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provide an overview of the unique challenges of designing electrical supply systems for e-LNG plants and outline specific measures for addressing harmonic disturbances and ensuring stable power.

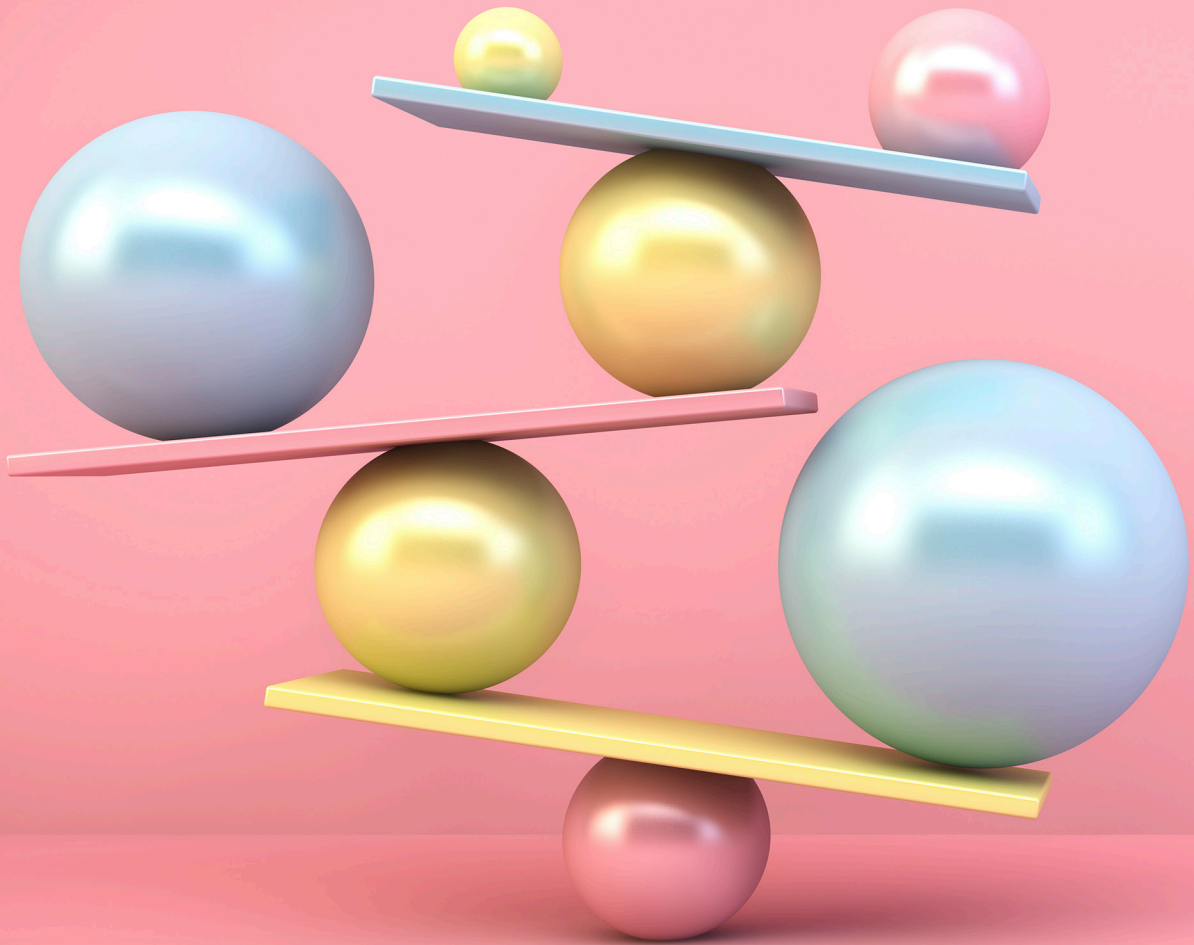
ENSURING STABLE POWER

With the growing focus on sustainability, it is becoming increasingly evident that the future of natural gas liquefaction is electric. e-LNG opens new possibilities for decarbonising the liquefaction process, while making plant operations more efficient, flexible, and reliable.

The energy efficiency of a typical gas turbine-driven main refrigerant compression (MRC) train is around 40%, whereas electric motor-driven trains have up to 95% efficiency. Despite the advantages, developing an e-LNG facility's power supply system presents unique technical challenges that are somewhat new to developers, given the industry's past reliance on mechanical drives. This is particularly the case for large capacity plants that require complex electrical infrastructure in a smaller footprint.

One specific concern that must be addressed very early on is harmonic distortions in the electrical system caused by the large power loads of the MRC trains and variable speed drives (VSDs). Failure to understand the impact of transient scenarios and implement proper mitigation measures can lead to disruptions in the electrical supply (whether from the utility or self-generated). As a result, utilities (i.e., grid operators) require e-LNG facilities to adhere to stringent power quality and power factor regulations.

