Load Commutated Inverter Modeling: Impacts and Solutions for an Isolated Power System

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This paper was presented at the 70th Annual Petroleum and Chemical Industry Technical Conference and can be accessed at: https://doi.org/10.1109/PCIC43643.2023.10414312

LOAD COMMUTATED INVERTER MODELING: IMPACTS AND SOLUTIONS FOR AN ISOLATED POWER SYSTEM

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Abstract—This paper explores the impact of several medium-voltage load commutated inverter motor drives on an industrial power system. The impacts of load commutated inverter transients on the facility's power system, the external utility grid, and its remedial protection and control systems are explored through modeling the load commutated drive system, protection devices, and the control system with a real-time control hardware-in-the-loop simulation.

Index Terms—LCI drive modeling, power management system, HIL.

I. INTRODUCTION

Refinery power systems use drives for various process applications with power requirements varying from a few kilowatts to tens of megawatts. Electronic drives are an ever-increasing part of the power load at these facilities. Depending on the application, some electronic drives use thyristors, whereas others use insulated-gate bipolar transistors (IGBTs). IGBTs are used for pulse-width modulated drives, whereas thyristors are used for alternate current (ac) commutated drives. IGBTs are generally preferred in high-megawatt applications due to their larger voltage blocking capability.

Voltage source converters are mostly preferred because of the high cost of direct current (dc) link inductors in current source converters (CSCs). The high cost of CSCs is justified as a tradeoff for reliability and robustness. The demanding environmental conditions posed by typical refinery systems require durability, and thyristor-based load commutated inverters (LCIs) are the preferred drives for medium-voltage multimegawatt applications.

The paper shares a study on the effects on ac power system dynamic behavior caused by the inclusion of large LCI motor drives. The usual practice is to study the dynamics of drives by a reduced equivalent model, such as static loads. The static load is not an equivalent representation of drives for all dynamic stability scenarios. For example, a fault at the terminal of a drive can gate off the valves if the voltage is beyond a certain threshold.

This paper discusses the impact of drives on power system dynamics and the required level of modeling to study the impacts on system stability, protection, and power management systems (PMSs).

II. BACKGROUND

A. Industrial Facility Power System

The industrial facility (further addressed as "facility") discussed in this paper has a bulk electric power system (BEPS) connection, and the grid's online generation capabilities are roughly the same size as the facility. Thus, the utility link is a weak system interconnection. The facility is further subdivided into plants that can operate independently, if necessary, with their own onsite generation. The system load in the present facility is approximately 70 percent direct connected motor load and 30 percent electronic (constant power) load. A recent expansion adds several adjustable speed drives (ASDs) with a total of more than 30 percent load to the existing plant. The ASDs are LCI-based drives with back-to-back converters and a dc link.

The simplified one-line diagram of the power system is shown in Fig. 1. The facility's power system is distributed across several plants, each with their own generation and loads. A power exchange happens through the central substation. The facility further connects to the utility through the point of common coupling (PCC) in the central substation. The generator and load distribution across the facility create a large number of event contingencies. For example, the loss of a transmission line between plants with drives results in a load rejection of about 150 MW. Further, the loss of two generators by itself is a severe event that can significantly affect the local BEPS. This facility employs a power management scheme to handle many such complex contingencies.

B. PMS Solution for Stability

PMSs restore the normalcy of the facility after unintended events, such as faults, loss of transmission lines, loss of generators, or loss of interconnections between substations. Many similar events usually cascade from N-1 contingencies to N-2 or more within tens of milliseconds. The PMS protects the facility by taking necessary actions, such as load shedding, generation shedding, or islanding from the grid [1].

The various PMS functionalities can only be validated on a power system model that replicates the behavior of the facility. The level of detail in power system modeling depends on the type of study, and the study itself depends on the purpose and problem. The power system shown in Fig. 1 is modeled in the real-time hardware-in-the-loop (HIL) simulation system. The components of the HIL setup are the power system controllers, such as the load-shedding controller, generation-shedding controller, and relays for decoupling system while the microgrid power system (including LCI drives) were modeled in the simulation software. The make, communications and logic algorithms are the same which were implemented in the field. The HIL setup helped test the control system algorithms in real time. Although all power system components are modeled in detail, the objective of this paper is to discuss the LCI system modeling and its dynamic impacts on the power system.

