# Variable-Frequency Drives – Three perspectives

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**SUMMARY**

Variable-frequency drives (VFDs) are used for efficient control of AC motors in various electro-mechanical systems like pumps, fans, and compressors. It is expected that the use of VFD systems will increase due to their energy saving potential. However, there are certain challenges in securing continuous operation of VFDs in safety-critical systems. In a recent pre-study, based on a literature survey and interviews, three main challenges have been identified. These are, (1) New techniques for improved power semiconductor monitoring to meet rising demands on reliability when VFDs are applied in critical applications, (2) New techniques to model the electrodynamics of VFD systems to allow for EMC studies, (3) Adopting and developing international standards for software frameworks to allow for robust operation of VFD systems. These three main challenges are now addressed in a recently started multidisciplinary project including three PhD students and will continue until 2018.

**KEYWORDS**
Variable-frequency drives, safety-critical, operation, control, software, and EMC.

## 1. INTRODUCTION

Variable-frequency drives (VFDs) are used for efficient control of AC motors powering equipment such as pumps, fans, and compressors [1,2]. If the VFDs are part of the auxiliary power system to a facility/industry, it is essential that the drive also is dimensioned to handle disturbances on the grid. Otherwise there is a risk that even if the generator and the turbine can handle the disturbance, the auxiliary power system is disconnected due to the disturbance.

Also in energy production plants VFDs are increasing in importance and one can expect an increased political pressure in this direction due to potential energy savings. These drives are normally operated under stationary conditions with a relatively constant voltage and frequency at the connecting network. However, there are times when disturbances occur in the power grid which affects the voltage and/or frequency. In connection with these disturbances, it is essential that production plants continue to function in a satisfactory manner so that the delivery capacity is maintained [3]. Disturbances in the power grid may be due to several factors such as short circuits, connection and disconnection of components and loads. If the plant is operated alone or with a few other production facilities, separated from the national power grid larger variations in voltage and frequency can be expected.

Actual tests of drives in industrial environments seem not to have demonstrated a remarkably high sensitivity to interferences. In [4], it was investigated why motor drives at a sewage plant tripped a number of times per year. Harmonic levels were measured and it was noted noted that transients occurred at certain switching operations, but it was concluded that the reason for the problems were due to incoming voltage transients from the 130 kV network, and that some type of external voltage stabilizing equipment was needed (but was too expensive to be justified). In [5], the economic aspects of different measures were considered. In neither of the two cases studied were UPSs considered to be economical, while replacing the access point in the grid to a higher voltage level with fewer dips in both cases was considered economically sound. In [6] it was concluded that problems with activated voltage protection circuits were due to a system design error. In that case, a breaker would cut the power when a protection circuit observed that certain conditions were met. However, the power to the breaker was not from an uninterruptible power supply, so at relatively small dips the breaker tripped even if the protection circuit was unaffected. From the literature study, it may be noted that the industry seems quite confident that dips and short interruptions are the main cause of unwanted tripping of drives.

According to [7], lightning strikes causes at least 60% of all dips and short interruptions. According to the same survey, material and equipment failures caused only 3% of the registered dips/short interruptions. How long a voltage dip lasts depends on how quickly the fault can be disconnected. Faults are usually disconnected faster in networks with higher voltages. Longer distances to the faults will usually result in a smaller, but longer voltage reduction. Faults in the national networks are normally disconnected within 50-100 ms, corresponding figures for the regional network is 100-200 ms [8]. As a comparison, SvKFS 2005:2 [9] provides requirements for robustness against disturbances for large and medium/small energy production plants indicating that voltage dips to 0% and 25%, respectively, over 250 ms, in the former case, followed by a gradual, otherwise direct, return to 90% of nominal voltage must not affect the ability of the plant to deliver energy to the grid..

## 1.2 TESTING OF DRIVES

IEC 61800 collect standards for various aspects of drives. Part 3 specifies electromagnetic compatibility, which here include demands for tolerance to variations in input voltage . It provides tolerance to interference in 3 levels:

> A - No observable impact, torque variation within specification, the power semiconductors unaffected, communication with external devices unaffected.
>
> B - Observable effects that are automatically reset, torque outside specification that is reset after the variation, and temporary impact on the power semiconductors that can not cause undesired shutdown of the drive is allowed. Temporary impact on the communication with external devices but no reporting of errors that can cause shutdown.

C - Shutdown or other changes in device operation requiring manual reset is allowed. Also reduction in the delivered torque that is not automatically returned to the normal level and communication errors with external devices are allowed. In contrast, no stored program or settings may be lost.

