Electric, Hybrid, and Fuel-Cell Vehicles: Architectures and Modeling

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Abstract—With the advent of more stringent regulations related to emissions, fuel economy, and global warming, as well as energy resource constraints, electric, hybrid, and fuel-cell vehicles have attracted increasing attention from vehicle constructors, governments, and consumers. Research and development efforts have focused on developing advanced powertrains and efficient energy systems. This paper reviews the state of the art for electric, hybrid, and fuel-cell vehicles, with a focus on architectures and modeling for energy management. Although classic modeling approaches have often been used, new systemic approaches that allow better understanding of the interaction between the numerous subsystems have recently been introduced.

Index Terms—Electric vehicle (EV), fuel-cell vehicles (FCVs), hybrid electric vehicle (HEV), modeling, powertrains.

I. Introduction

ALTHOUGH fossil fuel resources are limited, the demand for oil has significantly increased. In recent decades, the oil consumption of the transportation sector has grown at a higher rate than any other sector. This increase has mainly come from new demands for personal-use vehicles powered by conventional internal combustion engines (ICEs). Because some environmental problems, such as the green house effect, are directly related to vehicle emissions, government agencies and organizations have developed more stringent standards for fuel consumption and emissions.

Battery-powered electric vehicles (BEVs) seem like an ideal solution to deal with the energy crisis and global warming since they have zero oil consumption and zero emissions *in situ*. However, factors such as high initial cost, short driving range, and long charging time have highlighted their limitations [1]–[4]. Commercial BEVs have nonetheless been developed for niche markets, and some constructors are developing BEVs as small cars dedicated to short-distance trips.

Hybrid electric vehicles (HEVs) were developed to overcome the limitations of ICE vehicles and BEVs. An HEV combines a conventional propulsion system with an electrical energy storage system and an electric machine (EM). When HEVs are driven in the electric mode, it is possible to obtain zero
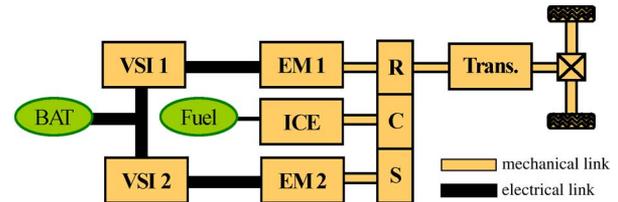
Fig. 1. Series–parallel HEV with planetary gear.

emissions. HEVs demonstrate improved fuel economy, compared with conventional ICE vehicles, and have a longer driving range than BEVs. Plug-in HEVs (P-HEVs) have an even longer range, because their battery can be recharged by plugging into an electrical grid. HEVs can help meet the challenges related to the energy crisis and pollution; however, their high purchase price is the primary obstacle to their widespread distribution. Still, the success of the first cars on the market (e.g., Toyota Prius) indicates that HEVs constitute a real alternative to ICE vehicles. Moreover, U.S. market trends suggest that P-HEVs are becoming a very attractive and promising solution [5], [6].

Fuel cell vehicles (FCVs) use fuel cells to generate electricity from hydrogen and air. The electricity is either used to drive the vehicle or stored in an energy-storage device, such as a battery pack or supercapacitors. FCVs emit only water vapor and have the potential to be highly efficient. However, they do have some major issues: 1) the high price and the life cycle of the fuel cells; 2) onboard hydrogen storage, which needs improved energy density; and 3) a hydrogen distribution and refueling infrastructure that needs to be constructed [2]. FCVs could be a long-term solution. Although prototypes have already been proposed by manufacturers, the potential of FCVs, including hydrogen production and distribution facilities, has yet to be proven.

This paper provides an overview of the state of the art for BEVs, HEVs, and FCVs [1]–[13] with a focus on powertrain architectures and modeling for energy management. In Section II, various powertrain architectures are presented. In Section III, different modeling methods for energy management are summarized.

