicts the fault event that led to the voltage dip. The fault location was known to be at an approximate distance of 25 km from the site, and was recorded by a power quality meter on 150kV incomer station as shown in Fig. 9, through the line voltage v-w. As per the discussion in section 2, this dip had a lowest residual voltage magnitude of 0.58pu with a duration of 65ms – making it of C1 class according to EN50160.

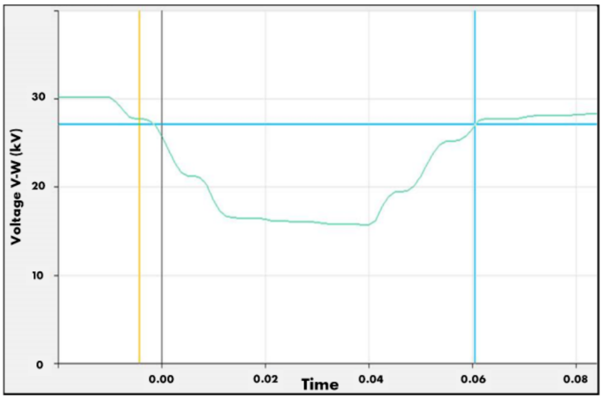

Fig. 9 Power Quality Meter Recording - Line Voltage U-V in kV during the voltage dip on 21st April 2023

Applying the voltage divider model from section 2, it was understood that the location of PCC and the fault itself were very close to each other. As a result, Z_F can be taken to only comprises fault impedance. Moreover, the connected grid has a very high short circuit power, implying a strong grid - Z_S can be determined as minimal.

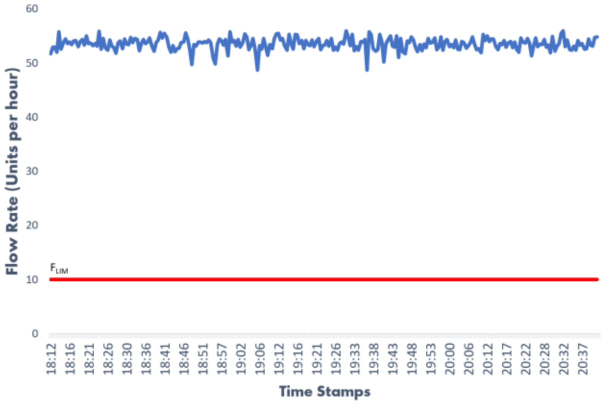

Fig. 10 Plant A - I Captured flow-rate data of one critical equipment during the dip event (19:43h)

Plant A: The previously mentioned strategy was employed in Plant A to implement a restart philosophy. In total, this plant process utilizes approximately 570 pieces of equipment. Out of the these, 95 pieces were identified to be critical to keep the process running and stable. For these equipment, the shortest PIT was identified to be 20 seconds. Thus, given that the equipment has a restart time of 10 secs, the process can withstand voltage dips with duration until 20 – 10 = 10 seconds.

The restart capability for all equipment was verified and was subsequently configured. For very short dips, the restart relays were configured to restart immediately, and for substantially longer dips, the relays were engineered to restart in a sequence based on the respective equipment PITs. This restart philosophy was put to test during the dip in Fig. 9. The flow-rate data related to one of the identified critical equipment was captured as shown in Fig. 10. It is evident from the graph, that the process was able to ride-through the event without any interruptions and the process parameter is well above the process point-of-no-return F_{LIM}. Due to the very short duration of the dip, all the relays initiated a simultaneous restart, and this response was too fast to be captured by the slow sample rate of the associated process instrumentation. The same resilience to dips was observed at other critical equipment and associated process parameters.

