ECPE Position Paper

on

Power Electronics and Digitalisation (Smart-Inverter)

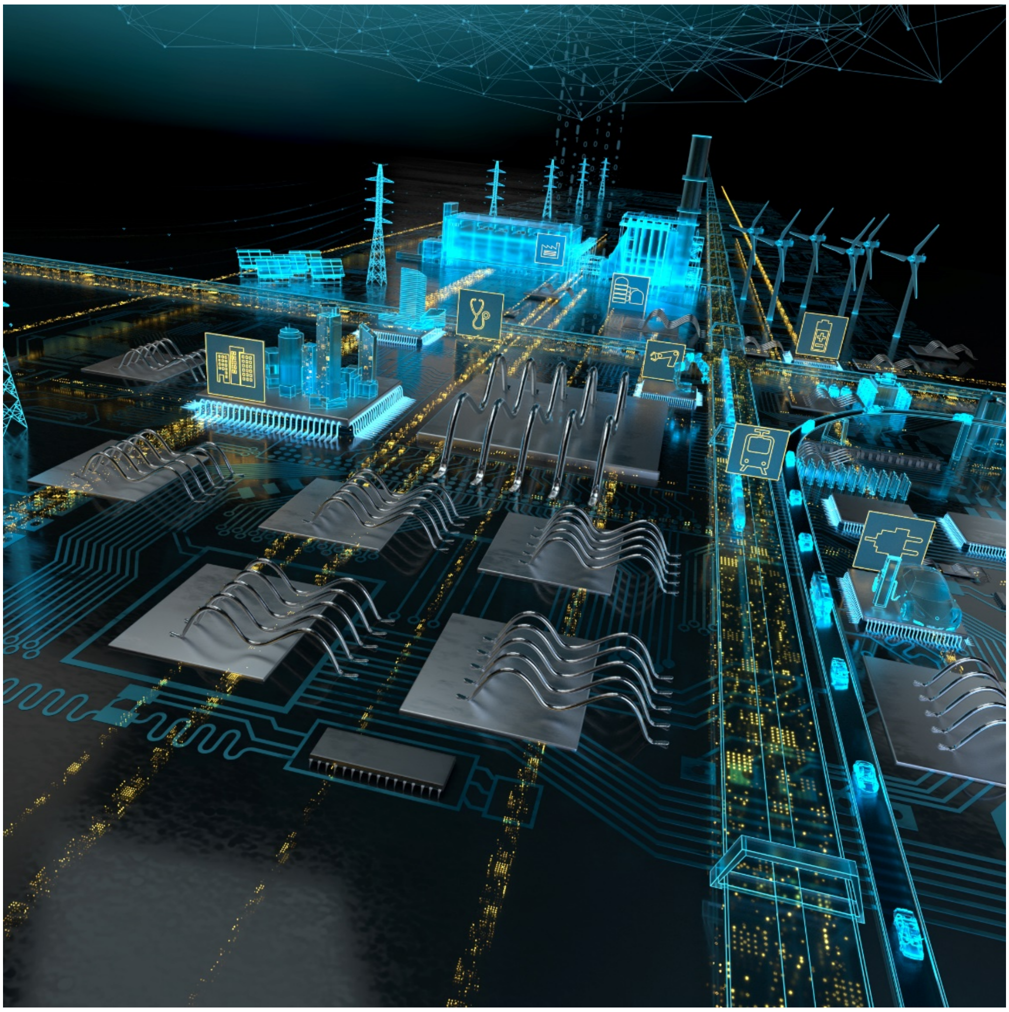


Image courtesy of Siemens

Focus: Industrial drives/industry automation (Industry 4.0)

Topics: Smart-Inverter, software-defined inverter, digital twin, condition monitoring, prognostics, lifetime prediction, Artificial Intelligence, machine learning, big data

Table of Contents

Table of Contents 2

1. Introduction 3

1.1. What is Digitalisation and what does a “Digital Twin” achieve? 4

1.2. What are “Intelligent- or Smart-Inverters”? 5

2. Identified benefits and targets for Smart-Inverters utilising Digital Twin technology – State-of-art and future requirements 6

