CONDITION MONITORING OF VARIABLE SPEED DRIVES

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Megha Singh
GE Power Conversion
Chennai
India

Dave Allcock
GE Power Conversion
Rugby, England
United Kingdom

Uyyuru, Koteswararao
GE Power Conversion
Chennai
India

Naga Durga Tirumala Rao Kasarabada
GE Power Conversion
Chennai
India

Abstract - Predictive maintenance through condition monitoring can help to improve availability of critical assets such as variable speed drives (VSD). It provides a view on the health of assets with early warnings of developing issues to take timely, corrective actions. This can unlock a shift from unplanned to planned downtime, or even avoid downtime altogether and optimization of asset maintenance cost. Condition monitoring of VSDs entails real-time monitoring of critical signals available in VSDs such as thermal, electrical, and mechanical signals which are collected from discrete sensors or estimated signals. Key Performance Indicators (KPIs) are generated by passing collected signals through specific algorithms followed by trending them with respect to time. The deviation of KPI trends is observed continuously between the healthy system and the system with fault. Typically, KPIs are related to bearing temperatures, cooling system, I/O filters, DC bus voltages, Auxiliary system, CPU temperature etc. Monitoring of KPIs for VSDs aids users to identify sub system fault before it propagates to entire system, providing sufficient time to plan corrective maintenance.

Index Terms — electrical drive, condition monitoring, KPI, data analysis, ESA.

I. INTRODUCTION

The paper deals with condition monitoring of variable speed drives (VSD) through measurement and analysis of key performance indicators (KPI) through an integrated automated process requiring no expert on site. Internet of things (IOT) has brought technical shifts in the electrical industry via inter-connecting sub-components to each other and to the cloud platform [1]. This enabled availability of data from sub-units which are processed and analyzed to predict fault-like events. Drive condition monitoring is now easier and accurate with the help of several measurements captured from drive sub-modules which are either trended directly or selectively combined to derive new variables, to predict deviations from the normal operation. This solution in general can be adapted for any assets. Proposed solution with data acquisition in this paper are applicable for low and medium voltage variable frequency drives.

In the proposed condition monitoring, only drive control measurements are used without any additional sensors to produce key performance indicators (KPIs) which are the real-time data for drive condition monitoring. The collected data is uploaded to the dedicated cloud platform for future analysis and improvisations.

Drive condition monitoring helps scheduled maintenance and planned downtime, which provides improved reliability and availability thus reduced financial loss. It assists in rendering a view on the health of critical assets with early warnings of developing issues and one can take timely, corrective actions. On the other hand, without early diagnosis of drives, it is possible that the customer can loss significant production hours, unplanned maintenance time and labor cost. Thus, drive condition monitoring can unlock a shift from unplanned to planned downtime, or it can even avoid downtime altogether with supporting maintenance staff.

II. DRIVE PROGNOSTICS

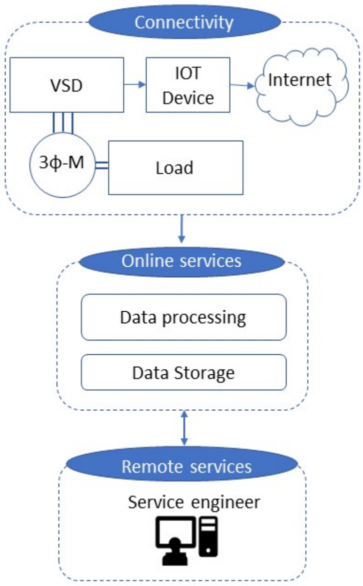

Fig. 1 General architecture of drive prognostics

A general architecture used for drive prognostics is shown in Fig. 1, representing different stages of data flow from the drive to a remote service engineer. At first stage, the measured variables i.e., KPIs from internal units of drive are acquired at drive control sampling rate and transmitted to the cloud platform via IOT device. With a certain time-lapse, the data is captured, processed, and stored in a specific file format with proper timestamps at the server. The cloud platform retrieves the data, runs over specific algorithms, and display all relevant measurements as a trending curve. This platform can be accessed by the customer, who can be informed about the alerts in case any KPI crosses the set fault thresholds. It provides early identification of potential failures and timely intimation to customers. Additionally, the remote service engineer can fetch the data from the server on a regular interval, investigate the drive's performance and can inform the customer about the drive condition.