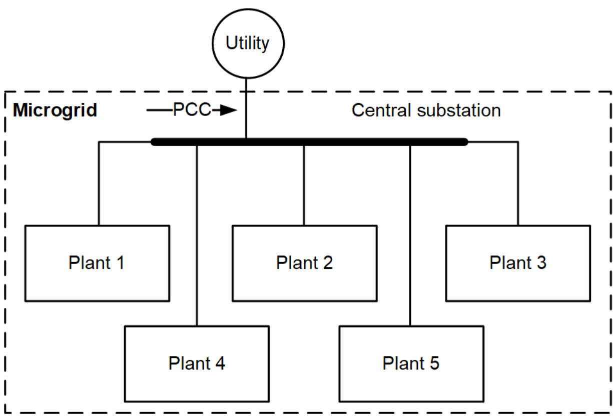

Fig. 1 Power System One-Line Diagram

III. DRIVE SYSTEM SIMULATION

The LCI drive is a back-to-back inverter configuration with an inductor as the dc link [2]. LCI is a current source inverter, as the inductor provides a source of stiff current. The drive one-line diagram is shown in Fig. 2. The drive model contains power system and control system details.

A. Drive Power System Model

The power system aspect of the drive comprises a four-winding transformer, filters, converter, dc link, inverter, multiphase synchronous motor (SM), motor excitation system, and motor load.

1) Multiphase SM

The six-phase, four-pole SM used in this application mitigates some mechanical and electrical resonance challenges. Reference [3] provides details on multiphase SM modeling. The machine zero-sequence impedances are often ignored for transient stability studies, but they have a significant impact on multiphase SM current and voltage waveforms. The zero-sequence impedances cause circulating currents between the converters and are usually dealt with during the design stages of the machine. The mechanical load is modeled as a fixed torque load attached to the SM output shaft.

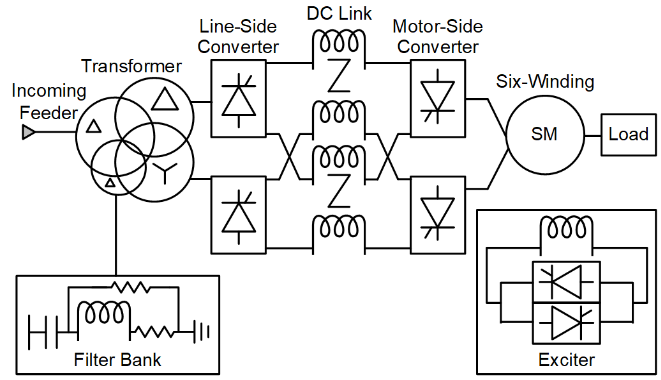

Fig. 2 LCI Drive One-Line Diagram

2) Four-Winding Transformer

The four-winding transformer serves as magnetic isolation between the ac power system and the LCI ASD system. This transformer has a three-phase winding on the incoming ac voltage side, another three-phase tertiary winding for the harmonic filter circuit, and two three-phase windings for a connection to the LCI ASD. The two LCI ASD windings are wound to provide a 30-degree phase shift between two separate LCI ASD converter sets. These two three-phase windings at a 30-degree offset create the six-phase power input to the LCI ASD. The two LCI ASD are then wound to individual three-phase inputs on the six-phase SM.

