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Chapter 8

Lightweight High-Efficiency Power Train Propulsion with Axial-Flux Machines for Electric or Hybrid Vehicles

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Additional information is available at the end of the chapter

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Abstract

The aim of this chapter is to present a new type of powertrain with dimensions and low weight, for vehicles with reduced carbon emissions, which have an axial synchronous machine with one stator and two rotor, with static converter that is simple and inexpensive, a broadcast transmission system using an electric differential, with the control of the two rotors so that they can operate as motor/generator, at the same rotational direction or in opposite directions, at the same speed value, at slightly different speeds or at much different speeds by using an original dual vector control with operating on dual frequency. This is a major concern of hybrid and electric vehicle manufacturers. Expected results: a lighter power train with 20% and an increase in 5% of electric drive efficiency, low inertia rotor at high speed, a compact electric drive system with high torque and simple control, intelligent energy management system with a new vision of technological and innovation development, and equal importance of environment protection. The electrical machines for hybrid (HEV) or electric (EV) drives include a variety of different topologies. According to outcomes of literature survey, induction machines alongside synchronous machines take the major place in HEV or EV power trains.

Keywords: axial-flux machines, dual rotor, single stator, single inverter control, hybrid vehicle, electric vehicle, lightweight power train

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1. Introduction

Automobiles use onboard fuels (energy carriers) in order to transport goods and people. The conversion of onboard energy to propulsion energy is performed by the power train. Some parts of this energy may be stored as conservative energy (kinetic or potential energy) in vehicle. Unfortunately, all of these conversion processes cause substantial energy losses and hence high fuel consumption. Nowadays, in order to obtain propulsion energy, most of the vehicles are based on the combustion of hydrocarbon fuels. Theoretically, the complete combustion of chemical fuel generates only heat, which is converted into mechanical energy, and carbon dioxide (CO_2) and water (H_2O), which are released into the atmosphere. These combustion products do not harm the environment [1]. However, actually combustion of hydrocarbon fuel is never complete, resulting also in a certain amount of nitrogen oxides (NO_x) and unburned hydrocarbons, all of these impacting people's health and the environment. Furthermore, even if CO_2 is assimilated by plants and captured by sees and oceans, these natural assimilation processes are saturated, which cause an accumulation of it in the atmosphere. These gases block re-reflected infrared radiation of the Earth, which comes from the Sun, and in this way keep the energy in the atmosphere (greenhouse effect). This energy increases the global temperature and causes climate change. Therefore, over the past decades, research and development activities related to road transport have highlighted the need to develop less polluting and safer transport. Because pollutant emissions and fuel consumption are directly proportional, a cleaner vehicle means a fuel-efficient vehicle. Different methods and tools, which analyze and assess the use of resources and impacts on the environment, are available. These are referred to as environmental system analysis tools. They can be categorized according to their object in focus (policies, plans, products, and functions or substances) and their studied impacts (natural resources and/or environmental impacts) [2]. Energy analysis, one of the methods suited to analyze the use of natural resources, is focused on energy or material flows (with a focus on input flows) in energy or physical units. Another very useful method is represented by the Life Cycle Assessment (LCA) which is based on an environmental assessment and is able to evaluate the impact of materials/products on the environments. LCA usually operates on the energy usage, environmental emissions (kg CO_2/kg of material), and the amount of materials used to make the final product. An LCA analyzes the potential environmental impacts of a product or a service along its entire life cycle. The life cycle includes all of phases (from cradle to grave): the raw material extraction, the production, use and any end-of-life treatment including recycling (ISO 14040:2006). For a passenger car, analyzed in use phase, a comprehensive analysis of the energy consumption involves at least three energy conversion steps: well-to-tank (WTT), tank-to-vehicle (TTV), and vehicle-to-miles (VTM) [3]. In a first step, WTT, the primary energy carriers (chemical energy in fossil hydrocarbons, solar radiation used to produce biomass or electric energy, nuclear energy, etc.) are converted into an energy carrier that is suitable for onboard storage, that is, to a "fuel" (examples are gasoline, hydrogen, etc.). Then, in the second step—TTV—this "fuel" is converted by the propulsion system to mechanical energy. The third energy transformation—VTM—is determined by the vehicle parameters and the driving profile. In this step, the mechanical energy produced in the second conversion step is ultimately dissipated to thermal energy that is deposited to the ambient. So, there are essentially three possible approaches to reducing the total energy consumption of passenger cars: improve the WTT efficiency, the TTV efficiency, and the VTM efficiency. *WTT efficiency improvement:* deriving from crude oil, the gasoline and diesel are the major liquid

fuels for internal combustion engine vehicles (ICEVs). Electric vehicles (EVs) are an excellent solution to rectify this unhealthy dependence because electricity can be generated by almost all kinds of energy resources: thermal power (oil, natural gas, and coal), nuclear power, hydro power, wind power, solar power, oceanic power, geothermal power, and biomass power. Even taking into account the emissions from refineries to produce gasoline for ICEVs and the emissions from power plants (PPs) to generate electricity for EVs, the overall harmful emissions of EVs are still much lower than those of ICEVs. The reduction of CO_2 emission can reach a level about 5% with the adoption of EVs and high-efficient PPs. The level of efficiency increase may be further extended when higher percentages of clean or renewable power generation are used. Certainly, the increase may even be negative when inefficient coal-fired PPs are used [4, 5]. *TTV efficiency improvement:* several possible directions are available for improvement: improvement on the component level and improvement on the system level [3], so we can mention here some of them: one may consider an improvement on the peak efficiency of the power train components; also, there is a possibility to improve the part-load efficiency of the power train components, and similarly, one may add the capability to recuperate the kinetic and potential energy in order to store it in the vehicle; also, there is another possible direction that considers the need to optimize the structure and the parameters of the propulsion system. All of this presumes the fact that the fuel(s) used and the vehicle parameters are fixed, and the control systems realize appropriate supervisory control algorithms that take advantage of the opportunities offered by the chosen propulsion system configuration. By taking crude oil as 100%, the total energy efficiencies (well-to-vehicle) for EVs and ICEVs are 18 and 13%, respectively. Therefore, even when all electricity are generated by oil-fuelled PPs, EVs are more energy efficient than ICEVs by about 40% [5]. Moreover, EVs possess a definite advantage over ICEVs in energy utilization, namely regenerative braking; EVs can recover the kinetic energy during braking and utilize it for battery recharging, whereas ICEVs wastefully dissipate this kinetic energy as heat in the brake discs and drums. With this technology, the energy efficiency of EVs is virtually boosted up by further 10% [4]. *VTM efficiency improvement:* there are a few ways to reduce fuel consumption in the vehicle, such as improved power train efficiency, new and advanced power trains like internal combustion-diesel hybrids and fuel cell vehicles, adoption of alternative fuels, but VTM efficiency improvement can be made by improving aerodynamics, and lightweight design. The weight of vehicles has increased continuously in the past four decades. Drivers for the weight increase are higher demands—of customers or legislation—on safety, performance, comfort, reliability, and other vehicle characteristics. These demands lead to additional and more complex parts in each new vehicle generation. Anyway, a spiral effect that sums all the recent technological outcomes forces an increase of the weight at a higher level even higher. Due to the interlinks and dependencies that are presented between components, it is possible to have a weigh increase. Weight increase is a tricky problem since it leads to the requirement for a more powerful and heavier power train and electric motor or engine. The heavier load on the chassis and the dynamic demands on the power train impose the need of reinforcements and an extra weight increase to the car manufacturers. In addition, in order to maintain the driving range, extra energy storage is needed. From the mechanical point of view, the stiffness of the vehicle body must be reconsidered again which again impose a supplementation in the available power of the engine, which is equal to the fact that we need a more powerful motor or an engine. And since the power density cannot be modified, we have a spiral effect called secondary weight effect. The good news is that if we want to reverse the case, general weight reductions turn the spiral effect around