2.1. Sensor fusion and quality/quantity of data measured and stored 7

2.2. Intelligent data processing and Artificial Intelligence (A.I.) 7

2.3. Condition monitoring and prognostics 8

2.3.1. Converter/Inverter monitoring 9

2.3.2. Motor monitoring 10

2.3.3. Energy supply/down-stream user monitoring 11

3. Problems identified as technology hurdles for early adoption of Smart-Inverters and digitalisation 11

4. Conclusions 12

5. References 13

1. Introduction

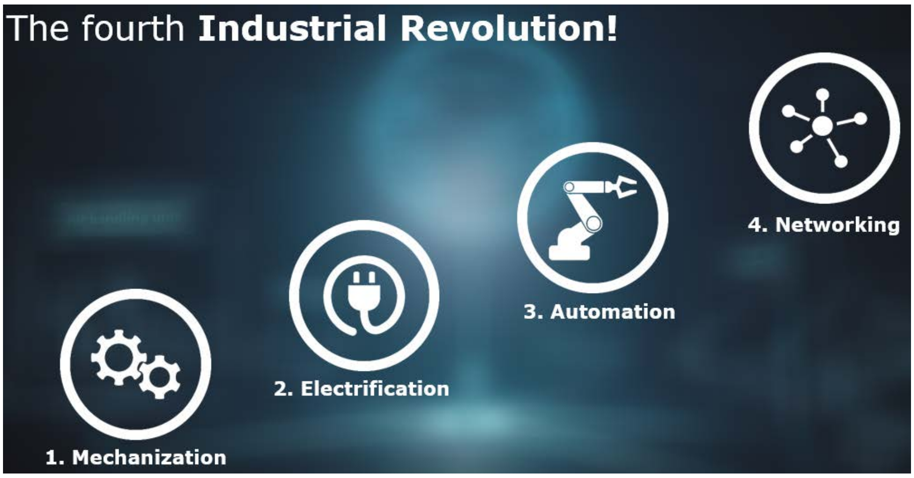


Fig. 1 Evolution of Industry 4.0
Image courtesy of Danfoss Drives

With the development towards Industry 4.0 (Fig. 1), the requirement for “Smart-Systems” and autonomy in industry drives and automation demands higher levels of intelligence from the power electronic systems used to facilitate correct power flow. With an estimated €36bn predicted to be spent on inverters and drive systems in 2022, academic and industrial research and development identifies the power electronic inverter as being the critical driver for Industry 4.0 in the coming years. The development of Power Electronic Building Blocks (PEBBs) has led to the ability to rapidly prototype and develop industry motor drives for a wide range of applications and power levels, but for true autonomy to be possible, the power electronic inverter must now be developed as a “Smart” unit - capable of not only adapting its operation to any electrical supply/load fluctuations, but also be self-configurable to account for changes in operational conditions. Such conditions include the ability to adapt to required circuit topology changes, whether customer-requested (application based) or because of fault conditions/damaged components (protection and reliability based). Improvements in efficiency may also be achieved through software-defined control of the topology and switching states of the semiconductor switches, whilst further modularity improvements may be incorporated with the ability to autonomously add/remove sensors and actuators to increase data collection and functionality of the system. This collection of data also affords the “Smart-Inverter” the ability to provide condition monitoring and lifetime prediction through Digital Twin concepts (digitalisation), allowing intelligent maintenance and end-of-life schemes to be formulated. In order to do this the requirements for on-board data storage, data manipulation and data communication become paramount, requiring intelligent data processors and connectivity technologies. Further, “Big Data” techniques will need to be required in order to fully exploit the capability of Artificial Intelligence that this “Smart-Inverter” would allow.

This Position Paper aims to identify which functionalities would be required in a “Smart-Inverter” as an enabling technology for Industry 4.0, based on current state-of-the-art and emerging developments explored in a recent Expert Discussion with leaders from academia and industry.

Despite the clear desire for energy efficiency, in a previous ECPE Position Paper [1], two other key drivers for the development of power electronics had been clearly identified for the new decade: **CO_2 reduction to stop the climate change and digitalisation.** It was also identified that the contributions of power electronics to the megatrend of digitalisation are manifold:

- Smart, self-learning systems in industry e.g. in automation

- In industry: distributed drives, DC grids for production plants
- Condition & health monitoring (Industry 4.0)
- Smart-grids including digital control and smart-meters
- Smart-homes, offices and stores incl. DC microgrids
- Power supplies for the digital infrastructure e.g. for data centre, base stations

From these identified contributions, the question of power electronics and digitalisation for use in Smart-Inverters with a focus on industrial drives are clearly covered by the first three topics.

1.1. What is Digitalisation and what does a “Digital Twin” achieve?

First conceptualised by Dr. Grieves in 2002 [2], the term Digital Twin was used to describe an entity having a physical product, a virtual product and the interconnections between the two products. In terms of a power electronic system such as an inverter for industrial automation, this digitalisation requires a physics-based model of the system (geometrical, electrical, thermal, mechanical etc) derived from known operational modes and real-time/historical data sets, in order to produce an ultra-fidelity simulation of that system from real-time input data taken from the physical system’s sensors (Fig. 2). The resulting simulation data can then be interfaced with the physical system in order to monitor and predict its states and behaviours determined by the set of use cases for which the digital twin is designed. The technique lends itself particularly to efficiency improvements, condition monitoring and prognostic estimates of the End-Of-Life (EOL) of the system components, but the process will require the collection, communication, storage and interpretation of large amounts of data depending on the complexity of the physical system and its use cases.

