The Integrated Electro-Mechanical Drive

A mechatronic approach

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To our families

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Appendices

Preface

To make progress, science should not accept the limitations placed on discovery by traditional methods, conventional approaches, or existing infrastructure.

Moselio Schaechter, Roberto Kolter and Merry Buckley 2004
Microbiology in the 21st Century: Where Are We and Where Are We Going?
(Washington DC: AMS)

The real voyage of discovery consists not in seeking new technologies but in having new eyes.

Marcel Proust

A particular new scientific result does not usually gain a victory in a way that the opponents suffer a defeat and declare that they are converted but much rather the opponents gradually die out and the new generations grow ab ovo familiar with the truth.

Max Planck

The resistance to a new idea increases as the square of its importance.

Bertrand Russell

The title of this textbook requires some explanation. 'Mechatronics' is the integration of physics—mechanics, fluidics, electrics and electronics, etc—and computer technologies into the research and development (R&D) of cyber-physical heterogeneous continuous dynamical hypersystems (Fijalkowski 2010, 2011, 2016, Tutaj 2012). Thus, mechatronics consists of the synergistic combination of different physical disciplines like mechanics, fluidics, electrics and electronics, as well as informatics, etc. Synergy is a very creative and therefore dynamic process, far more so than the usual co-operation of the different physical disciplines, and even more so than a close integration of machine hardware and software.

Mechatronics offers new solutions and unprecedented flexibility in transportation systems, industrial production processes, and aerospace, aviation, automotive and traction cyber-physical heterogeneous dynamical hypersystems, containing homogenous dynamical systems, hyposystems and components, etc. Its economic success is based on functional integration, i.e. the multiple use of mechano-mechanical (M-M), fluido-mechanical (F-M) and/or electromechanical (E-M) actuators (machines); the decentralisation of intelligence into cyber-physical heterogeneous continuous dynamical hypersystems, e.g. aerospace, automotive and industrial integrated electromechanical drives (IEMD) and/or traction direct-drive (DD) propulsion cyber-physical heterogeneous continuous or discrete dynamical hypersystems with their commutation, control, communication and automation homogenous dynamical systems, hyposystems and components, as well as the inherent options for sensorless self-monitoring and system protection.

Mechatronics is a rapidly developing interdisciplinary field of engineering. It deals with the synergistic integration of mechanical engineering, macro- and microelectronic engineering (macrocommutators and microprocessors), control engineering, computer technology, in the development of E-M products, e.g. an IEMD through a unified design, dynamical systems approach.

A mathematical model is as a rule a simplification of reality. In physics and engineering, the author discriminates three fundamental aims for a formulation of mathematical models of cyber-physical heterogeneous continuous or discrete dynamical hypersystems: analytical study, design and control.

In an identification of some real (existing) cyber-physical heterogeneous continuous or discrete complex and/or simple dynamical hypersystems there is usually a great degree of indeterminacy, connected with the existence of stochastic disturbances and often an inaccurate knowledge of the cyber-physical heterogeneous continuous or discrete dynamical hypersystem's structure. This indeterminacy often limits statistical identification methods (Manczak and Nahorski 1983).

In this textbook, the authors have confined themselves exclusively to 'deterministic identification methods', because in the considered mathematical models of cyber-physical heterogeneous continuous or discrete dynamical hypersystems, the stochastic disturbances may be neglected. Deterministic identification methods for cyber-physical heterogeneous continuous or discrete dynamical hypersystems are interesting for practitioners and designers.

Dynamical process identification is a complex work that comprises (Wegrzyn 1974): the formulation of mathematical models, experimental studies (collection of measurement data), analytical studies (physical-parameter computer-simulation of mathematical models) and the verification (and inspection) of mathematical models.

The most important and most difficult aspect of physically continuous dynamical hypersystems is the formulation of mathematical models, which is why this is a principal aim of this textbook.

In principle, the problems that exist upon the formulation of a simple mathematical model of the physical homogeneous continuous or discrete dynamical system may be considered to have been sufficiently studied.

In the case of the formulation of a synthetic mathematical model or a functional mathematical model of the cyber-physical heterogeneous continuous dynamical hypersystem, a suitable methodology of its formulation should be applied.

In the holor theory of abstract functional heterogeneous continuous dynamical hypersystems (including physically continuous dynamical hypersystems, among others) two modes of mathematical modelling methodology may be selected: an analytical mode with decomposition methods and a synthetic mode comprising aggregation methods.

The full advantages of both modes are taken into consideration in this textbook. That is why when considering cyber-physical heterogeneous continuous dynamical hypersystems two kinds of mathematical models may be created. Namely, synthetic mathematical models for a structure of the cyber-physical heterogeneous continuous dynamical hypersystem, as well as simple mathematical models for individual, functional and structural dynamical hyposystems or components of cyber-physical heterogeneous continuous dynamical hypersystems, that is, elemental homogeneous continuous dynamical systems, hyposystems and components.

The formalisation of cyber-physical heterogeneous continuous dynamical hypersystems provides everything about the mathematical models' methodology, comprising different operations, phases and connections in a synthetic dynamical process. However, this is not the case for identification, which most often resolves itself in the identification of the homological, functional and structural dynamical components of physically continuous dynamical hypersystems, that is, physically homogenous continuous dynamical systems, or dynamical hyposystems, by means of well-known methods.

Stating a generality of knowledge on a considered problem precisely in the domain of mathematical formalism is termed 'mathematical model formulation', and concrete mathematical relationships are termed 'mathematical models'. Because the mathematical model only simulates these features, which specify a purpose for which it has been created, a given cyber-physical heterogeneous continuous dynamical hypersystem may have no single mathematical model, but instead several, simulating heterogeneous viewpoints. It may be affirmed, going out from most generalised assumptions, that each of the simple 'component' mathematical models may be led out from a certain synthetic mathematical model of the physical heterogeneous continuous dynamical hypersystem, in which they are connected to each other.

A synthetic mathematical model that is solely in the domain of abstract mathematical models and uses the Euler–Lagrange second-order differential equations of dynamics for its formation may be formatted in the dynamical systems approach and holor matrix notation. In compliance with this, it is good to determine the physical heterogeneous continuous dynamical hypersystem by means of a structure, representing the so-called 'synthetic mathematical model'. The cyber-physical heterogeneous continuous dynamical hypersystem as a whole may be concerned or it may be divided into cyber-physical homogeneous continuous dynamical systems on the grounds of which form of energy is concerned (e.g. kinetic energy: radiant, thermal, motion, sound and electrical homogeneous continuous dynamical systems; potential energy: chemical, nuclear, stored mechanical, fluidic, and electrical and gravitational homogeneous continuous systems). Next, they may be divided as cyber-physical homogeneous continuous dynamical hyposystems and, as follows, they may be divisible as functional and structural cyber-physical homogeneous continuous dynamical components.

The authors' intention in writing this textbook is to submit 'generalised physical commutation matrixer holor analyses' in the easiest practicable dynamical systems approach (systems thinking).

The author believes that this can be best realised through the application of physical commutation matrixers and the functional and structural cyber-physical homogeneous continuous dynamical components. Nearly all mechanical and electrical engineering students have been educated concisely regarding physical commutation matrixers during their university physics courses.

In view of this, the physical model represents an exceptional structure with which to form a junction between static and dynamical analysis. It is probably particularly important that the generalised physical commutation matrixer concept lends itself systematically to analogy.

Owing to the application of the physical commutation matrixer method, one may confirm that it is practicable to consider the area under discussion in mechatronics (kinetic energy—radiant, thermal, motion, sound and electrical—as well as potential energy—chemical, nuclear, stored mechanical, fluidic, electrical and gravitational). For instance, the analogy between charging an electrical capacitor and saturating a fluidic container of water is made evident by equating the physical and mathematical models of these physical processes. Naturally, one might have identified this analogy instinctively.

In spite of this, one becomes aware that these physical processes are also comparable to the variation in linear/angular velocity of a mass/moment of inertia when a force/torque, respectively, is relevant. This is not practically so evident.

As a result, the physical commutation matrixer concept confirmation is exceptionally convenient in the absence of physical situations in various cyber-physical heterogeneous continuous dynamical hyposystems for a generalised cyber-physical heterogeneous continuous dynamical hyposystem from which a universal type of solution may be completed.

A new definition of the 'physical commutation matrixer', based on matrix interconnection cyber-physical heterogeneous continuous dynamical hypersystem theory concepts, is proposed. The definition may be used to evaluate physical commutation matrixers, which perform multivalent logical functions, and continuously operating physical commutation matrixers. The serial and parallel connections of two physical commutation matrixers and simplified formulae are defined, which are valid for high component physical commutation matrixers.

A comparison is made between results arrived at using the new and conventional definitions. It is found that the results differ little in the case of equal probability output letters. For instance, a physical commutation matrixer is a general term referring to a cyber-physical heterogeneous continuous dynamical hypersystem or part of a cyber-physical heterogeneous continuous dynamical hypersystem of matrixery conductive parts and their matrixery inter-connections through which an energy-transfer holor is intended to flow.

A physical commutation matrixer, i.e. a configuration of physically (electrically, magnetically, optically, or radiationally) connected dynamical components or analogue and/or digital devices, is made up of active and passive physical, functional and structural dynamical components or an assemblage of physical, functional and structural dynamical components, and their matrix-interconnected row and column conductive collectors. Thus, a physical commutation matrixer is a physical device powered by physical energy.

The active physical, functional and structural dynamical components are the sources of physical energy for the physical commutation matrixer; for instance, they may be chemo-electrical/electro-chemical (ChE/ECh) storage batteries, direct current (DC) or alternating current (AC) mechano-electrical/electromechanical (M-E/E-M) dynamotors (generators/motors), photovoltaic cells, or fuel cells.

