

# Energy-Efficient Motor Drives and Control Strategies

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## **Abstract**

*The widespread adoption of electrical motor drives has revolutionised the way we supply mechanical power to industrial and service sectors. These drives offer high torque-to-weight ratios, speed control, and position control, which have made machines smaller and operation smoother. The increase in installed electrical drives has raised concerns about energy consumption savings (BALAMURALI, 2018). A drive converts electrical energy into mechanical energy; therefore, it is necessary to define many parameters to find the most energy-efficient way of operation. Electrical motor drives and designs have been evolving continuously for a long time. The concept of designing a drive to maximise energy efficiency has emerged over the last two decades. Hence, various approaches have evolved to improve the energy efficiency of electrical machines. Measures can be taken in the electrical machines, in the power electronic converter used to feed the machine, in the control circuits, and in the application and the process. Various research studies depend on such assessments and have been presented in the literature. This paper describes various motor drives with energy-efficient control strategies and their impact on energy savings. An assessment of energy-saving measures for DC and AC motors supplied through variable frequency drives, the energy-efficient motors, and the best strategies to reduce vehicle energy consumption is also carried out. The study includes an analysis of mechanical energy and the impact of environmentally friendly energy sources through drives.*

**Keywords:** *Energy efficiency, motor drives, control strategies, variable frequency drives, and electric motors.*

## **1. Introduction**

Energy-efficient operation of electric motors is of paramount importance for sustainable economic development and environmental protection. Motors consume over 60% of the world's total energy supply. The efficiency of electric motors is expected to rise thanks to the new power electronics and energy-efficient control strategies, provided that national policy frameworks adequately direct investment towards the analysis and development of electric motor systems.

Many approaches exist to improve motor efficiency, and the potential gains vary significantly. The most impactful measures involve optimally matching the motor to the driven load, applying variable-speed drive technology, and implementing energy-recovery techniques. The choice of power electronics also strongly affects motor efficiency. New inverter topologies enable switching beyond the conventional 0–20 kHz range. To maintain control under these conditions,

the energy-efficient drive algorithms are reviewed and compared.

Improved efficiency thus directly translates into lower operating costs. Typical savings range from 10% to 40%, with even higher figures possible in some cases. Advanced energy-efficient motor drives offer additional benefits, including reduced machine size and weight, improved control, and added functionality.

Directive 2005/32/EC (Ecodesign Directive) of the European Parliament prompted the European Commission to carry out a market evaluation of low-voltage electric motors. Motors and speed variators are listed in Annex I of the Ecodesign Directive, with energy-efficiency values set out in Directive 2009/125/EC. The summary of power and efficiency levels provided in the table below shows that the efficiency of low-voltage (0.12 kW–1 000 kW) three-phase squirrel-cage motors has increased significantly over the past years since the adoption of the regulatory policy.

**Table 1: Summary of power and efficiency levels for low-voltage (0.12 kW-1,000 kW) three-phase squirrel-cage motors" (IEC 60034-30 efficiency classes).**

<b>Power Range (kW)</b>	<b>IE1 (Standard)</b>	<b>IE2 (High)</b>	<b>IE3 (Premium)</b>	<b>IE4 (Super Premium)</b>
<b>0.75-375</b>	80-90%	85-93%	88-95%	90-96%
<b>Changes over the years</b>	Baseline	+3-5%	+6-8%	+8-10%

The market availability of energy-efficient motors meeting the Ecodesign requirements (Regulation (EC) No 640/2009) also includes efficiency levels beyond IE3 from manufacturers that have invested in developing high-efficiency motors. Globally, over 25 countries actively promote the use of high-efficiency motors, and the International Electrotechnical Commission (IEC) has adopted the globally accepted energy efficiency classification in IEC 60034-30.

## **2. Fundamentals of Electric Motors and Drives**

In industrial applications, motors are typically used in a limited range of the torque-speed characteristic. Referring to Duty Cycles and Related Torque-Speed Profiles, electric motors can be correctly sized for different applications

depending on whether the characteristic is constant power, constant torque, or hybrid. This matching process is facilitated by theoretical load profiles indicating motor short-time ratings. Load profiles are defined in various international regulations for different types of equipment (Mirchevski, 2012).

Motor size has a direct bearing on efficiency because manufacturers provide a quality factor, sometimes referred to as an "E-class," indicating how efficiently the motor produces fluid or other work. Consequently, the installation of variable frequency drives (VFDs) has generated interest in motor size. Duty-cycle-oriented data are valuable during the procurement phase, as they can prevent over-sizing and promote subsequent efficiency savings (Rafael Nunez, 2016).