It stipulates that the equipment shall be able to manage an input voltage deviating from nominal voltage levels by ± 10% continuously and +10 to -15% for one minute with the tolerance level B. For tolerance Level C, dips with a voltage reduction to 0%, 40%, 70% or 80% of nominal voltage for 1, 10, 25 and 250 periods are specified. Also tolerance for the case that the power returns relatively quickly after a break is included in the Level C requirements. This has been formulated as tolerance to 250 times of voltage reduction to 0%. It is noted that these requirements have weakened (from a dip tolerance standpoint) from previous versions, where +1 kV-equipment had to manage voltage reduction down to 50% power for up to 100 ms (Level B). Other requirements include "total harmonic distortion" (THD) at a maximum of 8 or 12%, depending on the network type and ± 2% frequency variation for level A.

For comparison, we note that the standard for general electromagnetic compatibility for industrial environments IEC 61000-6-2 require the above, but also that equipment must cope (level B) with complete loss of voltage for one period.

The literature that focuses on drive immunity for dips and short interruptions usually mentioned the harder (general) industry standards. A frequently cited industry standard is SEMI F47-0706, developed by the "Semiconductor Equipment and Materials International", an industry association of equipment and materials for semiconductor manufacturing and related industries. This standard require that for the reduction of the supply voltage to 50%, 70% or 80% under 10, 25 and 50 periods should not affect the equipment and also recommends that the reduction to 0% for one period or 80% for 10 seconds does not affect the equipment. According to [7], only 16% of the dips were more than SEMI F47-0706 details.

The requirements the above standards set for continued operation without operator intervention, and the demands of SvKFS 2005:2 are plotted in Figure 1. As can be seen, the IEC standards are not as strict as the SvKs requirements while SEMI F47-0706 is closer, but not valid throughout. The figure used tolerance level B as necessary tolerance of equipment that in the short term must continue to work to ensure continued energy production. For other equipment, tolerance level C may be sufficient. It should be noted that SvKFS 2005:2 specifies the voltage at the connection point to the external grid. Depending on how the plant's internal power supply is designed, this can correspond to far more moderate variations in the facility's internal network. In at least one case, a larger energy plant has nevertheless chosen to apply this voltage profile as the specification at the connected equipment.

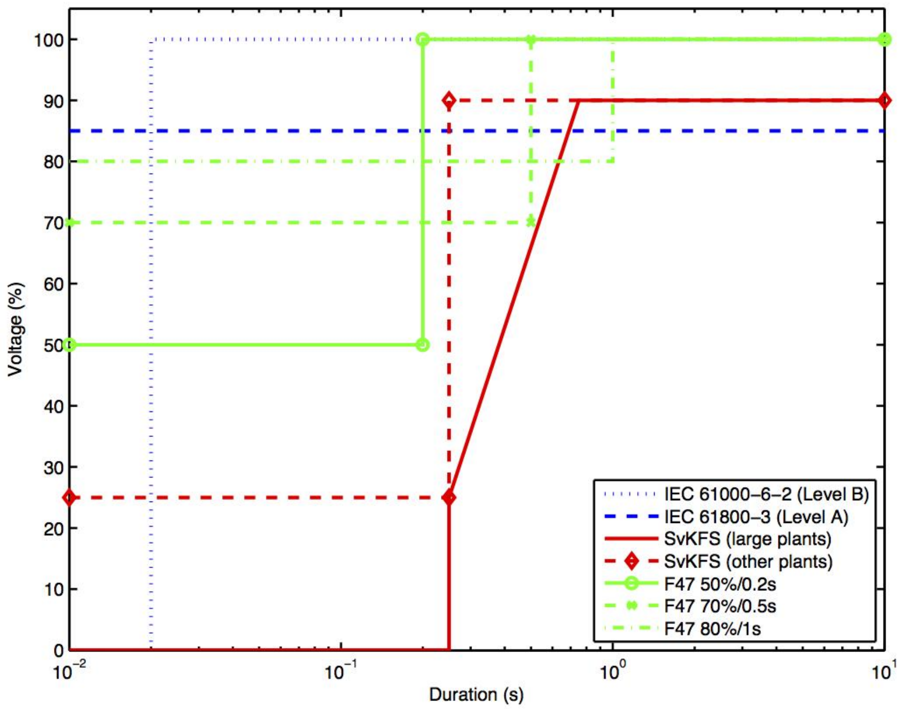


Fig. 1. Limiting lines for voltage dips/interruptions that equipment must withstand without operator intervention under different standards and requirements SvKFS 2005:2 prescribe for energy production plants. Unlike IEC 61800 as only specifies a minimum load of 85% (at most 1 minute) as a requirement for continued operational level A, IEC 61000-6-2 requires that the equipment shall meet (level B) up to 20 ms, with complete loss of power. SEMI F47-0706 specifies several test case which gives rise to 3 different curves. Only one is applied at a time, and the interference must stop within the limits of the same test.