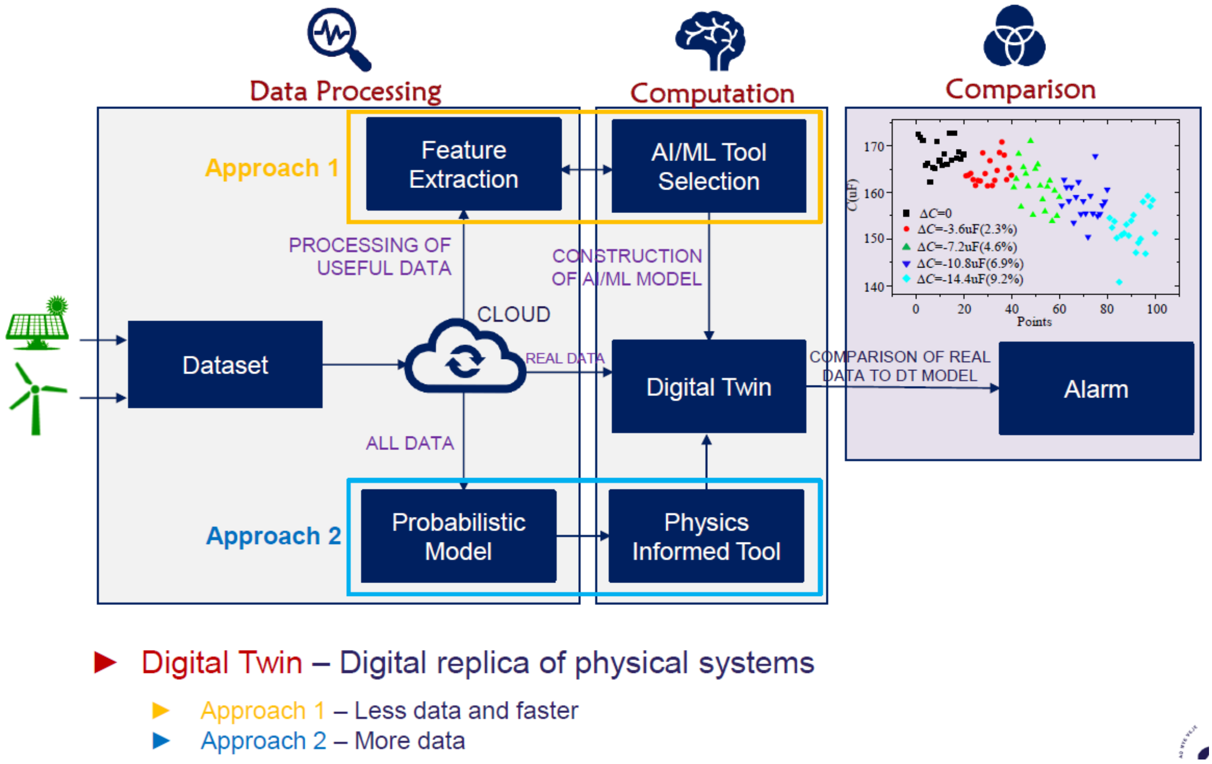


Fig. 2 Implementation of a Digital Twin for fault prediction [3]

The data required for a digital twin encompass real-time and historical information over the life of the physical system including design specification data, operational data and maintenance records, all of which need to be stored within the physical system or by cloud-based technologies for suitable interpretation by the previously mentioned physics-based modelling. In order for the digital twin to interact with the physical system, a series of interfaces allowing communication, control and visualisation of the desired system metrics could also be implemented depending on the desired level of modelling.

1.2. What are “Intelligent- or Smart-Inverters”?

In a traditional automated process, the fundamental function of the inverter is to control the motor output (speed or torque) by varying the electrical power supplied. In order to do this, there will be some form of sensing applied to the system that forms the mechanical load (process) on the motor (automation), so that some form of basic control (closed-loop feedback of the speed for example) can be applied. This makes the inverter the most important link between automation and process in order to achieve the desired system output – a constant speed process in this example. As long as the controller maintains a constant speed of the process, the functionality of the system is considered complete. Over the system’s lifetime, however, use cases and operation modes may change, components become worn or must be replaced with alternative technologies. This all requires operational changes and service intervals, stocking of spare parts and future-proofing the supply of these spare parts. By making use of the inverter as a sensor of the system as a whole (i.e. electrical supply, electrical drive, motor and load), the information that can be captured from the voltages, currents and temperatures etc. can be used in conjunction with other sensor inputs (in-situ or added after-market) as part of a digital twin concept to offer prognostics and condition monitoring, allowing efficiency benefits, prediction and mitigation of faults within the process, the automation (motor), the inverter itself and even in the electrical supply to the system.