The winding data for a four-winding transformer are typically provided as short circuit data, where impedances are provided as leakage inductance between two windings with the other two windings shorted (Z_{12}, Z_{13}, Z_{14}, Z_{23}, Z_{24}, and Z_{34}). The conversions to individual winding impedances (Z_a, Z_b, Z_c, and Z_d) can be obtained from (1) through **Error! Reference source not found.** [4].

$$Z_a = \frac{Z_{12} + Z_{14} - Z_{24}}{2} - K_3 \tag{1}$$

$$Z_b = \frac{Z_{12} + Z_{23} - Z_{13}}{2} - K_3 \tag{2}$$

$$Z_c = \frac{Z_{23} + Z_{34} - Z_{24}}{2} - K_3 \tag{3}$$

$$Z_d = \frac{Z_{34} + Z_{14} - Z_{13}}{2} - K_3 \tag{4}$$

$$K_1 = Z_{13} + Z_{24} - Z_{12} - Z_{34} \tag{5}$$

$$K_2 = Z_{13} + Z_{24} - Z_{14} - Z_{23} \tag{6}$$

$$Z_e = \sqrt{K_1 \cdot K_2} + K_2 \tag{7}$$

$$Z_f = \sqrt{K_1 \cdot K_2} + K_1 \tag{8}$$

$$K_3 = \frac{Z_e \cdot Z_f}{2(Z_e + Z_f)} \tag{9}$$

3) Filter Bank

The filter bank on the transformer tertiary is designed to prevent harmonics on the line side from escaping the LCI. The filters used at this facility prevent 5th-, 7th-, 11th-, and 13th-order harmonics. It is important to properly model the source, transformer, and SM impedance, because small changes in impedance can change filter performance.

4) LCI DC Link

The LCI dc link model is a combination of inductances that model the self- and mutual inductances of the real LCI [2]. Fig. 3 shows the dc link characterization, while **Error! Reference source not found.** and **Error! Reference source not found.** show the voltage and currents across inductances derived using basic electric circuit equations in Laplace frequency domain.

$$V11 - V12 = 2 \cdot (Rdc + s \cdot Ldc) \cdot Idc1 - s \cdot 2 \cdot Mdc \cdot Idc2 \quad (10)$$

$$V21 - V22 = 2 \cdot (Rdc + s \cdot Ldc) \cdot Idc2 - s \cdot 2 \cdot Mdc \cdot Idc1 \quad (11)$$

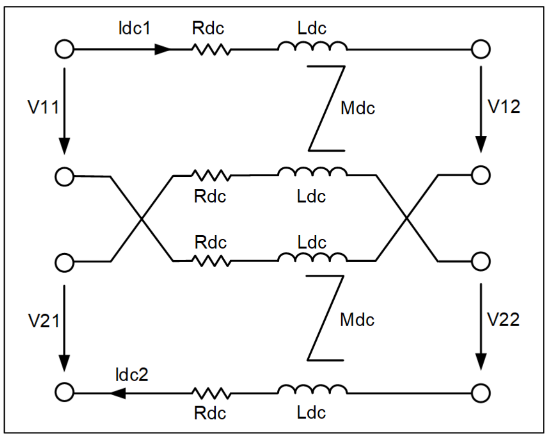

Fig. 3 DC Link Characterization

5) Converter and Inverter Model

The line- and motor-side converter models need a firing input that switches the thyristors on. The thyristors then naturally commutate off (switch off) at the natural ac voltage zero crossing. Snubber circuits then provide a short circuit path for momentary inductive kickback events. Models, therefore, need accurate snubber circuit data. Snubber circuits also act as damper circuits for numerical oscillations, naturally present in a full difference equation solution of the HIL environment.

6) Excitation System

The automatic voltage regulators and brushless SM excitation system are modeled to maintain the voltage on SM terminals. This provides natural zero crossings for the thyristors to commutate off. The polarity of the voltage induced by the excitation system must match the inverter voltage circuit to avoid overcurrent protection tripping the SM.

B. Drive Control System Model

The drive control system is primarily a twofold inner current control and outer speed control, as shown in Fig. 4 [5]. The input to the line-side converter (LSC) and machine-side converter (MSC) is a firing pulse signal that determines the conduction angle across the thyristor. The angle reference to the LSC is obtained from a phase-locked loop (PLL) on the line side, and reference to the MSC is obtained from a PLL on the motor-side bus. The MSC firing control loop is similar to the LSC firing control loop shown in Fig. 4. The firing angle is calculated based on the modulation signal from the current controller.

