ENHANCED MOTOR-LEVEL INTELLIGENCE: DEPLOYING INTELLIGENT MOTOR CONTROL IN VIEW OF INDUSTRY 4.0

A Thesis Presented

by

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Abstract:

The global business space is facing growing challenges from shortfalls in raw materials supply arising from increased regulation based on environmental concerns, and the intensive competition arising from globalization which means virtual open borders. To this end, for businesses to thrive, there is an inherent need to outperform the competition by doing things differently in the areas of asset care and operational data acquisition systems, and the prompt processing of this data for decision support initiatives and optimization of operational activities. The key issue in Industry 4.0 is clear and reliable asset visualization across a broad range of domains such as process control, enterprise resource planning, asset care, process optimization and efficiency improvement initiatives, which in total support today's business world, in the face of growing competition driven by globalisation, wherein continuous improvement is not only a prerequisite for survival, but the very basis of a competitive advantage and this is the main reason why this research is of prime importance to today's business and operations management teams.

Abbreviations:

AGA	American Gas Association
AS-I	Actuator-sensor interface
CPPS	Cyber-physical production systems
CPS	Cyber physical system
DCS	Distributed control system
ERP	Enterprise Resource planning
GTI	Gas Technology Institute
HART	Highway Remote Addressable Transducer
ICT	Information and communications technology
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IIoT	Industrial internet of things
iMCC	Intelligent motor control centre
ISA	International Society of Automation
ISO	International Organization for Standards
IoT	Internet of things
IT	Information technology
LAN	Local area network
MCC	Motor control centre
MES	Manufacturing execution system
NEMA	National Electrical Manufacturers Association
NIST	National Institute of Standards and Technology
OSI	Open system interconnection
PCSRF	Process Control Security Requirements Forum
PLC	Programmable logic controller
PROFIBUS DP	Process fieldbus with Distributed periphery
SCADA	Supervisory control and data acquisition
UL	Underwriters Laboratories
WAN	Wide area network

1. Introduction

The first three industrial revolutions came about as a result of mechanisation, electricity and IT. Now, the introduction of the Internet of Things (IoT) and Services into the manufacturing environment is ushering in a fourth industrial revolution. In the future, businesses will establish global networks that incorporate their machinery, warehousing systems and production facilities in the shape of Cyber-Physical Systems (CPS) [1]. The challenge of contemporary operations control systems is the interface with the enterprise management system which requires extensive field-level intelligence that can enable devices to communicate with extensive and seamless data exchange capabilities between operations control centres located long distances away and enterprise resource management centres providing a means of connecting components of a wider system together for the purpose of exchanging data and sharing resources. The wider system, in this case, can be a manufacturing process, aerospace or automotive applications, utilities plant, food or chemicals plant, Petroleum and Petrochemicals processing plants.

These modern manufacturing systems are inherently technology and data intensive making them big data consuming facilities leading to the "big data" phenomenon and the enterprise level of manufacturing systems automation hierarchy as shown in Figure 1 below. As shown in Figure 1, the whole system can be divided into three systems; the operations facility, the business or process control system, and the data processing system (Manufacturing execution system, MES, Enterprise Resource Planning system (ERP), and data storage/retrieval system.).

The concept of Industry 4.0 is built around secured and reliable connectivity across the factory and associated business management systems enabled the significant development in cloud-based storage systems, business management data and factory operations management data can be warehoused in the cloud or other storage infrastructure. To this end, Industry 4.0 is an 'internet of things, services, data and people' [27].

The thrust of this research will be to study the development and deployment of intelligent MCCs as a part of the industrial internet of things (IIoT) and to explore the impacts on Industry 4.0, given the need to optimize the overall operational efficiency of production facilities in a typically resource-intensive business environment and a resource-scarce world.

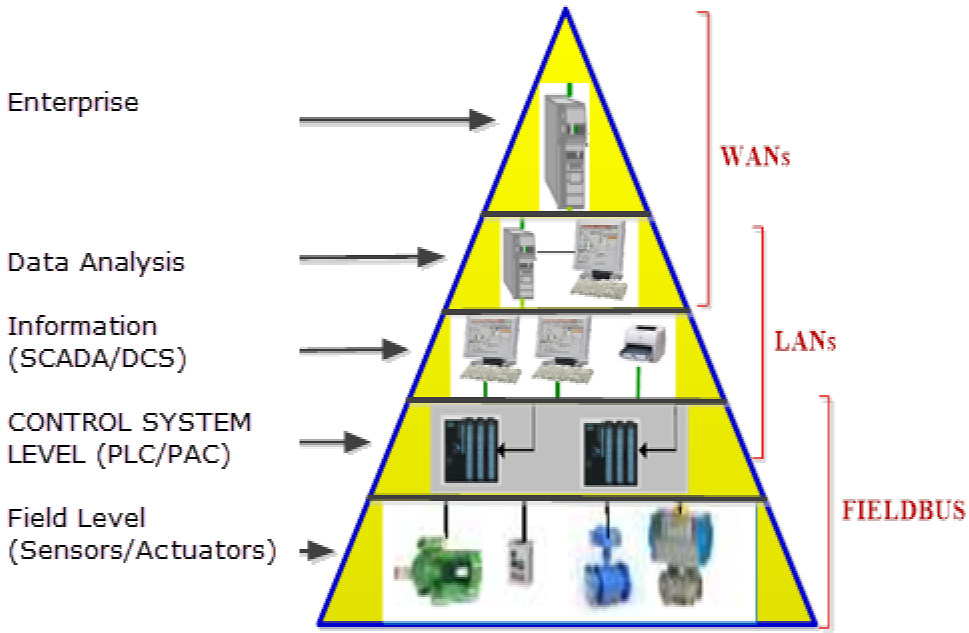


Figure 1: Basic components of a manufacturing control system (Source: Adapted from [2])

2. Objectives:

The objective of this work is to document a body of knowledge around a practical demonstration of the deployment of intelligent Motor Control Centres (iMCC) to provide access to the operating parameters of electric motors. This access to extensive data will improve the visibility of the operations of the electric motors to achieve efficient and effective control as well as protection of these electric motors. In a typical industrial setup, the electric motor is the major consumer of electrical power accounting for more than half world's energy consumption in a range of end-use applications such as fans, compressors, pumps, vehicles, and refrigerators [6]. To this end, there is need to gain access to the operation and performance of this category of applications which is controlled using Motor Control Centres (MCC) but the focus of this research will be to look at the development and deployment of intelligent MCCs to enable access to the body of motor operating data and to support maintenance planning activities.

3. Review of literature:

In the review of the literature, the researcher will look at the current concepts and the emerging body of knowledge centred on the UL 508, 845 and NEMA ICS 18 standards, the Industrial internet of things and Industry 4.0 with particular interest in exploring improvement initiatives and extracting practicable best practices in the development and deployment of intelligent MCCs and their interface with process control systems for the optimization of resource deployment and business processes management.

3.1 The electric motor and process operation:

The process operation refers to the basic value-creating transformational activities which form the core of the organization, simply put, this is the raison d'être for the organization. The value-creating transformational activities very often involve the movement of materials by the introduction of work using electric motors.

The business world today is populated with customers who have high value-intensive demand and one way to keep ahead of the game is to be visible in the market and to have access to data both within the business and the public space. This demand for visualization and data acquisition is met using the internet of things which today, is "big data" that can be deployed for the development of business improvement strategies.

The major parts of the motor are the main enclosure, rotor assembly, stator assembly, and cooling fan.

- Main enclosure: This is the external housing for holding the stator windings and also equipped with the terminal box.

- Rotor assembly: This is the moving part that is made up of a wound coil complete with shorted bars or laminated conductor bars with shorted end rings in the case of squirrel cage type. The rotor is the means of coupling to the mechanical load, and on it is mounted the axial bearings and cooling fan.

- Stator assembly: This is the stationary member of the machine, made up the core on which is mounted the magnetising windings that provide the rotating magnetic field.

- Cooling fan: This is mounted on the side of the rotor shaft opposite to the load end. It provides cooling for the machine components.

3.2 The motor control centre (MCC):

The motor control centre is a floor-mounted assembly of one or more enclosed vertical sections typically having a horizontal common power bus and principally containing combination motor-control units. These units are mounted one above the other in vertical sections. The sections normally incorporate vertical buses connected to the common power bus, thus extending the common power supply to the individual units. Power may be supplied to the individual units by bus bar connections, by stab connection, or by suitable wiring [7]. The primary function of a MCC is to control the starting, operation, and protection of electric motors within a larger system. In this case, we will be looking at a low voltage motor control centre equipped with different types of motor control units, feeders with current-protection devices, variable frequency drive units, power factor correction units, and various metering devices. The sub-systems in a motor control centre are highlighted below according to [7]:

- Full-voltage reversing or non-reversing combination motor-control units
- Full-voltage multispeed combination motor-control units
- Reduced-voltage part-winding, wye-delta or auto-transformer combination motor-control units
- Solid-state industrial controllers such as adjustable-speed drives, programmable controllers, and protective relays
- Lighting or distribution panel boards
- Feeder-tap units
- Incoming-line equipment, such as main lugs, fusible switch, isolation switch, or air circuit breaker
- Control or lighting transformers
- Special equipment assemblies

The foregoing equipment may contain such items as pushbuttons, selector switches, indicating lights, control transformers, control circuit fuses, and auxiliary contacts incorporated as an integral part of the above units [7].

The schematic drawing for a typical direct-on-line motor starter is shown in Figure 2 below.

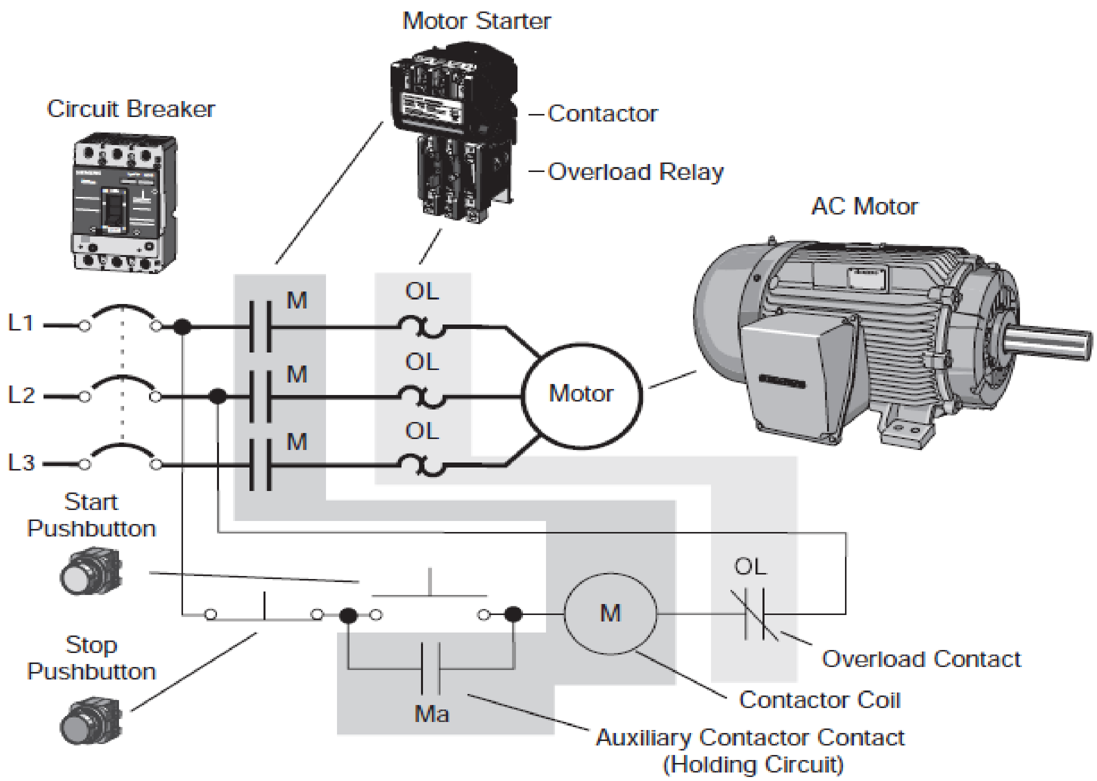


Figure 2: Basic motor control using direct-on-line starter (Source: [9])

The MCC is analogous to a black box with the motors connected to it as nodes, this is illustrated below in figure 3.