The passive physical, functional and structural dynamical components are impeders or admitters, i.e. resistors, inductors and capacitors.

The physical commutation matrixer described by a matrixer physical model (matrixery signal-flow diagram or map) shows the active and passive physical, functional and structural dynamical components and their matrixery interconnected row and column conductive collectors (conductors). For the purposes of analysis, apparatus (equipment) and devices with an individual physical identity are often represented by equivalent physical commutation matrixers. These equivalent physical commutation matrixers are made up of the basic passive and active physical, functional and structural dynamical components listed above. For instance, mechano-electrical (M-E) split-ring/flat or electrical commutation matrixers are used not only to convert electro-electrical (E-E) electrical energy as ME split-ring/flat commutators or macroelectronic commutators (macrocommutators) of electrical machines which are used in IEMDs, but also to transmit electrical energy in high-voltage power lines and E-E transformers or in low-voltage distribution in factories and homes. They are used to convert energy from or to its electrical form, for example, as in E-M motors, M-E generators, microphones, loudspeakers and lamps; to communicate information, as in telephones, radios, televisions and internet systems; to process and store data and make logical decisions, as in computers; and to form systems for the automatic control of equipment.

Physical commutation matrixer theory includes the study of all aspects of matrixers, including analysis, design and application. In it, the fundamental quantities are the 'energy-potential-difference holors' (i.e. generalised force or torque holors) between various points, the 'energy-transfer holors' (i.e. generalised translational or angular velocity holors) flowing in a number of row and column conductive collectors, and the parameters, which describe the passive physical, functional and structural dynamical components.

Other important physical commutation matrixer quantities, such as power, energy and time constants, may be computed from the fundamental physical variables. For a discussion of these parameters, physical commutation matrixer theory is often divided into special topics. This can be based on how the energy-potential-difference holors (i.e. voltage holors and current holors) in the physical commutation matrixer vary with time (i.e. DC or AC, sinusoidal, non-sinusoidal, digital and transient physical commutation matrixer theory). Moreover, they can be divided based on the arrangement or configuration of the energy-transfer holors' (i.e. electrical current holors) row and column conductive collectors (series, parallel, series parallel, parallel series, coupled, open circuited and short-circuited physical commutation matrixers).

The physical commutation matrixer can be divided into special topics according to which physical devices form the matrixer, or the application and use of physical commutation matrix theory can also be divided (power, communication, macro- and microelectronic, solid-state, integrated computers and programmable commutation matrixers). This textbook provides a comprehensive and careful development of the physical commutation matrixer base and the use of holor theory formulations of analytical methods.

No attempt is made to provide the required mathematical tools: matrixer theory, the functions of a complex variable, Laplace transforms, numerical methods and programming. However, some references in these areas have been included in the bibliography.

Holor analysis has been shown beyond doubt to be of prime importance in physics and engineering. Every current scientist and engineer must be systematically well acquainted with the symbolism and methods of manipulation.

Because both the nomenclature and routine manipulation are quite uncomplicated and may be learned in a short time, the question emerges as to whether an independent one-term subject on holors is adequate for a programme of scientific study.

If the subject is on the experiential level, it may be integrated into one of the necessary physics subjects, such as electronics and magnetics, mechanics, fluidics, photonics, electronics, etc. However, if one expects to use matrices as a systematically dependable tool, one must really understand them. This not only necessitates that an independent subject is taught in the programme of study, but also that there is a textbook that is dissimilar from the old school one.

An examination of the handbooks on matrix analysis since 2000 confirms that virtually all of them are founded on the same physical models. One considers these physical models to be inadequate on two counts (Moon and Spencer 1965):

- they do not refer to 'invariance', which is in reality the imperative factor that makes a matrix a matrix, a vector a vector and a scalar a scalar;
- they give too much weight to rectangular coordinates.

Matrix analysis as column matrix or vector analysis is the infant of quaternions and Ausdehnungslehre. The former are principally algebraic, and in them questions of invariance do not arise. The latter deals with geometrical figures that are tacitly assumed to be unconcerned by coordinate transformations. However, precise consideration of invariance under coordinate transformation (which has assumed such importance in the 20th century, especially after the advent of relativity) is not present in either parents or offspring. This is why some mathematicians have considered column matrix analysis or vector analysis to be a marginal subject: an ad hoc combinatory logic foundation.

The inexperienced confidence that a column matrix or a vector maintains its form and size is transformed when the coordinates are not adequate. One must also enquire, 'under what group of transformations'? Because matrix analysis has disregarded this question, it is concerned by imprecision. The unacceptable dissimilarity among free, bound and sliding column matrices or vectors is a paradigm. In addition, the old school treatment of matrices gives too much weight to orthogonal Cartesian coordinates. Even the definitions of 'gradient', 'divergence' and 'curl' are normally only provided for particular cases of rectangular coordinates, as if no other coordinates ever emerge in mathematics or physics.

Over the past couple of decades, the academic community has made considerable progress in developing educational materials and laboratory exercises for elementary mechatronics education. Students learn mathematical motion-control theory, board-level macro- and microelectronics, interfacing, and microprocessors supplemented with educational laboratory equipment. As new electrical and mechanical engineering graduates become practicing engineers, many are engaged in projects where knowledge of industrial electromechanical drive technology is an absolute must since industrial automation is designed primarily around specialised electromechanical drive hardware and software.

This textbook introduces new development trends and is in line with current trends in industry and technology, it will also help to design a modern integrated electromechanical drive (IEMD), which in the near future will replace the conventional electromechanical drive (CEMD). The textbook presents the methodology of creating mathematical models of integrated electrical machines, which is the basis for further computer-simulation studies of this IEMD.

With every passing year, it is getting more difficult to recognise the current crop of an IEMD as the descendants of Ward-Leonard, Kraemer and Scherbius systems.

At present, the IEMD is correctly stuffed with macroelectronic commutators (macrocommutators) and microelectronic controllers (microcontrollers) and human–machine interfaces (HMI) designed to take on functions once performed by these earlier Ward-Leonard, Kraemer and Scherbius systems.

IEMD users' demands are constantly varying in the market. Their challenges will be on the increase year on year. Minimising their risk as a manufacturing industry, saving energy and reducing downtime are always at the focus of all users' demands.

To continue to be competitive, IEMD suppliers often look towards technology and the latest innovations to enable their demands while reinforcing risk minimisation.

Now if IEMD users take these challenges into account and focus on IEMD cyber-physical dynamical hypersystem demands, with EM engineering complexities they will see that optimising the IEMD cyber-physical homogeneous continuous dynamical systems, hyposystems and components can be critical. IEMD users necessitate combining highly complex solutions with commutation, control, communication and automation cyber-physical homogeneous continuous dynamical systems that are high quality, reliable and are fully supported throughout the lifecycle. The IEMD cyber-physical homogeneous continuous dynamical systems, hyposystems and components need to be optimally combined to encounter the application demands, reduce transmission losses and ensure the IEMD cyber-physical heterogeneous continuous dynamical hypersystem is highly maintainable in the future. Therefore, implications further down the IEMD cyber-physical heterogeneous continuous dynamical hypersystem can be very critical for suppliers' operations as a whole.

IEMD cyber-physical heterogeneous continuous dynamical hypersystem is a concept that brings together a suite of products that connect to each other and integrate not only with each other, but also with the commutation, control, communication and automation homogenous continuous dynamical systems, hyposystems and components, all from a one-stop shop. For example, an integrated E-M motor coupled onto a gearbox and an adjustable-velocity IEMD doing the commutation, control, communication and automation integrate together in a way that it seamlessly adds value to the user.

Designing an IEMD cyber-physical heterogeneous continuous dynamical hypersystem means taking a step back to look at the bigger picture, listening to the user's demands and developing a solution that hits their exceptional demands, their future requirements and adds value way beyond just connecting IEMD cyber-physical heterogeneous continuous dynamical systems, hyposystems and components together.

The IEMD cyber-physical heterogeneous continuous dynamical hypersystem gives users more flexibility as the solution is viewed end to end rather than component by component, configured once and delivered as a package.

The benefit for the user is the reassurance that support on the IEMD cyber-physical heterogeneous continuous dynamical hypersystem is a single phone call away.

At suppliers, they bring together all their research and development (R&D) and innovation, all their engineering expertise for the given application in order to make a difference to the user. For the authors, optimisation is taking a step back and seeing the bigger picture; offering a solution that is better for the user.

At suppliers, they are in an exceptional position to have the breadth of portfolio that allows their scientists and engineers to propose a less biased perspective when offering a solution. For example, a conveyor solution could have centralised or decentralised control, which in turn would affect the type of IEMD cyber-physical heterogeneous continuous dynamical systems, hyposystems and components offered, which therefore has an impact on IEMD cyber-physical heterogeneous continuous dynamical hypersystem solution.

Most users currently are interested in gaining rich data quality from their plants. So again not only do they minimise the risk of putting the IEMD heterogeneous continuous dynamical systems, hyposystems and components together in an optimised solution so it meets their application demands, but they minimise risk by integrating cyber-physical heterogeneous continuous dynamical hypersystem seamlessly with their proven IEMD platform, which enables their users to make operational decisions based on the data presented to them.

Efficiency and productivity are decisive success factors for manufacturing industries. Engineering plays a central role in this especially as it relates to ever more complex machinery and plants. For that reason, a high level of efficiency is already demanded at the engineering stage, as the first step toward better production: faster, more flexible, and more intelligent. The supplier has an intelligent answer to this: uniform hardware and software interfaces. These shared characteristics minimise engineering time. The result: lower costs, reduced time to market, and greater flexibility.