The input dc current measured across the LSC (I_{dc_LSC}) is the variable to be controlled, and the reference dc current ($I_{dc}Set$) obtained from the speed controller is the set point to be reached. The error between the set point and actual current is the input to the proportional integral controller managing firing angles. Similarly, the physical rotor speed obtained from an encoder is controlled by raising or lowering the LCI dc bus reference. The six-winding SM speed reference is controlled by a plant process control system. All of these control loops are modeled in the HIL environment.

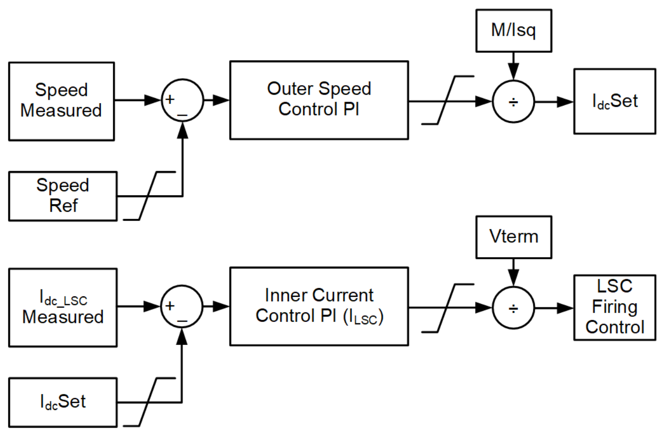

Fig. 4 Drive Control System

IV. DRIVE SYSTEM VALIDATION

The LCI drive model is connected to an ac power source and tested for various perturbations. The results are compared to the manufacturer-provided data. Fig. 5 and Fig. 6 show the voltage and current waveforms on the SM terminal compared to the manufacturer curves under steady-state rated load. The curve alignment with manufacturer data validates the ratings, steady state, and harmonic characteristics of the model developed, which further confirms the behavior of the six-winding SM, four-winding transformer, and the switching sequence of the converter.

Fig. 7 shows the current waveform comparison on the two windings of the SM, 30 degrees apart. The notches at the end of waveforms can be smoothed out by not considering zero sequences in modeling. The team increased the third-harmonic zero-sequence impedances and reduced the fifth-harmonic zero-sequence impedances to a low number to obtain a match on the manufacturer-supplied data plots.