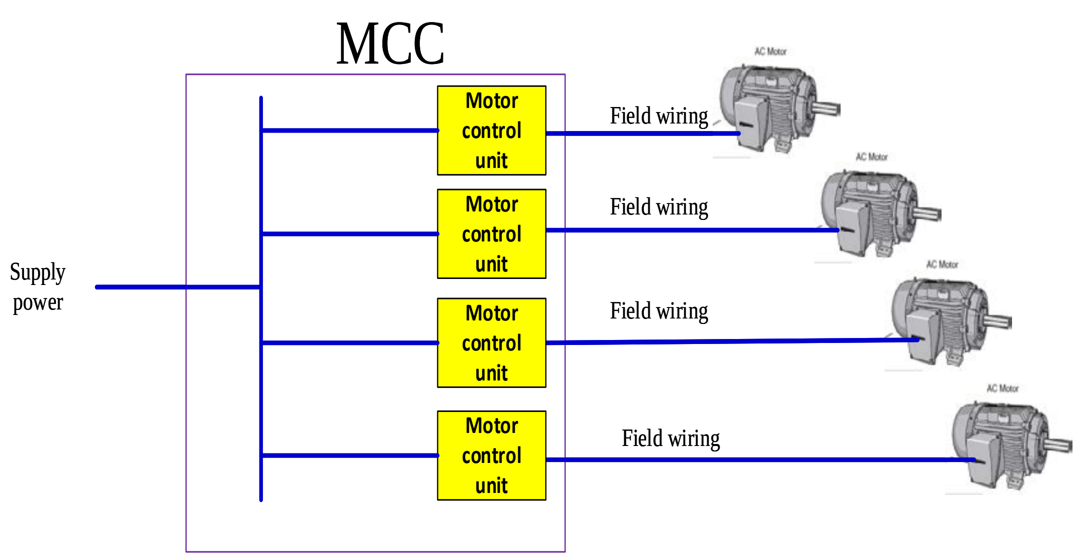


Figure 3: MCC as a black box connecting to motors as nodes

The method by which the motors are connected to the MCC and the orientation of the connecting terminals on the MCC determines the type of MCC wiring. According to [7], NEMA classified motor control centres into various types of wiring and below are the classifications of the MCC and their definitions:

- NEMA Class I
- NEMA Class II
- NEMA Class IS
- NEMA Class IIS

NEMA Class I: This is a stand-alone MCC wiring scheme wherein there is no interconnection with other systems, the motor controllers, power feeders, current protection devices, and power factor correction system are housed within a single enclosure. This type of MCC is applicable in small-sized projects.

NEMA Class II: This is an integrated MCC wiring scheme because it allows for interconnection with other systems such as safety interlocks, remote-mounted metring devices. The motor control units, power feeders, current protection devices, and power factor correction system are housed within a single enclosure. This type of MCC is applicable in larger projects.

NEMA Class IS and IIS: These are similar to Class I and Class II respectively except that additional drawings such as custom drawings include:

- Special identifications for electrical devices
- Special terminal numbering designations
- Special sizes of drawings

The drawings supplied by the manufacturer shall convey the same information as drawings provided with Class I and II motor control centres, additionally modified as specified by the user [7].

NEMA MCC Wiring Classification: According to [7] there are three different types of MCC wiring depending on how the field cables are connected to the combination motor control units:

- Type A Wiring
- Type B wiring
- Type C wiring

Type A wiring: In this type of wiring, cables from the field are directly connected to the terminals inside the MCC feeder units without using terminal blocks. This is applicable for class I motor control centres [7, 8].

Type B wiring: In this type of wiring, combination starters in a motor control centre are equipped with control terminal blocks. All the control wires from a combination starter are connected within a unit to marked terminals on a terminal block. The user brings field control wiring, if required, into each combination starter unit inside a motor control centre and connections are made at each marked terminal block. In 1994, NEMA standards ICS 18-2001(R2007) subdivide type B wiring into Type B-D and Type B-T depending on how the field cables connect to the master terminal units and the orientation of the terminal blocks.

Type C Wiring: With Type C wiring user (field) control wiring connects to master terminal blocks mounted at the top or bottom of the vertical sections that contain combination motor-control units or control assemblies. Combination motor-control units and control assemblies shall be factory wired to their master terminal blocks [7].

3.3 The intelligent motor control centre:

Legacy MCCs contained only electromechanical components with hardwired connections, but developments in microprocessor-based devices and power electronics drive components have resulted in intelligent programmable electronic devices that can monitor motor current and other motor operating parameters, and also possess detailed diagnostics capabilities to improve equipment availability. [12].

The MCC shown in Figure 3 is similar to having a data hub with communicating nodes attached to it but in this case the MCC does not have the intelligence of the switch in a data hub. It is possible to locally switch on or off each motor attached to the MCC and even read off its current from a panel-mounted multimeter but these do not provide intelligence. An intelligent system enables data to flow across an enterprise infrastructure, spanning the devices where valuable data is gathered by the back-end systems where that data can be translated into insights for decision support and action. With this capability, companies can unlock hidden value from data previously out-of-reach, and immediately act on new insights to increase business value [10]. Intelligence, in this context, is the ability of a system to identify devices within its connectivity and to individually source data and send data to these devices and to other systems to which it may be connected. Looking at current trends in business technology that include the proliferation of discrete devices, data explosion, and the complexity of bringing it all together, there is the need for businesses to unlock hidden value from the data located throughout their devices, software, and solutions by connecting them into an overarching “intelligent system.” This “intelligent system” will extend data analytics beyond discrete devices and solutions by creating intelligence for the enterprise that has historically been out-of-reach or too complex, risky and expensive to implement" [10]. Based on the foregoing, an intelligent MCC is one that "enables data about each motor control unit to flow across an enterprise infrastructure, spanning other devices within a back-end intelligent system" such that these electric motor operations can be assessed locally and remotely with increased visualization. This data availability for intelligent "analytics" is the basis for the deployment of intelligent motor control centres (iMCC) in industry. The intelligence resides in the MCC and not in the field as in the case of intelligent instruments wherein the intelligence resides in the field, the respective motors can be connected to any motor control unit within the MCC as long as the sizing of the motor matches that of the motor control unit. It is therefore within the motor control unit that the intelligence is built in using "solid-state industrial controllers such as adjustable-speed drives, programmable controllers, protective relays" [8]. An iMCC involves the use of open networks, distributed inputs/outputs modules, and electronic components which will give the iMCC three things in common:

- Control is achieved through a microprocessor-based system,
- The use of a communications platform to exchange data, and
- Enhanced diagnostic and protective functionality is included. [11]

The three major parts of the iMCC architecture are the hardware, software, and communications protocol [20] as shown in figure 4 and figure 5. The hardware includes the interface modules and intelligent relays, the software is meant to provide a basis for parameterization of drive units and interface with the control system and IT infrastructure, and the communications protocol provides a basis for data exchange and media access control by the respective drive units.

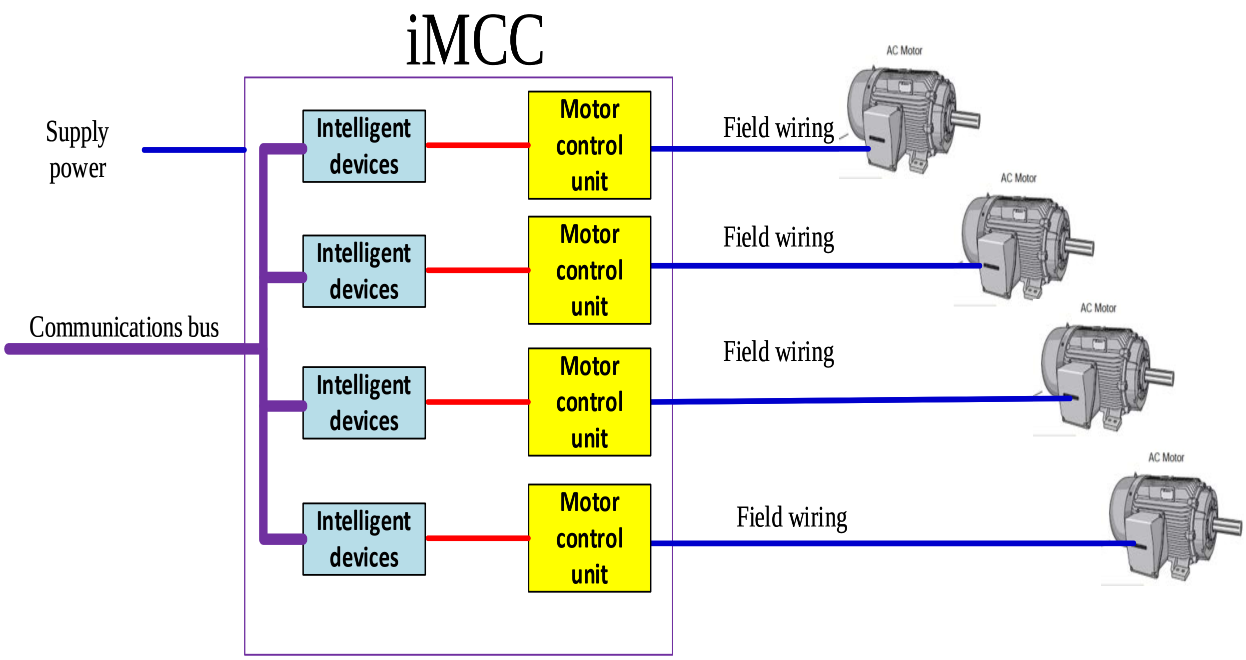


Figure 4: Typical iMCC architecture

The architecture in figure 4 shows the basis of an intelligent MCC as it includes the introduction of a microprocessor-based intelligent device in the motor control unit with the capacity to communicate with other systems outside of the MCC and will be able to protect, control, and report the operations of the motor as indicated by the motor control unit. The major driver of iMCC is the deployment of available technological innovation in the integration of bit-level devices, device-level intelligence, and communications software in enhancing the intelligence of motor control centres. Also, these networks provide greatly simplified wiring thereby eliminating the bundles of control interconnection wiring requirements [20].

3.3.1 iMCC intelligence architecture

The basic conceptual architecture for iMCC is shown in figure 4 wherein the conventional MCC in figure 3 is fitted with the microprocessor-based intelligent device that is included in the motor control unit with the capacity to communicate with other systems outside of the MCC. This conceptual architecture is realized in different schemes depending on the size and complexity of the whole system and also on the operational requirements of the design objectives. The three major variants of intelligence enhancement within the iMCC include:

- Using hard-wired analogue devices,
- Using distributed I/O modules, and
- Using microprocessor-based intelligent device.

The use of analogue devices such as voltmeters, ammeters, overcurrent protection devices, and phase failure indicators, is commonplace within industry especially where legacy MCCs are in use. These devices can be located in the field or in local control centres often limited by distance. The intelligence in this system is limited to human-machine interface with limited system-to-system interface.

The use of distributed I/O modules involve the deployment of a PLC or other dedicated data acquisition system to interface with the MCC and gather data from the combination motor control units as well as send commands to drive units using a combination of direct signalling or interposing relays. The distributed I/O are located in the MCC cabinets and connect directly with the motor control units.

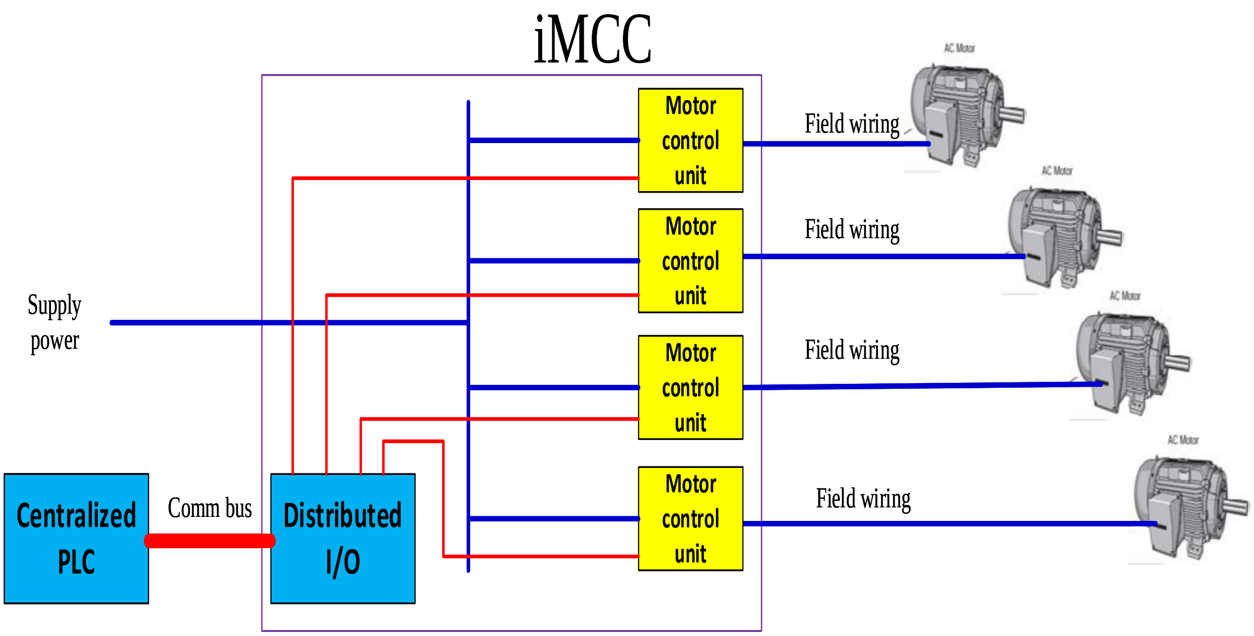


Figure 5: iMCC architecture using distributed I/O

The typical iMCC scheme shown in figure 5 illustrates the use of distributed I/O to enhance the intelligence wherein the I/O channels are connected directly using hardwire to collect such signals like motor statuses, run/stop commands, VFD speed references, motor current or voltages, and other signals of interest to the organization. The major challenge for this architecture is the expensive maintenance cost due to complicated and expensive, cabling requirement. This architecture does not possess detailed diagnostic capabilities that can support prompt decision making and asset care requirements. The use of a communications bus to connect the distributed I/O to the central PLC will enhance data transfer and improve diagnostics between the PLC and the remote I/O.