Suppliers have suffered with engineering resource over the years, and often their users are looking towards suppliers to support them in the design and implementation of solutions IEMD. IEMD is the name given to efficient interoperability of all IEMD heterogeneous continuous dynamical systems, hyposystems and components. The open IEMD cyber-physical heterogeneous continuous dynamical hypersystem architecture covers the entire production process and is based on the consistent presence of shared characteristics: consistent data management, global standards, and IEMD cyber-physical heterogeneous continuous dynamical hypersystem gives them access not only to their breadth of portfolio but also engineering resource and experience across the IEMD, from both suppliers and their partner network. Putting the risk back to companies who have the suite of products and the best in class engineering knowledge is a real advantage.

Users do not have to invest in the infrastructure in place to be able to maintain these complex solutions. They can then focus on their products and their R&D and they will not need to worry about everything else.

What they are trying to do here for the user is to say take the helicopter view with them; let us look at the overall solution, end to end. Let us design a solution that surpasses user demands. Then they ask their users: ‘What else do you need? What other value add would you like to see for this application?’ listening to the market and driving innovation and collaboration.

In conclusion, the major benefit of IEMD is risk minimisation. If anything fails, users know they need to only go to one company to sort it out. The authors really want the user to be feeling that, actually it is a supplier they can rely on. With IEMD, they aim to be the trusted partner for their users, focusing on a solution that really works for them, really advances their processes.

Ultimately, IEMD will minimise their risk, recover their efficiencies and increase their profitability. A real win–win for both partners.

The treatment presented in this interdisciplinary textbook differs from the old school one by introducing invariance into the theory and providing general definitions that are sensible in all coordinate systems. In this approach, matrix analysis is endowed with a concrete logical foundation. Irrespective of the forward thinking aspects of the textbook, the authors do not sense that the treatment is too difficult for ordinary readers. This interdisciplinary subject has been taught to undergraduates and postgraduates at the Cracow University of Technology in Krakow and the State Higher Vocational School in New Sandec (Nowy Sacz), Poland. This textbook has been written primarily for undergraduate students of physics and electrical, mechanical, fluidic and thermal engineering. Its logical structure, however, should also make it valuable for mathematicians, and it may serve as a helpful review source for graduate students.

The first few chapters of the book introduce a variety of concepts that may be unknown to some readers, but mastery of these concepts may provide a much deeper knowledge of matrix analysis than could otherwise be acquired. Index notation is employed where necessary, but applications to electronics and mechanics, etc, are performed in the well-known physical commutation matrixer nomenclature. Various problems are known to provide readers with satisfactory preparation in using holors.

We are the authors of this textbook and all the text contained herein is of our own conception unless otherwise indicated. Any text, figures, theories, results, or designs that are not of our own devising are appropriately referenced in order to give acknowledgement to the original authors. All sources of assistance have been assigned due acknowledgement. In this textbook, all the information has been obtained and presented in accordance with academic rules and conduct. We have fully cited and referenced all the material and results that are not original to this book.

We are also indebted to our international and national colleagues who contributed indirectly to this book. In addition, we are grateful to all of you who have adopted this text for your interdisciplinary classes or for your own use. Without you we would not be in business. We hope that you find this textbook to be a valuable learning tool and reference for students.

The authors are also grateful to their friends for helpful comments. The above declaration should not be interpreted as a suggestion that these benevolent friends concur with all the iconoclastic propositions presented in the text; quite the contrary!

For all the radicalisms and imperfections, we assume total responsibility. We would like to conclude this preface by sharing our life motto—with focus, motivation and concerted efforts, one can make the seemingly impossible, possible.

Bogdan Thaddeus Fijalkowski
Jozef Tutaj
Krakow, 31 August 2018

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Author biographies

B T Fijalkowski, Professor, Dr;

Professor Dr Bogdan T Fijalkowski was born in 1932 in Poland. He obtained an MSc in Electrical Engineering, PhD in Power Electronics and DSc in Physical Heterogeneous Continuous and Discrete Dynamical Systems from Szczecin University of Technology in 1959, Academy of Mining and Metallurgy in 1965 and Poznan University of Technology in 1988, respectively. He began his professional and electrical engineering carrier in 1955. He has been working for five years in industry and 50 years in academia; he was the Director of the Electrotechnics & Industrial Electronics Institute, Faculty of Electrical and Computer Engineering and he was the Head of Automotive Mechatronics Institution, Faculty of Mechanical Engineering at the Cracow University of Technology, Poland. He was a visiting professor at several well-known universities. He serves as Consultant to several organisations in Poland and the United States. He is the signatory of the MoU for the establishment of World Electric Vehicles Association (WEVA). He was Guest Editor of *Journal of Circuits, Systems and Computers*—Special Issue on Automotive Electronics, reviewer and referee, *IEEE Transactions on Circuits and Systems*—Part I, *IEEE Transactions on Fuzzy Systems*, *International Journal of Vehicle Design*, *USA*, *International Journal on Advanced Robotic Systems* and *International Journal of Technology Management (IJTM),* USA. He is a reviewer of books and book chapters on automotive electrics and electronics, electric drives systems dynamics and wireless information transmission, as well as information security, and is listed in *Who's Who in the World, Who's Who in Science and Engineering* and so on. He has published 30 books and book chapters as well as over 200 technical papers and 25 patents on mining and automotive electrics and electronics as well as mechatronics. Recent publications by him include books (monographs), book chapters, journal articles, and conference proceedings on topics such as mathematical models of selected aerospace and automotive discrete dynamical hypersystems as well as the civil and military, wheeled and tracked all-electric and hybrid-electric vehicles and also nanomagneto-rheological fluid (NMRF) mechatronic commutator, 'crankless' internal combustion engines with energy storage, termed the Fijalkowski engines and automotive gas turbines that are based on the Fijalkowski turbine boosting (FTB) system. Recently, Springer published two volumes of his book entitled *Automotive Mechatronics: Operational and Practical Issues* and IOP Publishing published his interdisciplinary book entitled *Mechatronics: Dynamical Systems Approach and Theory of Holors*. He made valuable contributions to several of ASME, ISATA, ISTVS, SAE, IEEE SMC, as well as EVS and WEVA, conferences as a track and/or session chair and speaker. His hobby is yachting. He has the rank of Ocean-Going Yacht Master.

J Tutaj, Professor, Dr;

Professor Dr Jozef Tutaj was born in 1957 in Poland. He obtained an MSc in Electrical Engineering, PhD in Electrical Engineering and DSc in Electro-Mechanical Drive Systems from Academy of Mining and Metallurgy in 1981 and 1996 as well as Cracow University of Technology in 2013, respectively. He began his professional and electrical engineering career in 1981. He has been working for one year in industry and 30 years in academia; he was the Head of Mechatronics Institution, Faculty of Mechanical Engineering at the Cracow University of Technology, Poland. He has published three books and book chapters as well as over 50 technical papers and five patents on automotive electrics and electronics as well as mechatronics. Recent publications by him include books (monographs), book chapters, journal articles, and conference proceedings on topics such as mathematical models of electrical machines and automotive drive systems. Recently, he published his DSc dissertation entitled *Dynamical Systems Approach of the Polyfunctional Generator-Starter for a Combustion Engine of the Automotive Vehicle*, which has received the Minister of Economy Award in 2015. He made valuable contributions to several SAE, IEEE, as well as other conferences as a session chair and speaker. His hobby is classical music.

Acronyms

ABW	absorb-by-wire
AC	alternating current
AEV	all-electrical vehicle
AI	artificial intelligence
AV	adjustable velocity
AWA	all-wheel-absorbed
AWB	all-wheel-braked
AWD	all-wheel-driven
AWS	all-wheel steered
BBW	brake-by-wire
BEMF	back electromotive force
BLG	brush-lifting and split-ring short-circuiting gear
CASE	computer-aided system engineering
CHINT	charge injection transistor
CHP	combined heat and power
ChE	chemo-electrical
CMOS	complementary MOS
COTS	commercially-off-the-shelf
CPU	central processing unit
CS	computer system
CS	current source
CUPL	computer for universal programmable logic
D	differential
DBW	drive-by-wire
DC	direct current
DD	direct-drive
DDPWM	direct duty-ratio PWM
DoF	degrees-of-freedom
DOL	direct-on-line
DSP	digital signal processor
DTC	direct torque control
ECE	external combustion engine
ECL	emitter-coupled logic
ECM	electrical commutation matrixer
ECU	electronic control unit
E2CMOS	electrically erasable complementary metal-oxide semiconductor
E2D	electrical energy distribution
EFD	electro-fluido-dynamical
EIC	electrical integrated circuit
EIM	electrical integrated matrixer
EMD	electro-mechano-dynamical
EMF	electromotive force
EOF	electro-osmotic flow
EPD	electro-plasmo-dynamical
EPROM	erasable PROM
EMU	electrical multiple unit
EE	electro-electrical

ECh	electro-chemical
EM	electromechanical
EMI	electromagnetic interference
FBW	fly-by-wire
FEM	finite elements method
FET	field effect transistor
FF	ferro-fluid
FFET	flow field effect transistor
FL	fuzzy logic
FLC	full-load current
FM	frequency modulation
FMMEA	failure mode and effect analysis
F-M	fluido-mechanical
FPGA	field programmable gate array
FPLA	field programmable logic array
FSLESL	freescale embedded software libraries
GaN	gallium nitride
GCM	generalised commutation matrixer
GERF	giant electro-rheological fluid
GTO	gate-turn-off
HBT	hetero-junction bipolar transistor
HD	heavy duty
HDI	high-pressure direct injection
HDL	hardware description language
HE	hybrid electrical
HEMT	high electron injection transistor
HEV	hybrid electrical vehicle
HMC	human–machine communication
HMI	human–machine interface
HOLM	holor modulation
HOLPWM	holor PWM
HPS	hybrid power source
HV	high voltage
HVDC	high-voltage direct current
I	integral
ICE	internal combustion engine
IEEE	Institution of Electrical and Electronics Engineers
IEC	International Electrotechnical Commission
IEMD	integrated electromechanical drive
IGBT	insulated-gate bipolar transistor
IGCT	integrated-gate commutated transistor
IP	internet protocol
IPM	interior permanent magnet
ISO	International Standard Organisation
IT	information technology
I/O	input/output
JFET JUGFET	junction-gate FET
KFL	Kirchhoff's first law
KSL	Kirchhoff's second law
LAN	local area network