II. Powertrain Architectures

ICE vehicles are propelled by an ICE using one of two fuels: gasoline or diesel. BEVs are propelled by EMs running on electricity stored in a battery. HEVs are propelled by a combination of the two powertrains. The ICE gives the hybrid vehicle an extended driving range, whereas the EM increases efficiency

TABLE I
CHARACTERISTICS OF BEV, HEV, AND FCV

	BEV	HEV	FCV
Propulsion	• Electric motor drives	• Electric motor drives • Internal combustion engines	• Electric motor drives
Energy storage subsystem (ESS)	• Battery • Supercapacitor	• Battery • Supercapacitor • Fossil or alternative fuels	• Hydrogen tank • Battery / supercapacitor needed to enhance power density.
Energy source & infrastructure	• Electrical grid charging facilities	• Gasoline stations • Electrical grid charging facilities (for Plug-In Hybrid)	• Hydrogen • Hydrogen production and transportation infrastructure
Characteristics	• Zero local emissions • High energy efficiency • Independent of fossil fuel • Relatively short range • High initial cost • Commercially available	• Low local emissions • High fuel economy • Long driving range • Dependence on fossil fuels • Higher cost than ICE vehicles • Commercially available	• Zero low local emissions • High energy efficiency • Independent of fossil fuels (if not using gasoline to produce H2) • High cost • Under development
Major issues	• Battery sizing and management • Charging facilities • Cost • Battery Lifetime	• Battery sizing and management • Control, optimization and management of multiple energy sources.	• Fuel cell cost, life cycle and reliability • Hydrogen production and distribution infrastructure • Cost

and fuel economy by regenerating energy during braking and storing excess energy produced by the ICE. Depending on the way the two powertrains are integrated, there are generally three basic HEV architectures: 1) series hybrid; 2) parallel hybrid; and 3) series–parallel hybrid [1], [14], [15]. Among these three architectures, the series–parallel hybrid architecture (which is also called the power-split architecture) with a planetary gear system (see Fig. 1) possesses a maximal number of subsystems, which allows series and parallel operations, or a combination of the two. For this reason, we chose this architecture as the basis of our discussion and comparison. The other architectures are derived from this basic architectural scheme. In the figures referred to in this section, batteries are denoted as BAT, the fuel tank as Fuel, the Voltage Source Inverter as VSI, the Electric Machine as EM, the Internal Combustion Engine as ICE, and the Transmission as Trans. Black lines are used to designate electric couplings, and orange lines represent mechanical couplings. The transmission may be a discrete gearbox with a clutch, a continuously variable transmission (CVT), or a fixed reduction gear.

A. Major Characteristics of BEVs, HEVs, and FCVs

Table I shows a comparison of the major characteristics of BEVs, HEVs, and FCVs.

Energy consumption is a major issue when comparing electric, hybrid, and ICE vehicles. Several authors have provided well-to-wheels analyses that assess the global energy consumption of these types of vehicles [17], [18]. BEVs and HEVs have been proven to provide real fuel economy, compared with the ICE vehicles, even when the electricity is generated using petroleum resources. Moreover, using BEVs and HEVs also leads to a global reduction of greenhouse gas emissions. For FCVs, the results are not so obvious, because they depend on the way hydrogen is produced.

Reliability is another important issue when comparing vehicles. However, it is a challenge to provide any definitive conclusion at the present time. Clearly, HEVs have a complex architecture including numerous subsystems, which decreases the global reliability of the system, compared with thermal
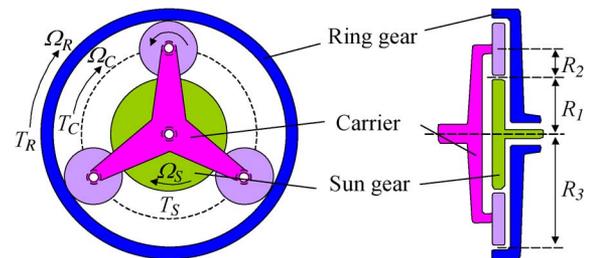

Fig. 2.   Planetary gear set (figure from [25]).