## **2.1 Motor types and characteristics**

Electric motors play a pivotal role in industry, accounting for over 70% of the electrical energy consumed by industrial enterprises. Given their widespread use, energy-efficient motor drives and associated control strategies remain important considerations for meeting energy savings targets (Kazakbaev et al., 2019). Industrial drives encompass a spectrum of motors, from small machines in fans and pumps to kilowatt-rated traction motors for light-rail transport (Rafael Nunez, 2016). The energy efficiency of the motor alone generally does not determine the efficiency of the entire drive; an improved motor may still result in lower efficiency overall. For motor drivers, energy savings from motor replacement range from 5% to 20% in full- or part-load scenarios (Mirchevski, 2012). Energy savings from replacing the motor or drive may also vary depending on efficiency classes, operating period, and duty cycles.

Selecting the right motor type for specific applications is a key consideration. The following motor classifications and their associated characteristics lead to a better understanding of different motor types and their adaptable applications. The motors under consideration can be categorised as follows: (1) continuously rated synchronous drive types, (2) intermittently rated synchronous drives, (3) continuously rated asynchronous

cage motors, and (4) intermittently rated asynchronous cage motors. Motors are assigned continuous torque ratings and drive speeds applicable to different operating ranges, with a rotating magnetic field generated. Torque capability is determined by speed and motor specifications, with a notable distinction between AC and DC motors.

## **2.2 Power electronics and inverter topologies**

Advanced motor-control solutions enable energy consumption reductions of up to 60% while increasing productivity and performance. Most motor applications are three-phase permanent-magnet synchronous machines, often fed by multilevel voltage-source inverters. Machines are equipped with integrated temperature, speed, torque, and position sensors. Integrated motor drives simplify installation, improve system reliability, and potentially halve the material cost. The selected wide-bandgap power-electronic technology offers a higher switching frequency, which enhances electromagnetic compatibility and reduces the application size. Most switching decisions are based on power integrity and power quality considerations, with little regard for efficiency and performance.

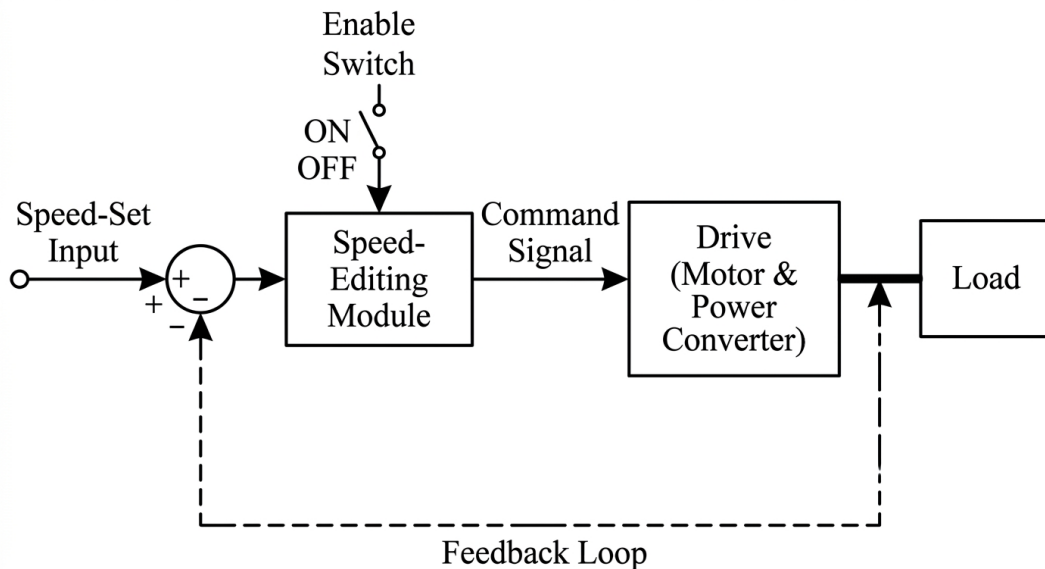
Permanent-magnet synchronous machines, fed from multilevel converters

and operated with advanced control strategies, significantly enhance productivity and performance in a wide range of applications. Common modifications to the basic motor-control scheme, aimed at improving energy efficiency, several of which can be implemented without additional hardware. The potential energy savings vary widely across applications, depending on how much control attributes such as speed, torque, harmonic current, power factor, and input power can be adjusted (Rafael Nunez, 2016).

### 2.3 Control circuits and feedback mechanisms

Control circuits comprise the circuits and activities designed to switch or control a

load, or to model the load to prescribe the control action for a given system behaviour. A control loop regulates the electric supply to the load through feedback signals. The sampled changes in the speed of a drive motor due to motor current and torque fed back from the electrical supply inductively feed through a feedback loop into a first-order, non-linear, second-order transfer motor model that predicts the anticipated future demand from the operating historical data. Consequently, less excess electrical supply energy is required (Narayan Mishra, 2018). A general classical control schematic for a drive system is shown in Figure 1, comprising enable, speed-editing, speed-set, command, feed-back, drive, and load components.