and lead to secondary weight reductions [2]. Generally speaking, the major automakers have adopted advanced technologies capable to improve the fuel economy of their vehicles, and among this, the reduction of the weight is still one of the approaches they make use very often. This is not only because this method improves fuel economy but also because of the emergence of advanced materials that may result in lower costs in association with good manufacturability. Weight reduction or lightweighting can be reached through careful redesign, component downsizing, alternative material substitution, multiple integrating parts and/or functions, or a combination of all these methods [6]. Redesigning aims at reducing aerodynamic drag force and rolling resistance, while downsizing focuses more on reducing the dimensions of the vehicle. Material lightweight design portrays a special case of lightweight design as it does not focus on the mere reduction of material but on the substitution of materials. In this way, a material is substituted with one of lighter densities or with a material of better properties. These properties can be the strength, a smaller distortion, or a reduced wear (e.g., replacement of conventional steel with a high strength steel). Functional lightweight design chooses either a strategy of integrating several parts and/or functions into one component or of separating the functions to achieve a lower weight. Vehicle mass is key factor for a lightweight design as well as in the operational performance of the vehicle in terms of mechanical resistance to the road and especially in the fuel economy. Optimization of the mass of the vehicle not only limits the friction force with roads by reducing rolling resistance but also modifies in a positive way the acceleration resistance and climbing resistance. A general rule of thumb says that a 100-kg savings in vehicle mass will result in a fuel savings of 0.12–0.15 l/100 km and 0.85–1.4 kg CO_2/100 km for ICEVs [7] or 0.347 kWh/100 km/100 kg for EVs [8]. Lightweight solutions reduce the energy demand of the vehicle in the use phase. The mix of both measures—the manufacturing of lightweight electric vehicles (LEVs)—has the potential leads to conduct to an even higher savings and a spectacular reduction of environmental impacts in comparison to the conventional solutions. However, aspects like the integration of different materials and more complex and energy-intensive production processes can also lead to higher environmental impacts. From what is known today, the production of the components for the electric drive train—particularly the battery—is energy-intensive process and uses complex chemical assemblies which demand complex recycling processes. Similarly, lightweight materials are usually more energy-intensive than the conventional material steel and can be less suitable for recycling. Thus, to avoid burden shifting—which means one type of emission is reduced while another is increased—it is necessary to assess all relevant types of emission. The environmental assessment over the entire life cycle—an LCA—calculates these trades-off. One of the promising approaches is the functional lightweight design. Optimized power train systems and appropriate control algorithms are instrumental to achieve this objective.

2. EV lightweight propulsion systems configuration

The EV offers the definite advantages of zero roadside emissions and minimum overall emissions (taking into account the emissions due to electricity generation by PPs). Previously, the EV was mainly converted from the ICEV, simply replacing the internal combustion engine IC (diesel of gas) with an electric motor (comparable in terms of power capability), while all the other components are kept the same. It is noticed early that the converted EV has not been a good solution

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because of the drawback of heavy weight, loss of flexibility, and degradation of performance/reliability. Currently, the modern EV is a dedicated built system. This EV configuration is specifically designed and is based on the original body and frame configurations capable to satisfy the structural requirements which are unique to EVs. An EV or HEV car needs a body and a frame which has to take advantage of the greater flexibility of electric propulsion [1, 5]. Compared with the ICEV, the configuration of the EV is particularly extremely flexible and thus is more capable to sustain body and frame improvements. This flexibility is the effect of several factors which are unique to the EV. The first characteristic element is represented by the fact that the energy/power flow in the EV is done mainly by flexible electrical wires rather than by mechanical couplings or rigid shafts. Thus, the concept of *distributed subsystems* or decentralization in the EV is really achievable. Secondly, different EV propulsion arrangements (such as independent four-wheel and in-wheel drives) involve a significant difference in the system configuration/organization. Thirdly, different EV energy sources have different weights, sizes, and shapes. The corresponding refueling systems also involve different hardware and mechanism. For EV propulsion, the system configuration can be a single motor or a multiple motor. The single-motor configuration uses only one electric motor and one PWM inverter, which can minimize the corresponding size, weight, and cost. For single-motor configuration, the first alternative consists of an electric motor, a clutch, a multi-speed gearbox, and a differential. By incorporating both clutch and multi-speed gearbox, the driver can shift the gear ratios and hence the torque going to the wheels. The differential enables the wheels to be driven at different speeds when cornering—the outer wheel covering a greater distance than the inner wheel. It should be noted that the driveline transmission losses of the transmission gear and mechanical differential can be up to 20% of the total power generated by the motor. With an electric motor that has constant power in a long speed range, a multi-speed gearbox can be replaced by a fixed gearing and reduce the need for a clutch. Because of the absence of a clutch and shifting gears, it can significantly improve the transmission efficiency and reduce the overall size, hence increasing both the energy efficiency and power density. In the third configuration, which is similar to the concept of transverse front-engine front-wheel drive of the existing ICEVs, the electric motor, fixed gearing, and differential are integrated into a single assembly, while both axles point at both driving wheels. The whole drive train is further simplified and compacted. The multiple-motor configuration uses multiple motors to independently drive individual wheels. A dual-motor configuration consists of two electric motors, two PWM inverters, and two optional fixed gears depending on whether using a direct drive or not. Since the two motors are independently controlled, the differential action can be electronically achieved, thus eliminating the bulky and heavy mechanical differential. For modern EVs, the use of in-wheel motor (hub motor) drives is becoming more and more attractive. Adopting a direct drive for in-wheel propulsion not only offers the differential action but also facilitates, many advanced vehicular functions such as the antilock braking system, anti-slip regulation, and electronic stability program. Furthermore, since regenerative braking can take place in each driving wheel, the corresponding energy recovery becomes more effective, which can extend the EV driving range.