The foundation of drive condition monitoring is key performance indicators (KPIs) which are time-varying quantities measured from different parts of the drive to predict its health. They can be directly used for trending and to obtain other parameters to cover larger aspects of drive's condition, enabling to distinguish the performance deviation over the period of drive operation.

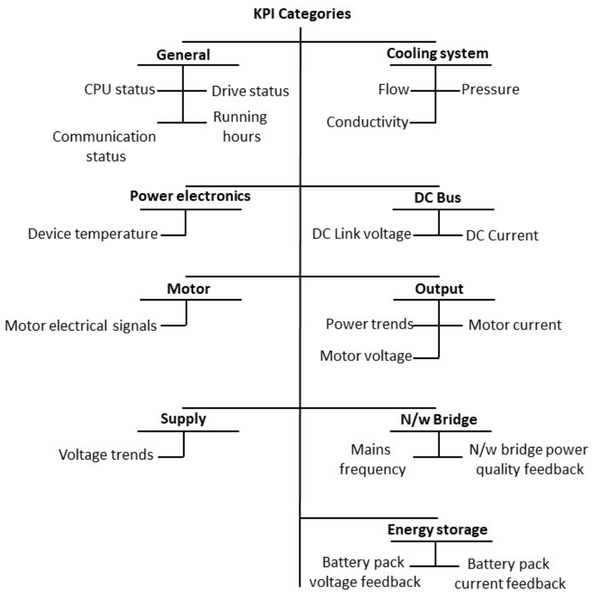

Fig. 2 KPIs under various categories

Fig. 2 shows some of the KPIs used for drive health monitoring categorised based on drive sub-modules. The drives are fitted with a software module providing access to KPIs data trending at configurable time periods such as 1, 30 and 60 seconds. They are also passed to predefined logic integrated in the drive software for making decisions. Making use of these KPI variables, it is possible to detect the operational deviation of drive compared to the base-lined installed performance condition. Proper use of these KPI variables will detect the early failure of drive components and enable to instruct the preventive maintenance requirements. The KPIs can be divided into two major categories based on the way they are obtained, i.e., measured KPI and calculated KPI.

A. Measured KPIs

These KPIs are directly measured from sensors placed at different locations of the drive components. Such KPIs can be further divided into following sub-types:

1) System KPIs: These KPIs provide status of the drive operation, which includes:

- Drive configuration
- Drive critical and non-critical fault and alarm status signals

2) Electrical KPIs: Following parameters will be monitored under electrical sub-category:

- Network side quantities of drive like, Input voltage, current and frequency
- Load/Machine side quantities like, machine voltage, current
- Drive input and output filter currents and DC capacitor voltages

3) Thermal KPIs: Installed temperature sensors are used to obtain following KPIs:

- Machine side quantities like, bearing temperature (NDE, DE), machine winding temperature
- Drive quantities like, IGBT heat sink temperature, cubicle internal temperature, CPU temperature, Input and output filter inductor temperature, pre-charge transformer temperature
- Network side quantities like, input transformer
- winding and core temperature

4) Mechanical KPIs:

- Primarily machine speed is measured

5) Cooling unit KPI

- In water cooled system quantities like, de-ionised water pressure, flow, conductivity, and inlet/outlet water temperature,

B. Calculated KPIs:

Parameters derived from the combination of measured KPIs are termed as calculated KPIs. Some examples include electrical quantities such as active power, reactive power, power factor, RMS voltage/current, voltage and current THD etc. Similarly, mechanical quantities like torque. System's and sub-systems availability and running hours are some of the calculated KPIs or key metrices for the drive under remote monitoring. Other KPIs could be details of number of starts and stops of the drive and the connected machine.

III. KPI BASED ANALYTICS

Drive KPI is used generally as direct data plotting with respect to time or other variable, providing quick status of drive's health. KPI based analytics uses measured and/or calculated KPI as an input to pre-defined logic to derive in-depth status of drive sub-systems. Using this approach, major components failures can be detected before going into actual break down such as DC capacitor, balancing resistors, input and output filter inductor, filter capacitors, cooling system sub-components etc. Some of these functionalities are explained below:

A. Cooling system leakage detection

Cooling system health maintenance is of great importance for overall drive's health and to avoid any catastrophic failure due to coolant leakage. For this purpose, two KPIs namely pressure and flowrate measured from the cooling system are regularly monitored. Additionally, these KPIs are used with a set of logical statements to raise alerts for any irregularity. For instance, following conditions on KPIs are regularly monitored for one of the drives:

1. Cooling system pressure is maintained between allowable limits greater than X bar and less than XX bar per day.
2. Rate of change of cooling system pressure loss per unit should be greater than X%.
3. In the event of alarm, the cooling pressure can stay in alarm level for number of days based on the pressure & rate of change of pressure.