Electrical drive systems control various types of motors using diverse switching strategies. The commonly used motors are permanent magnet synchronous, induction, and brushless direct current. The most common switching arrangement is the Voltage Source Inverter (VSI), which generates three-phase voltage for the motor, regardless of whether the power is balanced, unbalanced, or variable (Rafael Nunez, 2016). Thus, the control problem entails fast, accurate feedback on the electrical quantities being controlled. The commonly sensed electrical signals in drive systems are motor current and voltage, either sent to the control unit or fed into the current and voltage estimator to maintain sensor less operation. These electrical signals help maintain balance in energy flow and in the quality of the overall energy supply.

### **3. Methods for Improving Energy Efficiency**

Motor drives account for a significant share of global electricity consumption, with opportunities for sizeable savings through energy-efficient designs and controls. Power losses in electrical machines stem from multiple sources, with the dominant component depending on the machine type, size, and operating conditions. These losses can be characterised, mapped in an efficiency contour plot, and minimised through control techniques compatible with

traditional control and safety features. Implementation requires minimal additional hardware, which is often already present.

Every mechanical system has a speed-torque demand profile determined by the application. The motor and inverter must be correctly sized to maximise efficiency and provide the desired performance. In applications where only a duty cycle is specified, such as pumps or fans, it is possible to operate at variable speeds, often with significant efficiency gains.

A range of braking techniques is used to recover energy when the load motor is driving the inverter. A flywheel, mechanical brakes, hydraulic accumulators, or energy storage devices such as batteries or super capacitors can be employed to store the recovered energy, which may then be reused or fed back into the electrical system. System studies have shown that recovery techniques can benefit all drives operating with regenerative energy. Some methods improve energy recovery by 20% or more.

Drives operating below nominal speed can benefit from advanced digital techniques that enhance performance while maintaining low cost, if the application permits. Embedded intelligence can reduce low-frequency torque ripple and harmonics, smoothing the speed feedback. Simplified

phenomenological models allow the drive to identify extended pole or misalignment faults without additional sensors. These techniques avoid costly features such as multilevel inverters, permanent-magnet motors, and encoderless control, often yielding payback periods of less than 1 year (Mirchevski, 2012).

### **3.1 Motor sizing and selection for load profiles**

Sizing and selection of motor drives for a load profile focuses on matching the motor rating to the load the motor must drive. It includes taking into account the operating cycle in which the motor is to be operated, i.e., the shape, frequency, duty cycle, and duration of operation of all load curves, and, as far as possible, fitting the drive to the load profile with respect to its duty cycle.

Peak motor ratings, such as stall torque (breakaway torque) for short periods, and the difference between peak and constant-speed torque or current ratings (where these apply) must then be considered, along with the maximum continuous operation duration at the peak rating. The efficiency class at the selected motor rating across the most representative frequency ranges of expected operation must also be assessed (Ohene Anyang, 2011)

### **3.2 Variable speed and torque control**

Energy-efficient control strategies for motor drives can be based on machine-responsive, variable-speed, and torque control that focuses on the efficiency of the required operating point and its attainable range. This strategy enables the use of voltage-source inverter (VSI) control schemes, including the mainstream V/Hz, field-oriented control, and direct-torque control. The efficiency profile of each of these control technologies can be quantified as an unconditional performance indicator.

Variable-frequency and voltage-control schemes were first conceived for low-cost two-pole induction motors, intended for basic industrial drives. Performance has been improved and extended over the years to encapsulate high-performance, asynchronous, and sensory-fed designs using pulse-width-modulation power supplies. Machine-oriented variable-speed control regulates operating points and cycle times, yet the efficiency of adjustable-speed drives remains far from their steady-state levels.

Efficiency-oriented variable-speed and torque control can leverage well-proven inverter-side drive-control topologies. These configurations adapt to high-overload and torque-responsive process filtration while enhancing energy efficiency over fixed-speed operation. Indeed, frequency-voltage decoupling is the simplest means of improving system performance, and it still holds broadly

across permanent-magnet motor families. An alternative control approach, centred mainly on permanent-magnet synchronous machines and multilevel vector-switching supply structures, can also be implemented.

The braking energy required during speed-profile changes causes a rapid current build-up, indicating whether additional energy can be stored or a braking strategy needs to be activated. Regulation of consumption power is another commonly used energy-efficient operation, in line with torque-reduction control (Rafael Nunez, 2016).