3. HEV lightweight propulsion systems configuration

At this moment, EVs possess some noticeable advantages against conventional ICEVs, such as high-energy efficiency and zero environmental pollution. However, when we compare the

actual performance, and we are focusing upon the operation range per battery charge, we can observe that the EV is far less competitive than ICEVs. This fact is generated to the lower energy content of the batteries versus the extremely generous energy content of gasoline. Typically, for a passenger car under urban driving with air-conditioning, an EV using present batteries technology (that are heavy and bulky) can travel about 120 km per charge, whereas an ICEV can offer about 500 km per refuel. With such a short driving range per charge, the EV will suffer from the problem of range anxiety. Furthermore, differing from the ICEV, the EV takes time for battery charging. The short-term solutions are hybrid electric vehicles (HEVs). HEVs provide an opportunity for synergism with both technologies in order to have the advantages of both ICEVs and EVs and to overcome their disadvantages. In this category of synergistic exploitation, HEVs use two power sources—a mechanical power source and an electric one. Compared with the EV, the HEV can offer a comparable driving range of the ICEV and use the existing refueling infrastructure of the ICEV, but sacrificing the merits of zero roadside emissions. Given the nature of both mechanical and electrical powers, two classic layouts were most commonly used for the HEVs—hybrid versions of both series and parallel connections. The first one is regarded as the most common and least complicated type of HEVs. Having a direct connection between the engine and the generator makes it easier to fully convert the output mechanical power into electricity via the generator. The resulted electricity is used for either feeding the electrical motor (which is used to put the driving wheels into motion) or keeping the battery charged, all controlled using the load condition. Increased flexibility is the clear advantage in locating the engine-generator set, mainly due to the electrical wiring. Furthermore, the EV propulsion system's flexibility is also included in this configuration. The engine capability can easily be enhanced to a maximum because of its feature that allows it to operate within a precise range of speeds. The main difference between the series hybrid and the parallel hybrid is that the latter permits the driving wheels to be propelled by the parallel power delivered by both electric motor and the engine. The wheels have both the engine and motor connected to their driveline, so the propulsion power that is supplied is a result of the engine on its own, the electric motor on its own, or a combination of both. A smaller engine can operate under conditions yielding higher efficiency. Compared to an EV, for the same performance, the battery can also be downsized. Another advantage of a parallel hybrid is the single energy conversion for both electrical and mechanical. The parallel hybrid can respond to the demand for large, near instantaneous changes in either torque or power. In contrast, the series hybrid is slower. The fast response is an advantage in traffic. The detrimental effects of having two systems are partially mitigated by the fact that many components can be downsized. This way, a parallel hybrid, which can offer all hybrid features (electric launch, idle stop-start, regenerative braking, and downsized engine), enables an improvement of 30% in fuel economy. Series-only or parallel-only designs often do not meet performance requirements. As hybrid technology developed, the utility of series or parallel design became less significant. Mixed designs, rather than series or parallel designs, offer more flexibility [6]. The structure for series–parallel hybrid type blends features from both its components, but with an additional element compared to each of them taken on their own: a supplementary generator compared to the parallel hybrid and another mechanical connection compared to the series hybrid. Even if it holds the beneficial elements for both series and parallel hybrids, the combination between the two is more expensive and more complex. Pure electric and hybrid propulsion are additionally mixed into the complex hybrid. Among the disadvantages of parallel

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arrangement are the various added power train parts such as added clutches and transmissions that increase the weight. On the other hand, weight is a major impediment to performance. Thus, HEVs, by their very nature, are heavier than ICEVs. For HEVs, performance is measured by mileage and distance covered in electric-only mode. Another important factor is reduced emissions. The introduction of a gasoline HEV reduces CO_2 emissions by 27% for a lightweight car (900 kg) and 20% for a heavy vehicle (2500 kg). On the other hand, the introduction of a diesel HEV reduces CO_2 emissions by 24% for a lightweight car and 18% for a heavy vehicle. HEVs can help reduce CO_2 in a greenhouse gas but are not a panacea [10]. Typically for a HEV, a three-shaft transmission is needed: two input shafts and one output shaft (a three-way gearbox). Because of the need to mechanically connect the engine with the drive shaft, choices for the location of the engine are limited. For the ICEV, the engine rpm and torque can be determined by starting at the tire patch on the road and working upstream to the motor through the power train. In contrast to an ICEV, the HEV needs complex energy management system (EMS) involving the HEV information (computers, software, algorithms, etc.) and HEV power (power transistors, cooling system, etc.). The control system is extremely complicated and represents a tremendous challenge. By means of engaging or disengaging different clutch arrangements, the EMS can alter the structure to provide more flexibility for transmission control. The challenge is how to reduce the system complexity that involves both an electric motor and an engine for propulsion and how to coordinate these two propulsion devices to achieve optimal efficiency operation. The nontrivial decision must be made concerning the split between the motor and the engine. Once the hybrid engine torque and power are specified, the gear ratios in the transmission, the three-way gearbox, and the throttle settings must be selected to put the engine on the minimum fuel consumption line. All parts must be engaged and disengaged smoothly without jerks, shudders, shakes, or clanks. Further, perceived mismatches between driver commands and HEV responses are forbidden. Different gear ratios allow matching vehicle and wheel speed with the desired engine speed. The number of speeds in an automatic transmission affects fuel economy favorably. Multiple speed automatic transmissions begin to rival the manual shift transmission in efficiency. Speed automatic transmissions with five speeds, six speeds, and even eight speeds are beginning to appear in new cars. The ICEV engine operates from idle rpm to the maximum design rpm that yields maximum power. On the other hand, for HEVs, engines are designed specifically, having a narrower rpm operating band. Hence, the number of gears in the transmission affects the width of the engine rpm band within which the engine can be operated. The six-speed transmission gives a narrow range of engine rpm. The continuously variable transmission (CVT) has an infinite number of gear ratios between two rpm limits. CVTs are popular for hybrids because of their ability to match input/output rpms. They offer seamless acceleration and fuel economy. Locating engine operation within the rpm band for best fuel economy is only part of the solution for the hybrid control. The motor assist almost always enables operation of engine for best fuel economy by ensuring balance torques in the transmission. The key technology of the full hybrid is the electric variable transmission (EVT) system, also called the electronic-continuously variable transmission (e-CVT) system. Since the introduction of the first EVT system in 1997 by Toyota Prius, there have been many derivatives developed by different automakers. The key is to employ a planetary gear (PG) for power splitting of the engine output power, one via the ring gear to the driveline shaft while one via the sun gear to the generator, then back-to-back converters, motor, and finally the driveline shaft. On the one

hand, the most efficient path for engine torque is mechanically and directly to the drive wheels. On the other hand, because of the need to balance torques in the transmission, the path of a portion of the energy is engine-generator-motor- drive wheels, which is less efficient due to the numerous transfers of energy. However, through clever use of a PG set, several components are eliminated. The PG set replaces both the three-way gearbox and the CVT. Since there are no clutches, the system involves only one physical structure that can avoid mechanical disturbances due to mode changes. Hence, under varying road loads, the engine can always operate at its most energy-efficient or optimal operation line, resulting in a considerable reduction in fuel consumption. Yet, this PG-EVT system suffers from the reliance on planetary gearing, which involves transmission loss, gear noise, and regular lubrication. In addition, the overall system is relatively heavy and bulky. Thus, there are continual research and development to solve these shortcomings, such as replacing the mechanical planetary gear by a double-rotor machine or magnetic planetary gear. The double-rotor machine is a newly introduced gearless power-split device. However, it requires brushes and slip-rings, which are less reliable and incur need for a regular maintenance. In order to overcome these drawbacks, a new class of magnetic-geared (MG) electric variable transmission systems has been developed based on contactless magnetic gears, which can offer the definite advantage of brushless and pseudo-gearless power-split operation. By replacing the planetary gearing with magnetic gearing, the resulting MG-EVT system can inherit the distinct advantages of magnetic gearing, namely the high transmission efficiency, silent operation, and no maintenance, while avoiding the use of slip rings and carbon brushes [6]. Mechanical systems are increasingly integrated with actuators, sensors, and electronics. Besides the basic energy flow in the mechanical system, an information flow in the electronic system enables a variety of automatic functions. This leads to *mechatronic systems* which consist of *mechanics* (mechanical engineering) and coupled processes (e.g., thermal, electrical), *electronics* (microelectronics, power electronics, measurement and actuator technology), and *information technology* (systems theory, automation, communication, software design, artificial intelligence). The design of the functions within mechatronic systems is performed as well on the mechanical and on the digital electronic side. Hereby, interrelations during the design play an important role and create synergetic effects. Whereas the design and the local arrangement for a conventional system are done separately, the mechanical and electronic components of a mechatronic system must be considered as an integrated overall system from the beginning. This means that *simultaneous engineering* has to take place. Adding just sensors, simple analog or digital control systems, and actuators to existing mechanical processes is not sufficient with regard to overall dynamics, robustness, space, cables, and speed of processing. Integrated mechatronic systems allow the avoidance of these disadvantages and to approach more *autonomous systems,* for example, in the form of capsuled systems. Beginning with a classical mechanical–electrical system, which results from adding available sensors and actuators to the mechanical components, one can mainly distinguish two kinds of integration for mechatronic systems [9–12]: *integration of components* (hardware integration) and *integration by information processing* (software integration). The information processing within mechatronic systems may range between simple control functions and intelligent. An intelligent control system is organized as an online expert system and comprises multi-control functions (executive functions): knowledge base, inference mechanism, and communication interfaces. The online control functions are usually organized in multi-levels: L1-control, feedback for stabilization, damping, L2-supervision