The above standards require actual product tests for dips and short interruptions shall be performed in accordance with IEC 61000-4-11 (and for >16 A IEC 61000-4-34). One can consider using these as a reference when specifying more stringent requirements. Tests according to this standard can directly describe requirements for small and medium-sized plants (25% remaining voltage for 250 ms). The voltage step that the requirement for large plants have between interruptions and gradual return is however not directly addressed in this standard, but well the gradual return.

## 2. SURVEY ON OPERATIONAL AND RELIABILITY ISSUES WITH DRIVES

We asked a number of energy producers about the different types of drives used in a typical production plant and the associated problems. It turned out that voltage source pulse width modulated drive preferably driven by low voltage was used (almost exclusively). One exception was the use of a load commutated current source inverter to power a large synchronous motor.

A common problem that many pointed out was that drives often led to a maintenance problem. The hardware lifespan and the time during which the replacement units sold is significantly shorter than that of a lot of other equipment in certain plants. The amount of software needed to configure all systems was a challenge to manage, especially in combination with the older software in some cases demanded older PC hardware. Also problems, to different degrees, with the harmonics generated by the input stages of drives were reported and drives that trips during the thunder season. Most of the interviewees expressed that they are careful to build systems with drives where it was not needed to meet the direct needs of controllability or soft start to protect the power grid or mechanical systems.

At two sites, it was noted that the problem of harmonics increased by the fact that high resistance grounding was used for the internal grid, as this means that you can not simply install regular EMI filters, but first have to use an isolation transformer to create supply with a neutral that can be connected to ground.

It is clear that the production plants have a problem with drives that occasionally trips for unknown reasons. To overcome this problem, at one site, harmonics are being measured and quantified in the internal distribution network every three years. This is already done for the 10 kV level, but the intention is to extend this to lower voltage levels. It is also suspected that incoming transients from the 40 kV level can be a reason for the observed problems.

At least one power plant operator refrained from using automatic drive restart after tripping (from whatever reason) until someone had looked over the equipment to avoid damage to equipment, whereas another operator always had their equipment configured to restart automatically after blackouts.

## 3. CURRENT PROJECT

To further investigate three interesting tracks discovered in the pre-study, a research project was defined containing the following areas:

**3.1** *Monitoring of power semiconductor devices*. To meet rising demands on reliability when VFDs are applied in critical applications, improved power semiconductor monitoring is required. Parameters such as on-state voltage, switching time, gate voltage, and temperature can be used to identify and predict chip related failures, e.g. electrical overstress or ESD damages, as well as package related failures, e.g. bond wire lift off or solder joint failures [10]. Current work in the project puts focus on techniques for improved performance in temperature measurement. The desired temperature to be measured is often the actual temperature of the high voltage, high power, silicon device. Here, the installation of a measurement device on or adjacent to the high power device faces stringent isolation requirements. One possible solution to the isolation challenge which is under investigation in the project is the use of short range RFID communication. The measurement device is equipped with an on chip loop antenna. Power supply as well as data transfer is thereafter enabled by the use of a second antenna integrated in the substrate or printed circuit board on which the power device is mounted. This solution will enable temperature measurements previously not possible, and thus facilitate improved monitoring of the power semiconductor.

**3.2** *Improved electromagnetic modeling capabilities.* From the survey, reported in Sec. 2, it was obvious that electromagnetic compatibility (EMC) is a challenge for VFD systems. Both from regulatory side, observing Fig. 1, but also from practical point of view considering the grounding problems reported. Therefore, this project will focus on these aspects. One possible outcome is and updated set of requirements to complement Fig. 1. To capture the electromagnetic behaviour of the system, both measurements and simulations will be employed. For simulations, equivalent circuit based techniques will be explored since both cables, filters, and VFDs could be expressed in this type of framework. So far, cable models have been investigated and a new method to study multi-conductor transmission lines based on a Green's function approach has been proposed [11].