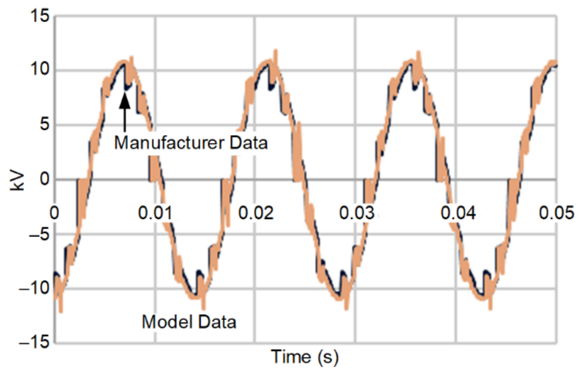

Fig. 5 Line-to-Line Voltage Comparison on Motor Winding 1 Terminal

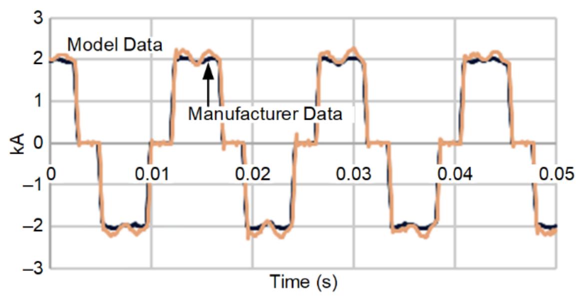

Fig. 6 A-Phase Current Comparison on Motor Winding 1

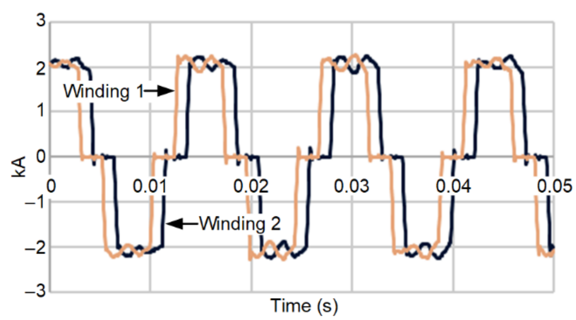

Fig. 7 Currents on Windings 1 and 2, 30-Degree Phase Apart

V. LCI ASD PROTECTION AND OPERATION CHALLENGES

A. Special Considerations for LCI ASD Protection

The feeder connecting the LCI ASD has several components needing protection individually and as a unit. Each LCI-based ASD feeder has an input transformer, harmonic filter, LCI drive, and motor connected to the load. An additional feeder was in the design to facilitate bypass switching for certain applications, such as soft starting. The input transformer to each LCI is a four-winding transformer requiring multiple types of protection elements ranging from differential (87) to distance elements (21). The complete protection for an LCI ASD feeder for the same facility, is discussed in detail in [6]. The significant lead time on replacement of four-winding transformers justifies an advanced protection system, which requires multiple, multifunction protective relays for each LCI lineup. If any of these protective relays trip, this will trigger an LCI ASD to go offline through a specific sequence of events. Tripping the large LCI ASD causes a sufficient excess of local generation on the facility that requires generation curtailment and possibly tripping. The timing requirements were challenging to prevent ac power system instability, as the LCI ASD shutdown process requires almost 2 seconds.

B. Special Considerations for a Facility PMS

Special considerations must be made when designing a PMS control system that has many large LCI ASDs. These considerations are particularly important for facilities with limited utility connections. The PMS must be able to rapidly reduce onsite generation to prevent a reverse power event at the utility PCC.

LCI ASD on a facility will commonly be the same model from a single manufacturer. This commonality can lead to common points of action and failure. For example, they can share a single undervoltage set point, which will stop the LCI ASD at the same time. When an individual LCI ASD stops, it will limit the impact to the plant power system, but when many ASDs stop simultaneously, it can cause a significant system event. Because of this, the PMS needs to be designed for the individual plant LCI ASD controller, and it needs to be able to rapidly reduce power production in the case of an event, such as losing all LCI ASDs.

Some ASDs include an automatic restart after a momentary fault event clears. It is important that the PMS be designed to detect situations when a restart is possible. For example, an ASD may stop commutation when a restart is possible but open upstream breakers during a full stop event. In this case, the PMS should not act on the commutation but should act on the upstream breaker opening.

The action taken by the PMS following a persistent loss of a significant number of LCI ASDs depends on the ac power system design. The action may also depend on whether the event occurs when the grid is connected or islanded. Running back (curtailing) generator sets (gensets) is a method of providing a new power and frequency set point for the genset to reduce power safely and rapidly. However, in applications that require a faster response, generation shedding (tripping) is required.

Generation shedding incurs the risk of overshedding, leading to an underfrequency or a cascading load-shedding event. Generation-shedding schemes (GSSs) should be designed to prevent this situation. One solution is to use an optimal selection technique to select sources for shedding as opposed to a predefined sequential selection scheme. Large genset power runback events incur the risk of a turbine flame-out; in this situation, the single shaft industrial turbines lose the ability to produce torque. One way to mitigate flame-out risk is to run back groups of gensets by a small amount, rather than a single generator by a large amount.

Load-shedding signals are carefully sent to LCI ASDs through load-shedding schemes. Load shedding is done to offload the gensets. Load-shedding signals typically require a high-speed signal to stop commutation rather than a command to open the breaker directly. An improper stop sequence can lead to damaging the LCI ASD.

C. Impact on Out-of-Step (OOS) Protection

The industrial power system is connected to the BEPS through a high-impedance link of buffer transformers, represented as the PCC link in Fig. 1. This high-impedance link makes the system susceptible to losing synchronism during adverse frequency voltage-related events.

The sudden loss of an LCI ASD produces excess generation within the system, causing it to export all the excess power to the system through these links for a short period of time. The voltage drop across the PCC link is high enough to trigger the OOS protection and isolate the system from the utility. PMS is designed to limit the number of corner cases that trigger OOS tripping and subsequent islanding from the BEPS.