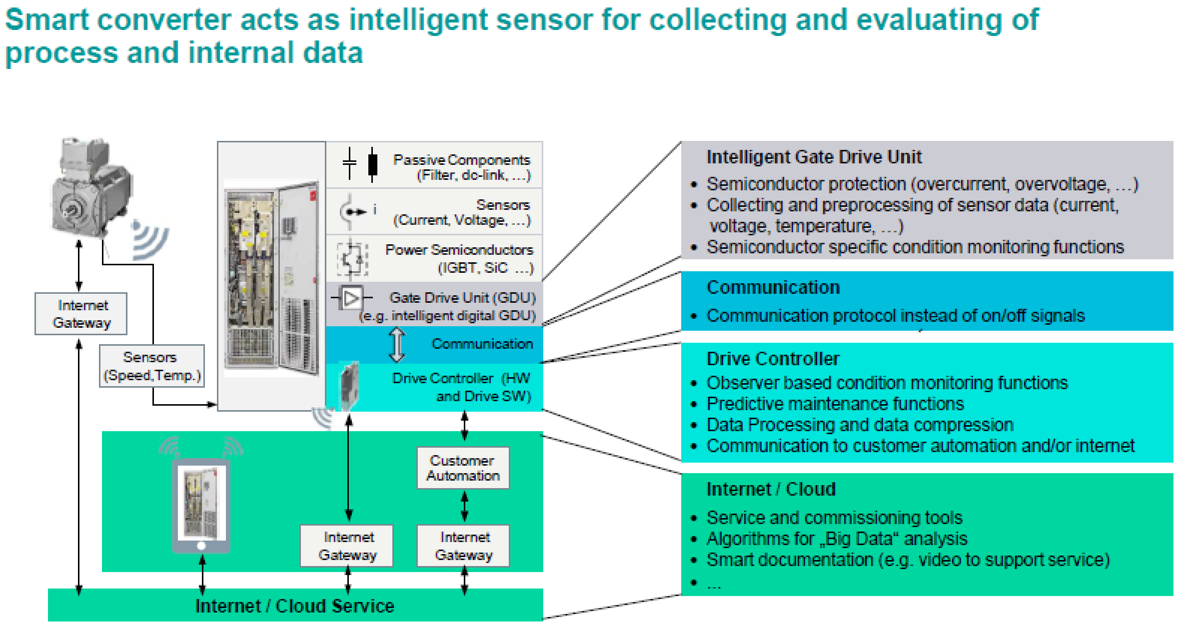


Fig. 3 Exemplary structure for a Smart-Inverter system
Image courtesy of Siemens

Fig. 3 shows an exemplary structure for a Smart-Inverter system. Some possible characteristics of the Smart Inverter structure and how Smart-Inverters will develop have been identified as:

- More intelligent use of sensors (in-built or added after-market):
    - Current, voltage, temperature, vibration (including acoustic), speed, torque, electromagnetic field and climate/humidity
    - Sensors with distributed intelligence (evaluation logic)

- Intelligent sub-components:
    - Intelligent Power Modules, Intelligent Gate drivers for “Smart” control but also estimation of device junction temperature etc.
    - Extended control procedures for known and new topologies for extended work processes and higher efficiency – capability of the system to reconfigure its operation to deal with customer specific operations, mitigate losses or work around failures

- Further use of communications – system bus, Powerline, wireless
    - Internal: Communication between assemblies and components i.e. between µController and sensors
    - External: Communication with equipment, supplies/loads, automation systems, control centres, storage centres e.g. hardware or Cloud-based

- Further use of internal and external data storage and “Intelligence”
    - Storage and evaluation of physical data (Voltage, current, frequency, power factor, THD etc.)
    - Necessary data-processing by Micro-Controller, FPGA etc. for power electronics (Intelligent Gate control, PWM, …) can take on additional system functionality
    - Mathematical methods to evaluate data – Fourier analysis, Kalman filter/observer techniques etc.
    - Optimisation of operating parameters
    - Co-simulation of physics modelling techniques whether on-board or in the Cloud
    - Analysis of trends, causal relationships, condition monitoring and prognosis e.g. Remaining-Useful-Life (RUL) or End-Of-Life (EOL) prediction
    - Machine Learning (ML), Artificial Neural Networks (ANNs) and other Artificial Intelligence (A.I.) techniques for condition monitoring and prognosis
    - Application/use of all of the above to provide a Digital Twin of the system

2. Identified benefits and targets for Smart-Inverters utilising Digital Twin technology – State-of-art and future requirements

Considering the desired functionalities of the Smart-Inverter listed above, there will be a cost implication associated with the necessary addition of intelligence, data storage, processing and communication. It is most likely then that the Smart-Inverter will be aimed at applications where high maintenance costs could be mitigated by suitable condition monitoring of components, or where high reliability is required e.g. safety-critical applications such as for HVDC, aerospace and automotive, where a component's EOL can cause expensive loss of operation or even loss of life.