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with alarming and automatic protection, fault diagnosis, redundancy actions or reconfiguration, L3-optimization, coordination of subsystems, and general process management. HEV is a truly mechatronic system. The major problems with the design and control of HEV are the packaging and integration of components, and control and coordination. The design engineers have different ways to increase conversion efficiency and design a hybrid: incorporate the latest proven technology, optimize existing power train components, use new power train components, and combine and integrate optimized power train components into the hybrid. The complex power distribution system is separated into two parts at vastly different power levels and voltages. One part is the information section, which mainly comprises electronic control units (ECUs)—computers and microprocessors at low power, low voltage—which communicate by means of the control area network. Another part is the power electronics that manages the power to/from the motors/generators and to/from the battery (high power, high voltage). For a HEV, integration and control software are as important as hardware, if not more so. Combining electric motors and gasoline engines opens up many more degrees of freedom that must be controlled. Major functions of the control system are to maximize fuel economy and to minimize exhaust emissions. Minor functions of the control system include component monitoring and protection. Examples are battery state of charge (SoC), battery temperature, electrical motor overheating, and gas engine overheating. The battery merits special attention to avoid failure and to assure long life. The control system generally provides a fail-safe mode in the event of failure. Another control function, which is minor in cost but valuable in practice, is onboard diagnostics. Controlling an HEV includes essentially two sets of tasks. One is the *low-level* or *component-level* control task, where each power train component is controlled by using classical feedback control methods. The second task, referred to as *high-level* or *supervisory control*, is responsible for the optimization of the energy flow onboard of the vehicle while maintaining the battery SoC within a certain range of operation. This layer of control, called EMS, receives and processes information from the vehicle and the driver to output the optimal set points sent to the actuators and executed by the low-level control layer. The EMS also selects the best modes of operations of the hybrid power train including start-stop, power split, and electric launch [13]. The potential for optimized control is illustrated by the Honda FCX fuel cell vehicle, in which range was increased by 30% over prior versions. Of the 30% increase, 9% is attributable to an increased fuel tank size. The rest is because of a better control system [10]. This potential can be realized only with a sophisticated control system that optimizes energy flow within the vehicle. It has been recognized that the adoption of systematic model-based optimization methods using meaningful objective functions to improve the energy management controllers is the pathway to go in order to achieve near-optimal results in designing the vehicle EMS. HEVs are complex and involve many different technologies: materials, electromechanics, electrochemistry, electronics, software, and testing facilities. Among them, the motor drive technology is most actively developed in recent years where there are many innovations and advancements in the design, analysis, and control of motor drives. Motor drives are the core technology for HEVs that convert the onboard electrical energy to the desired mechanical motion. Meanwhile, electric machines are the key element of motor drive technology. The requirements of electric machines for HEVs are much more demanding than that for industrial applications (high torque density and high power density, wide speed range, high efficiency over wide torque and speed ranges, wide constant-power operating capability, high torque capability for electric launch and hill climbing, high

intermittent overload capability for overtaking, high reliability and robustness for vehicular environment, low acoustic noise, and reasonable cost). On the other hand, when the electric machine needs to work with the engine for various HEVs, there are some additional requirements (high-efficiency power generation over a wide speed range, good voltage regulation over a wide speed generation, capable of being integrated with the engine).

4. State of the art in axial-flux electric machines for HEV and EV propulsion

The initial selection of electrical machines for hybrid (HEV) or electric (EV) drives includes a variety of different topologies. According to outcomes of literature survey, induction machines alongside synchronous machines take the major place in HEV or EV power trains. Both of these different families of machines topologies, in sense of operational principle, may be laid out in an axial or a radial plane. Out of radial synchronous machines, surface-mounted, inset and embedded-permanent magnet topologies, and switched reluctance machines are considered as competitive for traction purposes. Among the synchronous permanent magnet, axial-flux machines are subject of ongoing research and therefore recently the need to be included in selection process due to their advantageous axial length. The search for more efficient, cost-effective, and fault-tolerant layouts drives the design of electrical machinery up to its limits. The adoption of new materials and topologies for lightweight vehicle and power trains is extremely investment intensive. This chapter proposes to initiate the development and adoption of a new class of propulsion systems incorporating advanced electrical drives. By advanced electrical drive, it means the use of axial-flux dual mechanical output machines (the electrical machine has two independent rotors) with a single stator winding capable to control the mechanical output independently (**Figure 1**). Moreover, the requirements of many applications both in the industry and in the field of renewable energy conversion are so tough that traditional layouts are abandoned in favor of new topologies or new light is shed over older ones. We keep in mind the fact that the presence of the permanent magnet in the structure of the propulsion machine is rather a limitation which can be avoided. In order to build highly reliable propulsion systems, the use of a highly permanent magnet-depending generator/motor will limit the lifetime of the electrical machine and drive it.

Due to their high torque density capabilities, favorable aspect ratio, and the possibility to implement a large number of poles [14], axial-flux PM machines (AFPMMs) are used in many up-to-date applications. In fact, AFPMMs are applicable to fans, diesel and wind generation units, elevators, ships, and vehicles [15]. The first-harmonic approximation of the MMF field commonly used for design purposes is sometimes inadequate, for example, with trapezoidal back EMFs or with fractional slot windings. In fact, these windings operate with a high level of MMF harmonics, although they produce sinusoidal EMF. The technical literature offers many machine models, each one addressing specific issues. Some models provide a precise description of the MMF content [16], some focus on skewing [17], some provide guidelines for the use of finite element method (FEM) [18], and others account for saturation, iron losses, and temperature effects [19, 20]. Most models, however, are based on the reduction of the 3D problem to a 2D problem by the use of a cylindrical cutting plane at the main flux region