LCI	load commutated inverter
LED	light-emitting diode
LTQ	light triggered and quenched
MIMO	multi-input/multi-output
MCM	mechanical commutation matrixer
MCT	MOS controlled thyristor
MCU	microcontroller unit
MEMS	micro-electromechanical system
MESFET	metal–semiconductor FET
MFD	magneto-fluido-dynamical
MFOC	magnetic-field-oriented control
MIMO	multiple-input multiple-output
MISFET	metal–insulator–semiconductor FET
MMC	man–machine communication
MMD	magneto-mechano-dynamical
MMF	magnetomotive force
MNOS	metal-nitride-oxide silicon
MOS	metal-oxide semiconductor
MOSFET	metal-oxide semiconductor FET
MPD	magneto-plasmo-dynamical
MRV	Martian Roving Vehicle
MSI	medium scale integration
MSI	mild soft iron
ME	mechano-electrical
M-F	mechano-fluidic
MM	mechano-mechanical
M-P	mechano-pneumatic
M-V	mechano-vacuum
MPWM	multi PWM
N	north
NEMA	National Electrical Manufacturer Association
NF	neural network and fuzzy logic
NMOS	non-complementary metal-oxide semiconductor
NMRF	nanomagneto-rheological fluid
NN	neural network
OFET	organic field effect transistor
OTS	off-the-shelf
P	proportional
PBC	passively based control
PC	personal computer
PC	predictive control
PC	process control
PCC	point of common coupling
PF	power factor
PHEV	plug-in hybrid-electrical vehicle
PI	polarisable interference
PI	proportional-integral
PID	proportional-integral-derivative
PLC	programable logic controller
PLM	programmable logic matrixer

PML	programmable matrix logic
PROM	programmable read-only memory
PWM	pulse-width modulation
P-M	pneumo-mechanical
QUIT	bipolar quantum interference transistor
RB	reverse blocking
RBSOA	reverse-biased safe-operating area
RBW	ride-by-wire
RCGTO	reverse conducting GTO
RHC	real holor control
R&D	research and development
RMS	Root mean square
R–C	resistor–capacitor
R–L	resistor–inductor
R–L–C	resistor–inductor–capacitor
S	south
SCR	semiconductor controlled rectifier
SET	single electron transistor
SF	service factor
Si	silicon
SiC	silicon carbide
SINM	sinusoidal modulation
SINPWM	sinusoidal PWM
SISO	single-input/single-output
SIT	static induction transistor
SMES	superconducting magnetic energy storage
SM&GW	steered, motorised and/or generatorised wheel
SOP	sum-of-product
SPWM	single PWM
SR	semiconductor rectifier
SSI	standard scale integration
SUPER-HET	bipolar superconductor hot-electron transistor
TAB	tape automated bonding
TTL	transistor–transistor logic
UAS	unnamed aircraft system
UGV	unnamed ground vehicle
UPS	uninterruptible power supply
UV	ultra-violet
VAP	very advanced propulsion
VAT	very advanced technology
VECM	vector modulation
VECPWM	vector PWM
VDU	video display unit
VLSI	very large scale integration
VoIP	voice over Internet protocol
VPI	vacuum pressure impregnate
VR	variable reluctance
VS	voltage-source
V/F	voltage per frequency
V/Hz	voltage per hertz

XBW	X-by-wire
Δ2Y	delta-to-wye
Π2T	pi-to-tee
2-D	two dimensional
3-D	three dimensional
2 × 1	two-by-one
2 × 2	two-by-two
3 × 2	three-by-two
3 × 3	three-by-three
3 × 5	three-by-five
5 × 5	five-by-five
5 × 6	five-by-six

IOP Publishing

The Integrated Electro-Mechanical Drive

A mechatronic approach

B T Fijalkowski and J Tutaj

Chapter 1

General considerations

> *'… Absolutely amazing! I wish I had a tool like this when I was learning about motors. Five stars!'*
>
> Nikola Tesla
> Inventor of the AC induction motor

1.1 Introduction

Modern **electro-mechanical drive** (EMD) users are more likely to choose suppliers who are able to provide them with a comprehensive delivery. Such a solution gives them a sense of security because it avoids problems resulting from a possible incompatibility.

In the case of a modern EMD, it is often the case that the EMD suppliers do not recommend using **direct current** (DC) and **alternating current** (AC) commutator synchronous or asynchronous (induction) motors with macroelectronic commutators (macrocommutators), micro-electronic controllers (microcontrollers) and **human–machine interfaces** (HMI) from different manufacturers. This is all the more justified when the authors talk about an **integrated electro-mechanical drive** (IEMD) with macrocommutators, microcontrollers and HMIs as well as components of precision mechanics such as gears, rotary tables, cross tables, electric cylinders, etc. Buying an IEMD in a set is therefore completely natural. The only exception is when a very simple solution is sought, e.g. a stepper motor operating in an open feedback loop. Then the user can allow the EM motor and its driver to come from different suppliers. In the case of more advanced IEMDs, this solution has no reason to exist, because the **electro-mechanical** (EM) motor and driver are inseparable.

In this day and age, selling any automation components without providing adequate technical support is very difficult. These are the realities of the market and it is what users expect. An IEMD is more and more technologically advanced, new functions are constantly being added. New suppliers also appear on the market. It is

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difficult for users to keep up with all these new products. Especially because in the IEMD or other equipment some details are not always obvious, there are a lot of nuances. Of course, users can read all this in the detailed technical documentation, but it is much easier to ask for a technical advisor, which is very useful in this situation. Considerable competition also means that the suppliers themselves strive to provide their users with as much as possible within the so-termed added value. It happens that this is no longer just a help in the selection of components, after-sales technical support, or an efficiently operating service. Sometimes the suppliers participate in the implementation of the project, putting into practice and finally in commissioning.

Such a cooperation hypothesis means that on the one hand the recipient can count on comprehensive support at all stages of the implementation of the project, and on the other hand, the supplier will win the contractor's loyalty on subsequent projects. In short: without good technical support there is no good sale.

Over the past two decades there is have been several attempts to bring a modern EMD closer and more tightly integrated with novel **magneto-mechano-dynamical** (MMD) electrical machines. Such activities have intensified over the past several years. The drivers for this are technology breakthroughs in integrated power electronic devices, termed by the authors' macroelectronic commutators (macrocommutators), new materials as well as the increasingly cyber-physical heterogeneous dynamical hypersystem requirements for a wide range of applications.

This textbook will cover a wide range of applications highlighting the advantages and challenges of achieving such integration. The textbook will also highlight the current research trends.

The IEMD is a concept that brings together an arrangement of EMD electrical machines: macrocommutators, microcontrollers, and HMIs as well as gearboxes, clutches and actuators that connect to each other and integrate not only to each other, but also to the control and automation cyber-physical homogeneous continuous dynamical system, all from a one-stop shop. An EM motor coupled with a gearbox and an adjustable-velocity IEMD doing the control integrate together in a way that it seamlessly adds value.

Designing an IEMD means taking a step back to look at the bigger picture, listening to user requirements and developing a solution that hits the users unique requirements, user emerging and future IEMD cyber-physical heterogeneous dynamical hyposystem needs and adds value way beyond just connecting cyber-physical homogeneous dynamical systems, hyposystems and components together. The IEMD gives you more flexibility as the solution is viewed end-to-end rather than component-by-component, configured once and delivered as a package.

In general, an IEMD cyber-physical heterogeneous dynamical hyposystem (as illustrated in figure 1.1), can be defined as a power conversion means characterised by its capability to efficiently convert electrical energy from an electrical energy source (voltage and current) into mechanical energy (torque and velocity) to control a mechanical load or process. In some cases, this mechanical energy flow is reversed or can even be bilateral as regards the energy-flow direction.

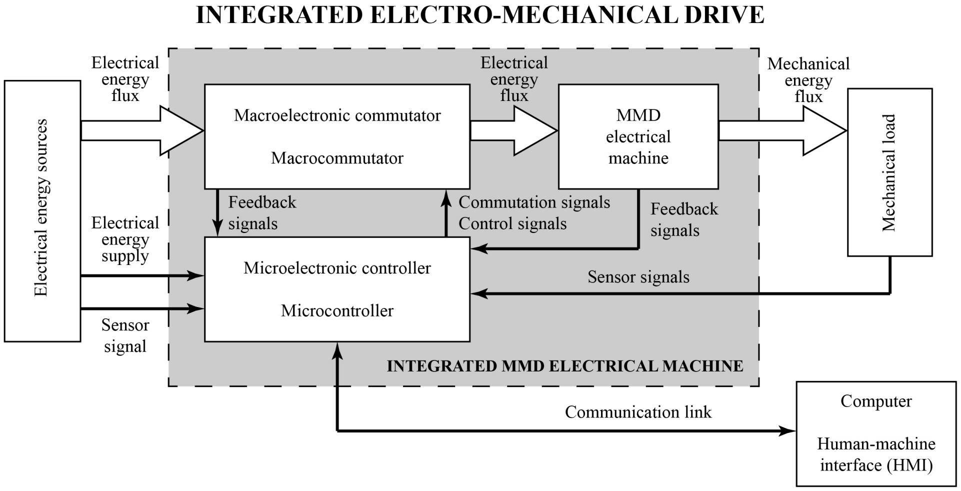

Figure 1.1. IEMD cyber-physical heterogeneous dynamical hypersystem.