### **3.3 Efficient operating points and loss minimisation**

Motor drives with selectable operational capabilities and limited drive dimensions are increasingly prevalent in battery-powered or low-power systems (Ivanov, 2010). Motor Downsizing in Space-Constrained Systems. Electric machines are commonly oversized (specially during the design stage), which induces an over sizing of the inverter resulting in a loss of energy efficiency excessive sizing of the inverter unnecessarily leads to, depending on the topology, either increase of conduction loss or switching loss and less an attractive motor design, loss determination and appropriate down sizing procedure are introduced (BALAMURALI, 2018). Selectable Operating Points in Compression

Systems. This approach enables a wider selection of motor and component combinations. A series of induction motor experimental setups, including an inverter, is designed with different characteristics and tested at selected operating points to demonstrate the design configuration. Careful selection of the electrical machine increases efficiency by about 70% and enhances the speed range. Thus, Energy consumption can be reduced – Duty-cycle optimisation for Non-Controllable Stationary Systems. The separation of the max current reference and the voltage reference-switching limit point is obtained from vector control theory. Drive-board duty cycle varies directly with comparative programming technology (Ivanov, 2010). The scrutiny of the basic motor model indicates that the stator current has a dominant impact on the motor energy efficiency. Hence, well-programming of the prior modulated scheme directly informs the input power modulation, and the modulated signal does not act on the switching control device directly but instead on the drive-board measurement system.

### **3.4 Regenerative and energy recovery techniques**

Recovering kinetic energy during braking and converting it for off-line applications improves overall system performance and reduces the sizing

requirements for regenerative systems. The recovery potential varies with the driving task, the vehicle and the accompanying time gap. The document synthesises information from various studies to provide an overall picture of the possibilities offered (Khalaf, 2019).

Wheeled vehicles convert kinetic energy into heat when the brakes are activated. This energy is converted to heat during braking; thermal dissipation is unavoidable with the current mechanical systems and wheels. However, in addition to suspension energy management, even when braking is limited. Recovery devices can utilise the energy stored in the suspension to mitigate energy loss during braking. Some technical limits must be observed, including maintaining a comfortable ride without significantly changing the suspension settings. This offers a supplementary, optimised dimension of overall vehicle fitness.

Around the 1990s, specialists began experimenting with energy recovery in vehicles to improve ride comfort and energy efficiency. By the 2010s, these approaches had matured for different purposes, such as traction slip for other stabilising tasks.

The integration of energy storage can be realised in different approaches. One of them is to utilise the suspension spring continuously, in combination with

speed-up hydro-pneumatic devices, and to reduce the material count as much as possible in a regenerative braking device (Barto, 2017).

#### **4. Advanced Control Strategies**

Advanced control strategies for reducing energy consumption in motor drive systems are increasingly important in applications where continuous energy savings are achievable. Such approaches aim to minimise electrical energy losses while maintaining a specified performance level, thereby directly improving the energy efficiency of the entire system (Narayan Mishra, 2018). Among the performance parameters of interest are output power, torque, speed, position, and current. Low energy consumption is generally expressed in terms of time intervals for solar systems, batteries, and electric vehicles (Rafael Nunez, 2016). Advanced control strategies for water pumping, blowers, and ventilation systems estimate energy consumption and act accordingly.

Energy savings comparing advanced control techniques with classical approaches are detailed using a simulated circuit laboratory. Several methods are characterised, such as switching logic, on-off control, sequence, overlap control, and the sprinkle concept, to illustrate particular advantages in energy savings at a warehouse space model. Steps to drive the selection of

energy-saving regulations have been well studied in the context of vertical transport equipment.

Presenting advanced control methods for pump motor drive systems to save energy would be helpful, such as multi-pump energy-saving drive control and other water-supplying schemes. Mini and micro water supply systems employ domestic water using pump control systems, and the unloading of photovoltaic water supply motors has recently become popular. Major energy-saving methods based on advanced control techniques are well known in domestic pumps, air-conditioning, and refrigeration.

#### **4.1 Model-based and predictive control**

The popularity of Model Predictive Control (MPC) in many industrial processes has prompted researchers to consider applying MPC to drive electric motors and converters (MOHAMED, 2018). Conventional motor controller design typically employs a linearised, time-invariant model of an electric motor. It uses either a linear-quadratic tracker (LQT) approach or a mixed-sensitivity disturbance model to specify control objectives. In contrast, complementing the standard electric motor model with a model of the connected load permits handling of machinery applications. In parallel with preserving motor and load models in the

MPC design, utilising degraded and simplified motor models enables validation of closed-loop performance against the conventional approach (Rafael Nunez, 2016).