ICE vehicles [19]. However, real current data are difficult to obtain for reasons of industrial property. In addition, some HEV architectures reduce constraints on ICE through downsizing or enable fault-tolerant operation. FCV reliability has yet to be proven. The reliability of HEVs and FCVs is a key issue for the commercial development of such vehicles.

1) Series–Parallel HEVs: A planetary gear set (Fig. 2) can be used in a series–parallel HEV [4]. As shown in Fig. 1, electric machine 1 (EM1) and the transmission shaft (Trans.) are connected to the planetary ring gear set (R), whereas the ICE is connected to the carrier (C) and EM2 is connected to the sun gear (S). This architecture is depicted in such a way as to allow the other traditional architectures (i.e., series and parallel HEVs, ICE vehicles, and BEVs) to be deduced. Using the dc voltage bus and the planetary gear set, a series–parallel HEV can operate as either a series HEV or a parallel HEV in terms of energy flow. The energy node can be located in the electric coupling components (e.g., the dc or ac bus) or in the mechanical coupling components (e.g., planetary gear set or others). Because of the planetary gear, the ICE speed is a weighted average of the speeds of EM1 and EM2. The EM1 speed is proportional to the vehicle speed. For any given vehicle speed (or any given EM1 speed), the EM2 speed can be chosen to adjust the ICE speed. The ICE can thus operate in an optimal region by controlling the EM2 speed. Although series–parallel HEVs have the features of both the series and parallel HEVs, they still require three motors and a planetary gear set, which makes the powertrain somewhat complicated and costly. In addition, controlling this architecture is quite complex.
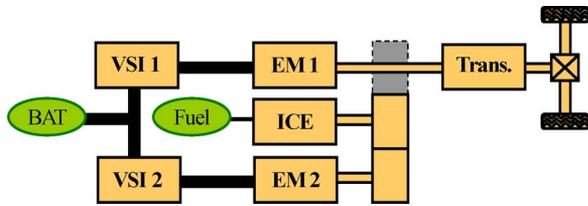
Fig. 3.   Series HEV.

Fig. 4.   Parallel HEV.

Fig. 5.   ICE vehicle.

Fig. 6.   BEV.

Instead of a planetary gear set, a second type of series–parallel HEV uses a combination of two concentric machines EM1 and EM2 as a power-split device [20]–[22]. To reduce the system weight and size, the two machines can be merged, creating a single machine with double rotor [24].

In both systems (planetary gear set and concentric machines), the speed ratio between the ICE shaft and transmission shaft is continuous and variable. Both kinds of systems can replace the CVT. For this reason, they are also called electric CVT (E-CVT or EVT) [24]. Two kinds of E-CVT have been developed: double-rotor induction machines [20], [23] and double-rotor permanent-magnet machines [24].

2) Series HEVs: In series HEVs, all the traction power is converted from electricity [26], and the sum of energy from the two power sources is made in an electric node that is commonly in a dc bus. The ICE has no mechanical connection with the traction load, which means it never directly powers the vehicle. If the connection between the EM1 and the ICE is eliminated, a series HEV can be obtained from the series–parallel hybrid architecture. The connection between the ICE and the EM2 can be a simple gear. In this series topology (see Fig. 3), the energy node between the power sources and transmission is located at the dc bus.

