OUTSHINE THE TURBINE

Eduardo DosReis and Manish Verma, TMEIC, USA, present the case for electrically driven motors as a more efficient, cleaner and cost-effective alternative to traditional gas turbines for powering compressors in LNG facilities.

uring the 2019 Gastech conference, one of the key recurring themes focused on the continued rise in demand for LNG imports in Asia. Since 2012, the US has been the world's largest natural gas producer and now exports its excess production. It was also mentioned that, in a few years, the US would export nearly as much as major gas producers such as Qatar and Australia.[1] In light of this, it is reasonable to expect an increase in the transportation of LNG on a large scale over long distances, and an increase in the

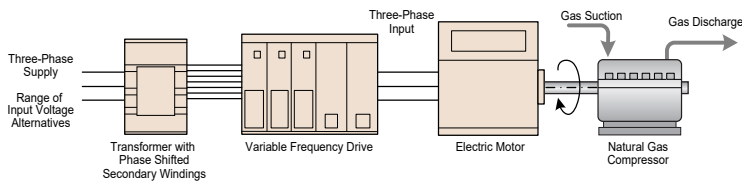**Figure 1.** High power motor variable frequency drive (VFD) system driving an LNG compressor.
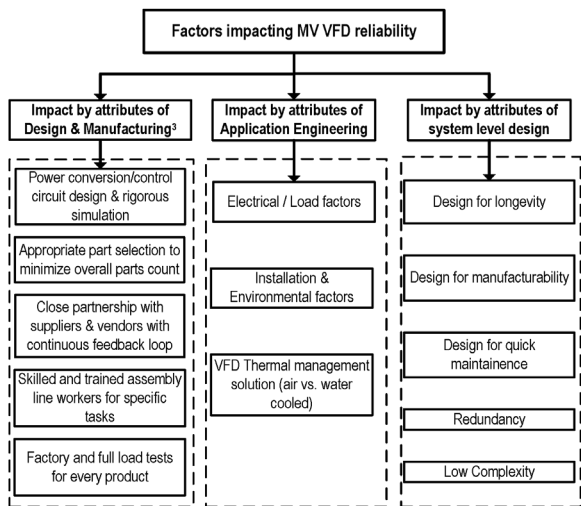

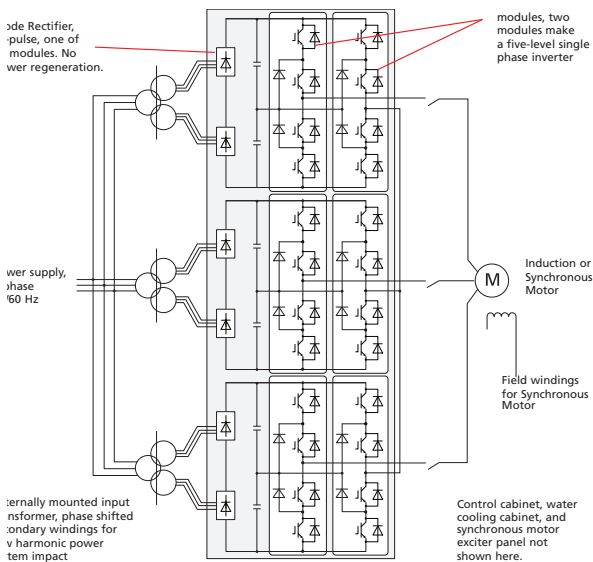**Figure 2.** Factors determining the reliability of large VFDs.

Figure 3. Configuration of a VFD using a small number of silicon devices.

use of very large gas compressors. For the best utilisation of cargo, large compressors ranging from 10 to 70 MW are used to compress gas to 1/600th of its initial volume.

Many of the large LNG compressors in use today are driven by gas turbines. These offer acceptable reliability, as well as the convenience of using some of the gas being compressed as a fuel source. However, burning gas as fuel releases nitrogen oxides (NO_x) – a family of poisonous, highly reactive gases known to cause asthma.[2] This hazard presented by NO_x prompted the US Environmental Protection Agency (EPA), on 6 April 2018, to retain, without revision, the current national ambient air quality standards (NAAQS) for oxides of nitrogen.[2] Taking this into account, large capacity electric motors, powered by variable frequency drives (VFDs), can offer a solution to help localities to reduce NO_x concentrations, and to manage their compliance with emissions and environmental regulations. Indeed, the primary benefit of electric motor-VFD systems is that they can be used to drive large compressors without directly burning fuel.