The iMCC architecture shown in figure 4 indicates a further development of system in figure 5 such that the integration of bit-level devices, device-level intelligence, and communications software are introduced into the motor control unit thereby enhancing the intelligence of motor control centers. These smart devices provide access to extensive diagnostic data and operations measurement functionalities such as:

- Operation mode (local/remote),
- Statuses such as: on/off, trip, overload, phase failure etc,
- Fault codes and alarm logging,
- Operation speed,
- Setting speed references for VFD,
- Torque current,
- Power factor measurement and correction,
- Voltage measurement,
- Setting acceleration and deceleration times for VFD,
- Drive unit parameterization,
- Maintenance planning and logging capabilities [13]

The major driver for the increasing need for iMCC is the access to extensive diagnostic data and operations measurement functionalities which will drive asset care initiatives, the enterprise resource planning capabilities are mainly resident in other systems within the overall IT infrastructure of the organization. To this end, the iMCC enables data to flow from the plant floor across the enterprise infrastructure to the back-end systems where the data can be translated into insights for decision support and action. With this capability, companies can finally unlock value from data previously out-of-reach, and immediately act on new insights to increase business value [10]. This is the major value proposition for the deployment of the iMCC within the framework of Industry 4.0 and the emerging trends within the industrial internet of things, and these constitute the thrust of this research.

3.3.2 iMCC communications platform

The major requirement in achieving the function of the intelligent MCC is the exchange of data between the control system and the smart devices within the iMCC. This data exchange was carried in legacy MCC using analogue signals such as voltage levels, current signals, or dry contacts, which, cannot deliver the requirements of intelligence expected from the iMCC.

The enhancement of intelligence in the iMCC involves the deployment of an industrial fieldbus in the exchange of data between the motor control unit and the control system infrastructure.

The OSI model splits the communication process into seven functional layers, each of which performs a clearly defined task ….. with respect to those above and below, the model ensures the compatibility of all devices using a particular network protocol, and between one network protocol and another [15].

The model covers the processing and transmission/reception of data for both networks, however, in practice industrial fieldbuses utilize only layers 1, 2, and 7 for data communications and in some cases, like DNP3 and wireless, the Network and Transport layers are also utilized.

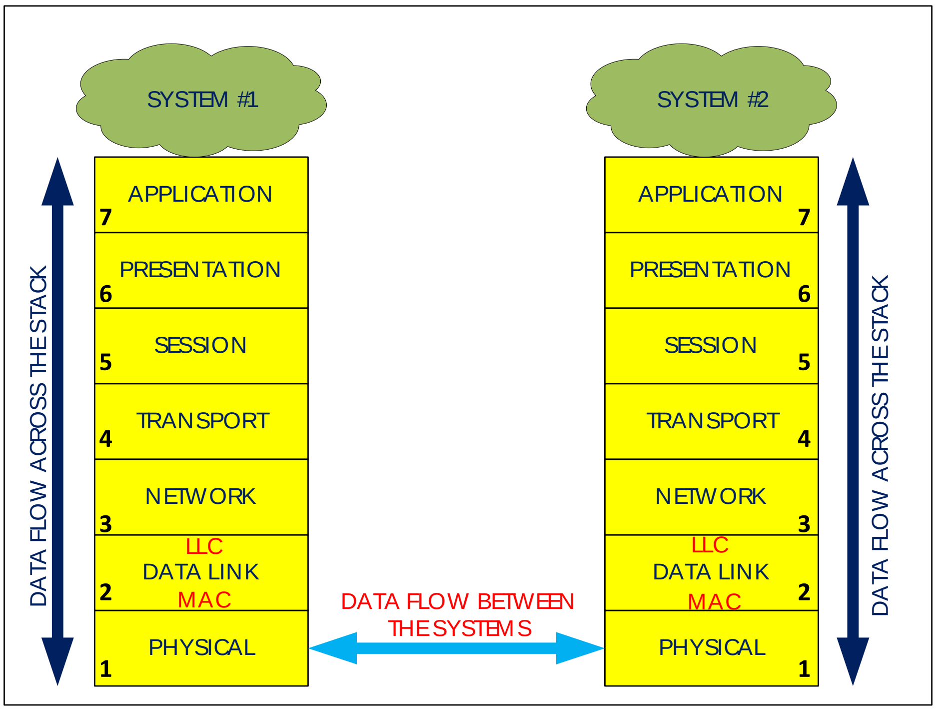


Figure 6: The OSI Reference model

Fieldbus systems provide communications links in a control system using digital, bidirectional, and structured signal flow along specific media. The devices on the fieldbus system must be compatible with the data flow and media control algorithms which is basically called the protocol. The user group responsible for each fieldbus defines the specifics of the protocol which dictate the network topology, timing and synchronization, data flow, frame packaging, and media control that happen within layers 2 and 7 while the modalities for putting the signal on the physical medium in layer 1 is determined by standards such as RS-232 and RS-485. The OSI Reference model in figure 6 illustrates the communication layers which form the basis for data exchange in industrial communication platforms [14]. Fieldbus is the low end of the automation pyramid figure 1 wherein all the field devices, mainly sensors, actuators, and electric motors are connected to some I/O interface through a network topology based on the specifics of the respective fieldbus in use. The deployment of fieldbus developed slowly due to need for stability and interchangeability across numerous equipment manufacturers.

The major challenges that affected the growth of fieldbuses are the following:

- The absence of a uniform standard that will regulate the operation and development of different fieldbuses that were arising in the market,
- The multiple fieldbuses developers often duplicating their works under different names and leading to various chipsets that do not allow interoperability between different devices and across different fieldbuses,
- Complicated installation guidelines and configuration procedures that required increased engineering/set up times and extensive technicians' training,
- In some cases, there were outright lack of qualified personnel to both install and maintain the fieldbus system, and
- Lack of trust by industry experts who were unsure of the reliability of these fieldbuses.

The subsequent standardization of the fieldbus systems resolved the duplication and stalemate that characterized the early development and deployment of fieldbuses which was then referred to as "the fieldbus war" [4]. This resolution happened when "*on June 15, 1999, the Committee of Action of the IEC decided to go a completely new way to break the stalemate. One month later, on July 16, the representatives of the main contenders in the debate (Fieldbus Foundation, Fisher Rosemount, ControlNet International, Rockwell Automation, Profibus User Organization, and Siemens) signed a "Memorandum of Understanding," which was intended to put an end to the fieldbus war, … to create a large and comprehensive IEC 61158 standard accommodating all fieldbus systems*" [16].

Since the introduction of the fieldbus in the late 1980s and following the development of the IEC 61158 standard, there has been a significant rise in its deployment as shown in figure 7 below, this is due partly to the increased need for field-level intelligence and interface with process/cell level coupled with growing total system integration covering all the way to the very top of the automation hierarchical pyramid, enterprise management systems, thereby making the system much more interactive and readily optimizable.

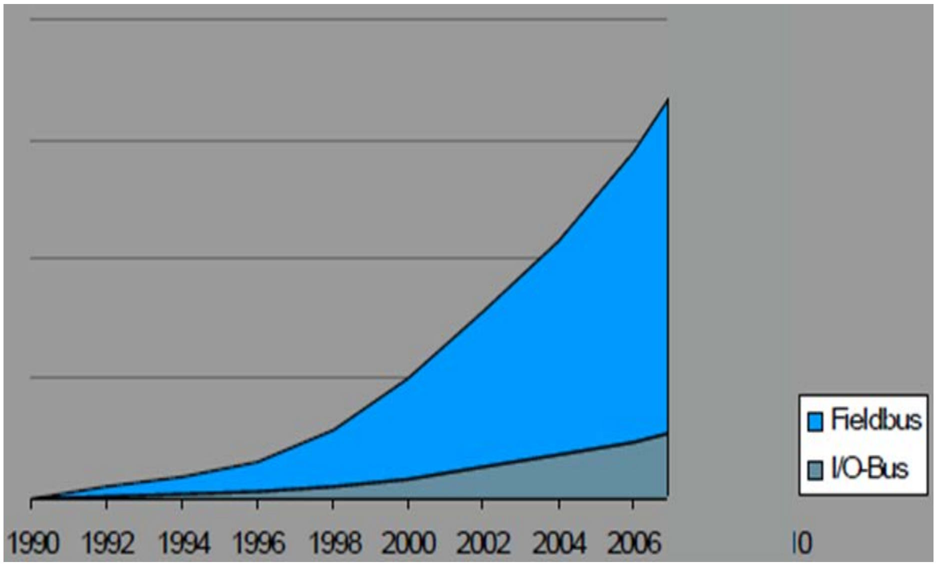


Figure 7: Growth of Fieldbus deployment [17]

One strong point of the fieldbus system is the "power over fieldbus", which allows the same signal line to transmit both device power and intelligence thereby reinforcing the case of reduced cabling requirement.

"*Looking at new installed nodes within factory automation globally, fieldbuses are still the most widely used type of networks with 58% of the market. Fieldbuses are still growing by approximately 7% per year as users ask for simplicity, tradition and reliability. The dominant fieldbus is PROFIBUS (17% of the total world market including industrial Ethernet) followed by Modbus (7%), and CC-Link (6%)*" [18].

The 2016 HMS Industrial network market share survey [18] have indicated a growth in the deployment of the different types of fieldbuses and industrial networks, below is a highlight of the 2016 HMS industrial networks market shares survey;

- Industrial Ethernet is fastest growing at a growth rate of 20% and now accounting for 38% of the market. EtherNet/IP is in first place within industrial Ethernet globally, followed by PROFINET [18].
- Classic fieldbuses remain the most widely deployed industrial networks with 58% of the global market share and PROFIBUS still the most widely used fieldbus with 40% of this sector [17]. From appendix A, there are three variants of Profibus, and out of these the distributed periphery (DP) is the most widely deployed due to its speed, availability and affordability of components, and it provides downward connection to AS-I network for field level actuator-sensor connectivity.

- The industrial internet of things (IIoT) is driving wireless technologies which account for 4% of the market share [18].

The development of Ethernet/IP-based communications system for field level networking will be a hugely disruptive innovation in the deployment of fieldbuses in process control systems. The major drawback in the deployment of Ethernet/IP is its non-determinism which makes it unfit for the field level communications. There are extensive improvements in the development of the Ethernet/IP system, such improvements like the increase in data speeds from traditional 10 Mbps to contemporary 100 Mbps, the deployment of intelligent switches that can help with some form of determinism, and the possibility of protocol tunneling it is possible to move Ethernet/IP into the field and that will transform the configuration of the automation pyramid. According to Schneider Electric [19], the leading communication protocols used in process industry and infrastructures are: Ethernet TCP/IP, Profibus-DP, Devicenet, and Modbus.

From [17], it is clear that Profibus DP is the most widely used fieldbus within industry and this also applies to a wide range of iMCC deployment, there are other proprietary deployments such as Devicenet for Rockwell-based systems, and Modbus for Schneider Electric-based systems.

3.3.3 Benefits and challenges of deploying iMCC

In this section, the researcher will be looking at specific benefits of deploying iMCC as it affects the objectives of the business. The major benefit of the deployment of iMCC is the speed of its data communications system typically in fractions of milliseconds which implies that intelligent programmable electronic devices can monitor motor current and other motor operating parameters, and also provide detailed diagnostics capabilities to improve equipment availability [12]. In the emerging era of Smart manufacturing, there is need to bring all of the devices into the central communications infrastructure of the business and “all devices” in this regard should include electric motors given the fact that the electric motor is the proverbial driving horse of this industrial age and the iMCC provides the data acquisition interface for electric motors.

Another major value proposition of the iMCC deployment is the speed of set up and remote programming capabilities due to the fact that all the motors are on the network and are easily assessible by the control and enterprise planning systems in order to support planning and decision-making processes.

The general benefits of iMCC are highlighted below:

- There is enhanced visualization of the operations and statuses of the motors, this way, more data could be acquired and seamlessly integrated with other enterprise information systems.
- The setup time for the iMCC is shorter because the intelligent devices can be delivered within the iMCC cubicles already configured and factory-tested with all the communications platforms, and the software fully tested and certified. It is possible to easily re-scale the system by either making a new motor configuration, or adding or removing motors from the network.
- Interfacing the iMCC with the plant control system is based on selected fieldbus which usually requires less cabling as opposed to the traditional MCC, and also communicate at higher speeds compared to using hard-wired MCCs.
- Deployment of iMCC can result in cost reductions due to reduced cabling requirements, low component density, and smaller space requirements.
- The iMCC provides the possibility of seamless integration with the plant PLC, SCADA or DCS infrastructure thereby making it easy to optimize the operation of the electric motors. This way, there is no need for interposing relays or other analogue devices that might compromise data fidelity.
- Due to the integration of the iMCC with the plant-wide automation system, there is access to higher level software to support control optimization and operational efficiencies which will then lead to energy savings and ultimately cost savings.
- Beside the conventional protection available in traditional MCC, the iMCC enhances special protection features for electric motors such as denying start permission after a preset number of starts to allow for the motor to cool down, thereby prolonging the useful life of such motors.
- The data made available from the data acquisition functionalities of the iMCC can lead to the improvement in maintenance planning and tracking which will result in higher equipment reliability and availability.