With the increase in computational power and speed available in Clouds, localised microcontrollers and field devices, the availability of more data in less time leads to the capability of more extensive data analysis, opening the way for much wider use-cases, energy savings and the increasingly important development of prognostics. A disadvantage of this is the large amount of data requiring to be transferred, producing more intense communication at all levels and needing a rethink of communications and security protocols in industrial automation – moving away from centralised control to perhaps a more 5G approach with decentralised inter-system communication.

Discussion between experts from industry and academia highlighted the following key benefits and targets of the Smart-Inverter with Digital Twin:

2.1. Sensor fusion and quality/quantity of data measured and stored

Ideally a Smart-Inverter becomes the sensing system in the automation process, allowing data to be recorded from existing inverter sensors (current, voltage, temperature), but then allowing an intelligent use of this data to identify issues with the electrical supply, inverter, motor or even load. Some applications may require additional sensors such as vibration or electromagnetic field, but these sensors must then be supplied with power and connected to the data processing units incurring additional costs, implementation effort and failure probabilities.

Ideally, life-dependent environmental parameters could be interpreted by use of humidity and corrosion sensors, but whilst humidity sensors can provide a good dynamic response, corrosion measurements are usually cumulative and suffer from their lack of dynamicity.

Coupling a well-matched Digital Twin and data-fusion techniques together would allow information such as speed, torque, power and relative humidity to be interpreted through use of observer techniques (such as a Kalman Filter), avoiding the need for extra sensors. This data-fusion could require low latency and high-speed communication in fast-speed applications, but then careful consideration should be given to the resolution of data collected from each sensor. Further issues are encountered when implementing the data into the Digital Twin since the simulated outputs from the various modelling strategies then form part of the physical control strategy of the Smart-Inverter itself. Therefore, there is a need to execute modelling within a given time limit and the speed of the data capture, communication and processing (e.g. FPGA) becomes crucial for correct control methods. This can in turn govern whether data is stored and processed locally (i.e. within the Smart-Inverter) or using cloud-based systems incurring risk of cyber-threats in critical/high-reliability applications.

2.2. Intelligent data processing and Artificial Intelligence (A.I.)

Whilst dynamic operational waveforms can be measured or observed from the collected data, for a Smart-Inverter with Digital Twin to provide accurate information, key system parameters may also need to be estimated from the same data, but perhaps at a different resolution. Data selection and pre-processing becomes paramount to sensible estimation of parameters by observer or A.I. methods. Data visualisation can provide important insights about data quality and pre-processing techniques whether that means baselining or normalisation of the data (to account for initial wear of components etc.). Context information helps to make sensor data much more valuable, but it is sometimes not easily available to the Smart-Inverter manufacturer and requires close partnership with the customer / end user to develop a robust solution for data collection and pre-processing. Some techniques such as Fast Fourier Transform (FFT) may provide valuable information of fixed frequency machine operation, but less so for variable speed drives on motor technology where frequency changes with the speed.

For estimation of key system parameters or fault mechanisms (and their fluctuation with age / temperature, for example), statistical and machine learning methods can be applied to suitable data sets. However, these machine learning techniques are not infallible and the right A.I. tool needs to be chosen for the application in question, requiring engineering judgement. Machine learning usually requires large amounts of training samples and in industrial applications, training and test data is expensive to undertake, with failure cases to quantify EOL being difficult to obtain.

Artificial Neural Networks (ANNs) remain a popular choice for estimation of key parameters such as Temperature Sensitive Electrical Parameters (TSEPs) in power electronics since they can model many nonlinear relationships, but they still require a lot of training samples and correct pre-processing of data. They are often used to estimate the junction temperature of a semiconductor within a module when physical temperature measurements (per semiconductor die) are impossible. ANNs can also be trained to identify and classify faults such as pump cavitation, misalignment, load deviations and stator faults.

2.3. Condition monitoring and prognostics

By combining the features of a Smart-Inverter with a Digital Twin, the capability to identify ageing effects, defects, parameter changes and causes of faults based on physical measurements allows the development of improved lifetime models of all of the components contained within the automation process. This in turn allows a more accurate RUL prediction for the relevant components and the ability to analyse and predict upcoming failures, thereby optimising the maintenance decisions, reducing maintenance costs and system reducing downtime.