Motor speed control should simultaneously fulfil productivity and quality specifications, while minimising energy consumption. Voltage- and frequency-inverters enable variable-speed drive systems. Under fixed-speed operation, most pump and fan loads exhibit approximately cubic torque characteristics, permitting demotivating or even targeting the selection of constant-frequency supply voltages with harmonics. For constant-speed applications, the design, dimensioning, and arrangement of machinery should be focused on process needs and requirements rather than on the manufacturer's catalogue curves.

The implementation of predictive controllers governs the selection of a time-varying horizon for operation and the measurement of dynamic quantities that affect the overall process. The input-output multivariable nonlinear Minnesota Model of the gasoline engine, based on the well-mixed tank approximation and algebraic equations, has been effectively tested. Direct-current motors represent basic drivers, aligning smoothly with the prescribed semiconductor device/technology specifications. The experimental

demonstration employs various VDC voltages to control the operating speed via adjustable electrical parameters. Actual measured speeds are used to gauge the speed-management capability.

#### **4.2 Sensorless and sensor-reduced methods**

Sensorless and sensor-reduced control techniques for permanent-magnet synchronous motors (PMSMs) can enhance overall system compactness and simplify the user interface. Nevertheless, they tend to compromise torque estimation accuracy and the broader operating range, leading to potential field-weakening loss overheads even at lower speeds (S. Mohamed et al., 2011).

Works proposing estimators for ultra-low-speed (or steady-state) control and initial rotor-position detection methods have garnered interest, particularly where robustness to parameter dispersion remains highly important. However, torque- and flux-observing solutions have also matured in recent years, particularly given the focus on extended endurance testing in electric vehicle applications and the importance of accurate necessity estimation during long periods of regeneration.

#### **4.3 Optimal control and machine learning approaches**

The development of modern control strategies, such as optimal control-based

methods and machine learning (ML) techniques, enables improved performance in efficiency and fault handling. Optimal control (Jose Plathottam, 2017) provides significant energy savings yet may be computationally burdensome for time-critical tasks. Reinforcement learning (RL) looks promising as a data-driven policy optimiser for other algorithms. Recent advances in deep-learning theory and population-based optimisation inform data-driven approaches, enabling multi-objective optimisation based solely on collected data.

Machine-learning (ML) approaches solve new classes of problems, e.g. fault detection, isolation and accommodation (FDIA) strategies. Though state estimation typically rests on physical models (e.g., mechanical), ML-driven substitution models may be feasible if sufficient training data from actual operation are available. Multi-task learning further informs training. Predictive maintenance models can assist component-component interaction understanding, in many cases facilitated by ML-assisted modelling.

#### **4.4 Fault-tolerant and robust control**

The embedded control strategies, such as fault-tolerant control (FTC), allow the electrical drive to maintain operation if a fault or open circuit occurs in one phase of a multi-phase system, with severely

restricted performance, in the technical sense of the motor devices, as specified by the underlying control laws. The same level of redundancy, PCI, can still be maintained because the same sampling period is assigned, and the motor's rotational speed can be obtained. In the research work above, fault detection, identification, and accommodation in an industrial multi-phase electrical drive have been investigated. From a control point of view, multi-phase electrical drives give the benefit of providing the same or better level of performance for the same load class, i.e., acceleration, speed regulation, and overload for a drive wheel under evaluation with a symmetrical multi-phase currents strategy than for an industrial three-phase electrical drive under monitoring based on PI-control (Scelba et al., 2018).

## **5. Demand-Side Management and Grid Interaction**

In industrial applications, motor-driven equipment, electrical machines, and drives consume significant amounts of energy and are considered key contributors to overall energy consumption across sectors. According to the U.S. Department of Energy (DOE), AC induction motors accounted for 58% of total energy use in industrial applications. Motor efficiency improvements are said to have a great impact on demand-side management

and demand response programs (Tung Nguyen, 2016).

VFDs can participate in electric demand response programs implemented by utilities, facilitate the implementation of customers' Energy Management Systems, and support peak load shedding schemes. Where applicable, an important factor in developing Demand Response capability in adjustable-speed drives is dynamically changing the frequency reference without altering the operating point defined by a speed command. Electric demand response can be implemented in many ways across multiple time frames. A) Continuous load modulation during steady state. B) Load curtailment during transient periods. C) Adaptive control changes in the drive. D) Time of use modulation, load cessation and other approaches (Rafael Nunez, 2016).

### **5.1 VFDs in demand response**

A Variable Frequency Drive (VFD) controls the speed and torque of AC motors by adjusting the frequency and voltage, offering advantages such as improved process control, extended equipment life, and reduced maintenance. VFDs are used across various industries, from small appliances to large compressors, and can improve energy efficiency in industrial applications. Integration with programmable logic controllers (PLCs)

enables precise control of motor speed, allowing switching between low, medium, and high speeds. Future developments include wireless control via Ethernet, enhancing system connectivity. Overall, VFDs contribute significantly to demand response by optimising motor operation and energy consumption in diverse settings (Waste & Al-Azdee, 2018).