VI. System Dynamics with Drives

The facility power system is validated once individual components (such as gensets and LCI) are validated against the manufacturer-provided data. The transient stability challenge for critical industrial systems is more dynamic than it is for utilities due to the complexity of the loads, process, and gensets. Once a facility is islanded, frequency and voltage excursions can be severe. The range of test cases for an industrial facility PMS differs compared to utility BEPS PMS. The disturbances considered in this paper are confined to test stability problems related to LCI ASDs.

From a steady-state power and frequency perspective, an LCI ASD can, in some cases, be modeled by constant power load models. Different manufacturers have different ratings on thyristors or other power electronic switches to protect them from transient surges. The thyristors in this plant gate off when the bus voltage drops below 80 percent and turns back on when the voltage exceeds 85 percent. Since the drives are closely located and the impedance between plants is not significant, any fault that dips the voltage below 80 percent impacts all the drives.

For example, for a three-phase fault that drops the voltage below 80 percent, all parallel connected LCI ASDs gate off at once and restart if the protective relay clears the fault fast enough. A properly isolated three-phase fault causes a momentary 330 MW load rejection on the entire facility, dramatically impacting power flow and system frequency.

Fig. 8 and Fig. 9 show the impact of a three-phase fault on genset speeds across several plants. Fig. 10 shows the impact on the tie-line power and voltage angle disturbance between the facility and utility grid due to the three-phase fault. Fig. 11 shows the power flow upset for one genset and one LCI ASD. The drive active power goes to zero during a fault, whereas the SM connected driven by the LCI ASD slowly ramps down speed. The reactive power across the drive transformer rises quickly due to the large capacitance in the circuit.

The dynamics reflect the instability caused by the drives when thyristors switch off for a drop-in voltage. If the voltage recovers slowly because of the genset automatic voltage regulator limitations, the response becomes more catastrophic, which leads to the loss of synchronism and a system-wide blackout. The disturbance magnitude can be sufficient to trigger OOS protection and separation of the facility from the BEPS.