4. The cooling system flow rate can deviate till X% from normal, where normal is the site average flow rate per day.

In addition to it, cooling unit pump health is also monitored indirectly by the measured KPIs like pressure, flow inlet/outlet, de-ionised water temperature. These real time measured KPIs are continuously monitored against base-line threshold at the time of new installation. Any performance deterioration of pump functionality will be raised by the deviation in measured KPI trend over a period. This creates an alert to the customer for an early maintenance.

B. Capacitor health monitoring

DC link capacitors in power electronic converters are used to attenuate the voltage ripple, absorbing harmonics, and to balance the instantaneous power between front end converter and load side converter. DC capacitors face failure due to internal and external factors like excess ripple, over voltage stress, high ambient temperature. The degradation of capacitor leads to decrease in capacitance and will lead to fault in converters. Hence, monitoring of capacitance in real time will give an indication about the healthiness of DC link and can be used for proactive measures to prevent possible catastrophic failures.

DC capacitance value of MV drive is estimated in the running system using the measurement of machine AC currents and derived Diode Front End converter AC currents available in the application control software. Dedicated software function module is developed to estimate KPIs like DC capacitor currents and DFE positive and negative currents. This estimated KPIs of DC capacitor currents and direct measured KPIs of DC voltages are used with cloud-based algorithm to estimate the capacitance value of the running drive system.

High frequency diagnostic files are used to capture capacitor current and voltage.

C. DC Pre-charge time

DC bus pre-charging action is mandatory to increase the lifetime of entire product and system. This pre-charging action is done for every start of the MV and LV drives. Measured KPIs like DC bus voltages and calculated KPIs like time-based voltage level and number of drive's start and stop, interval between each start are used to predict the condition of pre-charging system and if required, a logic is integrated to prevent the frequent re-starts of the drive without allowing sufficient breathing time of the system. These actions are remotely monitored to advice customer for proper operation of the system to improve the system availability.

D. Module to Module Differential Temperature

Measured KPI like heat sink temperature of power modules are compared in real time and are monitored for any deviations developed from the designed threshold at different load conditions and throughout operation. Alert will be sent to customer for immediate action.

E. DC Bus unbalance and Flying capacitor unbalance

DC bus and flying capacitors play a major role in the proper operation of drive system to produce quality output voltage. Early detection of capacitance deterioration by monitoring the calculated KPI deviation from the baseline threshold will help to prevent the sudden failure of the system. Also, by looking at the increased demand on calculated KPI in the drive control software, will help to confirm the deviation of capacitance value. This metrics can be informed to customer for early shutdown to check the healthiness of drive sub-systems.

F. Common Mode Voltage deviation

Medium voltage drives have the common mode voltage measurements which are compared against pre-set alarm threshold in the software. By monitoring the real-time measured KPIs of common mode voltage deviation from the commissioned condition, will help customer and remote service engineer to get an alert on requirement of maintenance before getting in to drive trip.

G. Motor analytics using Drive as a sensor

With drive as a sensor, the diagnosis of rotating machines is made accessible using readily available electrical data with low touch installation. The data is used with electrical signature analysis (ESA) technology to identify potential failures at their onset to avoid unplanned downtime and optimize maintenance cost. It utilizes the data with physics-based algorithms and machine learning to compute relevant indicators indicating a degrading asset. It provides a wider range of failure mode detection such as shorted stator turn, bearing faults, broken rotor bars and eccentricity. For example, at a customer site, the early identification of bearing fault saved around 3 hours of production loss equivalent to ~250K$. For one customer, early detection of motor fault saved around 2 hours of production equivalent to ~350K$.