More uptime and higher efficiency

The facts above and the steady development of power semiconductors have revealed the advantages of using the electric motor-VFD system. For example, an electric motor-VFD system, as depicted in Figure 1, permits controlling flow and pressure through speed control and can improve the power factor of the power supply. Concerns with regards to harmonics have been addressed with proper isolation transformers and by the continuous development of VFD technology.

As with all new technology, or a new application of an existing technology, some operators are cautious about using the electric options of a motor-VFD system. Most reservations about the use of electronic apparatus and VFDs have origins in bad experiences caused by procurement decisions, misapplications and maintenance difficulties due to the intrinsic quality of the VFD. Conversations often start with the question, "how reliable is the VFD?", and, naturally, the invoking of the word 'reliable' elicits many responses. The two most relevant questions are whether the system can operate uninterrupted between planned shutdowns, and, in the case of unplanned maintenance, how soon the system can return to production? These concerns are swiftly put to rest by a comparison of the upside and performance of the motor-VFD system with that of a gas turbine.

A motor-VFD system provides more uptime than a gas turbine, thus it is less expensive to own. Furthermore, a motor-VFD system boasts superior efficiency compared to a gas turbine: 97% versus 20 – 40%, respectively, depending on the load and temperature.[4] Table 1 shows some quick cost comparisons of a gas turbine and an electric motor-VFD. The comparisons do not reflect the costs with precision, but they are effective in highlighting the proportions.

In terms of LNG production, unplanned and long interruptions can cause losses of thousands of dollars per hour, not only due to maintenance costs, but due to loss of revenues at a rate of US$1 million per day.[5]

Reliability is defined as the probability that a product or service will operate properly during its lifespan, under intended operating conditions. It must be intrinsically designed into the product (in this case, into the VFD).[6] At the design stage, in the name of 'building-in' reliability, significant effort is expended to ensure longevity, manufacturability and ease of operation and repair.

Besides the intrinsic quality of the design, the manufacturing practices and the correct application of the VFD are also determinants of reliability (as summarised in

Figure 2). For example, Figure 3 shows the configuration of a high power VFD, designed and built with three power modules, each employing eight medium voltage rated injection enhanced gate transistors (IEGTs); a total of 24 silicon devices.

In order to deliver the same power, another VFD topology, such as a cascade H-bridge, would use 42 power modules connected in series with four low voltage insulated gate bipolar transistors (IGBTs), each totalling 192 IGBTs. Fewer IEGTs results in a more reliable VFD, as there are fewer silicon devices to fail and hence less complexity. An example of assured quality during the design phase, leading to reliable equipment, is the use of press-pack IEGTs (PPI), as illustrated in Figure 4[7] and Figure 5. In the PPI, in addition to the reduced number of devices, the full contact between IEGTs makes them less vulnerable to thermal fatigue, and a hermetically sealed structure provides high resistance to the effects of environmental contaminants, such as moisture, humidity and dust. If necessary, the PPI can be water-cooled for greater heat transfer.

Many electrical connections between the semiconductor devices and the heat sink are housed inside the PPI and the IEGT stack, thereby eliminating many cables and connectors in the VFD. This quality, intrinsic to the design, delivers many desirable characteristics. It creates ease of access for maintenance and inspections, reduces the inspection points for loose connections, and reduces the problems caused by weak electrical contacts. The quick and user-friendly changeover of a stack-based power module restores production with as little downtime as possible.

VFD reliability is expressed in terms of the mean time between failure (MTBF). For water-cooled VFDs that are commonly applied to LNG compressors, the MTBF can, in some cases, exceed 38 years.