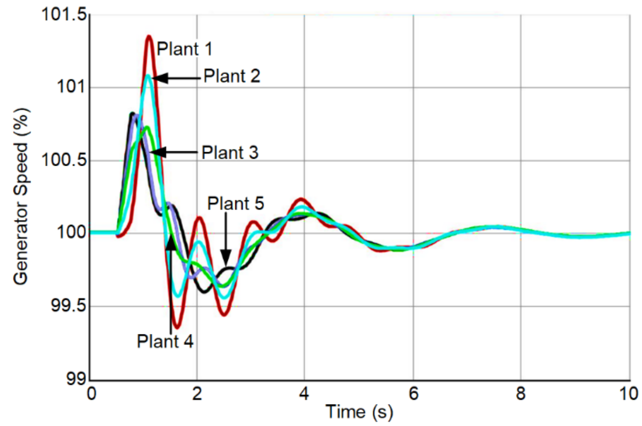

Fig. 8 Generator Speeds in Various Refinery Plants

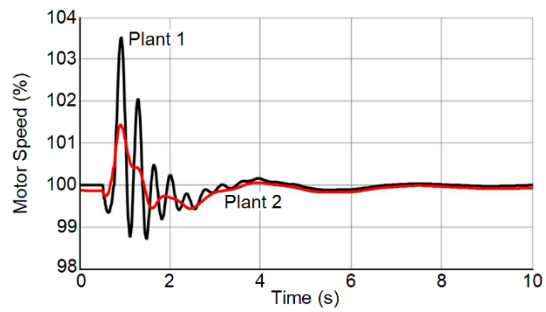

Fig. 9 Motor Speeds in Refinery Plants 1 and 2

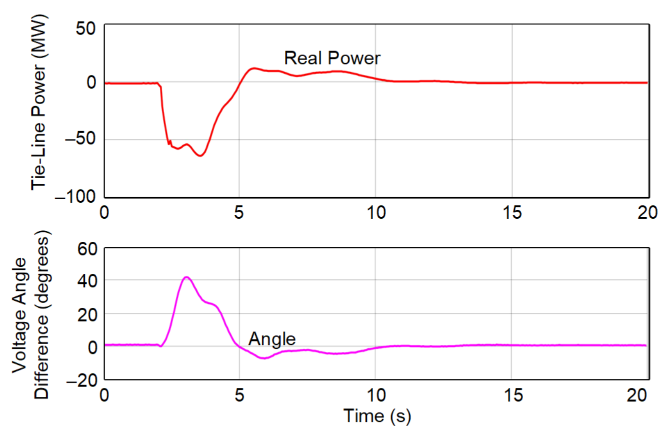

Fig. 10 Impact on Tie-Line Power and Voltage Angle After a Three-Phase Fault

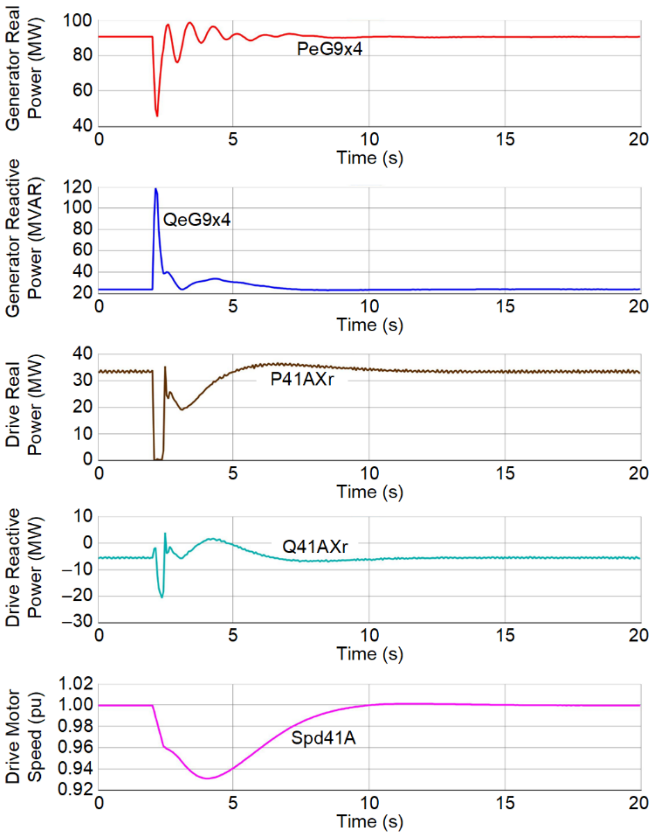

Fig. 11 Genset and LCI ASD Electrical Power Production and Consumption

VII. GSS SOLUTION TESTING

HIL testing has proven to be very successful in functional testing of PMS controllers. Large LCI ASDs add another level of complexity for PMS controllers, so it is even more important to validate PMS controllers with accurate real-time models.

Fig. 12, Fig. 13, and Fig. 14 show the system response to the same three-phase fault with and without GSS operation, where the system frequency, tie-line power, and voltage angle difference across the PCC are plotted respectively. The case with no GSS controller action results in instability, which is evident in the voltage angle difference measurement. This would have caused an OOS trip of the PCC, but it was disabled for this test. The case with GSS controller action mitigates the disturbance on the grid, and the GSS with generator shedding quickly brings frequency back to nominal.

Comparing the following plots, we observe that the system stabilizes faster with generation shedding; however, GSS runback takes longer to settle but without taking any generators offline. Usually a combination of both these GSS solutions is implemented after studying it through HIL testing.