**3.3** *Software frameworks.* Robust operation of VFD systems requires dependable and verifiable software implementations. One way to achieve this is by adopting and developing current international standards, for example IEC 61113 or IEC 61499. A first study on the upcoming IEC 61499 standard has already been conducted, focusing on reliability and real-time properties of embedded (control) software existing tools (both from academia in industry) [12]. In particular we find that existing solutions are inappropriate, due to their heavy resource requirements and lack of real-time support, in effect precluding the application to small embedded systems, such as upcoming intelligent sensors and local embedded controllers in distributed systems. To this end, we propose an alternative approach that allows a device level IEC 61499 models to translated into efficient executables for light-weight targets (such as the ARM-Cortex based micro-controllers commonly used in embedded devices). Execution is controlled by the RTFM-kernel, which provides an outset for reasoning on resource requirements and real time properties. Furthermore, the proposed approach addresses ambiguities in the IEC 61499 standard, while still remaining standard compliant. This in turn, gives a formal underpinning to verifying behavioural properties, thus is a step forward towards establishing correct by design solutions to critical control systems.

## 4. CONCLUSIONS

It is expected that the use of VFD systems will increase due to their energy saving potential. However, there are certain challenges in securing continuous operation of VFDs in safety-critical systems. This project is set out to improve reliable operation of VFDs in energy production plants. The approach is to develop (1) New techniques for improved power semiconductor monitoring, (2) New techniques to model the electrodynamics of VFD systems to allow for EMC studies, (3) Adopting and developing international standards for software frameworks to allow for robust operation of VFD systems. The project will run until 2018 and employ three PhD students focusing on the same problem, from three different perspectives.

## 6. ACKNOWLEDGEMENT

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## BIBLIOGRAPHY


[1] B. K. Bose, "Power Electronics and Motor Drives Recent Progress and Perspective". *IEEE Transactions on Industrial Electronics* 56(2): 581–588, 2009.

[2] P. Waide and C. Brunner. (2011). "Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems". IEA. Retrieved 2014-03-12. Online: www.iea.org/publications/freepublications/publication/EE_for_ElectricSystems.pdf

[3] Kärnkraftsäkerhet och Utbildning AB, "Operating Experience from Swedish Nuclear Power Plants", Tech. Rep., 2008. [Online]. Available: http://www.ksu.se/wp-content/uploads/2011/05/Engelsk-2008.pdf

[4] M. V. Petersson, "Mätningar och undersökning av elkvaliteten i elnätet på reningsverket GRYAAB, i Göteborg," Master's thesis, Chalmers Tekniska Högskola, 2008.

[5] M. Didden, "Application Node - Voltage Dips: Case Study," European Copper Institute, Tech. Rep., 2011. [Online]. Available: http://www.leonardo-energy.org/sites/leonardo-energy/files/Cu0125_Voltage%20dips%20Case%20Study_v1.pdf

[6] M. Aroovatanaporn, "Circuit Breaker Tripping in a Semi conductor Plant Caused by Voltage Dips," European Copper Institute, Tech. Rep., 2009. [Online]. Available: http://www.leonardo-energy.org/sites/leonardo-energy/files/root/pdf/2009/CaseStudyCircuitBreakerTrippinginSemiconductorPlant.pdf

[7] U. Johansson et al., "Förberedande kartläggning av spänningsdippar i olika typer av nät" ELFORSK, Tech. Rep. 4-43, 2004.

[8] E. Thunberg, "Teknisk beskrivning av spänningsdippar och korta avbrott" ELFORSK, Tech. Rep. 4-41, 2004.

[9] SvKFS 2005:2, Affärsverket svenska kraftnäts föreskrifter om allmänna råd om driftsäkerhetsteknisk utformning av produktionsanläggningar, 2005. [Online]. Available: http://www.svk.se/Tekniska-krav/Foreskrifter/

[10] S. Yang, D. Xiang, A. Bryant, P. Mawby, L. Ran, and P. Tavner. "Condition monitoring for device reliability in power electronic converters: A review.", *IEEE Transactions on Power Electronics*, 25(11):2734-2752, 2010.

[11] M. De Lauretis, J. Ekman, and G. Antonini, "Delayed impedance models of two-conductor transmission lines", accepted for *EMC Europe*, Gothenburg (SE), 2014.

[12] P. Lindgren, M. Lindner, A. Lindner, J. Eriksson, and V. Vyatkin, "RTFM-4-FUN", accepted for *IEEE International Symposium on Industrial Embedded Systems (SIES 2014)*, Pisa (IT), 2014.