A VFD is a system of components connected in series, thus the failure of one component will result in the failure of the VFD. Since each component can fail independently of another component, the reliability of the VFD can be represented by the multiplication of the reliability of each component. Since there are many components, the reliability can be estimated using the reliability of some key modules such as the diode assemblies, power module assemblies, etc. The reliability of the VFD will be less than the reliability of the least reliable module:

$$R_{VFD}(t)= R_{M1}(t) \times R_{M2}(t) \times ....\times R_{Mn}(t)$$

Where 'R_{VFD}' is the reliability of the VFD, and 'R_M' is the reliability of each module. For example:

$$R_{VFD}(t) = 0.999 \times 0.999 \times 0.99 \times 0.998 = 0.986$$

Other than intrinsic reliability, redundancy can be built in many configurations with the increased number of components. One form of creating redundancy is installing duplicate systems in parallel, known as hot redundant systems. In this configuration, the components or modules operate all the time, sharing the load. When a path fails, other paths continue to operate, ensuring power delivery. Only when all paths fail will the entire system fail. Because the parallel circuits run at the same time and share the load, they age equally and can be affected by large technical failures.

When the failing rates of each chosen module (F_M) have been accounted for and recorded, the reliability of the VFD can be estimated using:

$$R_{VFD}= 1 - [F_{M1}(t) \times F_{M2}(t) \times ....\times F_{Mn}(t)]$$

Where 'n' is the number of modules under consideration, 't' is the time of operation and 'F' is the probability of failure.

But, since failure rate can be expressed as $F_i(t) = 1 - R_i(t)$, where 'F' represents the probability of failure of the 'i[th]' module, and 'R_i' represents the reliability of 'i[th]' module, the reliability can also be calculated using:

$$R_{VFD}(t)= 1 - \{[(1 - R_{M1}(t)) \times (1 - R_{M2}(t)) \times ....\times (1 - R_{Mn}(t))]\}$$

There are other configurations of circuits or components in use in VFDs to create redundancy, as well as many combinations of redundancy methods, all of which add more components and complexity to the equipment.

When standby modules, circuits or components exist, the reliability can be calculated as:

$$R(t)= e^{-\lambda t} \sum_{i=0}^{n} \frac{(\lambda t)^i}{i!}$$

Where 'n' represents the number of standby modules or circuits or components, 't' represents time, and 'λ' represents the failure rate. When only one standby module, circuit or component exists, the expression becomes:

$$R(t)= e^{-\lambda t}(1 + \lambda t)$$

The same expression can be used when a whole VFD is used to standby for many other equal VFDs in a production facility, or the operation employing one VFD is supercritical.

VFDs are maintainable and, in most cases, preventive maintenance is economically viable and highly preferable over corrective maintenance. To plan for maintenance works, the uptime availability of the VFD can be used.

The uptime or steady-state availability is defined by:

$$A = \frac{MTBF}{MTBF + MTTR}$$

Where 'A' is the availability of the VFD, MTBF means mean time between failure, and MTTR means mean time to repair exclusively dedicated to the repair. In

Table 1. Maintenance costs of a gas turbine and a motor-VFD system

	Gas turbine[3]	Estimated costs	Electric motor-VFD	Estimated costs
Minor maintenance	Every 4000 – 8000 hr (6 – 10 days downtime)	US$23 000 – US$38 400	Every 8670 hr (excluding motor, 24 hr downtime)	US$5760
Major overhaul	Every 20 000 – 30 000 hr (30 days downtime)	US$115 200 every 3–4 years	Not required	US$0
Reliability (mean time between failure)	6 – 13 months	–	38 years	–
Repair time (mean time to repair)	0.5 – 3 days	US$11 520	30 min.	US$120

Notes: US$240 000 per hour of labour; 16 hours per day; no material; no travel and living; no overtime; one man.

other words, excluding, for example, waiting times for parts, tools and setup time. Figure 6 highlights steps accounted for as MTTR.

Over time, the availability of a VFD can be retained through weekly-monthly inspections observing the following:

- Changes in the installation environment, such as temperatures, appearances of dust, humidity and gases.
- Abnormal sounds or vibration in the transformer, or cooling fans.
- Unusual smells of insulating substances, peculiar to electric circuits failure.

In addition to regular inspections focusing on:

- Maintaining the interior of the cubicle and keeping the air filters clean.
- Looking for part discoloration, deformation, leakages of components, circuit boards and wiring.
- Checking for loose contacts and torque marks.