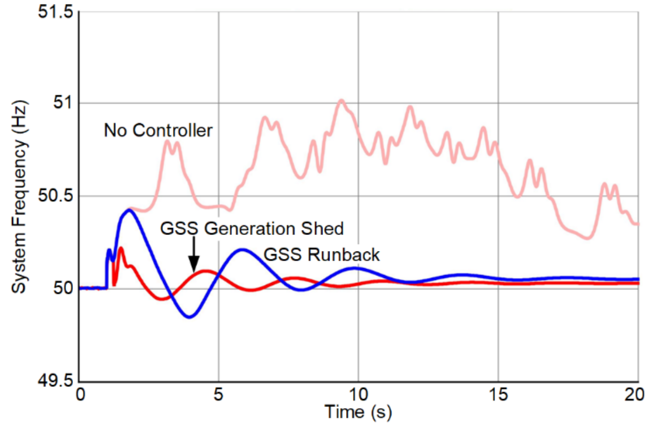

Fig. 12 System Stability With and Without GSS Controller (System Frequency)

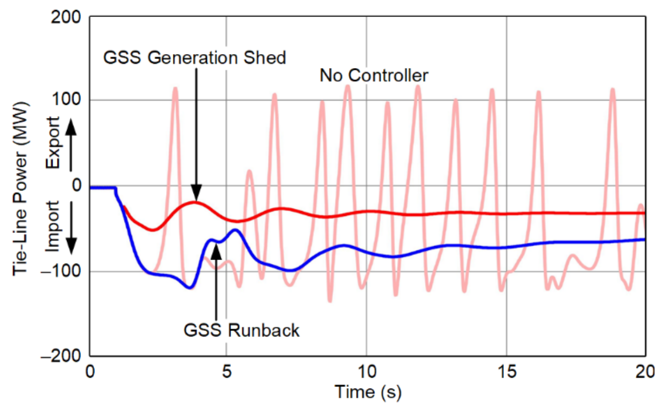

Fig. 13 System Stability With and Without GSS Controller (Tie-Line Power)

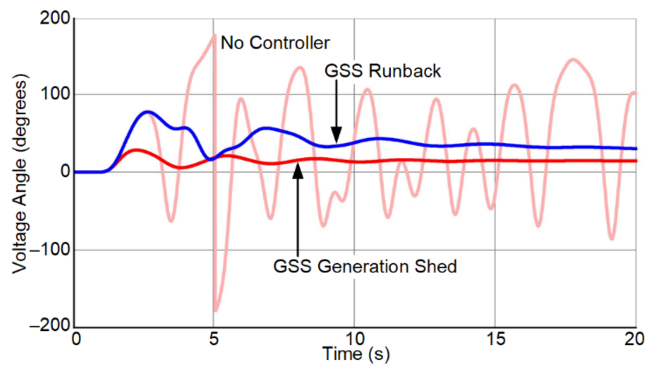

Fig. 14 System Stability With and Without GSS Controller (Voltage Angle)

VIII. CONCLUSIONS

The dynamic interaction of an ac power system and large LCI ASDs was simulated by developing an accurate HIL model, depicting the electrical, control, and mechanical systems. LCI ASD protection features can result in severe unplanned contingencies and can be mitigated by a PMS.

The following situations should be carefully considered around usage of large LCI ASD:

1. Normal LCI ASD self-protection and operation can cause significant ac power upsets.
2. The substantial loss of the LCI ASD load can trigger grid disturbances beyond the facility PCC and can result in facility islanding from the BEPS.
3. Generator shedding and runback solutions are effective at keeping the power system stable and avoiding blackouts.

IX. NOMENCLATURE

Idc	DC current across DC link.
Ldc	DC link inductor inductance.
Mdc	DC link mutual inductance.
Rdc	DC link inductor resistance.
V11, V12	Voltage across LSC1 and LSC2.
V21, V22	Voltage across MSC1 and MSC2.

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XI. VITAE

Asad Mohammad received his BE in electrical engineering from Andhra University, India, in 2011 and MS in electrical engineering in 2017. He previously worked as a substation design engineer and has been working as a power system studies engineer at Schweitzer Engineering Laboratories, Inc. (SEL) since 2017. He has been a member of IEEE since 2015.

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Scott Manson received his MSEE from the University of Wisconsin–Madison and his BSEE from Washington State University. Scott is a fellow engineer at Schweitzer Engineering Laboratories, Inc. (SEL). Scott is a registered professional engineer in six states and holds 25 patents.

Previously presented at the 70th Annual Petroleum and Chemical
Industry Technical Conference, New Orleans, Louisiana, September 2023.

20230406 • TP7093