IV. BENEFITS

KPI monitoring gives immense benefits in predicting drive health ultimately leading to many larger system level benefits such as:

1. It reduces unplanned downtime (monitor equipment degradation) using pre-defined threshold for alerts, which also reduces the maintenance speed.
2. There is a provision of auto-notification of alerts to the customer and remote service engineer based on the logic which enables if any KPI threshold exceeds.
3. Early warnings of change in trend for KPIs can help plan maintenance more effectively.
4. Drive monitoring helps in enhanced efficiency, predictability, reliability, and safety of operations
5. It also reduces through life cost of assets.
6. The data gathered is available for a long duration for reporting purposes.
7. Displays the health of customer assets in near-real time
8. Charts/trends to indicate when assets are nearing threshold or warning limits
9. Allows to view any combination of signals as plot for easy and quick analysis
10. Allows to download raw KPI data for further manual analysis

Fig. 3 highlights the major categories of benefits offered by drive monitoring solutions.

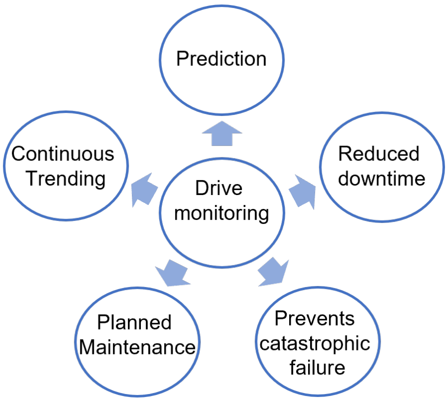

Fig. 3 Major benefits of deployed drive monitoring

V. ROOT CAUSE ANALYSIS OF DRIVE ISSUES

The customers can use KPI trending and its analytics on-site for complete access of drive status to make quick decisions. However, there is a possibility that the operator could not understand and decipher the pattern or trend of the KPI, then he can request the remote service engineer to intervene and navigate him. For this purpose, there is a special file format to store the data which is downloaded by a remote service engineer from cloud services. This file format keeps record of a KPI in a manner that its start and end timestamps can be set based on the event under consideration. For instance, for any change in a KPI trend, remote engineer can download the relevant KPI with a window of X seconds before and after the event in the specific file format via the cloud platform. The trip information with high frequency data captured for critical parameters will directly go to the remote service engineer

Some of the case studies including remote drive health monitoring are discussed below:

A. *Increased conductivity of high-speed balancing testing bench drive*

In a drive-fed pump application, an active front-end based induction machine drive was used along with IOT device to store and transfer the data to the cloud platform. This drive is used for testing purposes, thus not regularly operated. However, drive controllers are always switched on and necessary signals can still be monitored even without drive under operation. During its monitoring in this case, an increasing trend of pure water conductivity was reported by remote engineer as shown in Fig. 4. Customer was reported and recommended inspection of the drive. Subsequently, leakage in the coolant system was confirmed by the customer as a probable cause of increased conductivity. This saved 2-3 hours of production time. As conductivity parameters are monitored continuously, it provides pre-health status for a drive before every start after a shutdown.

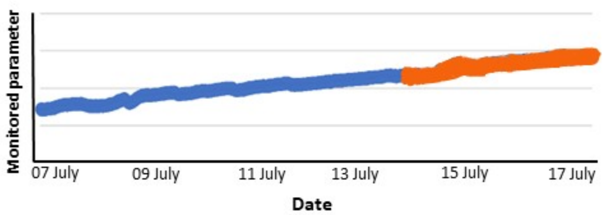

Fig. 4 Increase in conductivity over a period

B. *Remotely handling of drive tripping issue in a power turbine generator company*

A site has an active front-end drive for an induction machine, with IOT device to store and transfer the data to the cloud platform. The customer reported multiple drive trip issue whose prima-facia identified cause by the customer was repeated communication failure. Upon intimation to the remote engineer, an in-depth analysis was conducted using a set of KPIs over a desired time length, collected through the online service platform as shown in Fig. 5. The reason of trip was found to be main circuit breaker feedback failure. The customer confirmed some wiring disturbance at circuit breaker side due to maintenance activities performed. The issue was resolved, and the drive came to healthy and operational state again.