VSDs are increasingly used in refrigeration systems to meet energy-efficiency standards, often with BLDC motors and variable-speed compressors. These systems' contribution to FFR has received limited attention, but their potential could be significant. Studies estimate the theoretical demand-response potential for refrigeration and freezers in Europe, with volumes far exceeding current spinning reserves. Refrigeration units, typically located indoors, offer a less fluctuating reserve compared to heat pumps, which face challenges due to outdoor temperature variations (Vorwerk et al., 2020).

A scheme to acquire the optimal power factor command is proposed, generating near-optimal commands during commissioning using a fuzzy logic compensator. An online tuning controller adjusts the power factor to its optimal value during normal operation. The scheme is practical, does not require prior knowledge of motor parameters, and has been validated through

simulations and experimental results, confirming its effectiveness in minimising losses (2010).

## **5.2 Power quality considerations**

When four-quadrant operation is not needed, a motor drive should ideally operate along a defined minimum-loss trajectory that directly connects the optimum-loss operating points for a given speed and torque. The switched operation must still respect the machine's safe torque-speed envelope, and the time to reach a new optimum point may need to be limited (Mirchevski, 2012). Drives without a WHZ or with significantly higher switching frequencies are not constrained to follow the minimum-loss trajectory, opening up exciting possibilities. Almost all loss components strongly depend on the load. Therefore, it is possible to define a family of minimum-loss operating points indexed by the load, yielding an optimal duty cycle that varies with operating conditions and thereby accurately defining the best trajectory to follow when switching between operating points.

## **5.3 Energy management in industrial systems**

Many processes in industrial ecosystems involve electrical-drive systems. Different plants have unique needs, yet the drive generally serves a common purpose: to achieve a given output.

Energy management involves analysing how these drives interact with business and electrical systems. In this context, it is essential to obtain the following information:

- Which process is performed?
- How many drives are involved?
- What is the energy consumption of each drive?

Signals can be retrieved from various sources, such as an energy data logger or directly from the drive via a field-bus protocol (Mirchevski, 2012). This data can then feed a supervisory control and data acquisition (SCADA) system, an energy management system (EMS), or an energy dashboard. Industrial organisations are guided by their energy management policies and by needs imposed by internal or external regulations.

An industrial EMS typically comprises two levels. The first, referred to as strategic planning or stochastic planning, develops medium- to long-term plans for achieving various energy objectives (Rafael Nunez, 2016). The second is termed operational or deterministic planning. Several different EMS tools are currently on the market and are generally referred to as production-integrated (PI) planning systems. These tools take into account, for example, orders to be processed and resource availability.

Energy dashboards enable equipment operators to visualise energy consumption or determine the change in energy consumption associated with changes in working practices.

## **6. Applications and Case Studies**

Energy-efficient, control-driven advanced AC motor and VFD systems are widely used in stand-alone and distributed drive services across building, industrial, and transportation applications. Reduction in energy consumption and CO<sub>2</sub> production enables prudent operation, prolongs lifetime, decreases maintenance, and lowers overall system costs (Rafael Nunez, 2016). Energy-related services, addressed by diverse energy management systems globally, also optimise the operations of components, devices, and building envelopes to boost efficiency.

Systematic, ongoing tracking of worldwide installations, experience exchange, coordinated measurement efforts, collaboration, and feedback inform key developments in electrical drives and products. Globally, electrical drive installations number close to 1 billion, with the building sector accounting for 55% of energy consumption and industrial processes for 40% of it. AC drives account for half of the total drive power. More than 20 countries collaborate on the

implementation, development, and evaluation of electric and fuel-cell drive projects, contributing to energy reduction and CO<sub>2</sub> emission decreases of about 50%. Investment in drive systems typically yields high returns, encouraging the deployment of energy-efficient products across drive systems and advancing associated research for further improvement.

### **6.1 Industrial drives**

Industrial electric motor drives are a cornerstone of the economy, powering machines in manufacturing and process applications. In Europe, nearly three-quarters of total electricity consumption is attributed to such drives (Mirchevski, 2012). Despite their growing role in the economy, energy efficiency metrics have deteriorated considerably since 1998, and electric drives have become the leading consumers of electrical energy on the continent. For an average drive operating approximately 8,000 hours per year and consuming 40 kWh/day, the cost of electricity over the lifecycle can reach 100 to 200 times the initial investment. Regulatory standards and guidelines are powerful tools for promoting improvements and achieving payback periods of less than 3 years. The European Union has proposed a vision to promote energy efficiency, estimated to yield savings of 202 billion kWh annually and a reduction of 45 GW in new power plant capacity over 20 years.