Though the deployment of iMCC has the benefits highlighted above, there do exist some challenges in its application arising mainly from the stability and availability of the communications protocol and its associated components.

These challenges include:

- Reliability and flexibility shortcomings in the “daisy chain” drop-line architecture connecting units to the main trunk line.
- Adding new units or accidental breaks in the chain affected any downstream units in that connection, potentially shutting down equipment.
- The need for the conversion of one communications protocol to the other using appropriate gateways constitute a challenge when it comes to network speeds and bandwidth.
- Establishing initial network communications with MCC unit devices is often unreliable and could lead to high failures during commissioning.
- Due to the risk of electromagnetic interference, power and communication cables must be separated within the MCC cubicles to meet code requirements and within these confined wire ways, adequate separation was difficult at best [20].

3.4 The iMCC and industrial internet of things (IIoT):

The IIoT is an industrial internet infrastructure which connects industrial control equipment (operation technology) with business information systems (information technology) such that by this connectivity data available within different equipment and business units can be gathered and deployed in ways that can provide decision support for value-adding actions. According to the CFE Media 2016 Report on the industrial internet of things [5], the internet of things (IoT) can either be the commercial internet of things or industrial internet of things in which case the term “things” refer to different entities which could either be mobile, personal, and business devices for the commercial internet of things, or in the case of the IIoT, “things” refer to “*Hundreds of millions of connected wired and wireless pressure, level, flow, temperature, vibration, acoustic, position, analytical, and other sensors are installed and operating in the industrial sector*” [5]. In general, “things” refer to a combination of both entities leading to a pseudo-convergence of commercial and industrial internet of things, but the thrust of this research will be the inclusion of electric motors in the “things” of the IIoT. The IIoT provides connectivity between sensors, controllers, process control centres, and enterprise management in order to “improve performance, safety, reliability, and energy efficiency” [5]. The IIoT requires the exchange of data between intelligent devices made possible with the development and deployment of microprocessor-based smart devices which cover sensors, personal devices, office equipment, and operating consoles which can communicate over different fieldbuses, different variants of Ethernet, communications protocols, and even wireless platforms. A typical deployment is at the *Ergon Refining’s Vicksburg, Mississippi facility. This IIoT implementation connects vibration, acoustic, level, position, and* *other sensors to an asset management system via both a wired fieldbus network (Foundation Fieldbus) and a wireless network (Wireless HART). [Foundation Fieldbus and Highway Addressable Remote Transducer Protocol (HART) protocols are governed by FieldComm Group.] The wireless network connects instruments to the plant's control and monitoring systems via a wireless mesh network consisting of wireless instruments and access points* [5].

The intelligent MCC is developed by the introduction of smart interfacing modules that can collect operational data from electric motors and present these data to process control systems through appropriate fieldbuses, to allow for the following:

- Communications across a fieldbus infrastructure,
- Operations and control functions,
- Configuration setup and parameter adjustment,
- Diagnostic functionalities and,
- Status monitoring and protection of the respective drive units.

The iMCC brings the electric motors into the cyber physical space of the IIoT using the smart interface of the microprocessor-based modules so that the major aspects of IIoT are applicable to electric motors. These aspects of IIoT include:

i. Making motors part of the "things" on the IIoT, thereby providing visibility to these motors,
ii. Providing connectivity across process control systems to enterprise resource planning systems,
iii. Extensive motor operational data acquisition capabilities.

Looking at the inclusion of the iMCC in the IIoT, the security concern is mainly on the part of the embedded information system that forms the backbone of the data high way and the data processing infrastructure which is outside the scope of this research. The iMCC is in itself not prone to cyber-attacks but the main IT system could be attacked which will compromise the whole system and put the factory at risk.

3.5 The iMCC and Industry 4.0:

The manufacturing evolution shown in figure 8 indicates a progress from Industry 1.0 where the focus was mainly the development and deployment of mechanical systems powered by either water (hydraulics) or steam (Thermal in this case the steam engine); this was followed by the Industry 2.0 where the focus was the development and deployment of electromechanical systems driven by electrical energy; this was followed by the Industry 3.0 driven mainly by the electronic systems that powered the automation systems wherein the industry deployed automatic control systems to further improve the electromechanical systems of Industry 2.0; and now we at the cutting edge of Industry 4.0 which is also referred to as the ’fourth industrial revolution’. It involves a further developmental stage in the organisation and management of the entire value chain process in the manufacturing industry.

In recent times, industrial processes have increasingly embraced modern information technology, but the most recent trends go beyond simply the automation of production which was the underpinning concept of Industry 3.0, but there has been a widespread adoption by manufacturing industry and traditional production operations of information and communications technology thereby increasingly blurring the boundaries between the real world and the virtual world in what are known as cyber-physical production systems (CPPSs) [27].

The concept of Industry 4.0 is built around secured and reliable connectivity across the factory and associated business management systems and given the significant development in cloud-based storage systems, business management data and factory operations management data can be warehoused in the cloud or other storage infrastructure. To this end, Industry 4.0 is an ‘internet of things, services, data and people’ [27] and it is therefore apparent that the pre-requisite for Industry 4.0 is a communication network that must be secure, reliable, comprehensive and of high-quality [1].

Industry 4.0 is heavily data-dependent and designed to connect all the different business units within an organization such that there is a seamless data exchange and storage for the purpose of decision support for optimum operations and maximum throughput to improve productivity and profitability. A survey of 235 German industrial companies was conducted by the market research institution TNS Emnid and respondents expect that the digital transition will lead to a significant transformation of their companies that will require considerable investment. They estimate the share of investments in Industry 4.0 solutions will account for as high as €140 billion per annum in the European industrial sector [3].

Industry 4.0 is capable of improving visualization arising from the convergence of the physical world and the virtual world (cyberspace) in the form of a cyber physical space (CPS) [1]. The key improvement prospect here is the increased business-customer contact for the exchange of business value.

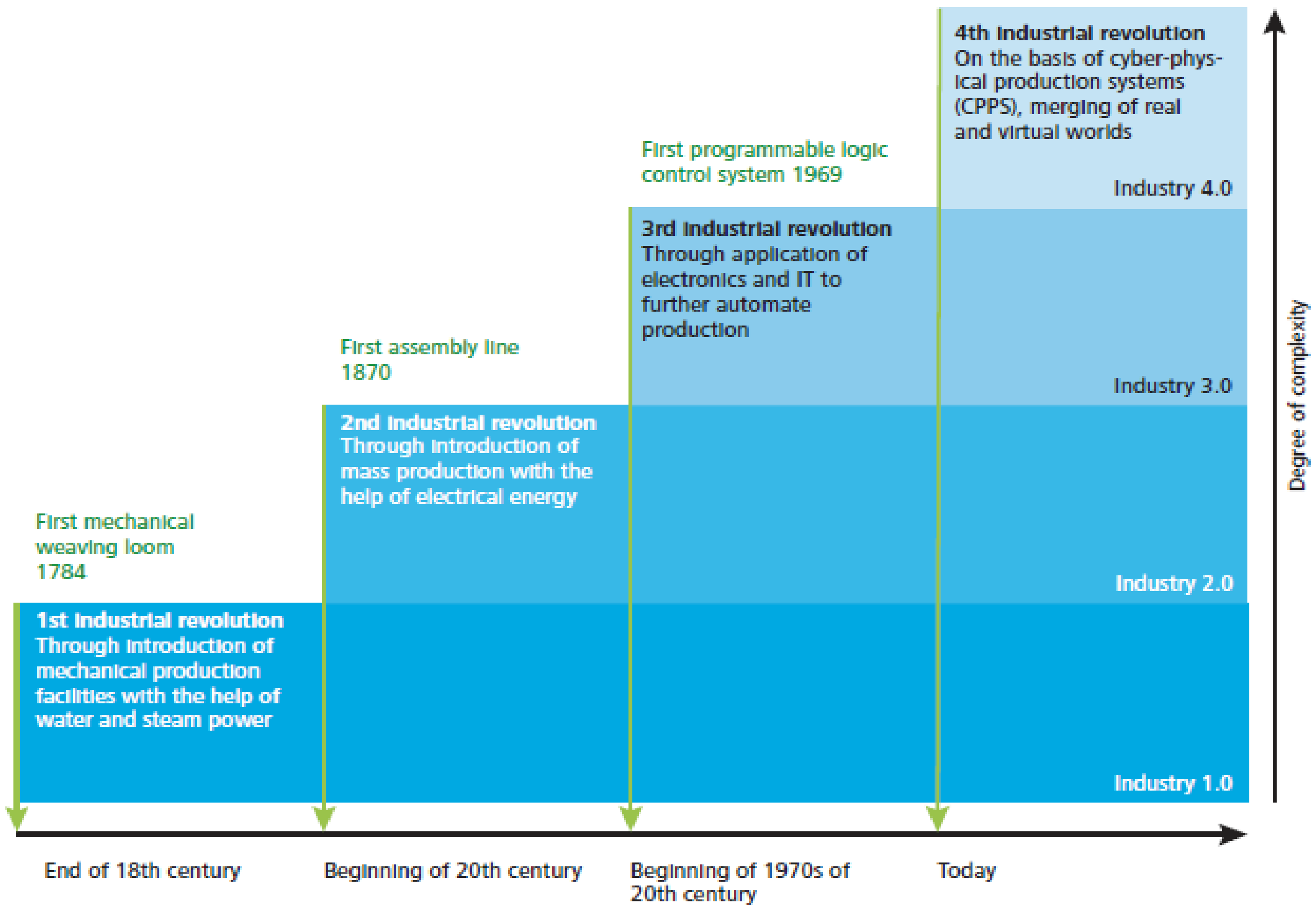


Figure 8: The Evolution of Industry 4.0 [27]

The Industry 4.0 is an application of both the IoT and IIoT, and its major focus is the "internet of things and services" within the plant floor, value support services, and decision support activities all embedded in the value chain [3] leading to a Smart Factory [1] which is not an end in itself, but a move meant to optimize the deployment of resources and enhancement value delivery within the business value chain such that smart machines continually sharing information about current stock levels, problems or faults, and changes in orders or demand levels. Processes and deadlines are coordinated with the aim of boosting efficiency and optimizing throughput times, capacity utilization, and quality in development, production, marketing, and purchasing [4].

When supply chains are Industry 4.0-empowered, they are optimized with the following four capabilities:

- Visibility into operational status at the device level throughout all physical locations via real-time information collected and processed by intelligent sensors.

- Interconnectivity of equipment, machinery, facilities and people for transparency throughout all levels.
- Autonomous performance of equipment and systems to complete tasks as efficiently as possible with minimal human intervention.
- Predictive analysis of all data to identify patterns and trends in inventory, purchasing, equipment usage and more, thereby enabling proactive decision-making [22].

The focus of this research is to make the MCC, a major energy consuming unit within industry, to be a part of the IIoT and by extension a major component of the emerging Industry 4.0 architecture with extensive visibility in order to enhance energy optimization and overall efficiency. The only way to make the MCC part of the Industry 4.0 is by designing into it, communications and device identification intelligence using a smart interface of the microprocessor-based modules, thereby making it an intelligent MCC, an iMCC. In this case, the Industry 4.0 architecture will comprise of the IIoT and the other business systems such as the supply chain management systems, manufacturing execution system (MES), and business management systems.

Finally, in principle, the Industry 4.0 is an embedded system that comprises of the IoT and the IIoT, where the IIoT will be an internet of the iMCC in communication with the plant SCADA, DCS or PLC system (operations technology), and the IoT is the enterprise information system that connects all business information systems (information technology).

4. Methodology and Field work:

In the review of literature, the researcher looked at current concepts and the emerging body of knowledge centred on the development and deployment of intelligent MCCs and how this relates with Industry 4.0. The particular interest here is to explore improvement opportunities in asset care activities, and to extract practicable best practices in the optimization of resource deployment and optimum business processes management. The developed concepts will be looked at with respect to the case organization and improvement prospects extracted for further analyses. For this work, the case organizations will be BUA Sugar Refinery, Apapa - Lagos Nigeria.

At this stage, the researcher will look at the engineering details of the iMCC deployment at the case organization in order to assess it against the requirements of the Industry 4.0 framework.

4.1 The iMCC and SCADA architecture at the case organization:

The iMCC architecture at the case organization was based on Profibus DP protocol and all the components of the drive units are of the ABB range of products. There are three types of combination drive units namely:

- The direct-on-line units using the universal motor controller UMC100-FBP with the PDQ22 FBP gateway, and each can connect four drive units,
- The ACS range of variable speed drives with the FPBA-01 interface module, and
- The PST range of soft starters with built-in interface cards.

The main control system runs on Ethernet/IP communications with a combination of multimode fiber optic connection for plant connections and a untwisted pair ethernet cable for connection within the control rooms, this scheme is to provide noise immunity within the communication system. The main control algorithm runs in a total of five units of Allen Bradley CompactLogix™ PLCs in conjunction with thirteen units of Siemens S300 PLCs.