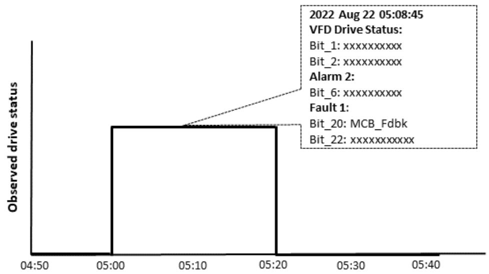

Fig. 5 Drive status monitored through the online platform

C. *Inverter Coolant Leakage and gassing in coolant circuit*

As explained above, for liquid-cooled inverters, pressure, and flowrate KPIs are used for coolant related issues. Monitoring of coolant pressure is of utmost important as it provides indication for refilling, and its unexpected behavior can indicate a rising issue in the coolant system, for example, cracks in the pipe or coolant leakage. If the drive continues to operate with such damages, it can often lead to catastrophic failure. For this purpose, the coolant pressure is regularly monitored, and related analytics is also continuously tracked.

In one of the case studies of drives which were not under maintenance period, developing issues in the coolant system were observed, following which quick action has led to substantial savings by preventing failures in cooling unit, and total inverter failures. There are following observations made for two units and informed to the customer at respective times:

1. The coolant system pressure loss over a short period of time, customer was informed for required action. Post-diagnosis, a crack leading to the coolant leakage was confirmed by the customer.
2. In one case, the unit experienced an increased loss rate over the day and reached X bar threshold level (pre-defined limit). Customer was recommended to inspect and refill.

Fig. 6 is a representative figure to the coolant issues indicative of a real-world problem. Remote service engineers were able to detect deviation in the trend and a report was sent to the customer and necessary action was taken on specific inverter to correct leakage. As per the customer briefing, the probable cause was corrosion and early identification of the issue saved time and money for the unplanned downtimes. The early identification prevented significant power production loss due to failed units.

Some parameters are monitored when the drive is not running which must remain within a range under no operation. However, any deviation can be a measure of underlying issues. In one case, an increase in the recorded parameter was observed. Fig. 7 shows the observed offline parameter of the cooling system in three independent random units, where the parameter unusually increased compared to its normal value. This was later related to gassing effect, which can cause damages like pipe breakage or cracks. It was intimated to the customer for quick action who later confirmed about the gassing issue.

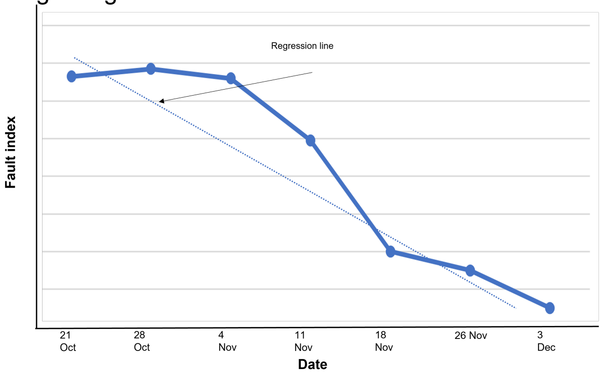

Fig. 6 Fault index depicting unusual trends in coolant health monitoring

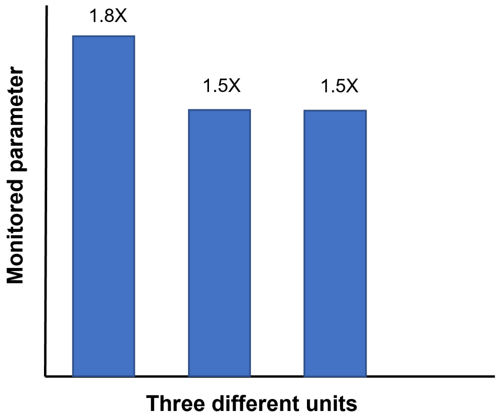

Fig. 7 Unusual rise in Offline monitored parameter for some units

A. ESA case study

Drive can be used as a sensor for monitoring and diagnosing the connected induction machines. The electrical data from drive can be stored, transferred via cloud, and analysed for any growing defects. For instance, heavy noise was observed in the motor which was initially suspected to originate due to motor issues. After the analysis of drive data, it was concluded that bearing ball defect was likely the reason of the noise. The analysis utilized the physical dimensions of the bearing recorded taken from the specification sheet of the motor. Using these dimensions along with the spectral analysis of the electrical signals at characteristic frequencies of bearing, ball defect was identified as the root cause.