### **6.2 Traction and mobility**

Rigid, cost-efficient drive architectures constitute one of the most critical technology considerations determining the viability of electric propulsion for heavy trucks. The range of energy-recovery and propulsion strategies varies widely across applications and configurations; even within commercial vehicles, energy-recovery and distribution strategies differ between on-road, heavy-haul trucks and off-road, mixed-service hauliers. Continuous, on-highway, hammer-lane speeds and torques typically range from above 25 kW to below 600 Nm. Continuous, off-road, mixed-service driving instructions provide the inputs for heavy-haul tests. Off-road vehicles operate over terrain governed by soil conditions rather than fixed geometry. Even when curb weight or upscale information is lacking, power and torque inputs are available. The integration of electric systems into the embedded structure of traditional mechanical systems generally improves the autonomy and efficiency of these vehicles (Lin & Cheng, 2014); other types of electric vehicles offer an opportunity to carry over a strategy for torque allocation (M Dizqah et al., 2019).

### **6.3 HVAC and building automation**

Heating, ventilation, and air conditioning (HVAC) systems use fan and pump motors to regulate indoor

environments in response to external conditions. The motors account for approximately 60% of annual energy consumption in residential and commercial buildings. Energy use varies significantly across buildings, cooling set points, and HVAC types, with estimates of auxiliary systems' energy use ranging from 24–90% of overall electrical consumption. Most of this demand is linked to fan and pump motors, which account for 55–68% of total HVAC expenditure. The impact of pumping and cooling loads is directly correlated with motor size; given the wide variety of applications, pump motors come in a broad range of sizes. Common building types rely heavily on HVAC systems and typically consume more than 50% of their total energy for HVAC. The largest consumers of HVAC energy in such buildings are fan motors associated with central air-handling, variable-air-volume, and unit-ventilator systems. Energy-efficiency improvements have focused on chiller and control-technology enhancements.

Based on an in-depth analysis of the thermodynamic principles governing building climate control, it is found that a well-designed, multi-zone, variable-speed HVAC system using chilled water as a thermal transport medium offers significant advantages over widely used on-off and constant-volume systems. A chilled-water, variable-speed HVAC

system saves more than 30% in cooling energy and provides better temperature control than typical design alternatives under metropolitan Toronto operating conditions. A proportional-integral-derivative (PID) controller is capable of maintaining temperature set points within  $\pm 0.2$  °C of the desired temperature, and the heating, ventilation, and air conditioning load does not exceed the equipment's nominal capacity. Mothballing redundant components can reduce energy consumption; cycling on a chilled-water temperature master can offer additional savings by modulating valve positions, pump speeds, and fan speeds (Thomas Paulus, 2019). With proper occupancy-based operation and equipment staging, electricity savings can reach 45% (Marozas-Aliaga, 2018; Anuarul Hoque et al., 2019).

## **7. Standards, Metrics, and Testing**

In this framework, large losses, sensitivity to operating conditions, the need for auxiliary components, and poor disturbance rejection severely limit the applicability of energy-efficient algorithms to industrial motor drives.

Energy-efficient drives are actively promoted through voluntary initiatives, efficiency targets, and energy-management principles. Various standards quantify drive and motor efficiency; however, evaluating motor

and drive efficiency in industrial processes remains elusive. Standards exist for motor and drive efficiency, with the primary governing levels defined by IEC standards and ISO 50003 certification.

The uniformity of existing benchmarking standards needs improvement, particularly regarding the adequacy and physical meaning of various characterisation parameters. Even one motor has unique behaviour in terms of geometry, loading, and arrangement that is generally required to meet industry reference standards for the test. Therefore, adding components such as a shaft extension, permanent magnets, and an inverter to a hybrid stepper motor is not well reflected in the literature, as there is only limited characterisation through stator temperature or winding resistance (Mkando Mzungu, 2009).

The implementation of an isolated supply to an induction motor with a load, using a 22-6 step-down ratio and a voltage of 205.5 A, results in instantaneous noise (Ohene Anyang, 2011).

Although such configurations violate standard characterisation, the objective was the same for the request for the permanent magnet motor, whether required with rotor-deviation inertia or with the rotor positioned to provide a similar static equilibrium.

## **7.1 Efficiency metrics and standards**

The selection of suitable electric machinery, electric motor drive and power control techniques, and energy management systems can potentially greatly enhance a system's energy efficiency. Efficiency metrics and approaches for assessing the potential for efficiency improvements in an electric drive system with frequency-inverter control, relative to a conventional control system, are discussed here (Mirchevski, 2012). The International Efficiency Classifications, namely the IE Code, are defined in IEC 60034-2. The typical reference standards for the efficiency classes of three-phase AC motors are given.