This research will focus on the main PLC connected to the iMCC architecture as shown in figure 9 below, and the intent is to explore the visibility of the electric motors given the communications functionality provided by the iMCC.

The Profibus DP connection uses the conventional shielded twisted 2-wire and 4-wire American gauge 22 purple cables such that the 2-wire connects the inverters and soft starters, while the 4-wire connects the gateways in order to provide 24 volts power for the gateway operation. The Profibus DP cable specifications deployed are:

- Typical Impedance: 135 up to 165 Ω
- Cable capacity: <30 pF per meter
- Core diameter: American Wire Gauge 22
- Cable type: copper shielded twisted-pair cable of 1 pair and 2 pairs
- Typical resistance: <110 Ω per km with maximum signal attenuation of 9 dB

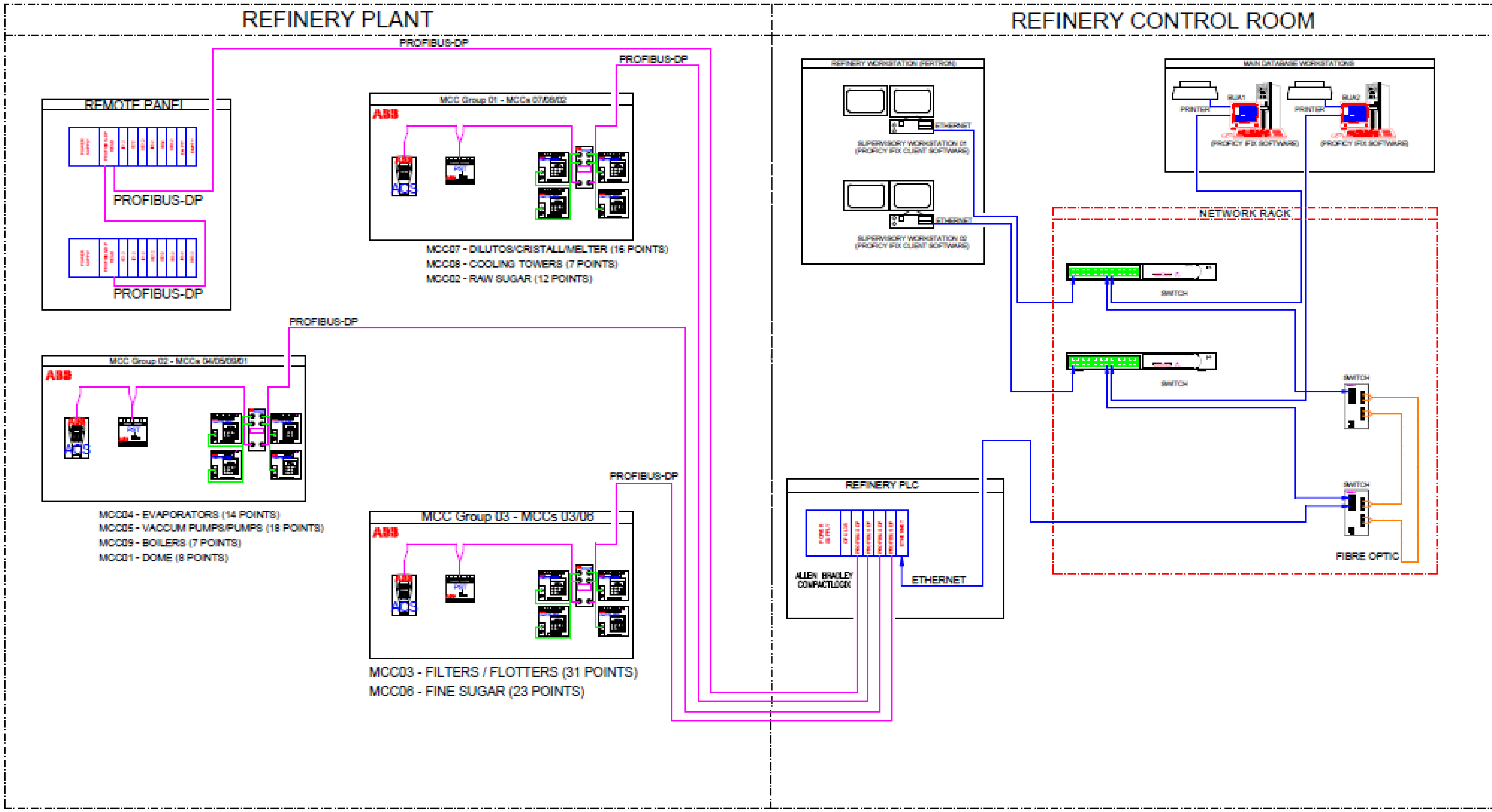


Figure 9: The control system architecture at the case organization

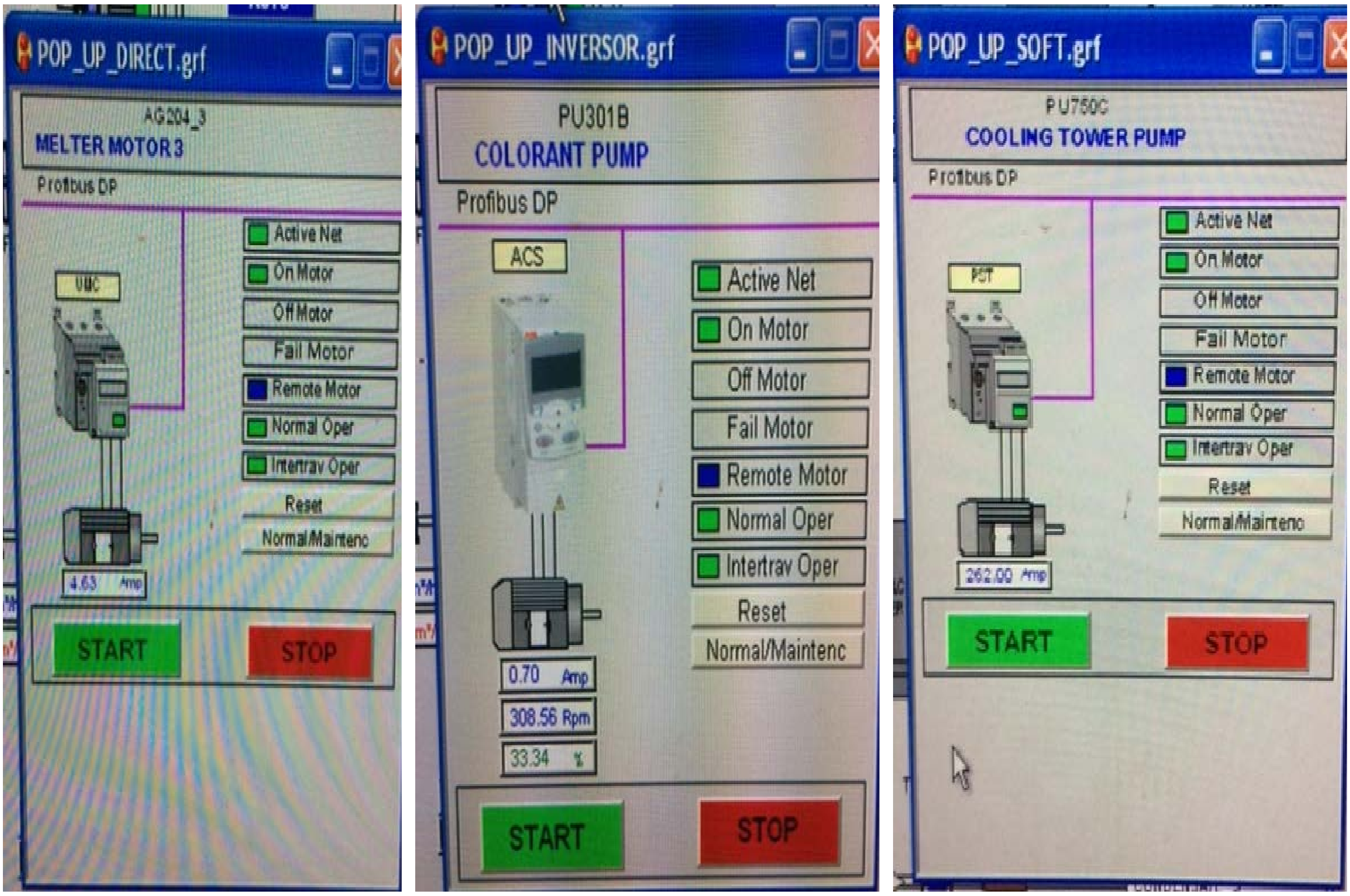
The iMCC are divided into three groups based on the location and the device density so that the data exchange is balanced for each group, within, the Profibus DP recommended segment capacity. In the cases where the device density exceeded the segment capacity, a repeater is deployed to prevent timeout errors. The groups and the respective device density are listed below and the architecture is shown in figure 11 below:

- MCC group #1: 35 combination drive units
- MCC group #2: 47 combination drive units
- MCC group #3: 54 combination drive units

The iMCC architecture at the case organization is shown in figure 11 below wherein the combination drive units are connected in a parallel drop-down topology using Profibus DP interface modules for the soft starters and inverters, and the PDQ 22 FBD gateway for connecting 4 units of direct-on-line-starters. What the network sees are the drive units which by implication are indicative of the operations of the electric motors connected to these drive units,

The operating parameters that can be monitored by the drive units are extensive and depends on the OEM design and the specific requirements of the end users and looking at the operations at the case organization, only the following parameters were monitored as shown in figure 10 below:

- For the direct-on-line starter, the current is monitored and displayed,
- For the inverter, the current, rpm, and speed reference are monitored and displayed, and
- For the soft starter, the current is monitored and displayed.



iMCC interface for UMC100 | iMCC interface for inverter | iMCC interface for soft starter

Figure 10: The iMCC graphic interface at the SCADA system

The main application of the iMCC at the case organization deals with the following:

- Control power factor thereby improving system energy efficiency,
- Control and protection of the motors using UMC22 and the PST range of soft starters,
- Safety interlocking of electric motor-driven equipment, and
- Fluid flow control using inverters to control pump speed depending speed reference signals coming from the control algorithms within the Refinery control system.

The researcher took a close look at the Profibus DP data stream and the configured message map for each drive unit so that the available parameters can be reviewed and selected for display. The lists of parameters that are available from the iMCC network which can be configured for display and storage on the SCADA system are shown in Appendices B, C, and D.

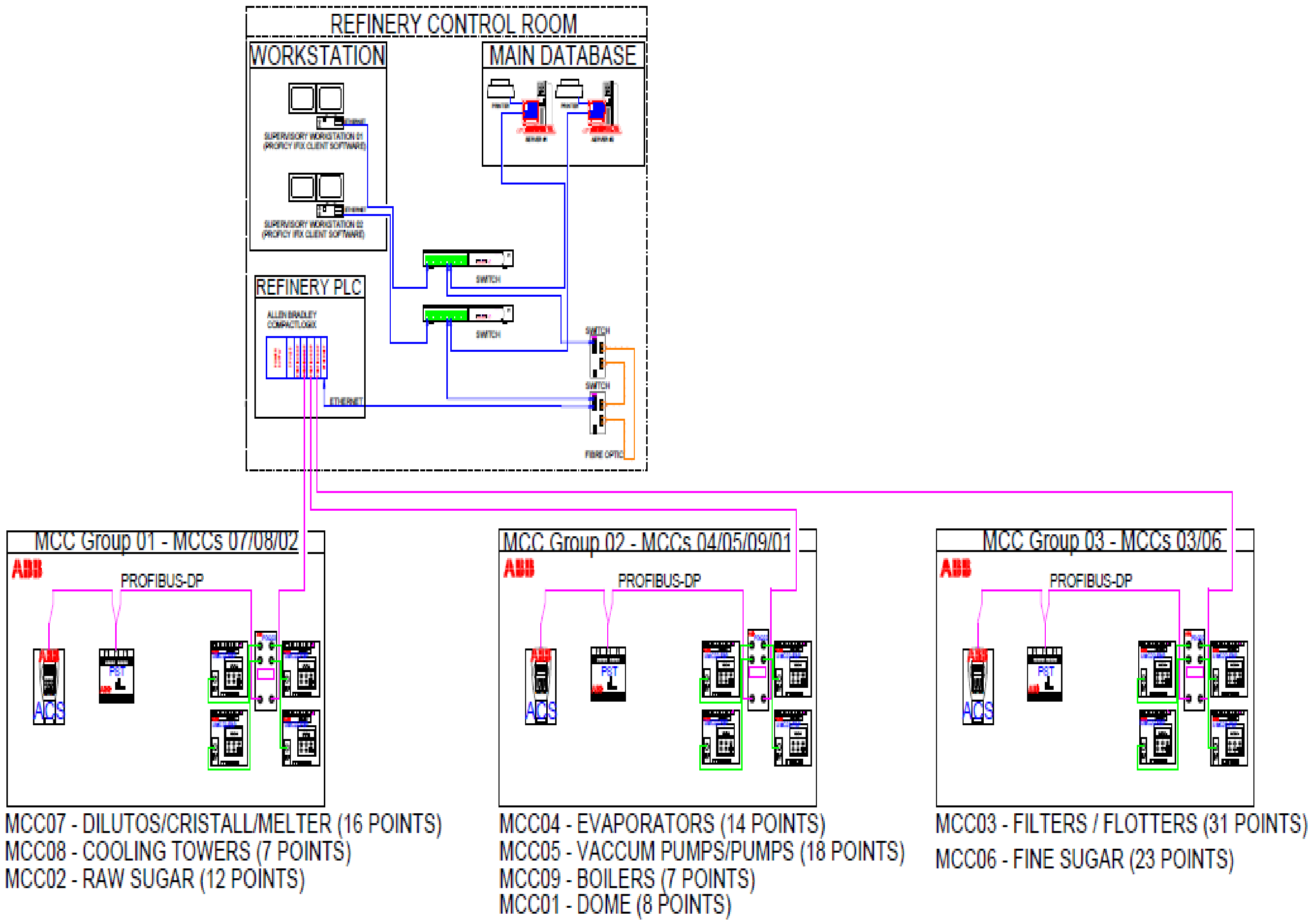


Figure 11: The iMCC architecture at the case organization

5. Hypothesis:

The focus of this research is to show that with more device-level data acquired from electric motors, these motors can be better monitored and properly managed to improve uptime capabilities and energy efficiency. Conventional MCCs provide the following operational parameters: Start and stop commands, fault/trip alarm, and in some cases multimeters for current and voltage measurements. On the other hand, Intelligent MCCs will, in addition, provide more data such as: current, voltages, frequency, speed, voltage/frequency curves for variable frequency drives, voltage/current curves for soft starters, detailed alarms, temperature profiling, energy consumed, maintenance profile, and hour-meters.