Functional safety issues may also be mitigated such as:

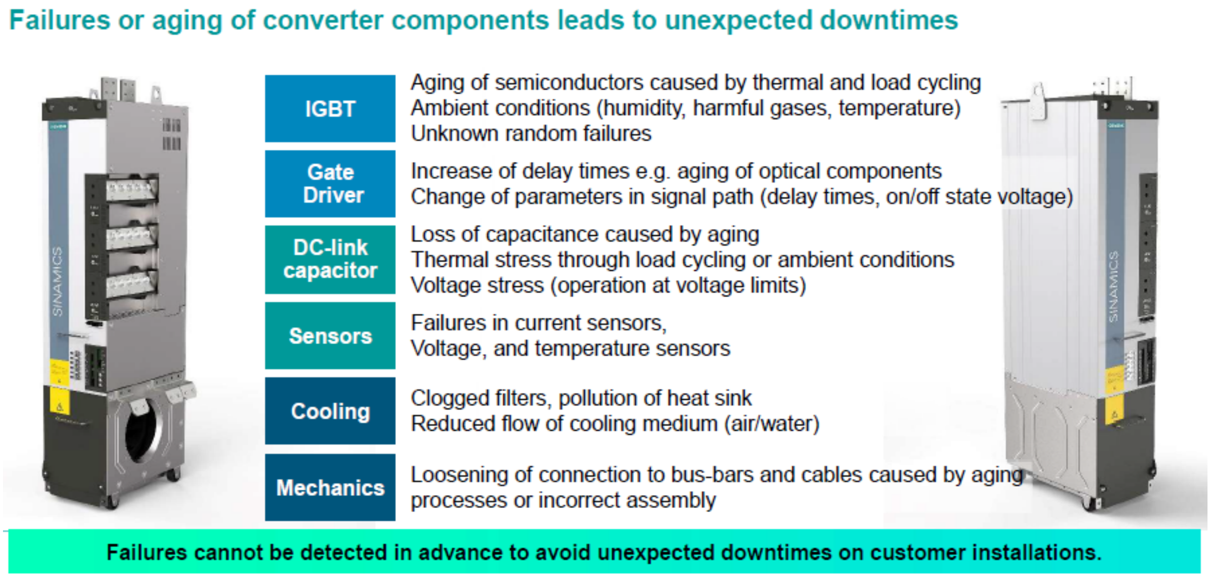
- Prediction of isolation/insulation failure
- Fault ride-through capability
- Detection of false alarms
- Deactivation of faulty modules
- Reconfigure switching devices to maintain operation

The topics of Condition Monitoring and Prognostics can be generally sub-divided into the inverter/converter stage (power electronics unit) and the motor stage (including cables and load). In each case it is generally agreed that:

- Where possible, measured data is obtained by usage of existing standard sensors (located in the inverter)
- Methods should not add additional costs to the system
- Methods should be realised within the converter control and give a clear indication of a failure and the corresponding part

2.3.1. Converter/Inverter monitoring

Looking at the sub-assemblies of a typical inverter unit (Fig. 4), the following capabilities have been identified:



Failures or aging of converter components leads to unexpected downtimes

IGBT	Aging of semiconductors caused by thermal and load cycling Ambient conditions (humidity, harmful gases, temperature) Unknown random failures
Gate Driver	Increase of delay times e.g. aging of optical components Change of parameters in signal path (delay times, on/off state voltage)
DC-link capacitor	Loss of capacitance caused by aging Thermal stress through load cycling or ambient conditions Voltage stress (operation at voltage limits)
Sensors	Failures in current sensors, Voltage, and temperature sensors
Cooling	Clogged filters, pollution of heat sink Reduced flow of cooling medium (air/water)
Mechanics	Loosening of connection to bus-bars and cables caused by aging processes or incorrect assembly

Failures cannot be detected in advance to avoid unexpected downtimes on customer installations.

Fig. 4 Failure and ageing mechanisms of converter components
Image courtesy of Siemens

1. **IGBT and gate driver circuit:**
    - Detection of junction temperature based on electrical parameters to improve thermal models and lifetime calculation
    - Lifetime prediction under consideration of load and thermal cycling based on measurements instead of lifetime models
    - Detection of changes in semiconductor or gate driver behaviour to avoid unexpected failures

2. **DC-link capacitors**
    - Detect and monitor changes of capacitance
    - Changes of internal resistance (ESR)
    - Give a lifetime prediction based on continuous condition monitoring and lifetime models

3. **Sensors**
    - Detection of drift and offset failures especially current sensors and temperature sensors
    - Detection and masking out of sensors providing incorrect signals to avoid unnecessary turn off of the converter system

4. **Mechanics and cooling system**
    - Detect increase of contact resistances in cables and bus bar connections
    - Detect increase of thermal resistance by reduced cooling, by pollution, or reduced coolant flow

2.3.2. Motor monitoring

As an example of motor monitoring, looking at the possible fault conditions of a typical Permanent Magnet Synchronous Motor (Fig. 5), the following capabilities have been identified:

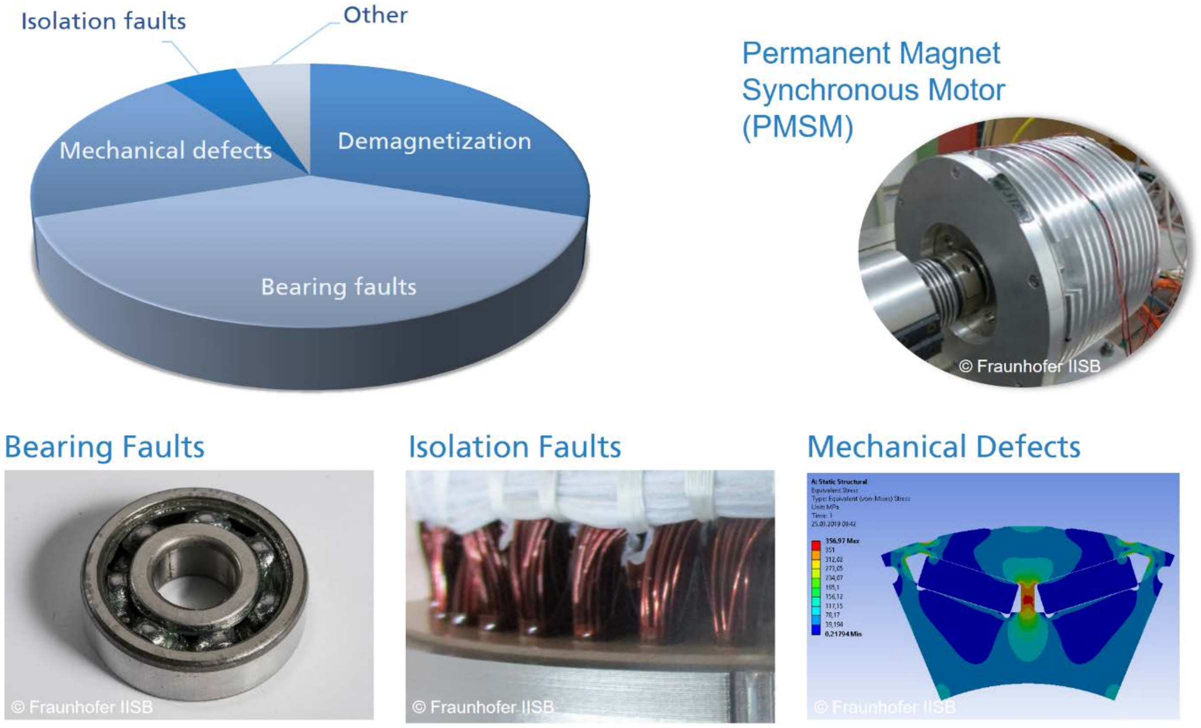


Fig. 5 Typical fault conditions of Permanent Magnet Synchronous Motors
Image courtesy of Fraunhofer IISB

1. **Stator winding monitoring (and rotor bar monitoring on induction-based machines)**
    - Based on motor current signature analysis
    - Inter-turn/inter-phase/winding-to-ground faults can be detected

2. **Vibration monitoring**
    - External sensor, drive as sensor hub – damage to bearings or mechanical defects can be detected
    - Motor current signature analysis – no extra sensor required to detect bearing faults

3. **Magnetic monitoring**
    - Motor current signature analysis applied to Finite Element modelling to detect demagnetisation (Co-simulation)
    - External sensor – Electromagnetic field measurements

4. **Load envelope monitoring**
    - Based on torque estimation from motor control

2.3.3. Energy supply/down-stream user monitoring

Whilst traditional inverter systems can provide system functions in and for electrical networks such as power-factor and voltage and current waveform quality by control of harmonics fed back to the network, a Smart-Inverter could also allow improvements in energy efficiency / energy management / power management by adaptation of the power electronics to specific requirements of the application. This development of variable speed drives to “Service Oriented Drives” allows the Smart-Inverter to adjust the switching operation of an inverter for pumps, fans or conveyors etc. so that optimum efficiency is achieved instead of constant speed demands. In this way efficiency gains of up to 30% and significant reduction in CO_2 can be achieved by control of the whole process in a partly bidirectional way (i.e. monitoring both the electrical supply input and the output automation) through adjusting the inverter switching patterns accordingly. With European Commission commitment to climate and environmental-related challenges such as the “European Green Deal” (published 11.12.19) which has a policy for sustainable industry [3], such savings by control / regulation of down-stream consumers will become imperative to large industrial drives operators by 2050.