The National Electrical Manufacturers' Association (NEMA) established efficiency standards for three-phase squirrel-cage motors ranging from 1 to 500 HP, with three motor designs classified by electrical torque. Three-phase induction Motors comply with NEMA standards, such as Squirrel-cage induction motors. The National Electrical Manufacturers' Association published the NEMA MG1 standard, which covers the efficiency of the three-phase induction squirrel-cage motor used for constant-torque, variable-speed, and dynamic-simulation applications, and specifies three separate rating classes based on standard NEMA motor designs.

Efficiency Classes are classified based on the nominal power of the motor.

The International Electro-technical Commission (IEC) is an international standards organisation that publishes technical standards for electrical, electronic, and related technologies. Efficiency standards are two forms of standards that set the minimum energy performance requirements of a low-voltage electric machine. The classes are associated with a family of curves that allows the determination of the motor's efficiency for any combination of rated voltage, rated rotor frequency, and number of pole pairs. The ISO standard guides the efficiency of electric motor drives and their energy-efficiency classification.

## **7.2 Testing protocols and validation**

A performance evaluation procedure for a motor drive system, such as testing methods to evaluate the performance of a Torque Motor Drive System for Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs), is crucial for the selection of Electric Drive Components for Hybrid Electric Vehicles (HEVs). Performance testing of a motor drive system is necessary to verify whether the actual properties meet the manufacturer's specifications (Xie, 2018). The motor drive system parameters that need to be verified for Electric Motor Drive Systems applied to Hybrid and

Electric Vehicles include, among others, the electric motor drive system efficiency, maximum performance operation, speed control performance, and position control performance. By understanding the specifications and curves obtained from the performance test, it is possible to select (or develop) appropriate controller algorithms for the Electric Motor Drive System, taking into account target vehicle dynamics and control strategies. The selection of parameters for a test procedure to measure the aforementioned key electrical and mechanical performance characteristics is formulated in a Hardware-in-the-Loop simulation platform, as illustrated in the context of Electric Drive Systems for Hybrid and Electric Vehicles (Awadallah et al., 2018). Specifying Electromagnetic (EM) Transient characteristic performance is a major challenge for standard performance evaluation procedures for various electrical Machine Types, such as Induction Motors, Switched-Reluctance Motors, and Permanent-Magnet Synchronous Motors. Those Transient tests are visualised but cannot induce the driving capability to synchronise the Electro-Mechanical system with the drive controller.

## **7.3 Reliability and lifecycle assessment**

Electrically driven systems have achieved high average efficiencies in standard drives, yet actual efficiency

losses can exceed the rated values. These losses vary by location and time due to transient operation, gradual wear, interactions among components, and changes in operating conditions. Although specific figures depend on a broader range of motor drives at the annual level and across different applications, average efficiency is a strong indicator of expected performance at the nominal operating point.

Degradation is another important factor that determines the operational lifespan of electrical machines. These machines, employed in electric vehicles, for instance, are expected to operate for 15,000 to 20,000 hours without discernible degradation, yet the corresponding costs are significant (Samaranayake & Longo, 2017). In large industrial drives, premature degradation and wear may halt operation unexpectedly, thereby incurring additional costs for the system (Scelba et al., 2018). To mitigate degradation influencing this critical component, it is important to select proper operating conditions (BALAMURALI, 2018).

## **8. Challenges and Future Directions**

Research gaps remain in energy-efficient motor drives and control strategies despite substantial technical developments. Motor and inverter data are often sparse or non-public, underscoring the importance of

manufacturers providing better baseline data for the energy performance of systems fitted with different control strategies. Advanced control techniques—such as model predictive, sensorless, and optimal control—have not yet been widely adopted, partly due to technical challenges in communication, estimation, and state representation. Distributed systems that prioritise energy efficiency and provide real-time, integrated, high-level supervision and optimisation are also still at a concept stage (Rafael Nunez, 2016).

## **9. Conclusions**

Energy-efficient and smart motor-drive systems have become indispensable in advanced industrial applications and high-tech electrical products. There are numerous approaches to improving the energy efficiency and performance characteristics of motor-drive systems, which can be implemented individually or in combination. Many are simple and inexpensive, while others are complex and costly (BALAMURALI, 2018).

Machine learning, fault detection, sensorless technology, embedded systems, and the integration of circuits, circuits and networks have greatly increased energy efficiency and performance in motor drives (de Pelegrin, 2013). Energy-efficient drives can also integrate with advanced smart

electrical networks and demand-response management systems, using smart digital-analogue control and embedded control systems to become even smarter (Rafael Nunez, 2016). Smart variable-speed drives serve as the control core for induction motors, improving energy efficiency across the entire load-duty cycle.

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