At present an IEMD makes use of a macroelectronic commutator (macro-commutator) to (digitally) control this EM energy conversion process. In addition, as an IEMD is being integrated more and more in cyber-physical heterogeneous dynamical hypersystems, communication links to higher level computer networks are essential to support commissioning, initialisation, diagnostics and higher level process control.

Consequently, the main IEMD components consist of an EM energy converter (usually an MMD electrical machine or actuator), an embedded macroelectronic **electrical-to-electrical** (EE) energy converter, i.e. a macrocommutator and an embedded digital control unit. The digital control unit directly controls the macroelectronic semiconductor electrical valves (electronic switches) of the macroelectronic converter. To this end not only suitable control hardware, sensors, high-speed digital logic devices and processors are needed but also suitable control algorithms. From this perspective, IEMD technology is a fairly modern development. Indeed, although MMD electrical machines were first developed over 160 years ago, power electronic converters have been available for only 45 years, dynamic torque control algorithms for AC–DC–AC commutator induction motors (magnetic-field oriented control) have been around for about 40 years and high-speed digital control using **digital signal processors** (DSP) have been available for less than 60 years. Even now with all components (integrated electrical machine, macroelectronics, control hardware and software) being developed, IEMD technology is still evolving at a rapid pace. Over the past two decades, new integrated electrical machine types have been developed, optimised and investigated, such as surface **interior permanent magnet** (IPM) and buried IPM electrical machines, commutated-reluctance electrical machines, transversal magnetic-flux electrical machines, axial magnetic-flux electrical machines, linear electrical machines, etc.

Each electrical machine type requires its specific control and sensors. During the past 10 years, the position of sensorless IEMDs have been investigated to eliminate expensive sensors and make an IEMD more robust (reliable). The power range of a modern IEMD spans many decades, from milliwatts up to hundreds of megawatts, which demonstrates the flexibility and the broad application of this technology.

In the following several technology trends of state-of-the-art EMD are being discussed. An attempt is made to derive future trends based on the development of an IEMD over the past 20 years.

IEMD technology represents growing markets, albeit less impressive than recent **information technology** (IT) and nanotechnologies, but has proven to be a robust market segment which has been affected less by speculation and global market fluctuations or crises. One can say that an IEMD literally is a robust cyber-physical heterogeneous dynamical hypersystem which keeps the world's economy moving towards higher prosperity (more work done by machines) and more efficient use of primary energy (as an adjustable-velocity IEMD is more efficient when production rates need to be adapted).

The needs of users are varying in the market all the time. The challenges users deal with ought to be increasing year on year. For original suppliers, reducing users risk as a business, minimising downtime, saving energy, and decreasing engineering time are always a requirement of users'. To remain competitive, suppliers routinely look towards technology and the most recent innovations to supply their needs while minimising risk.

In this textbook the authors bring together all their years of innovation and engineering expertise for the given application in order to make a difference to you, the user.

The IEMD cyber-physical heterogeneous dynamical hypersystems is a trend-setting answer to the high degree of complexity that characterises the IEMD and its automation technology currently.

The world's only proper one-stop answer for the whole IEMD cyber-physical heterogeneous dynamical hypersystems is particularly characterised by threefold integration: horizontal, vertical, and lifecycle integration demonstrate that every dynamical system, hyposystem and/or component fits seamlessly into the whole IEMD cyber-physical heterogeneous dynamical hypersystem, into any automation environment, and even into the entire lifecycle of a plant.

The vision of the IEMD treatment is to develop the necessary technology so that IEMD capabilities can be economically embedded inside emerging and future integrated EM motors with minimal impact on their size, mass, and environmental robustness.

The long-term goal is to develop integrated EM motors with adjustable-velocity capabilities that, from their external appearance, show minimal evidence of the internally-packaged IEMD macroelectronic commutators (macrocommutators) and microelectronic controllers (microcontrollers).

Equally important, this IEMD must be manufacturable with a minimal cost premium while demonstrating environmental robustness and reliability characteristics that match those of conventional EM motors currently.

Consistent with these minimal impact objectives, the input power quality and **electromagnetic interference** (EMI) characteristics of an emerging and future IEMD must approach those of the integrated EM motor fed directly from the utility grid.

One of the most important rewards accompanying the success of emerging and future IEMDs will be major energy savings resulting from the cyber-physical heterogeneous dynamical hypersystem efficiency improvements made possible by introducing adjustable-velocity capabilities into applications that use fixed-velocity conventional EM motors today.

As the cost of electrical power inevitably increases during the coming years, the lifetime cost savings generated by the introduction of an IEMD will make the integrated EM motor increasingly attractive for new applications.

If the demanding technical challenges associated with the development of an IEMD can be successfully surmounted, the day will arrive when integrated EM motors will be promoted with the baseline expectation that they have adjustable-velocity capabilities.

Since the IEMD macrocommutators and microcontrollers ought to be embedded inside the electrical machine, many users may not even be aware that it is there. That is, adjustable-velocity capabilities will become an assumed inherent feature of integrated EM motors.

Development of mature, low-cost IEMDs will greatly accelerate the penetration of the IEMD into a wide variety of applications ranging from aerospace, aviation, automotive, metallurgy, mining and cement, and home appliances. Early steps towards achieving this vision can already be seen in industry today, and the objective of the IEMD is to develop technology that will accelerate the practical realisation of this ambitious vision. Thus the effective integration of emerging and future IEMDs require the development of technology that allows for volume and mass reduction of critical components.

The **research and development** (R&D) teams are studying the potential for volume and mass reduction through the integration of macrocommutators and microcontrollers into an integrated EM motor. Integration of macrocommutators and microcontrollers into the integrated EM motor frame offers space saving advantages, allowing the EM motor macrocommutators and microcontrollers to share the same housing and cooling cyber-physical homogeneous dynamical system. Accordingly, significant volume and mass reductions are possible in the macroelectronics and microelectronics housing and cooling auxiliaries.

The aim of the integrated high-power electronic (macroelectronic) commutators (macrocommutators) is to develop technologies that will enable emerging and future, macroelectronic-based electrical energy processing units. The state-of-the-art electrical energy processing unit is still largely the mechanical split-ring or flat (rotary disc) commutators, developed in the late 19th century.

Although it has long been argued that macroelectronic commutators can help improve IEMD controllability, reliability, and overall energy and power efficiency, their penetration in electrical energy processing units is still quite low.

The often-cited barriers of higher cost and lower reliability of the macrocommutators are quite high if high-power macroelectronics is used as a direct, one-to-one, replacement for the existing mechanical split-ring or flat commutators. However, if the whole IEMD was designed as a cyber-physical heterogeneous dynamical hypersystem of controllable macrocommutators, the overall cyber-physical heterogeneous dynamical hypersystem cost and reliability could actually improve, as is currently the case at low-power microelectronics within computer and telecommunications equipment.

The vision of the macrocommutators is to develop concepts for macroelectronic-based electrical energy processing units that can impact applications in an IEMD. The new macrocommutators thrust inherits the previously existing mechanical split-ring or flat commutators thrust, with scope expanding to a wider power and application range.

With the new vision, there are four major research focuses:

- macrocommutator and microcontroller architecture design and optimisation;
- electrical energy processing and control;
- high-density macrocommutator integration;
- physical and mathematical modelling, analysis, simulation and management.

The application focus will be on autonomous, electrical energy processing units, and on emerging and future applications such as portable, alternative, and sustainable energy sources.

The emerging and future of AC or DC motor IEMDs is the driving force behind all cyber-physical heterogeneous dynamical hypersystems used in industry, commerce and buildings. They are used in a wide range of applications in many industries such as aerospace, aviation, automotive, metallurgy, mining and cement, and home appliances, improving the efficiency and reliability of these processes while at the same time improving safety and energy savings.

As many technologies continue to evolve, R&D teams continue to work on making the AC or DC motor IEMDs even smaller and more affordable. However, it is not only size that matters.

Scientists and engineers are designing an AC and DC motor IEMD that is more intelligent, has better communications and is easier to install and control. Such an AC or DC motor EMD will open the door to many new markets, such as chemical, pulp and paper, metal and oil and gas, and contribute enormously to increasing applications and provide manufacturers with a whole host of new market IEMD opportunities (Barnes 2003, Wilamowski and Irwin 2011, Chan and Shi 2011, Wach 2011, Hughes and Drury 2013, Holmes and Lipo 2003, Geyer 2017, Rashid 2018).

Three main torque and energy conservation mechanisms, for integrated AC and DC MMD electrical machines, exist.

- *Synchronous:* Electromagnetic torque results because of the interaction of a time varying electromagnetic rotational field generated in the stator windings and a stationary electromagnetic or magnetoelectric field established by the windings or interior permanent magnets (IPM), respectively, in the EM motor.
- *Synchronous (variable reluctance):* Electromagnetic torque produced to minimise the reluctance of the electromagnetic system. Thus the torque is created in an attempt to align the minimum reluctance path of the rotor with the time varying rotating air gap.

- *Asynchronous (induction):* Electromagnetic torque is the result of a time varying electromagnetic rotational field present due to time varying voltage or motion of the rotor with respect to the stator.

The R&D teams' most recent innovation, the vision of the AC or DC motor IEMD is considered a 'revolution' in terms of size and simplicity, with 'extensive' performance and overall functionality.

An AC and a DC motor IEMD ought to consist of its individual units, as a microcontroller, a macrocommutator and an EM motor windings, fully integrated as a single intelligent EM power module, which is an integrated AC–AC or AC–DC–AC or DC–AC commutator synchronous or asynchronous (induction) motor.

The macrocommutator and microcontroller are compactly built into the integrated AC–AC or AC–DC–AC or DC–AC commutator synchronous or asynchronous (induction) motor, effectively saving space in the equipment due to the small amount of installation and wiring space required.