The hypothesis of this research is to prove that increased data will enhance decision making capabilities that can support energy efficiency, motor performance monitoring, and optimized asset care initiatives. The intelligent MCCs make it possible to put the electric motors in the industrial internet of things (IIoT) by providing visibility thereby making it possible for the acquisition of data that will enhance insight into the operations of these motors.

Data is not useful when it does not provide decision support that can form the basis for action that ultimately delivers value. The challenge is to ensure that data is first mined by deploying intelligent infrastructure, in this case the iMCC, and then this data is stored within the enterprise IT infrastructure where it is explored and exploited to gain insight using appropriate analytical tools, and this insight can drive actionable plans for overall performance improvement. In the case of electric motors, there are some critical operating parameters which when properly monitored and tracked over time will provide a basis for optimum asset care planning and performance improvement. As seen in Appendix B, Appendix C, and Appendix D, the parameters that can be obtained from the iMCC include:

- Phase voltages and currents,
- Phase voltages and currents balance,
- Temperature of windings (depending on sensor type),
- Real, reactive, and apparent power,
- Start/stop counter,
- Run time counter,
- Watt-Hour counter,
- Motor torque, and
- Faults and alarms history.

The motor runs on current and voltage supply which when properly monitored and analysed can give insight into the operating health of the motor and its efficiency. It is a general rule of thumb that for a 10^0C rise in temperature of a motor winding above rated winding temperature, the life of the motor is reduced by half [23], and the current drawn by the motor can be related to the motor winding temperature. The current drawn by the motor is particularly critical when starting, that is its starting current, which could be as high as six times the full load current thereby making it a critical activity of the MCC as it concerns starting, protection, and control of electric motors.

The typical characteristics of induction motors illustrated in figure 12 show that the operating parameters of the motor depend on the profile of current consumed over its operating range at given voltage. Such parameters as the torque, speed, and efficiency of the motor depend on the current consumed with respect to the mechanical load driven by the motor. This reality further proves the hypothesis herein proposed, that data concerning the motor operating parameters especially current, torque, and speed will support the planning and management of maintenance programs that will lead to the optimization of productivity and profitability of the business, this data can be effectively and efficiently mined using the intelligent MCC interfaced directly with the plant control system and the enterprise ICT infrastructure.

According to [24], the speed versus current curve of the electric motor can be considered to be an accurate characterization of the performance of the electric motor under the specific operating conditions, and any deviation from this characteristic curve outside of preset control limits will be considered an indication of the occurrence of an undesirable condition. This can then trigger the start of further root cause analyses so that latent cause of failure can tracked early and resolved.

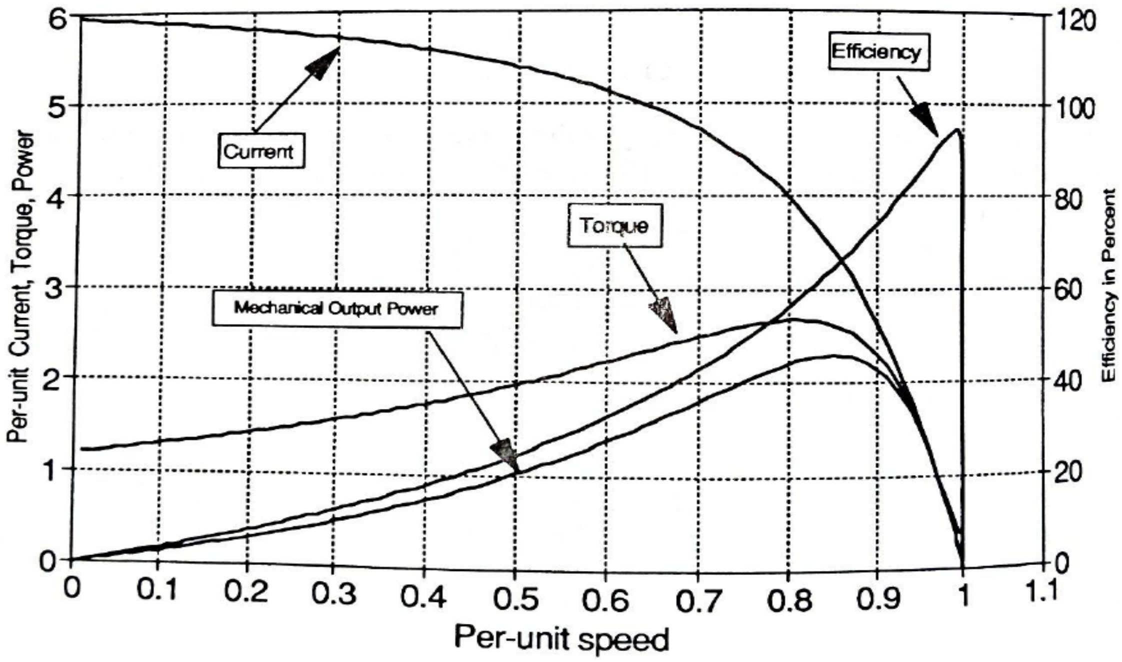


Figure 12: The operating characteristics of induction motors [24]

5.1 The identified gaps:

The deployment of the iMCC at the case organization deals with the control of the power factor, control and protection of electric motors, and fluid flow control using the pump speed. In the light of the expectations of Industry 4.0 where data acquisition and analysis are the source of insight for asset management. At the case organization, the researcher has identified the following gaps in the deployment of the iMCC to the extent that it concerns asset management initiative:

- No data storage infrastructure is in place, data is sourced instantaneously and applied in the solution to process control questions after which they are discarded except specifically required for any other purpose.
- There is no storage of critical equipment operating parameters that can be called up for analysis.
- No equipment operating hour meter is deployed throughout the plant operation and equipment failure logged including:
    - Two units of 55KW motors, two units of 75KW motors, and one unit of 5.5KW motor were reported to have failed within a time frame of sixteen weeks (April 2017 to July 2017) due to burnt field windings. The identified causes of failure include phase failure, over-current

due to collapsed bearings, and repeated start/stop attempts by operator even after several trips.

- o Standby units of pumps left too long without operating them leading to stiffness as a result of product encrustations, and mechanical degradation due to rust.
- o Bearings are allowed to run to failure because equipment operating life could not be estimated in order to determine bearing life and develop bearing replacement schedules.
- o Mean time before failure cannot be accurately monitored leading to failures as a result of equipment running beyond the useful lifespan of components.

5.2 Improvement opportunities:

Following the assessment of the iMCC deployment at the case organization, and the gap analysis that was carried out, the major improvement opportunities center around the analysis and deployment of the acquired data to support predictive and preventive maintenance. The following are identified improvement opportunities:

- The Typical data application is the plot of current profile of a motor against load and when there is a deviation from the established load profile, this could be interpreted as a maintenance red flag indicating the onset of a likely fault condition.
- The run time metering of the different motors to indicate when the drive is due for routine maintenance and to also track the impact of maintenance on the overall performance of the motors.
- To detect the onset of stator failure in continuous cavity screw pumps following the variation outside of tolerance limit of the pump speed versus calibrated dosing rates.
- Profiling of starting current for all electric motors.
- Counting the number of attempted start/stop and disable restarting after set threshold attempts have been exceeded.
- Profile motor current and voltage levels to ensure they are within the nominal values for the application.
- Failure rates can be deployed in root cause analytical tools like failure modes, effects, and criticality analysis (FMECA), fish bone diagrams, and fault tree diagrams. This data can be mined to support reliability centered maintenance and predictive maintenance initiatives,
- Profile failure rates and develop bath tub curve in the management of business asset life cycle

5.3 Implementation:

The implementation of the improvement opportunities indicated above will significantly improve the performance of the assets given the fact that more data acquired from the iMCC will support asset care planning and better process control. During one of the field trials, the researcher characterized a syrup pump by injecting speed references corresponding to 0-100% commands at an interval 10% as shown in Table 1 below, we then got the responses in terms of current consumed, and process flow rates. The outcome of this scheme is the plot of pump speed references versus current consumed, and process flow rates, see figure 13 below.

Given the plots in figure 13, the syrup pump in question is considered to have been characterized and this plot stored in a database. The performance of this syrup pump will then be monitored against this plot to identify any unacceptable deviation which will then be flagged up for further investigation in order to determine its root causes.

Table 1: Syrup pump operating parameters

OPERATING DATA: SYRUP PUMP

COMMAND (%)	CURRENT (A)	FLOW (m^3/hr)
10	30.00	0.00
20	30.00	0.05
30	30.30	0.07
40	31.80	0.12
50	34.20	0.19
60	36.80	19.00
70	45.20	65.00
80	55.40	99.00
90	68.30	132.00
100	88.00	158.00

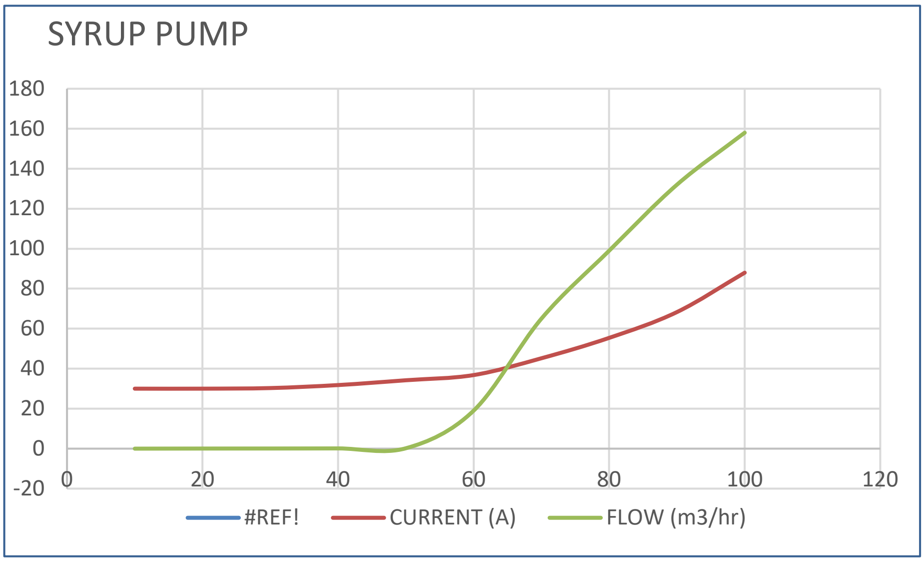


Figure 13: Pump curve derived for an inverter-driven pump at the case organization

The plot in figure 14 follows the data gathered from the same pump under actual operating conditions and this is shown in table 2 which indicated that there an increase in the operating current under operating conditions which could be attributed to the changing density of the syrup following process control dynamics and syrup temperature changes. In this case, further investigation would be needed to drill down to the actual root cause of this increase in operating current, and to ensure that this current profile is safe for the electric motor. This comparison can be activated using scripts such that the operating current profiles of different critical electric motors can be monitored and stored within a database. The expected functionality is such that when there an unacceptable deviation in the operating current profile, this flags off a maintenance need and the pump is investigated further.