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[21–25]. Moreover, 2D and 3D FEM analyses fail to account for iron losses, especially in fractional winding machines with soft magnetic composite (SMC) core [25, 26]. Some models rely on FEM simulations [27]. The influence of rotor eddy currents on the efficiency of fractional slot AFPMM is significant, as emphasized in [23]. As a result of the fundamental intricacy of the magnetic circuit, extensive papers have been devoted to the design and modeling of AFPMM. Actually, the usual first-harmonic approximation of the MMF wave is not suitable for designing windings with a fractional slot number per pole. These windings present short links, compact poles, and sinusoidal EMF, even if the MMF wave has higher- and lower-order spatial harmonics. The harmonic content does not alter the quasi-sinusoidal terminal EMF, but it alters core loss and machine inductance. The professional data available show specific models addressing certain issues: provides a detailed MMF portrayal even if the analytic model cannot be held responsible for machine curvature and presumes that the coil pitch is detailed

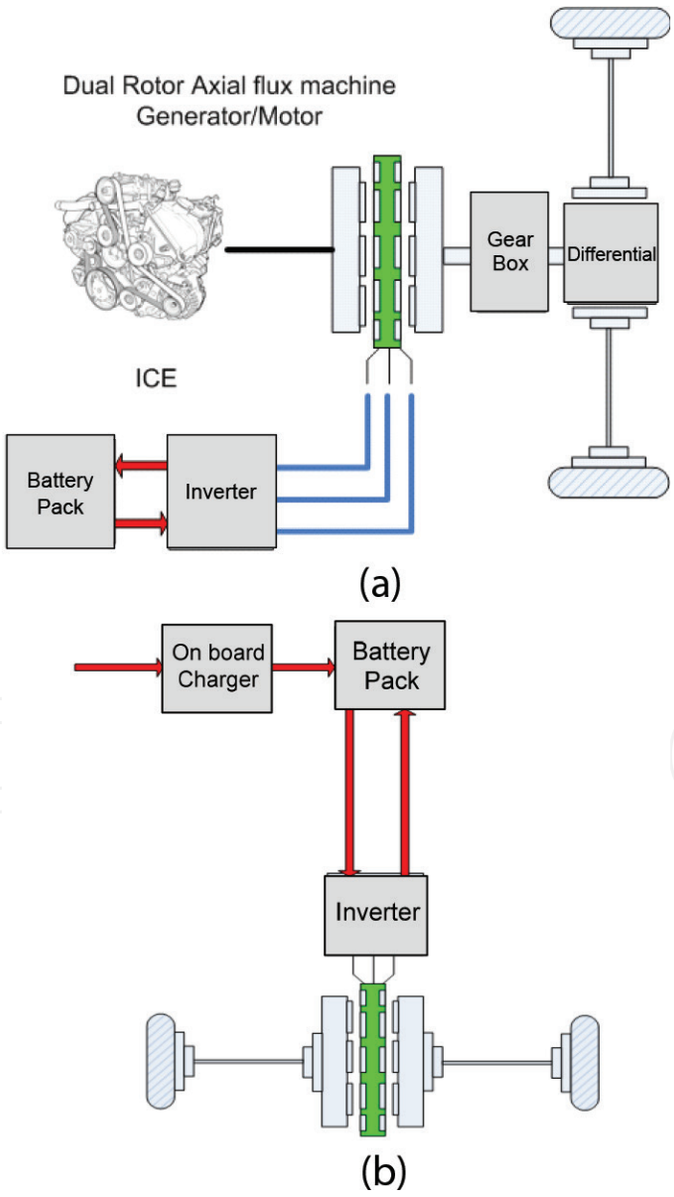


Figure 1. Lightweight power train solution based on axial-flux dual rotor. (a) Hybrid vehicle and (b) electric vehicle.

at the mean core radius, skewing-focused, aids in using the finite element method (FEM), and others are saturation, iron losses, and thermal effects accountant. However, a fair amount of models cut down the 3D issue to a 2D portrayal of a cylindrical cross section. Thermal models require a detailed analysis of rotor iron losses. Mention is based upon FEM simulations and emphasizes the impact of rotor eddy currents. The thermal transfer in axial-flux machine geometries was explained. Thermal simulations done on a machine with a massive iron rotor core showed that the rotor temperatures are above those measured over the windings surface. Actually, a considerable contribution to losses comes from the rotor and is basically due to the sub-harmonic and high-frequency parts of the stator MMF, including slotting. Recent investigations on the subject demonstrated that the sub-harmonics are, however, the main causes of rotor losses. Axial-flux induction machines are also possible. The Australian company Evans Electric has developed induction axial-flux machines for electric car as in wheel motors. These motors deliver 625 Nm and a peak power of 75 kW in an AFIM (axial-flux induction machines) configuration. This machine has the particularity that the stators cover only a part of the machine and not the complete disc. This enables a better air cooling of the machine but reduces the performance. In-wheel direct-drive motors represent the simplest and lightest method for propelling wheeled vehicles, but due to the reduced suspension performance of vehicles with increased wheel mass, the mass of in-wheel motors is a major concern. The axial-flux switched-reluctance motor (AFSRM) topology for in-wheel drive vehicle applications is presented. For a high-speed automotive generator, the axial-flux reversal machine was proposed. The high-speed AF FRM electrical machines offer great advantages of reduction in size per unit output and improved efficiency [25–27]. Small-scale generating sets of high power densities, previously used predominately in military and aircraft applications, are attracting growing attention for a wide variety of automotive applications: onboard charger, compact range extender, and turbine-based HEV. One salient feature of these sets is the use of a high-speed generator directly coupled to a small gas turbine, resulting in a significant reduction of weight and size. The path of the magnetic flux distribution in the air gap is in the axial direction. The rotor of the machine has no permanent magnet and field winding. The permanent magnets and armature windings are on the stator cores being very easy to be cooled. For this reason in the future, we start our investigation including the induction machine, the SRM machine, and the flux reversal machine. The building experience will be valuable for industry as well to the scientific community.

5. Lightweight traction motor/generator using dual-rotor single stator split shaft axial-flux PMSM

5.1. Topology description

In an effort to simplify the design of the two configurations (series and parallel), publications in the latest years released by the authors' team members, among which an international patent is present, treat a topic belonging to a complex scientific field of significant interest and certain actuality, being oriented toward identifying appropriate solutions regarding some proficient electromechanical converters and control structures of the drive systems based on axial machines excited by permanent magnets with a high number of poles, with applications in

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electric traction, operating in different modes: engine, generator, the brake, or combinations in between [28–35]. It proposes **an international original solution** [32] in which the two electrical machines (generator and motor) and static converters related are replaced by a single synchronous permanent magnet machine having an axial air gap, a central stator with slots on both sides, and two different windings supplied from a single PWM inverter having two output frequencies, and two independent rotors. This machine efficiency is high, and the torque density developed by the two rotors is also high. The inverter output voltage ripple contains a combination of voltages each having different frequency and determining a different rotational speed Ω1, Ω2, for the two rotors. The first rotor, coupled with the combustion engine, together with the corresponding stator winding operates as a generator most of the time (**Figure 2**) [29].