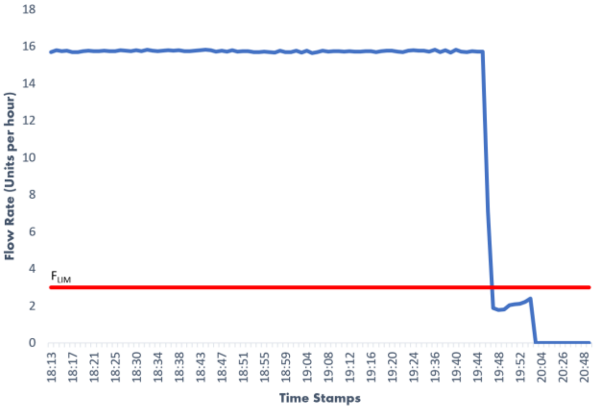

Fig. 11 Plant B - Captured flow-rate data of one equipment during the dip event (19:43h)

Plant B: Unlike in Plant A, the mentioned strategy was only partially implemented in Plant B. In total, this plant process employs approximately 600 pieces of equipment. Out of the these, 170 pieces were identified as critical, and the restart relays were installed with the same methodology as in Plant A. With this dip event, it was evident that the identified list of critical equipment was incomplete. The flow-rate data related to a piece of equipment which had not been identified as critical was captured as shown in Fig. 11. From the graph, it is clear that equipment shuts down at 19:43h and due to an absent restart relay, is unable to restart before the flow-rate falls below the limit of F_{LIM}, leading to a collapse of the process.

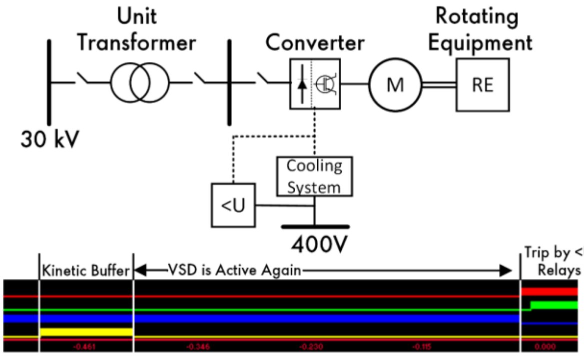

Fig. 12 Single line diagram of the MV VSD in consideration, and its corresponding behaviour to the dip event

Another cause for the process collapse was the anomalous tripping of a critical MV VSD-driven compressor-motor. This VSD serves the process of Plant B and is fed from the 30kV installation via a transformer as shown in Fig. 12. The VSD system tripped despite an enabled kinetic buffer function – which by design is capable of riding through such considerably short dips. The activation of this kinetic buffer is also shown in Fig. 12. On initial investigation, it was found out that the drive itself was successfully able to ride through the dip. However, two undervoltage (<U) relays monitoring two auxiliary pumps of the VSD cooling system, detected this dip event and initiated a trip sequence after a few hundreds of milliseconds to protect the VSD from loss of cooling. This protection logic was found to be too conservative as the <U relays initiated a trip despite no loss of cooling and subsequent deviation of the cooling process

from its normal operating window. Further examination revealed that the threshold settings of these relays were too strict, and could be further relaxed to avoid such nuisance trips of the VSD. Another alternative solution was to provide critical system auxiliaries with a UPS feed. Ultimately, this VSD case showcased the importance of considering auxiliaries and the trip sequences they initiate, when dealing with the restart design of critical VSD systems.

V. CONCLUSIONS

The increasing drive to electrify conventional process equipment as a means of decarbonization opens plant operation to new challenges in terms of voltage dip disturbances. As discussed, one of the reasons is electrically-latched contactors that are not facilitated with a restart function. However, this can also be because the electrical alternative more than often includes power electronic devices, (like in VSDs, controllable E-heaters, etc.), that employ sophisticated but sensitive control systems that fail on a voltage dip event. Thus, it has become crucial to understand the many implications of voltage dip disturbances to the process and to eventually improve its resilience to better the plant availability.

This paper looked back at the concept of a voltage dip and revisited the ground rules for establishing a restart philosophy. As a study case, the implementation of restart philosophies for two plants were explained, and the following inferences were drawn. Plant A is a vanilla example of a successful implementation of dip ride-through capability. The process collapse of Plant B showcases an opportunity to utilize the dip event as a quality check to mitigate gaps in a restart philosophy. Furthermore, the case of the VSD trip emphasizes the importance of considering auxiliary systems as a part of the restart function of the bigger system. It can also be concluded that for a successful restart philosophy, the philosophy needs to be developed and assessed at multiple levels – equipment level, sub-system level, system level and plant level.

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VII. VITA

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