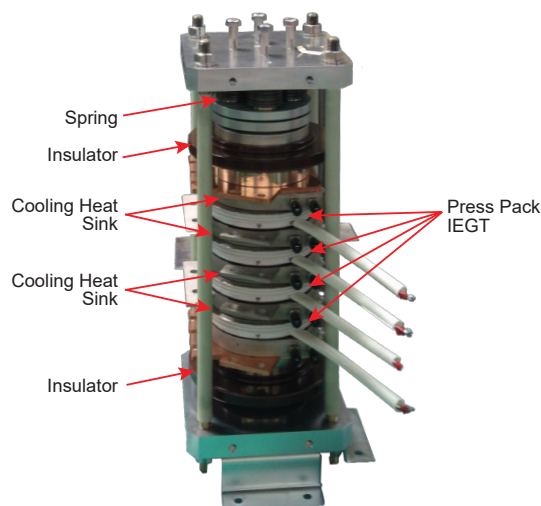**Figure 4.** Injection enhanced gate transistor (IEGT).[7]

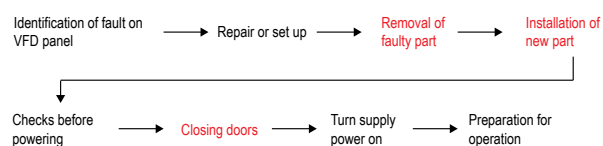**Figure 5.** Example of a PPI assembly (stack).

Figure 6. High-level repair process.

- Cleaning the main circuit and control circuit.

The difficulty of maintenance tasks depends on: the ease of access to the interior of the VFD; the number of parts and connections; and the intrinsic quality carefully built-in during the design stage.

To repair a VFD expeditiously, with minimal downtime, it is necessary to maintain an inventory of critical spare parts. However, not all parts can be repaired onsite, such as a power module, which is assembled in modules for quick changeover. In order to minimise the potential for lengthy disruption, it is recommended that a spare power module be stored onsite, in order to enable swift restoration of production.

Conclusion

Electrically driven compressors are the future of LNG facilities. Over time, wind and solar energy generation should reduce the cost of electricity to the extent that it falls below the cost of fossil fuel-based electricity generation.[8] Weighing this projection alongside the fact that the initial cost, added to the cost of ownership, of an electric motor-VFD system is substantially less than the cost associated with a gas turbine, establishes a compelling case in favour of the use of electric motor-VFD systems.[4] Furthermore, the pressing necessity to comply with environmental regulations is a significant incentive to drive demand for all-electric gas compression in LNG facilities.[2] Nevertheless, it remains necessary to employ due diligence when selecting an electric motor-VFD system for an LNG facility. The selection of a reliably configured electric motor-VFD system is crucial to ensuring that the greatest technological and economic benefits are reaped. **LNG**

References

1. Gastech 2019 post-show report, p. 21, https://www.gastechevent.com/media/42400/gastech-2019-post-show-report.pdf, (Accessed: 6 January 2020).
2. 'Primary National Ambient Air Quality Standards (NAAQS) for Nitrogen Dioxide', *United States Environmental Protection Agency*, https://www.epa.gov/sites/production/files/2018-04/documents/no2_naaqs.final_action.fact_sheet_4.6.18.pdf, (Accessed: 23 January 2020).
3. HOSODA, H., MAMUN, M. A., and YOSHINO, T., 'Trends in MW-rated VSI technology and reliability for adjustable speed drives', *2010 Twenty-Fifth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, (2010), pp. 1261 – 1265.
4. BLAIKLOCK, P., VERMA, M., BONDY, S., 'When should an electric adjustable speed drive be used instead of a gas or steam turbine', *TMEIC*, (8 February 2013).
5. 'Grassroots LNG Plant Increased Availability and Optimized Project Cost with Vortex Technology', *Emerson*, https://www.emerson.com/documents/automation/case-study-grassroots-lng-plant-increased-availability-optimized-project-cost-vortex-technology-rosemount-en-89230.pdf, (Accessed: 23 January 2020).
6. BORROR, C. M., 'The Certified Quality Engineer Handbook – third edition', *ASQ Quality Press*, (2008).
7. 'TMdrive®-XL75 Product Application Guide', *TMEIC*, https://www.tmeic.com/Repository/Others/TM-XL75_Product_Brochure_Ltr_LowRes.pdf, (Accessed: 11 February 2020).
8. SMITH, J. C., and CLARK, C., 'The future's energy mix, the journey to integration', *IEEE Power & Energy Magazine*, vol. 17, no. 6, (November – December 2019), pp. 16 – 23.