Ensuring compliance can be challenging, as traditional VAR compensation technologies used for



power factor correction are bulky, slow to react with limited control capability, and expensive to maintain. Newer technologies, such as frequency converters, have been used to develop modular static synchronous compensator (STATCOM) solutions that have a much smaller footprint, can react rapidly and precisely to maintain high power factors, and provide additional benefits in terms of reliability and lower maintenance costs.

Designing electrical supply networks for e-LNG plants

The liquefaction process consumes a large amount of energy. To liquefy 1 kg of natural gas, around 0.25 kWh of electrical power is required. For a 5 million tpy liquefaction facility, this translates to roughly 140 MW of power supply (not including grid losses). For an 18 million tpy plant, as much as 800 MW could be needed.

While many of the e-LNG plants in operation today are supplied by self-generated power using dedicated gas and/or steam turbine generators (i.e., microgrids), an increasing number of developments are considering grid connections to capitalise on clean energy sources, such as wind, solar, hydro, and nuclear. Others are considering hybrid designs, using a combination of on-site generation and 'across-the-fence' power from utilities. Hybrid configurations offer the potential for the e-LNG facility to export power to the external grid under low utilisation conditions.

The type of electrical source and its distance from the plant significantly influence the design of the electrical system. In all cases, transmission and distribution infrastructure is required to feed power from the generation source to the liquefaction plant.



Figure 1. A typical high-voltage switch-yard.

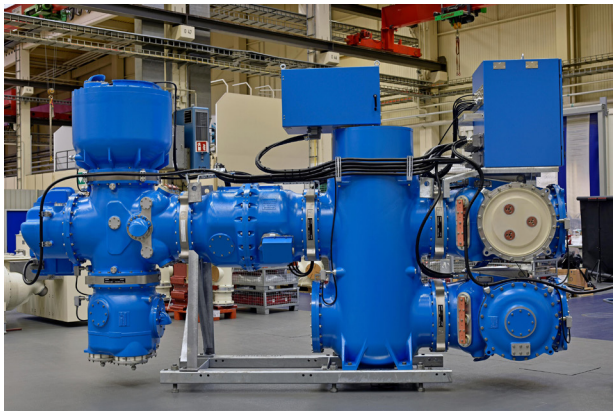


Figure 2. Gas insulated switchgear (132 kV).

This includes transmission lines, step-up and step-down distribution transformers, high-voltage switchgear, compensators, and remotely monitored and controlled protection devices and/or relays.

Generally speaking, as the power supply increases, so does the complexity of the electrical system. It is not uncommon for 132 kV or higher transmission lines to be used as feeders to e-LNG facilities (Figure 2).

Interactions and feedback from various consumers in the system mean that each component must be carefully selected and designed to ensure that power remains stable under all operating conditions. Maintaining high power quality is critical in this regard. Power quality can be affected by various events and component behaviour within the distribution network (e.g., switching speeds, arc flash and short circuit management and protection, lightning, voltage recovery speed, etc.)

Transient conditions caused by the start-up or shutdown of large induction electrical motors and VSDs (with either LCI or VSI converters) driving MRC trains can also impact the power quality of the supply network. For many e-LNG plants, electrical motors (ranging in size from 35 – 85 MW) can represent as much as 90% of the plant's overall electrical demand. The harmonic distortions they create upstream and downstream (particularly in the case of LCIs) can lead to several undesirable effects, including:

- Overheating of transformers, motors, and other electrical equipment.
- Voltage distortion, leading to malfunctions in sensitive electronic equipment and reduced power quality.
- Resonance in electrical systems, leading to excessive current flow and equipment damage.
- Power losses, leading to reduced efficiency and increased energy costs.
- Non-compliance with power quality standards, resulting in potential fines and legal liabilities.

The importance of grid studies and dynamic modelling

Harmonics and electrical system stability are issues that the LNG industry needs to become more deeply familiar with, given its history of mechanically driven MRC trains. As a result, stakeholders often tend to view e-LNG development as a simple driver swap (i.e., replacing a gas turbine with an electric motor). However, the reality is far more complex.

Performing grid studies and dynamic modelling is crucial to predicting how electrical systems will behave under the various operating conditions of the e-LNG plant, including during faults and transient scenarios. The objective is to develop a digital twin of the plant's electrical infrastructure to be tested and optimised before physical implementation.

Grid studies involve analysing the entire electrical supply system – from the generation source to the LNG facility's point of consumption. Studies normally encompass a steady-state (i.e., static) analysis of the network and, for complex distribution systems like those required for e-LNG plants, dynamic modelling, and simulation.