It can be used and as a starter for the combustion engine startup. The second rotor, coupled with the differential mechanism and the drive wheels together with the associated stator winding, operates as a motor (in traction) as well as a generator (regenerative braking

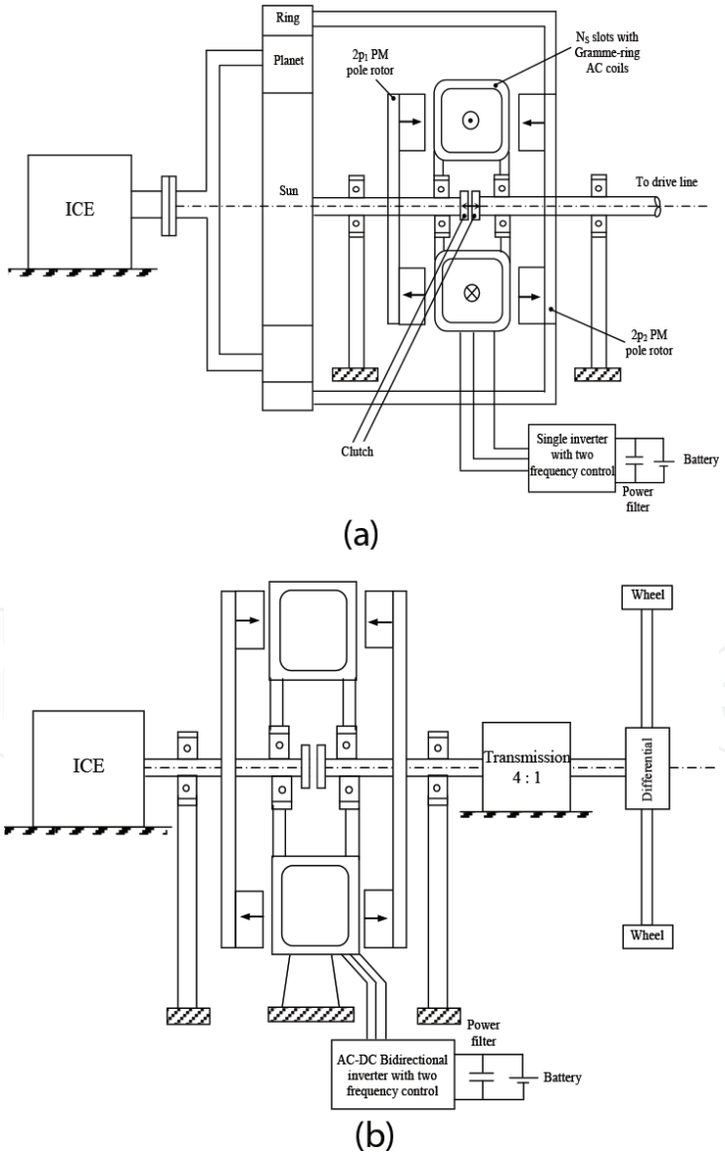


Figure 2. Principle of construction of the proposed solution: (a) parallel planetary mechanism; (b) series version [28].

regime). Fuel economy, which is obtained for the regime of urban movement, can reach 33%. For pure electric vehicles, two solutions have been found for the use of this electric drive system (**Figure 3**) where R is rotors, S is the stator, Inv. is the inverter, TM is the mechanical transmission, TD is the differential transmission, and RM are wheels.

An important advantage of using the synchronous axial air-gap single stator dual-rotor permanent magnet machine is representing the smaller length, this being able to be introduced in the clutch's place between the motor and the gearbox. A 3D drawing of the machine is shown in **Figure 4**.

5.2. Control algorithm

Traditionally, a three-phase three-leg bidirectional power converter is used in an EV. For this topology, the most appropriate power converter is the three-phase four-leg converter.

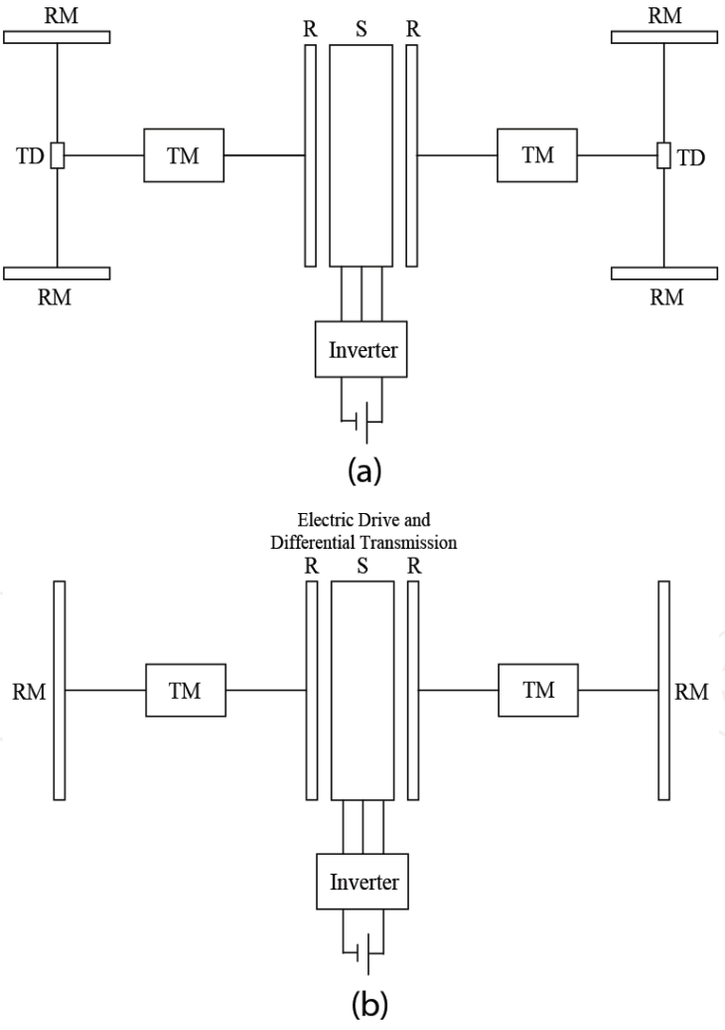


Figure 3. Using the synchronous machine with a stator and two axial rotors: (a) electric drive system for an electric vehicle with a four-wheel drive; (b) an electric drive system and a differential transmission at the same time.

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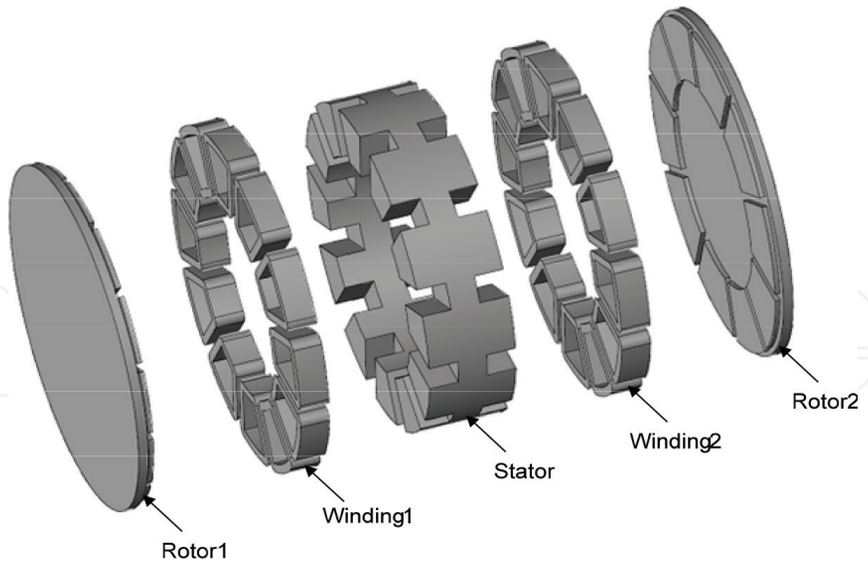


Figure 4. A three-dimensional exploded view of the proposed machine [28].