Fig. 8 shows the distinction of the faulty points from the normal/healthy data points. These points are based on fault index identified for ball defect only. Similar deviation was observed with machine learning based techniques for anomaly detection as shown in Fig. 9

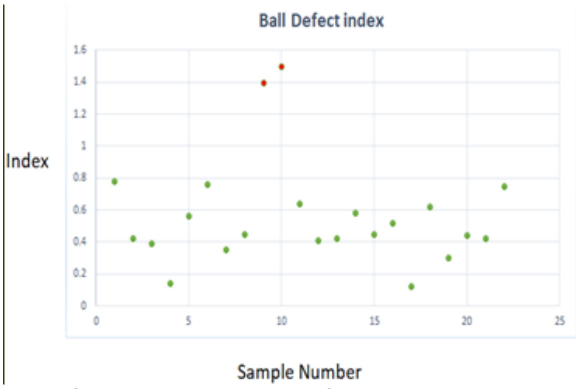

Fig. 8 Spectral analysis-based fault index

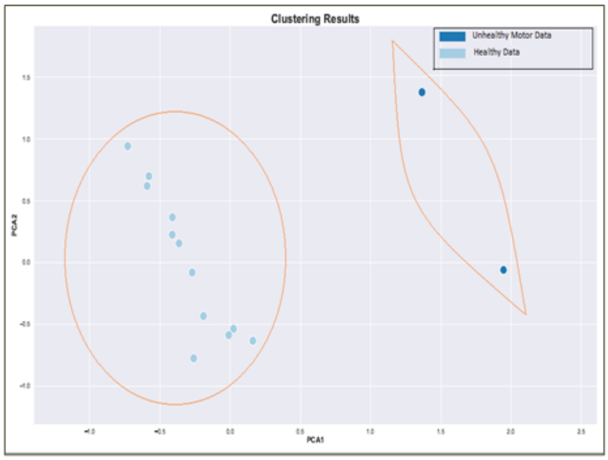

Fig. 9 Ball defect detection using machine learning

VI. CONCLUSION

The paper presents the use of KPIs and based analytics for the predictive monitoring of the drive. KPI monitoring is a proven technique for on-site drive status updates for the customers. This is a direct online monitoring tool serving a go-to medium for introspecting a drive along with rapid action-based drive maintenance. With an additional feature to analyze the parameter trends using cloud services, the customers can leverage the support of remote experts for complicate patterns of the monitored parameters. Drive KPIs and related parameters can not only support for drive health monitoring, but with using drive as a sensor, motor prognostics can also be carried out parallelly. Thus, the solution of drive monitoring and analytics can significantly bring down the production and financial loss and several hours for unplanned downtime.

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II. VITA

Megha Singh holds a Ph.D. degree from Indian Institute of Technology Jodhpur in 2020. She has been a lead data analytic engineer with General Electric power conversion since 2020. She works on developing solutions for machine fault monitoring with the help of electrical as well machine learning tools and techniques. Her interests are signal and data analysis using statistical, signal processing and machine learning tools.
megha.singh@ge.com

Dave Allcock CEng holds a Master's degree in information systems and has 30+ years' experience in the design and development of industrial protection & control products including asset prognostics. He is also expert in automation systems and OT cyber security. He has led the design and development of various automation projects in EMEA, Asia, Europe & USA including Power management and Microgrids.
dave.allcock@ge.com

Dr. Koteswara Rao Uyyuru received B.Tech. degree from Jawaharlal Nehru Technological University, Hyderabad, India, in 2003 and Ph.D. degree in the Department of Electrical Engineering, Indian Institute of Technology (IIT) Madras, Chennai, India in 2010. From 2009, he is working with GE Power Conversion, Chennai, India and currently serving as Senior Engineer, Systems Engineering. His current research interests include power quality, power converters design and sizing, Modelling of power electronic systems and power electronics applications in power systems.
koteswararao.uyyuru@ge.com

Naga Durga Tirumala Rao holds a Master's degree in Power Electronics and Drives from Manipal Institute of Technology, Manipal in 2019. He has been a drive control engineer with General Electric power conversion since 2020. He works on remote monitoring of electric machines and developing solutions for electric machine faults detection with the help of electrical signals. His area of interests are condition monitoring of electric machines and Power electronic converter applications.
nagadurgatirumalarao.kasarabada@ge.com