No cables are required to connect the integrated AC–AC or AC–DC–AC or DC–AC commutator synchronous or asynchronous (induction) motor, macrocommutator and microcontroller. Problems caused by electrical noise can also be expected to decrease.

The compactness and optional mounting are made possible by using the latest technologies, such as the newest-generation of electrical valves, for instance, **reverse blocking** (RB) **insulated gate bipolar transistors** (IGBT) or **integrated gate commutated thyristors** (IGCT) and an innovative **ferro-fluid** (FF) cooling homogeneous dynamical system.

Technologies such as macroelectronics, microelectronics and nanoelectronics, software, sensors, industrial communication and materials science are making these individual units smaller and smarter. The overall result is a more complex, technologically advanced, not to mention cost effective IEMD family with a broad range of industrial and consumer applications.

The use of very advanced semiconductor or superconductor electrical valves (electronic switches) or intelligent EM power modules enable the application of control techniques that, a few decades ago, seemed only a vision.

In the last decades, the integrated AC–AC or AC–DC–AC or DC–AC commutator synchronous or asynchronous (induction) motors themselves have improved in efficiency by an average of 5%. Moreover, the journey does not end here. The integrated AC–AC or AC–DC–AC or DC–AC commutator synchronous or asynchronous (induction) motor and IEMD technologies such as high-energy **interior permanent magnets** (IPM), semiconductor or superconductor commutated EM motors, silicon micromotor technology and soft magnetic materials are developing at a record pace. In fact, scientists and engineers have further developed IPM and very high-voltage integrated EM motor technology to satisfy various user requirements.

In industry, conventional EM motors and EMD powering mechanical equipment account for about 65% of the total electrical energy consumed. Reducing this figure is therefore of prime importance when it comes to electrical energy savings. The longer EMD and EM motors are in operation, the higher the savings. Over the total running time, more than 97% of the total cost of an IEMD cyber-physical heterogeneous dynamical hypersystem is accounted for by its power consumption and only 3% by the capital investment, hence the vital importance for high standard EM motor efficiency.

With years of experience and know-how, the authors are showing the way in the development of AC and DC IEMD technology. One such development has been a radical new control technique termed **holor control** (HC).

The HC contributes directly to energy efficiency by an integrated AC–AC or AC–DC–AC or DC–AC commutator synchronous or asynchronous (induction) EM motor's magnetic-flux optimisation. Sinusoidal waveform on voltage and current ensures that will be absolutely no interferences from the IEMD to other sensitive electronic equipment, such as radars, echo sounders, and seismic research instrumentation, as well as guaranteeing no bearing damages, and an absolute minimum of acoustic noise from the integrated EM motor and IEMD.

Original closed loop HC technology maintains positioning operation even during abrupt load fluctuations and accelerations. The rotor position detection sensor monitors the rotation. When an overload condition is detected, the HC will instantaneously regain control using the closed loop mode.

When an overload condition continues the HC will output an alarm signal, thereby providing reliability equal to that of an integrated AC–AC or AC–DC–AC or DC–AC commutator synchronous or asynchronous (induction) motor.

Another striking development affecting the AC or DC IEMD is miniaturisation. Increasing individual unit integration means **integrated matrixer** (IM) and **integrated circuit** (IC) boards are becoming smaller, which in turn leads to more cost- and energy-efficient manufacturing. On top of this, environmentally-friendly and energy-efficient technologies combined with sound manufacturing processes and increased recycling of resources contributes enormously to the environmental health of the planet.

AC and DC IEMD technology is a field that inspires scientists and engineers to develop better cyber-physical heterogeneous dynamical hypersystems with innovative technology. In addition, it contributes to the efficient use of electrical energy, which in turn improves the economy of the users. Finally, yet importantly, IEMD technology supports a sustainable development for all people.

In this textbook, let the authors 'drive' the readers through the interesting world of the IEMD and integrated AC–AC or AC–DC–AC or DC–AC commutator synchronous and asynchronous (induction) motors. The authors wish the readers of this textbook an interesting journey.

1.2 Definitions of integrated electro-mechanical drive (IEMD) cyber-physical heterogeneous dynamical hypersystems

Whenever the term of an EM motor or ME generator is used, one tends to think that the translational or angular velocity of these MMD electrical machines are totally controlled only by the applied voltage and frequency of the AC power source.

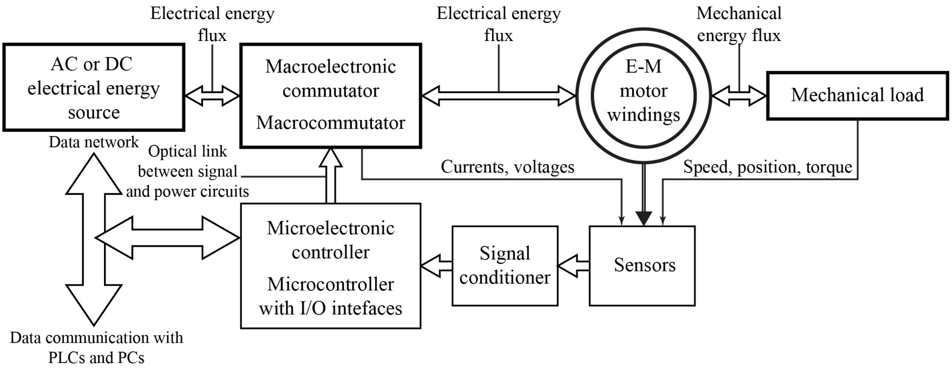

Figure 1.2. General structural and functional diagram of the emerging and future AC or DC motor IEMD cyber-physical heterogeneous dynamical hypersystem.

However, the translational or angular velocity of an electrical machine can be controlled precisely, also by implementing the vision of the AC or DC motor IEMD.

The main advantage of this concept is that the motion control is easily optimised with the help of the AC or DC motor IEMD. In very simple words, the cyber-physical heterogeneous dynamical hypersystem, which controls the motion of the electrical machines, is known as the AC or DC motor IEMD.

A typical cyber-physical IEMD dynamical hypersystem is assembled with an integrated EM motor (there may be several) and a sophisticated control cyber-physical dynamical system that controls the translational or angular velocity of the EM motor's mover or shaft, respectively.

Currently, this control can be done easily with the help of software. Therefore, the controlling becomes more and more accurate and this concept of AC or DC motor IEMD provides the ease of use. This IEMD cyber-physical heterogeneous dynamical hypersystem is widely used in a large number of industrial and domestic applications like factories, transportation systems, textile mills, fans, pumps, motors, robots etc. The IEMD is employed as the prime mover (starter) for diesel or petrol combustion engines, gas or steam turbines.

At present, almost everywhere the application of the IEMD ought to be seen. The very basic general structural and functional diagram of the emerging and future AC or DC motor IEMD cyber-physical heterogeneous dynamical hypersystem is shown in figure 1.2. The mechanical load in figure 1.2 represents various types of equipment, which consists of an integrated AC–AC or AC–DC–AC or DC–AC commutator synchronous or asynchronous (induction) motor, like fans, pumps, washing machines etc.

Integrated AC–AC or AC–DC–AC or DC–AC commutator motor and microcontroller packages are designed to simplify IEMD cyber-physical dynamical system integration, minimise interconnection cabling, and reduce or eliminate noise and EM motor/IEMD compatibility issues. The AC or DC motor IEMD is a cyber-physical heterogeneous dynamical hypersystem, in particular IEMD cyber-physical heterogeneous dynamical hypersystems convert electrical energy into mechanical energy and control the converted mechanical-energy flux according to a specific law.

Technically, a cyber-physical heterogeneous dynamical hypersystem is a smooth action of the reals or the integers on another object (usually a manifold). When the reals are acting, the cyber-physical heterogeneous dynamical hypersystem is termed a cyber-physical heterogeneous continuous dynamical hypersystem and when the integers are acting, the cyber-physical heterogeneous dynamical hypersystem is termed a cyber-physical heterogeneous discrete dynamical hypersystem.

Cyber-physical heterogeneous dynamical hypersystems integrate computing, communication and storage capabilities with the monitoring and/or control of entities in the physical world dependably, safely, securely, efficiently and in real-time:

- cyber-physical heterogeneous dynamical hypersystems is an exciting prospect for the next decades!
- involves multi-disciplinary R&D works;
  - high confidence software;
- cyber-physical heterogeneous dynamical hypersystems have the potential to change the way people interact with their surroundings;
- applications in the emerging and future for cyber-physical heterogeneous dynamical hypersystems are limited only by human imagination;
- affordability and ease of application will drive adoption.

The AC or DC motor IEMD in general plays a key role in power generation, aerospace, aviation, automotive metallurgy, mining, industrial cement applications and household appliances. The rapidly expanding area of IEMDs as used in robotics, wind turbines and all-electric or hybrid-electric vehicles is driven by innovations in electrical machine design, power semiconductors and superconductors, **digital signal processors** (DSP) and simulation software.

Cyber-physical heterogeneous dynamical hypersystems are expected to play a major role in the R&D of emerging and future physical heterogeneous dynamical hypersystems, in particular IEMD cyber-physical heterogeneous dynamical hypersystems with new capabilities that far exceed today's levels of autonomy, functionality, usability, reliability, and cyber security.

Advances in their R&D can be accelerated by close collaborations between academic disciplines in computation, communication, control, and other engineering and computer science disciplines, coupled with grand challenge applications. Selected recommendations for R&D in cyber-physical heterogeneous dynamical hypersystems:

- Standardised abstractions and architectures that permit modular design of cyber-physical heterogeneous dynamical hypersystems are urgently needed.
- Cyber-physical heterogeneous dynamical hypersystems' applications involve components that interact through a complex, coupled physical environment. Reliability and security pose particular challenges in this context—new frame-works, algorithms, and tools are required.
- Emerging and future cyber-physical heterogeneous dynamical hypersystems will require hardware and software components that are highly dependable, reconfigurable, and in many applications, certifiable and trustworthiness must extend to the system level.