The main feature of a three-phase inverter four-leg inverter, with an additional neutral leg, is its capability to handle load unbalance. In an automotive power system, the main goal of the three-phase four-leg inverter is to maintain the desired sinusoidal output voltage over all the ranges of loading conditions and transients [34]. Typically, the EV electric machine phases have a Y-connected winding. In order to maintain the phase voltage at the same level as in three-leg inverters, one may choose a Δ connection of the two windings. This means will result in the fact that the wire diameter will be smaller, the winding may be built easier and, for an existing machine, no rewinding is needed (**Figure 5**), and in **Figure 6** for serial HEV.

Alternatively, a matrix converter solution can be used to operate the two rotating rotors (**Figure 7**). The matrix converter is an array of bidirectional switches that can directly connect any input phase to any output phase to create a variable voltage and frequency at the output.

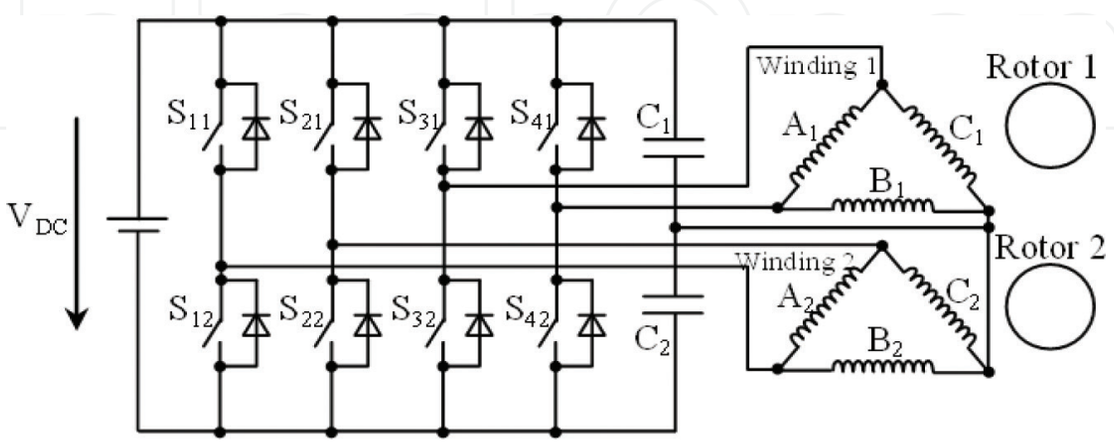


Figure 5. Three-phase four-leg inverter [28].

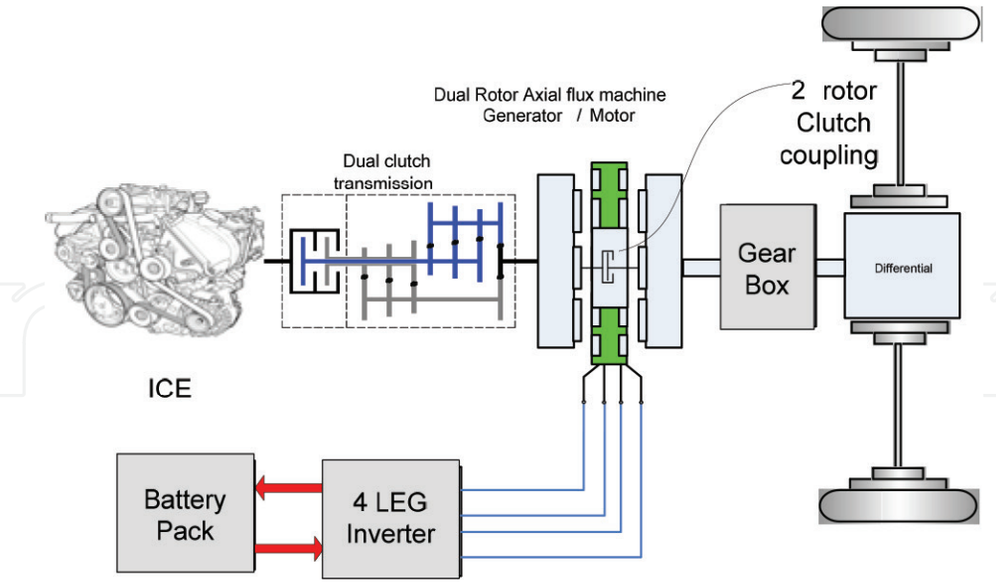


Figure 6. The four-leg inverter for serial HEV.

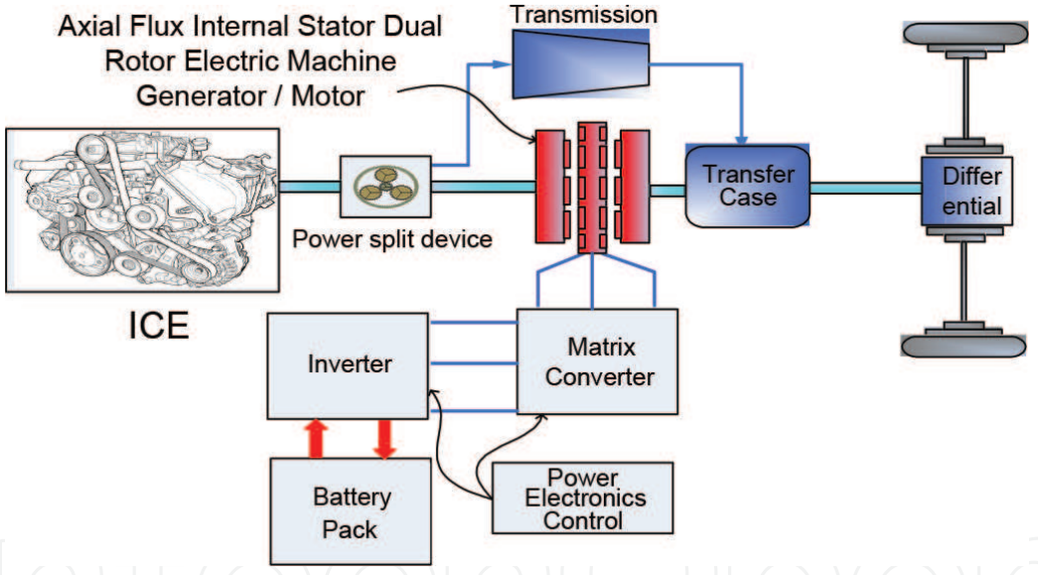


Figure 7. Parallel HEV based on matrix converter topology.

However, despite the benefit of very compact construction (no DC capacitors), this type of converter is not very easy to control, and for this reason, we only mention it as an alternative topology to be used.