Table 2: Syrup pump operating parameters

OPERATING DATA: SYRUP PUMP		
COMMAND (%)	NORMAL CURRENT (A)	OPERATING CURRENT (A)
10	30.00	33.00
20	30.00	33.00
30	30.30	33.33
40	31.80	47.70
50	34.20	51.30
60	36.80	55.20
70	45.20	67.80
80	55.40	72.02
90	68.30	88.79
100	88.00	114.40

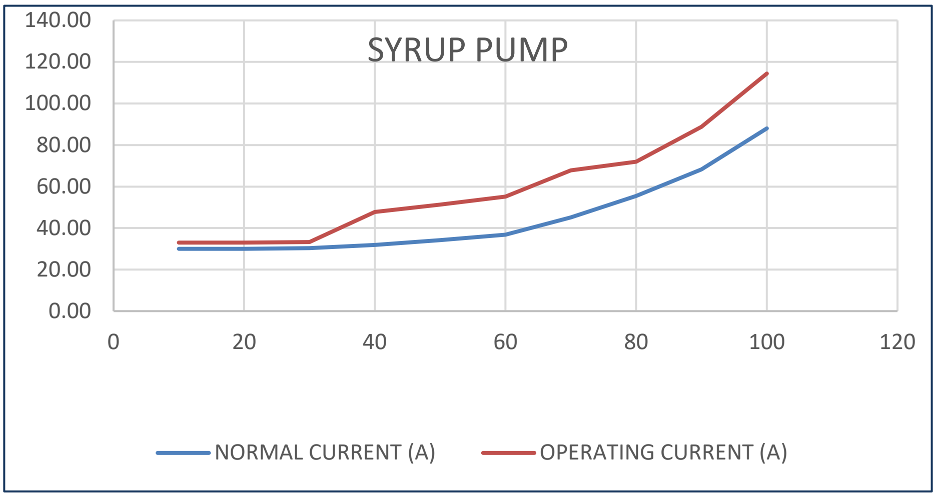


Figure 14: Pump curve derived for an inverter-driven pump at the case organization

6. Future work:

Given the scope covered by this work, the researcher considers it necessary to indicate the areas for future research work in the direction of creating cyber-physical production systems within the framework of Industry 4.0 and Smart manufacturing systems. The iMCC can now form part of the emerging cyber-physical production systems and that comes with some challenges which require further research work. These challenges include security concerns, compatibility of communications protocols, skilled manpower needed to install, operate, and maintain these systems, and the migration of present system to cater for these upscaling demands.

The following are recommended for further work:

- The simplification of the configuration of iMCC architectures such that setup times are shorter and level of technical manpower required is within reach.
- The main characteristic of industry 4.0 is the networking of different business systems into smart production systems to enable plants to both envisage and respond optimally to complexities within the supply chain. The inclusion of the iMCC must now introduce a new layer of complexity especially in the area of energy efficiency and critical asset care initiatives. This conforms to the fact that Smart factories enable production that is customer-specific and extensively integrated smart sensor technology to help with monitoring and autonomous organisation of production management as well as maintenance management [27].
- The complete integration of fieldbus systems deployed in production control, industrial internet of things, and commercial internet of things such that there is bi-directional compatibility of communication protocol to support the evolution of Industry 4.0 systems.
- The development of security systems to ensure the Industry 4.0 system which will integrate critical asset management systems is secured against cyber-attacks.
- The bandwidth design of the communications backbone system to ensure the data exchanges are noise-immune by providing isolation of communication systems in order to mitigate electromagnetic interference.

6.1 Cyber-security concerns

Fieldbus systems originally operated within closed process control systems in that they communicated within the confines of the process control system without integration with open internet-based systems, but the situation is different with the increasing interconnection between fieldbus systems, which include iMCC networks, and enterprise-based computer networks making them susceptible to security breaches, especially in building automation systems, where networks are naturally larger and more complex such as factory and process automation with the prevalence of vertical integration thereby making security a critical concern [28].

According to the SANS 2016 state of the industrial control system (ICS) security survey that focuses on the security risk posed to ICS, the great majority of the 234 participants who completed the survey work for companies headquartered in the United States (69%), with the remainder distributed widely around the globe, below in Table 3 is an indication of their perception of the exposure of their systems to security threats. It is evident that their perception indicates that control systems are facing a higher risk in 2016 than they faced in 2015 [29].

Table 3: End-users' perception of risk level of ICS [29]

SECURITY RISK LEVEL	2015 SURVEY	2016 SURVEY
SEVERE	8%	24%
HIGH	35%	43%
MODERATE	38%	23%
LOW	13%	8.3%
UNKNOWN	5.5%	1.8%

Given the fact in [28], security has never been a real issue in the development and deployment of conventional fieldbus systems until the advent of vertical integration and wireless networking which is the framework for Industry 4.0 systems, this invariably opened the fieldbus system and its associated systems to the recurring threats of cyber breaches, and internal security breaches within the system [29]. This now brought to the fore the need to ensure that these systems are protected against the activities of cyber terrorists and cyber criminals.

According to [28, 30], much work has gone into the enhancement of control systems network security especially the different work groups of standards agencies as show below:

- ISO/IEC 15408: Common Criteria for IT Security Evaluation.
- ISA SP99: Manufacturing and Control Systems Security. It can be expected that this U.S. activity will have significant influence on the WG 13 work.
- AGA/GTI 12: Cryptographic Protection of SCADA Communications.
- NIST: PCSRF.

Common network security approaches include the use of firewalls, encryption, and security token passing. Though these provide reasonable level of network security, they come at an additional computational load on the communications system which may contradict real time demand of production systems interfaced with Industry 4.0 systems [28]. The development of security protocols for enterprise level networks have reached advanced stages, though a lot still has to be done. This is, however, a point of focus for the deployment of cyber security since it constitutes the high-risk exposure to the global internet of things as an underpinning factor in the Industry 4.0 systems.

7. Conclusion:

So far in this work, the researcher has looked at the development and deployment of intelligent MCC within the emerging trends driven by Big Data, Industrial internet of things (IIoT), and Industry 4.0 systems [8]. Fieldbus systems are developing to become the apparent device level local area network due mainly to the increased intelligence, reduced cabling requirements, noise reduction capabilities, low power consumption, and the increased number of OEMs offering intelligent fieldbus-compatible devices, which now improves availability and affordability.

The development and deployment of device-level fieldbus systems has provided a basis for the realisation of intelligence in the traditional MCC leading to the development and deployment of iMCC thereby making it possible to integrate them into the emerging Industry 4.0 system.

The major challenges facing the widespread deployment of iMCC are the availability of required manpower with the requisite skills, and the willingness of businesses to migrate legacy systems into the Industry 4.0 architecture.

The researcher has demonstrated the possibility of integrating the iMCC into the business management systems thereby providing a broad spectrum of device-level intelligence inherent in the intelligent motor control units. This intelligence will make available data that can be gathered and deployed to provide insight in order to better manage, protect and control the operation of electric motors while ensuring comprehensive visualization.

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9 Appendices:

Appendix A: List of Fieldbuses

Protocol	*Standard*	*Industry*	*Special Features*	*Processing*	*Medium Access*	*Nodes*[a]	*Medium*	*Segment Length*	*Bus Safety Concept*	*Further Information*
Ethernet	IEEE 802.3	Office, factory, process	Most widespread network protocol	Decentral	CSMA/CD	Max 30[b]	100BaseT4, copper 100BaseFL, fiber optics 100BaseTX, copper	Max 100 m Max 3000 m Max 100 m	None	Industrial Ethernet Association, www.industrial ethernet.com
Foundation Fieldbus FF HSE	IEC 61158	Factory, process	Function blocks for decentralized control	Decentral	CSMA/CD	Max 30	Copper or fiber optics	Max 100 m	None	Fieldbus Foundation, www.fieldbus.org
Foundation Fieldbus FF H1	IEC 61158	Process	Function blocks for decentralized control	Central/decentral	Token passing	Max 32	Copper	Max 1900 m	Exd or Exi	Fieldbus Foundation
PROFIBUS-DP	IEC 61158	Factory, process	Optimized for remote I/O	Central	Token passing	Max 126	Copper or fiber optics	Max 1200 m (copper) Several kilometers with optical fibers	None	PROFIBUS User Organization, www.profibus.com
PROFIBUS-PA	IEC 61158	Process	Standard certification process for hazardous areas	Central	Token passing but normally operated as master/slave	Max 32	Copper	Max 1900 m	Exi to FISCO model	PROFIBUS User Organization
World FIP	IEC 61158	Factory	Distributed real-time database	Decentral	Token passing	Max 256	Copper or fiber optics	Max 10 km	None	WorldFIP organization, www.worldfip.org
Interbus	IEC 61158	Factory	Optimized for remote I/O	Central	Single master with synchronized shift register	Max 256	Copper	Max 13 km	None	Interbus Club, www.interbusclub.com
ControlNet	IEC 61158	Factory	Optimized for factory applications	Central	TDMA	Max 99	Copper (coax)	Max 6 km (with repeaters)	None	ControlNet International, www.controlnet.org
SwiftNet	IEC 61158	Aircraft	Optimized for aircraft	Decentral	Token passing	Max 1024	Copper	Max 360 m	None	SwiftNet
P-Net[a]	IEC 61158	Factory, shipbuilding	Multinetting capability	Central	Token passing	Max 32 masters Max 125 slaves	Copper	Max 1200 m	None	International P-NET User Organization, www.p-net.com
MODBUS	Industrial standard	Process	Simple structure, widely used	Central	Master/slave	Max 247	Copper	Max 1200 m	None	MODBUS users Web site, www.modbus.org
DeviceNet	EN 50 325	Factory	High immunity to electromagnetic interference	Decentral	CSMA/CD	Max 200	Copper (4-wire)	Max 500 m	None	ODVA, www.devicenet.org
ASI	EN 50 295	Factory, process	Power over bus, for simple actuators and sensors	Central	Master/slave	Max 124	Copper	Max 100 m	None	ASI association, e.g., www.infoside.de/ infida/asi/asi000.htm
HART	Industrial standard	Process	Integrates into existing 4–20 mA systems	Central	Token passing	Max 16	Copper	Max 3000 m, dependent on number of devices	Exi, Exd, or Exe	HART Communication Foundation, ww.hartcomm.org

Source [1]

Appendix B: Typical operating functionalities of the UMC 22-FBP available on the iMCC

Universal Motor Controller
UMC22-FBP
Technical Description

Data structure (2)

Monitoring, command and diagnosis data

Digital monitorings ** (sent from the UMC22-FBP to the control system)

Bit No.	7	6	5	4	3	2	1	0
Byte No.0	WARNING	FAULT	LOCAL CONTROL	REVER-SING LOCK-OUT TIME	-	RUN FORWARD	OFF	RUN REVERSE*
Byte No.1	DI5 (UMC input)	DI4 (UMC input)	DI3 (UMC input)	DI2 (UMC input)	DI1 (UMC input)	DI0 (UMC input)	-	-

Analog monitorings ** (sent from the UMC22-FBP to the control system)

Wrd No.	Byt No.	Group	Byte weight
0	0	MOTOR CURRENT	low
	1	(% of Set current)	high

Digital comands (sent from the control system to the UMC22-FBP)

Bit No.	7	6	5	4	3	2	1	0
Byte No.0	-	FAULT RESET	AUTO MODE	-	SELF TEST	RUN FORWARD	OFF	RUN REVERSE
Byte No.1	DO2* (UMC output)	DO1* (UMC output)	DO0* (UMC output)	-	-	-	-	-

Diagnosis (sent from the UMC22-FBP to the control system)

Bit No.	7	6	5	4	3	2	1	0
Byte 0	-	Self test failed	Fault input signal	-	-	-	-	-
Byte 1	Overload fault	Motor blocked*	Commu-nication fault	Parameter out of range	Current check-back fault*	Relay 2 check-back fault*	Relay 1 check-back fault*	Relay 0 check-back fault*
Byte 2	Motor current high threshold*	Motor current low threshold*	Parameter unknown	Cooling time running	Reversing lock-out time running*	Self test running	-	-
Byte 3	Parameter number (refers to Byte1, Bit 4)							

* some signals are used depending on the parameter 'Control function'
** Some fieldbuses transfer digital input signals together with analog input signals in words.