In this textbook, the authors will focus on the cyber-physical heterogeneous dynamical hypersystems, in particular IEMD cyber-physical dynamical hypersystems of the application area of AC or DC motor IEMDs, and measure their performance to compare with the theoretical holor analysis.

An AC or a DC motor IEMD comprises an EM motor, i.e. an EM energy converter, which is a mechanical split-ring or flat commutator or macrocommutator, i.e. an EE converter operating as an energy processing unit, and a microcontroller and communication unit. An AC or a DC motor IEMD may be also used as propulsion and/or dispulsion systems in elevators, escalators, rolling mills, mine winders, as well as high-speed trains, all-electric and hybrid-electric ships, all-electric forklift and platform trucks, all-electric or hybrid-electric vehicles. Advanced control algorithms (mostly digitally implemented) allow translational/angular velocity and/or force/torque control over a high bandwidth. Hence, precise motion control can be achieved. Examples are an IEMD in robots, pick-and-place machines, factory automation hardware, etc.

Principally an AC or DC motor IEMD can operate in motoring and generating mode. Wind turbines use an AC or DC motor IEMD to convert wind energy into electrical energy. More and more, AC or DC motor IEMDs are used to save energy for example, in air-conditioning units, compressors, blowers, pumps and home appliances. Procedures to ensure stable operation of an IEMD in the aforementioned applications are translational/angular velocity and/or force/torque control algorithms.

In a very advanced AC or DC motor IEMD, a unique approach is followed to derive model-based translational/angular velocity and/or force/torque microcontroller/communication units for all types of Lorentz-force MMD electrical machines, i.e. DC and AC synchronous and asynchronous (induction) electrical machines.

The rotating-transformer physical model forms the basis for this generalised modelling approach that finally leads to the development of universal field-oriented control algorithms. In the case of variable-reluctance (commutated-reluctance) MMD electrical machines, force/torque observers are proposed to implement direct force/torque algorithms.

Changes in engineering are transforming the AC or DC motor IEMD from purely mechanical machines into hubs of complex macroelectronics and microelectronics. From an engineering perspective, this means that in many respects, the IEMD is undergoing a major redesign, and the rate of change is not likely to decelerate anytime soon. If anything, it will probably accelerate even more over the years ahead.

Formerly, a variety of terms have been used to describe an IEMD cyber-physical heterogeneous dynamical hypersystem that permits a mechanical load to be driven at user-selected translational or angular velocities.

An ‘adjustable-velocity IEMD’ is the abbreviated form of terms, which include, but are not limited to:

- adjustable-speed IEMD;
- variable-speed IEMD;

- adjustable-frequency IEMD;
- variable-frequency IEMD.

As the comprehensive explanation better conveys, it allows one to adjust the translational or angular velocity of an integrated EM motor (by varying the voltage and frequency of the supply power delivered to the integrated EM motor).

The term variable means a change that may or may not be under the control of the user. Adjustable is the chosen term since this relates to a change directly under control of the user. The term frequency can only be attached to an IEMD with an AC output, while the term velocity is preferred since this includes both AC or DC motor IEMDs. Thus, the term most universally known is adjustable-velocity IEMD.

Just as angle or distance and displacement or position have distinctly different meanings (despite their similarities), so do speed and velocity.

Speed is a scalar quantity that refers to 'how fast an EM motor's shaft or mover is rotating or moving'. Speed can be thought of as the rate at which an EM motor's shaft or mover covers angle or distance, respectively.

A fast rotating or moving EM motor's shaft or mover has a high speed and covers a relatively large angle or distance in a short amount of time. Contrast this to a slow rotating or moving EM motor's shaft or mover that has a low speed; it covers a relatively small amount of angle or distance in the same amount of time. An EM motor's shaft or mover with no movement at all has a zero speed.

Velocity is a holor or vector quantity that refers to 'the rate at which an EM motor's shaft or mover changes its displacement or position'. Imagine an EM motor's shaft or mover rotating or moving rapidly—one-step forward and one-step back—always returning to the original starting displacement or position. While this might result in a whirl of activity, it would result in a zero velocity.

A holor or vector is quantitative, it has magnitude, direction and sense of direction. The magnitude represents the holor or vector size or physical quantity. The direction represents the holor or vector position with respect to a holor elements (merates) or reference axis, respectively. The sense of direction represents the holor or vector orientation and its arrowhead represents it. This contrasts with the definition of a scalar, which has only magnitude. Examples of scalar quantities include temperature, resistivity, voltage and mass.

In comparison, examples of holor or vector quantities would include velocity, force, acceleration and position. The most familiar and intuitive use of holors or vectors is in the two-dimensional (holor merates or x, y coordinates) or **three-dimensional** (3-D) holor merates (x, y and z coordinates) Cartesian coordinate system.

Because the EM motor's shaft or mover always returns to the original displacement or position, the motion would never result in a change in displacement or position. Since velocity is defined as the rate at which the displacement or position changes, this motion results in zero velocity. If an EM motor's shaft or mover in motion desires to maximise their velocity, then that EM motor's shaft or mover must make every effort to maximise the amount that they are displaced from their original displacement or position. Every step must go into moving that EM motor's shaft or mover further from where it started.

The EM motor's shaft or mover should never change senses of direction and begin to return to the starting displacement or position. Thus, velocity is a holor or vector quantity. As such, velocity is 'sense of direction aware'. When evaluating the velocity of an EM motor's shaft or mover, one must keep track of direction. It would not be enough to say that an EM motor's shaft or mover has a velocity of 25 rad s^{-1} or 75 m s^{-1}.

One must include sense of direction information in order to fully describe the velocity of the EM motor's shaft or mover. For instance, one must describe an EM motor's shaft or mover velocity as being 25 rad s^{-1} or 75 m s^{-1}, right- or leftwards. This is one of the essential differences between speed and velocity. Speed is a scalar quantity and does not 'keep track of direction'; velocity is a holor or vector quantity and is 'sense of direction aware'.

The task of determining the sense of direction of the velocity holor or vector is easy. The sense of direction of the velocity holor or vector is simply the same as the sense of direction that an EM motor's shaft or mover is rotating or moving. It would not matter whether the EM motor's shaft or mover is speeding up or slowing down.

If an EM motor's shaft or mover is rotating or moving forwards, then its velocity is described as being forwards. If an EM motor's shaft or mover is rotating or moving downwards, then its velocity is described as being downwards. Therefore, an EM motor's shaft or mover rotating or moving in a forward direction with a speed of 25 rad s^{-1} or 75 m s^{-1} has a velocity of 25 rad s^{-1} or 75 m s^{-1}, forwards.

Note that speed has no sense of direction (it is a scalar) and the velocity at any instant is simply the speed value with a sense of direction. As an EM motor's shaft or mover rotates or moves, it often undergoes changes in speed. For example, during an average EM motor operation, there are many changes in speed. Rather than the tachometer or speedometer maintaining a steady reading, the indicator constantly moves up and down to reflect the stopping, starting, the accelerating, and decelerating. One instant, the EM motor's shaft or mover may be rotating or moving at 25 rad s^{-1} or 75 m s^{-1} and another instant, it might be stopped (i.e. 0 rad s^{-1} or m s^{-1}).

Yet during the EM motor operation the EM motor's shaft or mover might average 25 rad s^{-1} or 75 m s^{-1}. The average speed during an entire motion can be thought of as the average of all tachometers or speedometer readings. If the tachometer or speedometer readings could be collected at 1 s intervals (or 0.1 s intervals or …) and then averaged together, the average speed could be determined.

The average value of speed during the course of a motion is often computed using the following formula:

$$\text{Average value of angular speed} = \frac{\text{Angle}}{\text{Time}}$$

$$\text{Average value of translational speed} = \frac{\text{Distance}}{\text{Time}}$$

In contrast, the average value of velocity is often computed using this formula:

$$\text{Average value of angular velocity} = \frac{\text{Angular displacement}}{\text{Time}}$$

$$\text{Average value of translational velocity} = \frac{\text{Translational displacement}}{\text{Time}}.$$

Since a rotating or moving EM motor often changes its speed during its rotation or motion, it is common to distinguish between the average value of speed and the instantaneous value of speed.

The distinction is as follows:

- instantaneous value of speed—the speed at any given instant in time;
- average value of speed—the average of all instantaneous values of speed; found simply by a distance/time ratio.

One might think of the instantaneous value of speed as the speed that the tachometer or speedometer reads at any given instant in time and the average speed as the average of all the tachometer or speedometer readings during the course of the EM motor operation. Since the task of averaging tachometer or speedometer readings would be quite complicated (and maybe even dangerous), the average speed is more commonly calculated as the angle or distance/time ratio.

Rotating or moving EM motors do not always operate with variable and changing speeds. Occasionally, an EM motor will rotate or move at a steady rate with a constant speed. That is, the EM motor will cover the same angle or distance every regular interval of time. For instance, an EM motor's shaft or mover might be rotating or moving with a constant speed of 25 rad s^{-1} or 75 m s^{-1} for several minutes. If EM motor's shaft or mover speed is constant, then the angle or distance rotated or moved every second is the same.

The EM motor's shaft or mover would cover an angle or a distance of 25 rad or 75 m every second, respectively. If one could measure the EM motor's shaft or mover displacement or position (angle or distance from an arbitrary starting point) each second, then we would note that the displacement or position would be changing by 25 rad or 75 m each second. This would be in stark contrast to an EM motor that is changing its speed. An EM motor with a changing speed would be rotating or moving a different angle or distance each second.