5.3. Field-oriented control with four-leg inverter

The proposed configuration of a dual mechanical rotor with a single stator requires a single-phase AC current flow through the capacitors. This is due to the connection of the machine

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line voltages to the center point of the DC link. However, by connecting a second two-phase inverter and motor to the same DC bus, as shown in **Figure 5**, it is possible to compensate for the single-phase current in the DC link capacitors. A specially designed vector control is required for this reason. In this way, the compensation current influence on the torque is limited in the case of surface PM machines (with no saliency) [34]. The neutral voltage regulation with different current compensation is based on a simple PI controller since the motor divides the current compensation effort to both motor sides, rotor 1 and rotor 2 (in a direct ratio with their rated current) and at the same time avoids power oscillations (power pulsation occurs when two independent controllers are used). In **Figure 8**, the proposed vector control strategy is presented.

In order to evaluate the behavior of the combined solution dual-rotor single stator axial-flux PMSM machine powered by a three-phase four-leg converter, a digital simulation was performed. Using the equivalent model of the axial-flux permanent magnet machine, a Matlab Simulink model was implemented. The actual test conditions were represented by a step in the speed reference consisting of a value of 150 (rad/s) which is given for first electric machine M1 at the starting moment (t = 0) and a second step in the speed reference consisting of the value 230 (rad/s) which is given for machine M2 at t = 0.8 s (**Figure 9a**). In this scenario, the machine M1 reaches the reference speed in 0.175 s at a rated torque as load. In an EV configuration after the thermal engine starts, at t = 0.5 s, the machine M1 switches to a generator mode with 20% load at the same speed (**Figure 9b**). The speed overshooting during starting process and torque perturbation is around 2 [rad/s] (under 1.5%) which represents a very good feature of the proposed vector control. The second machine M2 is started at t = 0.8 s (**Figure 9a**), with 10% of the rated torque as load (**Figure 9b**), and it reaches the reference speed in 1.3 s. A small perturbation on machine M1 speed occurs during the machine M2 starting (**Figure 9a**, **b**). The machine M1 is starting with a two-time rated torque, and it runs at a rated torque between 0.2 and 0.5 s and then at 25% of the rated torque as generator. Small torque perturbation could be

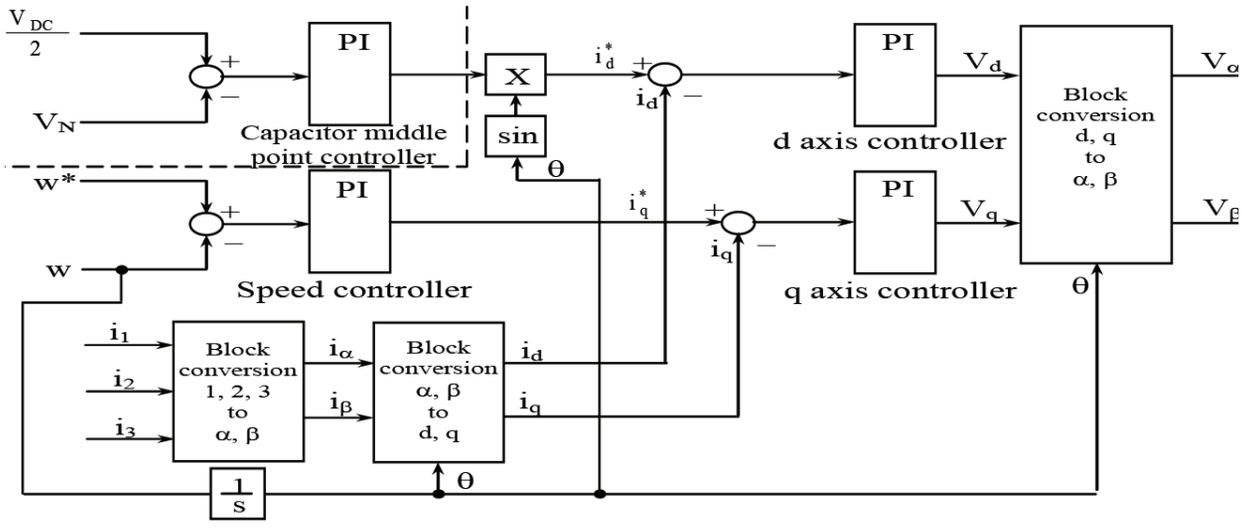


Figure 8. The proposed vector control strategy [28].

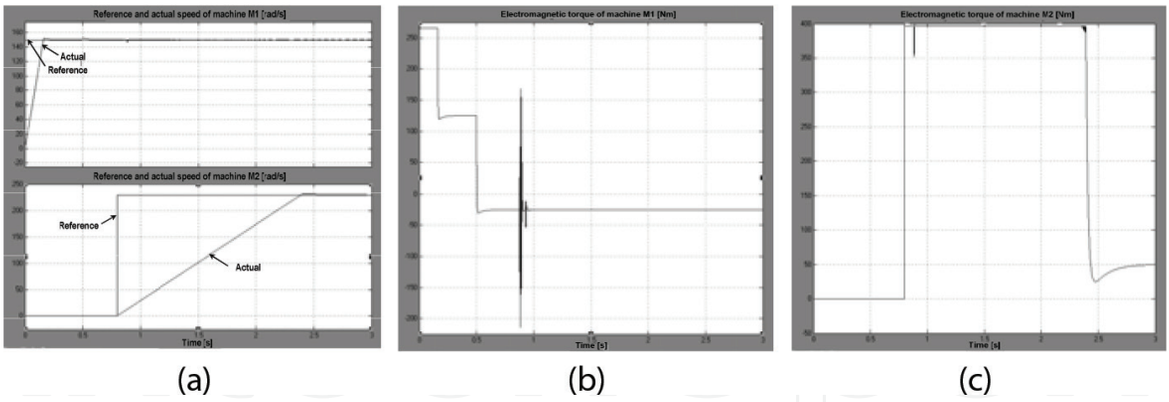


Figure 9. (a) Machine M1 and M2 reference and actual mechanical speeds; (b) achieved torque by machine M1; (c) achieved torque by machine M2 [28].

observed in machine M2 while starting. The machine M2 is starting with electromagnetically rated torque while the load torque is 10% (**Figure 9c**).

In terms of reliability, the presented topology combined with an adequate power converter allows to have the highest reliability in the single inverter configurations for EV.

6. Conclusions

The use of a very compact electrical drive will have the benefit of considerably reducing the weight and complexity of the power train. As it is known, the mechanical complexity of the power train is responsible for as much of 20% of the weight of the vehicle. The mechanical system of internal combustion engine (ICE) vehicle required a rather complex system of adaptation of speed and torque to the travel conditions. Our chapter is developed around the concept of a reduced number of mechanical elements included in the power train. This is possible by the close integration of electrical drive with the ICE and the use of the electrical differential concept. Special consideration is given to the power electronics required for the drive. Using a new approach, the number of converters is limited to one for each axle, each converter being capable to independently control the motion of the side wheels. Instead of a complex sophisticated gearbox, we propose to use a simplified gearbox or no gearbox in case of the electric differential, much of the function being fulfilled by the dual mechanical output electric machine controlled by a single power converter. A special control based on the dual vector control with operating on dual frequency will be investigated. In order to increase the ruggedness of the system, we investigate special power converters with a high degree of reliability (the four-leg converter and the matrix converter that makes no use of DC capacitors in the DC link), the multilevel inverter concept applied to EV which brings the benefit of a very reliable topology, a reduced harmonic pollution, and easy battery cell balancing. Although this seems to be an unnecessary complication to a rather proven technology, our chapter considers the fact that the existing power train solutions are not considering the problem of extra weight/complexity given by the electrification.

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