Source [25]

Appendix C: Typical operating functionalities of the inverter available on the iMCC

No. Name/Value		Description	
01 OPERATING DATA		Basic signals for monitoring the drive (read-only)	**FbEq**
0102	SPEED	Calculated motor speed in rpm	1 = 1 rpm
0103	OUTPUT FREQ	Calculated drive output frequency in Hz. (Shown by default on the panel Output mode display.)	1 = 0.1 Hz
0104	CURRENT	Measured motor current in A. (Shown by default on the panel Output mode display.)	1 = 0.1 A
0105	TORQUE	Calculated motor torque in percent of the motor nominal torque	1 = 0.1%
0106	POWER	Measured motor power in kW	1 = 0.1 kW
0107	DC BUS VOLTAGE	Measured intermediate circuit voltage in VDC	1 = 1 V
0109	OUTPUT VOLTAGE	Calculated motor voltage in VAC	1 = 1 V
0110	DRIVE TEMP	Measured IGBT temperature in °C	1 = 0.1°C
0111	EXTERNAL REF 1	External reference REF1 in rpm or Hz. Unit depends on parameter *9904* MOTOR CTRL MODE setting.	1 = 0.1 Hz / 1 rpm
0112	EXTERNAL REF 2	External reference REF2 in percent. Depending on the use, 100% equals the maximum motor speed, nominal motor torque, or maximum process reference.	1 = 0.1%
0113	CTRL LOCATION	Active control location. (0) LOCAL; (1) EXT1; (2) EXT2. See section *Local control vs. external control* on page *93*.	1 = 1
0114	RUN TIME (R)	Elapsed drive running time counter (hours). The counter can be reset by pressing the UP and DOWN buttons simultaneously when the control panel is in Parameter mode.	1 = 1 h
0115	KWH COUNTER (R)	kWh counter. The counter can be reset by pressing UP and DOWN buttons simultaneously when the control panel is in Parameter mode.	1 = 1 kWh
0120	AI1	Relative value of analog input AI1 in percent	1 = 0.1%
0121	AI2	Relative value of analog input AI2 in percent	1 = 0.1%
0124	AO1	Value of analog output AO in mA	1 = 0.1 mA
0126	PID 1 OUTPUT	Output value of the process PID1 controller in percent	1 = 0.1%
0127	PID 2 OUTPUT	Output value of the PID2 controller in percent	1 = 0.1%
0128	PID 1 SETPNT	Setpoint signal (reference) for the process PID1 controller. Unit depends on parameter *4006* UNIT, *4007* UNIT SCALE and *4027* PID 1 PARAM SET settings.	-
0129	PID 2 SETPNT	Setpoint signal (reference) for the PID2 controller. Unit depends on parameter *4106* UNIT and *4107* UNIT SCALE settings.	-
0130	PID 1 FBK	Feedback signal for the process PID1 controller. Unit depends on parameter *4006* UNIT, *4007* UNIT SCALE and *4027* PID 1 PARAM SET settings.	-
0131	PID 2 FBK	Feedback signal for the PID2 controller. Unit depends on parameter *4106* UNIT and *4107* UNIT SCALE settings.	-
0132	PID 1 DEVIATION	Deviation of the process PID1 controller, i.e. the difference between the reference value and the actual value. Unit depends on parameter *4006* UNIT, *4007* UNIT SCALE and *4027* PID 1 PARAM SET settings.	-
0133	PID 2 DEVIATION	Deviation of the PID2 controller, i.e. the difference between the reference value and the actual value. Unit depends on parameter *4106* UNIT and *4107* UNIT SCALE settings.	-
0134	COMM RO WORD	Relay output Control Word through fieldbus (decimal). See parameter *1401* RELAY OUTPUT 1.	1 = 1

No.	Name/Value	Description	
0135	COMM VALUE 1	Data received from fieldbus	1 = 1
0136	COMM VALUE 2	Data received from fieldbus	1 = 1
0137	PROCESS VAR 1	Process variable 1 defined by parameter group *34 PANEL DISPLAY*	-
0138	PROCESS VAR 2	Process variable 2 defined by parameter group *34 PANEL DISPLAY*	-
0139	PROCESS VAR 3	Process variable 3 defined by parameter group *34 PANEL DISPLAY*	-
0140	RUN TIME	Elapsed time counter (thousands of hours). Runs when the drive is running. Counter cannot be reset.	1 = 0.01 kh
0141	MWH COUNTER	MWH counter. Counter cannot be reset.	1 = 1 MWh
0142	REVOLUTION CNTR	Motor revolution counter (millions of revolutions). The counter can be reset by pressing UP and DOWN buttons simultaneously when the control panel is in Parameter mode.	1 = 1 Mrev
0143	DRIVE ON TIME HI	Drive control board power-on time in days. Counter cannot be reset.	1 = 1 days
0144	DRIVE ON TIME LO	Drive control board power-on time in 2 second ticks (30 ticks = 60 seconds). Counter cannot be reset.	
0145	MOTOR TEMP	Measured motor temperature. Unit depends on the sensor type selected by group *35 MOTOR TEMP MEAS* parameters.	1 = 1
0146	MECH ANGLE	Calculated mechanical angle	1 = 1
0147	MECH REVS	Mechanical revolutions, i.e. the motor shaft revolutions calculated by the encoder	1 = 1
0148	Z PLS DETECTED	Encoder zero pulse detector. 0 = not detected, 1 = detected.	1 = 1
0158	PID COMM VALUE 1	Data received from fieldbus for PID control (PID1 and PID2)	1 = 1
0159	PID COMM VALUE 2	Data received from fieldbus for PID control (PID1 and PID2)	1 = 1
0160	DI 1-5 STATUS	Status of digital inputs. Example: 10000 = DI1 is on, DI2...DI5 are off.	
0161	PULSE INPUT FREQ	Value of frequency input in Hz	1 = 1 Hz
0162	RO STATUS	Status of relay output. 1 = RO is energised, 0 = RO is de-energized.	1 = 1
0163	TO STATUS	Status of transistor output, when transistor output is used as a digital output.	1 = 1
0164	TO FREQUENCY	Transistor output frequency, when transistor output is used as a frequency output.	1 = 1 Hz
0165	TIMER VALUE	Timer value of timed start/stop. See parameter group *19 TIMER & COUNTER*.	1 = 0.01 s
0166	COUNTER VALUE	Pulse counter value of counter start/stop. See parameter group *19 TIMER & COUNTER*.	1 = 1
0167	SEQ PROG STS	Status Word of the sequence programming: Bit 0 = ENABLED (1 = enabled) Bit 1 = STARTED Bit 2 = PAUSED Bit 3 = LOGIC VALUE (logic operation defined by parameters *8406...8410*).	1 = 1
0168	SEQ PROG STATE	Active state of the sequence programming. 1...8 = state 1...8.	1 = 1
0169	SEQ PROG TIMER	Current state time counter of the sequence programming	
0170	SEQ PROG AO VAL	Analog output control values defined by sequence programming. See parameter *8423* ST1 OUT CONTROL.	1 = 0.1%
0171	SEQ CYCLE CNTR	Executed sequence counter of the sequence programming. See parameters *8415* CYCLE CNT LOC and *8416* CYCLE CNT RST.	1 = 1

No. Name/Value	Description	
03 FB ACTUAL SIGNALS	Data words for monitoring the fieldbus communication (read-only). Each signal is a 16-bit data word. Data words are displayed on the panel in hexadecimal format.	
0301 FB CMD WORD 1	A 16-bit data word. See section *DCU communication profile* on page *246*.	
0302 FB CMD WORD 2	A 16-bit data word. See section *DCU communication profile* on page *246*	
0303 FB STS WORD 1	A 16-bit data word. See section *DCU communication profile* on page *246*.	
0304 FB STS WORD 2	A 16-bit data word. See section *DCU communication profile* on page *246*	
0305 FAULT WORD 1	A 16-bit data word. For the possible causes and remedies and fieldbus equivalents, see chapter *Fault tracing*.	
	Bit 0 = OVERCURRENT	
	Bit 1 = DC OVERVOLT	
	Bit 2 = DEV OVERTEMP	
	Bit 3 = SHORT CIRC	
	Bit 4 = Reserved	
	Bit 5 = DC UNDERVOLT	
	Bit 6 = AI1 LOSS	
	Bit 7 = AI2 LOSS	
	Bit 8= MOT OVERTEMP	
	Bit 9 = PANEL LOSS	
	Bit 10 = ID RUN FAIL	
	Bit 11 = MOTOR STALL	
	Bit 12 = Reserved	
	Bit 13 = EXT FAULT 1	
	Bit 14 = EXT FAULT 2	
	Bit 15 = EARTH FAULT	
0306 FAULT WORD 2	A 16-bit data word. For the possible causes and remedies and fieldbus equivalents, see chapter *Fault tracing*.	
	Bit 0 = UNDERLOAD	
	Bit 1 = THERM FAIL	
	Bit 2...3 = Reserved	
	Bit 4 = CURR MEAS	
	Bit 5 = SUPPLY PHASE	
	Bit 6 = ENCODER ERR	
	Bit 7 = OVERSPEED	
	Bit 8 = Reserved	
	Bit 9 = DRIVE ID	
	Bit 10 = CONFIG FILE	
	Bit 11 = SERIAL 1 ERR	
	Bit 12 = EFB CON FILE. Configuration file reading error.	
	Bit 13 = FORCE TRIP	
	Bit 14 = MOTOR PHASE	
	Bit 15 = OUTP WIRING	

No.	Name/Value	Description	
0307	FAULT WORD 3	A 16-bit data word. For the possible causes and remedies and fieldbus equivalents, see chapter *Fault tracing*.	
		Bit 0...2 = Reserved	
		Bit 3 = INCOMPATIBLE SW	
		Bit 4...10 = Reserved	
		Bit 11 = MMIO ID ERROR	
		Bit 12 = DSP STACK ERROR	
		Bit 13 = DSP T1...T3 OVERLOAD	
		Bit 14 = SERF CORRUPT /SERF MACRO	
		Bit 15 = PAR PCU 1/2 / PAR HZRPM / PAR AI SCALE / PAR AO SCALE / PAR FBUS MISS / PAR CUSTOM U/F	
0308	ALARM WORD 1	A 16-bit data word. For the possible causes and remedies and fieldbus equivalents, see chapter *Fault tracing*. An alarm can be reset by resetting the whole alarm word: Write zero to the word.	
		Bit 0 = OVERCURRENT	
		Bit 1 = OVERVOLTAGE	
		Bit 2 = UNDERVOLTAGE	
		Bit 3 = DIRLOCK	
		Bit 4 = IO COMM	
		Bit 5 = AI1 LOSS	
		Bit 6 = AI2 LOSS	
		Bit 7 = PANEL LOSS	
		Bit 8 = DEVICE OVERTEMP	
		Bit 9 = MOTOR TEMP	
		Bit 10 = UNDERLOAD	
		Bit 11 = MOTOR STALL	
		Bit 12 = AUTORESET	
		Bit 13...15 = Reserved	
0309	ALARM WORD 2	A 16-bit data word. For the possible causes and remedies and fieldbus equivalents, see chapter *Fault tracing*. An alarm can be reset by resetting the whole alarm word: Write zero to the word.	
		Bit 0 = Reserved	
		Bit 1 = PID SLEEP	
		Bit 2 = ID RUN	
		Bit 3 = Reserved	
		Bit 4 = START ENABLE 1 MISSING	
		Bit 5 = START ENABLE 2 MISSING	
		Bit 6 = EMERGENCY STOP	
		Bit 7 = ENCODER ERROR	
		Bit 8 = FIRST START	
		Bit 9 = INPUT PHASE LOSS	
		Bit 10...15 = Reserved	

No. Name/Value		Description	
04 FAULT HISTORY		Fault history (read-only)	
0401	LAST FAULT	Code of the latest fault. See chapter *Fault tracing* for the codes. 0 = Fault history is clear (on panel display = NO RECORD).	1 = 1
0402	FAULT TIME 1	Day on which the latest fault occurred. Format: Date if the real time clock is operating. / The number of days elapsed after the power-on if the real time clock is not used, or was not set.	1 = 1 days
0403	FAULT TIME 2	Time at which the latest fault occurred. Format on the assistant panel: Real time (hh:mm:ss) if the real time clock is operating. / Time elapsed after the power-on (hh:mm:ss minus the whole days stated by signal *0402* FAULT TIME 1) if real time clock is not used, or was not set. Format on the basic panel: Time elapsed after power-on in 2 second ticks (minus the whole days stated by signal *0402* FAULT TIME 1). 30 ticks = 60 seconds. E.g. Value 514 equals 17 minutes and 8 seconds (= 514/30).	
0404	SPEED AT FLT	Motor speed in rpm at the time the latest fault occurred	1 = 1 rpm
0405	FREQ AT FLT	Frequency in Hz at the time the latest fault occurred	1 = 0.1 Hz
0406	VOLTAGE AT FLT	Intemediate circuit voltage in VDC at the time the latest fault occurred	1 = 0.1 V
0407	CURRENT AT FLT	Motor current in A at the time the latest fault occurred	1 = 0.1 A
0408	TORQUE AT FLT	Motor torque in percent of the motor nominal torque at the time the latest fault occurred	1 = 0.1%
0409	STATUS AT FLT	Drive status in hexadecimal format at the time the latest fault occurred	
0412	PREVIOUS FAULT 1	Fault code of the 2nd latest fault. See chapter *Fault tracing* for the codes.	1 = 1
0413	PREVIOUS FAULT 2	Fault code of the 3rd latest fault. See chapter *Fault tracing* for the codes.	1 = 1
0414	DI 1-5 AT FLT	Status of digital inputs DI1…5 at the time the latest fault occurred (binary)	

Source [26]

Appendix D: Typical operating functionalities of the soft starter available on the iMCC

Display text	Function
Frequency	Measured frequency.
Phase seq.	Phase sequence indication.
Connection	Type of connection, In Line/Inside Delta.
Phase L1	Phase current L1.
Phase L2	Phase current L2.
Phase L3	Phase current L3.
Line Voltage	The incoming line voltage [U].
cosPhi	Power factor.
P kW	Active power [kW].
P hp	Active power [hp]
Q kVAr	Reactive power [kVAr]
S kVA	Apparent power [kVA]
Run Time	Total run time of the motor.
No. Of Starts	Counted number of starts.
SW Ver. CU	Software version CU.
SW Ver. FU	Software version FU.
SW Ver. KP[1]	Software version Ext. keypad.
DB version	Database version
MAC Address	Internal addressing.
LV Board No	Serial No of the LV PCB.

1) only if connected

Source [31]