To sum up, speed and velocity are kinematic quantities that have distinctly different definitions. Speed, being a scalar quantity, is the rate at which an EM motor's shaft or mover covers angle or distance. The average speed is the angle or distance (a scalar quantity) per time ratio. Speed is 'ignorant of direction'. On the other hand, velocity is a holor or vector quantity; it is 'sense of direction aware'. Velocity is the rate at which the EM motor's shaft angle or mover position changes. The average velocity is the displacement or position change (a holor or vector quantity) per time ratio.

1.3 Emerging and future AC or DC motor integrated electro-mechanical drives (IEMD)

Emerging and future AC or DC motor IEMDs are impressively smaller than their counterparts from the 20th century, meaning that installing them is now easier than ever before. For example, control rooms have become more compact and less costly because panel builders are now able to fit other IEMDs into a standard cubicle. Suppliers have also benefited in that it is now much easier for them to fit an IEMD into their equipment. With many R&D teams working to make AC or DC motor IEMDs smaller, the question arises as to just how small AC or DC motor IEMDs can get. All suppliers believe that there are few restrictions, particularly in the lower power range, and that over the next ten years, AC or DC motor IEMDs in this range will shrink by another 60%–70%.

So how is all of this possible? To begin with, there seems to be no end to how small macroelectronics, microelectronics and nanoelectronics can get, and these developments are rapidly finding their way into the high-power semiconductor and superconductor industry. In addition, lower losses are being achieved from the same area of **silicon** (Si) or **silicon carbide** (SiC) and **gallium nitride** (GaN). These two factors combined not only mean smaller semiconductors, but also the amount of heat generated within the AC or DC motor IEMD is reduced, so smaller heatsinks (radiators) are now possible. There is one limitation though: the cable terminations have to be big enough to accommodate the electrical power-carrying cables.

The development of high-power semiconductors and superconductors is an important factor that influences IEMD miniaturisation, but so too is the technology used for cooling.

Even though air-cooling is likely to become the dominant technique, a considerable amount of R&D effort is being invested in developing new cooling techniques as well as in reducing the need for cooling:

- Developments in numerical modelling mean that advanced computer flow modelling techniques are used to design heatsinks that achieve more effective cooling.
- Scientists and engineers are looking at new materials, integrating the heatsink with the high-power module for better cooling performance and improving fan performance with variable-velocity control.
- Liquid-cooling, especially the innovative FF method, is finding increasing use in wind power, transportation and marine.

  Scientists and engineers developed a new way of pumping FFs without the use of any mechanical components. They claim that their technique, dubbed 'ferro-hydrodynamic pumping', can be easily scaled up or down to be used in micro-fluidic devices or industrial-scale pumping devices, and anything in between.

  Using a FF can provide significant compactness while retaining original (or better) cooling performance:

  - The thermomagnetic effect can completely replace the natural convection driving force, while still retaining a cooling performance enhancement of

50% or more. This eliminates the required rig height, enabling more compact solutions.

- Using a FF can allow reductions of heatsink size to about 25% of original size while retaining original performance.

In addition to the ongoing developments mentioned above, new cooling technologies, such as heat pipes and thermosyphons may be applied over the next few years. Thermosyphons use evaporation followed by condensation to transfer heat directly out of the AC or DC motor IEMD. Even though the principles of these devices are well known, cost and performance issues must be solved before they can be commercially applied.

Another area that holds much promise for the emerging and future of AC or DC motor IEMDs is the 'cool chip'. The cool chip is an early application of nanotechnology that uses electrons to transfer heat from one side of a vacuum diode to the other. It uses the principle of electron tunnelling in which a voltage bias is applied to make energetic electrons 'jump' across a tiny gap between two surfaces. These electrons transfer heat energy between the two layers, and because of the gap, the heat cannot be conducted back.

Applied to IEMD technology, the cool chip principle could be used to carry heat from the semiconductor directly to the heatsink, thereby vastly improving the heatsink's efficiency. This would mean smaller active power devices, generating a lot less heat than would be expected for the rated power. To achieve this, relatively large surface areas with a gap of less than 10 nm need to be manufactured. In addition, the manufacturers must ensure no contact between the surfaces at any point.

Reducing the cost of an IEMD is a goal for all suppliers, and miniaturisation contributes enormously in achieving this goal. Three smaller and cheaper AC or DC motor IEMDs will find new applications as diverse as running machines and small centrifuges used in honey production. Not only is it intended for small industrial applications, but also for user products such as air conditioners, exercise machines and washing machines.

Component integration also contributes to a cheaper AC or DC motor IEMD. Suppliers predict that over the next 25 years, a combination of tighter semiconductor and mechanical part integration will lead to even fewer parts within a modular adjustable-velocity IEMD. Fewer parts mean fewer interfaces and fewer mechanical fixings, and this means improved reliability. In the future of the AC or DC motor IEMD, another form of integration, that of the IEMD and integrated EM motor with the application will have its place. This is already happening in some specialised applications.

One supplier, for example, has developed a fully integrated tubular submersible pump. This form of integration is also seen as being important in the field of robots where true mobility will be obtained with a fully-integrated AC or DC motor IEMD.

Naturally, software has a big part to play in the future. As software continues to develop, the AC or DC motor IEMD can expect to have increased capability with less hardware. All suppliers play a major part in the overall cost-reduction process. They do this by looking at ways of improving every aspect of their products.

For example, improvements can be made by means of:

- improved components;
- more integration;
- up-to-date design techniques;
- very advanced and efficient manufacturing processes;
- better logistics.

As the IEMD market continues to grow, economies of scale in volume production will be needed to cover the substantial investments needed in R&D to maintain the steep decline in prices seen in recent years.

The intelligent AC or DC motor IEMD are certain to benefit from the growth of ethernet communications by becoming an integral part of control, maintenance and monitoring cyber-physical dynamical systems. Decentralised control cyber-physical dynamical hypersystems will be created in which multiple IEMDs share control functions, with one taking over in the event of a fault or error in another IEMD. The advantage of this is that reliance on costly **programmable logical controllers** (PLC) would be greatly reduced and automation reliability would improve dramatically.

The authors think that ethernet-based AC or DC motor IEMDs will become a valuable source of data for preventive maintenance programs. Taking advantage of ethernet's wide bandwidth, these intelligent IEMDs would be able to communicate greater amounts of monitoring information than would standard web-based cyber-physical dynamical hypersystems.

In addition to this type of information, the IEMD would also collect data that describes the state of the process being controlled.

If each IEMD had its own **internet protocol** (IP) address, it would be easy to gather a log of every IEMD on a central server via ethernet, and build-up a highly detailed picture of the entire process and its performance. A detailed analysis of this data could be used to adjust the process and improve productivity. It could also be used to increase process availability through proactive fault management and asset optimisation.

Taking the intelligent AC or DC motor IEMD a step further; it could even have the capability of detecting the cause of a fault and providing a course of action for its resolution. All of this fits properly with the intelligent technology concept, in that the AC or DC motor IEMD with advanced communication capabilities can be seamlessly integrated into larger real-time automation and information cyber-physical homogeneous dynamical systems.

The increase in AC or DC motor IEMD intelligence will meet a growing demand from users for IEMDs that are easier to set up and control. As reliability is now taken for granted, ease of use and ease of commissioning are becoming the most important demands of emerging and future IEMD users.

The ultimate goal of all suppliers is to have a completely self-commissioning AC or DC motor IEMD, requiring no manual setting of parameters. They believe that achieving this goal is getting closer with advanced set-up wizards installed in the latest AC or DC motor IEMD.

The dynamic performance of the AC or DC motor IEMD in general has improved dramatically over the years. However, with **real holor control** (RHC) technology, the authors believe it has reached the ultimate in control performance. Using RHC applications that were only feasible with other IEMD technologies, such as the DC motor IEMD and servo EMD, are now routine for the AC motor IEMD. For example, the control of the new low-speed AC–AC or AC–DC–AC or DC–AC commutator IPM synchronous motors using new developments in RHC technology is likely to find increasing use in a variety of industries.

To control the EM motor, the authors have adapted the control algorithms in its RHC technology to achieve highly accurate control at low speeds without encoder feedback.

Standard AC asynchronous (induction) motors, normally designed to run at 750–3000 rpm, have poor efficiency at low speeds and often cannot deliver sufficiently smooth torque across the speed range. This problem is normally overcome by using a gearbox, but gearboxes are complex and take up valuable space and maintenance resources.

A **direct drive** (DD) IEMD cyber-physical dynamical hypersystem, using the integrated AC–AC or AC–DC–AC or DC–AC commutator IPM synchronous motor with the macrocommutator, provides a high-torque IEMD directly coupled to the driven application, thus eliminating the need for a gearbox. This cyber-physical dynamical hypersystem saves on integrated EM motor maintenance because the integrated AC–AC or AC–DC–AC or DC–AC commutator IPM synchronous motor is robust, and in maintenance terms, similar to standard AC asynchronous (induction) motors.

The DD IEMD cyber-physical dynamical hypersystem has already been applied in the paper industry, as paper machines require large numbers of a high-accuracy, low-speed IEMD. Another application is in ship propulsion dynamical systems. Suppliers, designed to give ships extreme manoeuvrability, uses a DD IEMD with a fixed-pitch propeller mounted directly onto the integrated EM motor shaft. The integrated EM motor's small size enables the outer diameter of the pod to be reduced, thereby improving hydrodynamic efficiency. The DD IEMD cyber-physical dynamical hypersystem is well suited to smaller vessels. Overall, the future looks very good for AC or DC motor IEMD users. It will be possible to buy an AC or DC motor IEMD that is smaller, more intelligent, easier to install and suitable for many applications, particularly at low power and low speed. However, the best news of all is that this IEMD will be cheaper than ever before.

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