3. Problems identified as technology hurdles for early adoption of Smart-Inverters and digitalisation

Considering the range of benefits that a Smart-Inverter can provide given above, a number of technological hurdles have been identified during the Expert Discussion which are summarised below:

- Definition of the boundaries between the various layers is needed i.e. from the physical/sensing layer through to the modelling layer and then data processing layers.
- Which effects can/should be represented with “physics-based” models, which effects with “data-based” models, which with “hybrid models”? Can older modelling methods be utilised now that data processing techniques are faster (need for literature survey)? Can model order reduction techniques be used to reduce complexity/data size?
- Which quantities should be determined directly and which quantities could be “observed/estimated” through models? This could be different for the inverter, motor or process e.g. Power flow measurements and efficiency calculation or estimation, impedance measurements, PWM voltage measurement (time and amplitude), dv/dt measurement, on-state voltage measurement, gate voltage measurement, gate current measurement, torque and vibration measurement.
- Need for highly compact / very low cost high-bandwidth current measurement (E.g. Hall-effect transducers, field-plate transducers, flux-gates, Rogowski coils, combination of low frequency and HF concepts). Could di/dt measurements be implemented?
- Problem regarding the sheer amount of data requiring to be transferred bidirectionally, requiring more intense communication at all levels and a rethink of the communications protocol. What are the resolution, accuracy and bandwidth requirements of the measured data? Are peak values, average or normalised values required? Will there be an issue with the data acquisition time vs. measurement time of the identified signal?
- Is there a need for decentralised computational power e.g. smarter gate drivers and if so, which functionality can they control?
- Can “Embedded monitoring” be utilised in the control, modulation and sampling processes?

- Development is required of the methods for detection of failures and parameter changes based on available electrical measurements.
- Integral (A.I. or signal processing) evaluation of data could be made at the inverter level - different failures can introduce the same fault signatures e.g. open switch phase leg/sensor failure/open stator windings could all be indicated by a 0 Amps output of a current sensor. FFT fault detection processes are not possible for changing frequencies as seen in variable speed drives.
- When considering machine learning/A.I. techniques, what is the number of data sets and resolution required for accurate decision making?
- Does the combination of so many sensors interpret more false negatives in A.I. analysis?
- How is it possible to handle “identification” in highly dynamic processes - which signals/patterns could be superimposed in regular operation for status/condition monitoring and dynamic system identification (FFT, wavelets etc?)? Does sensor fusion allow a simultaneous measurement of several quantities at once e.g. current & temperature?
- Variable speed diagnostics are now needed vs. traditional steady-state methods.
- Development of improved life-time models of power electronics components is required based on ongoing physical measurements. How and where is this amount of data to be stored?
- Development of improved life-time models of the mechanical components is also required (e.g. bearings/windings/insulation) based on ongoing physical measurements.
- Incorporation of existing (possibly low accuracy) standard sensors in various combinations could improve accuracy?
- Hardware and software diagnostics and prognostics should be co-developed to ensure compatibility. This may require the development and integration of sensor systems in all components and inverter processes with sufficient computational capabilities/memory – e.g. infra-red/magnetic field/acceleration/vibration sensors instead of after-market addition and modification of the system.
- Development of injection techniques for sensorless control could allow simultaneous diagnostics.
- With the reliance on sensor data, and use of that processed data in control schemes at semiconductor level, does Cyber-security become an issue?

4. Conclusions

Smart-Inverters offer the capability of increased process optimisation, advanced condition monitoring capability and accurate End-Of-Life prediction by means of sensor fusion combined with classical analysis techniques and A.I. learning, coupled with an ultra-fidelity Digital Twin modelling environment that feeds into the control scheme for the process. With the development of FPGA chips, Hardware-In-the-Loop (HIL) modelling could soon be integrated into the inverter itself allowing side-by-side implementation of the real and virtual systems that comprise a digitalisation concept.

This however comes at a cost, and the major trend seen with Smart-Inverters is that the end-user desires this flexibility to allow full exploitation of the information available, in order to obtain accurate EOL prediction and maintenance schedules, whereas manufacturers would prefer that reliable solutions for life-time prediction of Smart-Inverter functions should not add additional costs to the system (e.g. sensors, storage, processing and communication) and should be realised completely within the inverter control unit. Both parties agree that accurate estimation of junction temperature of the switching devices will be of utmost importance in order to obtain valid parameter ageing estimates, and that this will require the development of intelligent gate drivers that can "sense" junction temperature and di/dt variations etc. especially as faster switching Wide Band-Gap (WBG) semiconductor devices are introduced.

It can also be seen that software and hardware developments need to synergise in order to best achieve this Digital Twin concept so that manufacturers are providing accurate model parameters from measurements to be used in the virtual estimation, using A.I. machine learning techniques developed in coordination with the end-user. Efficiency savings can be realised with suitable control schemes resulting in reduced CO_2 output in line with future European legislation concerning the sustainability of industry.

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