Static models provide the advantage of being able to rapidly develop the guidelines for the design of an electrical system and

reduce the complexity of the modelling effort. These studies are helpful in the early design phases to decide and evaluate the basic design requirements needed for the electrical system. For grid-connected plants, available power from the utility is a limiting factor, as it will dictate the size of the electrical motors that can be used. Performing a power flow analysis early on is critical in this regard, as it can help with sizing the electrical components to ensure adequate current rating and load capacity, which affects the facility's design and cost.

Dynamic modelling can then be used to evaluate the design with much more detail and understand the interactions between the various components within the electrical network. The inherent complexity of creating dynamic models for electrical components and configuring models for bespoke developments requires time and intensive engineering effort. As a result, dynamic modelling is typically only utilised after the basic design of the electrical network has been finalised.

Despite the effort involved in dynamic modelling, ensuring that the electrical network remains stable and safe under all circumstances, both during normal operation and under fault conditions, is crucial.

The interactive capability of such models, combined with the use of electromagnetic transient simulation engine (or EMTDC) analysis, allows for the accurate prediction of harmonic disturbances in the plant's electrical network. Electrical providers can then use this information to determine mitigation measures to provide stability and maintain compliance with grid regulations.

Options for addressing harmonics

Several options are available for addressing harmonic effects in electrical systems. Static var compensators (SVCs) have been widely used in industrial applications for reactive power compensation, enhancing voltage stability, and mitigating flicker. However, when it comes to mitigating harmonics in e-LNG plants, SVCs have several disadvantages.

One drawback is the potential of SVCs to alter the system's resonant frequencies. Their integration into an electrical system changes the inductive and capacitive balance, inadvertently setting the stage for harmonic resonance. This phenomenon can amplify certain harmonic frequencies and limit motor operation at specific speeds, which is undesirable. The harmonics also pose risks to equipment and degrade power quality.

Additionally, addressing harmonics in e-LNG plants often requires going beyond the capabilities of SVCs, necessitating the deployment of additional filtering solutions, such as passive or active harmonic filters. This complicates the harmonic mitigation strategy and escalates costs in terms of equipment, footprint, and maintenance expenses. As more and more e-LNG facilities are planned for offshore installation, the footprint of equipment becomes a significant consideration. The requirement for supplementary filtering solutions underscores the limitations of SVCs in directly confronting harmonic disturbances.

A STATCOM, on the other hand, is a type of reactive power compensation device used in electrical power systems to regulate voltage and control reactive power. It is a flexible and dynamic solution designed to compensate for fluctuations in voltage and reactive power caused by varying loads and changing system conditions.

Historically, STATCOMs have been viewed as more sophisticated and expensive than traditional solutions like SVCs, making them less economically viable, especially for smaller or



Figure 3. Example of a modular STATCOM.

cost-sensitive applications. In recent years, however, the use of new silicon-based VSD technologies, coupled with increased modularisation and standardisation, has reduced costs, and minimised the complexities associated with bespoke developments.

Modular STATCOM technology is available across the entire power range, and is especially advantageous for power consumers with ranges between 5 – 30 MW and offers rapid reaction times, along with additional benefits in terms of reliability and maintenance costs vs SVCs (Figure 3). Until recently, very few VAR compensation options were available for consumers of this size. Newer STATCOM solutions are especially relevant for e-LNG plants with plans or aspirations to harness electricity from intermittent sources like wind and solar, as they can assist in grid stability.

With advancements in VFD technology, VSI type/control technology is also being considered for large motors (>35 MW) to mitigate the adverse impact of harmonics and low power factor. Site-specific factors will ultimately dictate the choice of technology used to mitigate harmonic effects. In particular, the plant's location, layout, and available footprint must be considered and carefully evaluated before selection.

Conclusion

e-LNG continues to emerge as an attractive solution for decarbonising liquefaction and improving the efficiency and flexibility of LNG production. Compared to gas turbine-driven compression, electrical-driven compression can dramatically reduce the amount of energy consumed for each kilogram of LNG produced.

Capturing these benefits, however, requires stakeholders to adopt a holistic development approach that focuses on optimising the entire electromechanical system. This necessitates understanding the complex interactions and feedback between the motors and VFDs, and refrigerant compressors. Traditionally, the compressor original equipment manufacturers and electrical system provider have operated in silos, often with different approaches, leading to issues such as lower efficiency, unnecessary plant trips, and production downtime.

Given the complexity of these projects, it is advantageous for developers to select partners with the expertise to handle the equipment scope for both the compressor design and electrical system. Doing so not only minimises interface and execution risk but also facilitates the development of a robust electromechanical system design capable of ensuring stable power during all scenarios, including during steady-state operation, start-up/shutdown, and upset events. In all cases, project developers should prioritise early engagement with these parties, just as with the liquefaction licensor. LNG