In series HEVs, the ICE mechanical output is first converted into electricity by the EM2. The converted electricity can either charge the battery or directly go to propel the wheels via EM1 and the transmission, thus bypassing the battery. Due to the decoupling of the ICE and the driving wheels, series HEVs have the definite advantage of being flexible in terms of the location of the ICE generator set. For the same reason, the ICE can operate in its very narrow optimal region, independent of the vehicle speed. Controlling series HEVs is simple due to the existence of a single torque source (EM1) for the transmission. Because of the inherently high performance of the characteristic torque speed of the electric drive, series HEVs do not need a multigear transmission and clutch. However, such a cascade structure leads to relatively low efficiency ratings, and thus, all three motors are required. All these motors need to be sized for the maximum level of sustained power. Although, for short trips, the ICE can relatively easily be downsized, sizing the EMs and the battery is still a challenge, which makes series HEVs expensive.

3) Parallel HEVs: If EM2 is removed from the series–parallel hybrid architecture, a parallel HEV is obtained (see Fig. 4). In a parallel powertrain, the energy node is located at the mechanical coupling, which may be considered as one common shaft or two shafts connected by gears, a pulley-belt unit, etc.

The traction power can be supplied by ICE alone, by EM1 alone, or by both acting together. EM1 can be used to charge
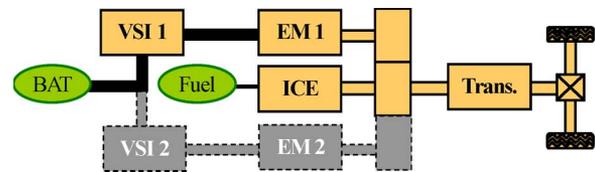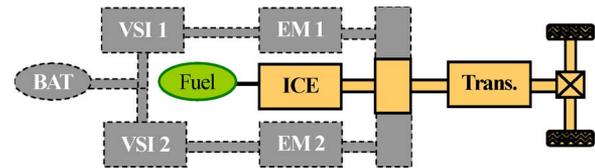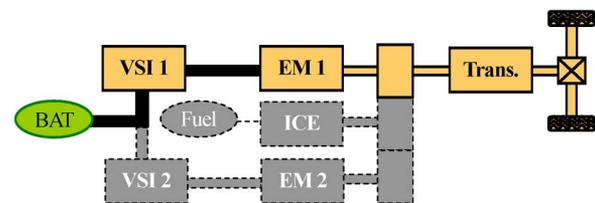
the battery through regeneration when braking or to store power from the ICE when its output is greater than the power required to drive the wheels. More efficient than the series HEV, this parallel HEV architecture requires only two motors: the ICE and the EM1. In addition, smaller motors can be used to obtain the same dynamic performance. However, because of the mechanical coupling between the ICE and the transmission, the ICE cannot always operate in its optimal region, and thus, clutches are often necessary.

4) ICE Vehicles: An ICE vehicle (see Fig. 5) is obtained when only the ICE powertrain remains from the series–parallel hybrid architecture. ICE vehicles have a long driving range and a short refueling time but face challenges related to pollution and oil consumption.

5) BEVs: BEVs (see Fig. 6) result when only the EM1 powertrain remains from the series–parallel hybrid architecture. Because the vehicle is powered only by batteries or other electrical energy sources, zero emission can be achieved. However, the high initial cost of BEVs, as well as its short driving range and long refueling time, has limited its use. Still, new BEV architectures have been proposed that use several energy sources (e.g., batteries, supercapacitors, and even reduced-power fuel cells) connected to the same dc bus [27], which should eventually reduce the refueling time, expand the driving range, and drive down the price.

6) FCVs: From a structural viewpoint, an FCV can be considered as a type of BEV, because an FCV can also be equipped with batteries or supercapacitors [11]. Thus, FCVs can be considered as a type of series hybrid vehicle, in which the fuel cell acts as an electrical generator that uses hydrogen [28]. The onboard fuel cell produces electricity, which is either used to provide power to the machine EM1 or is stored in the battery or the supercapacitor bank for future use [29].

TABLE II
DIFFERENT FUNCTIONS OF THE VARIOUS HEV ARCHITECTURES

	Micro HEV	Mild HEV	Full HEV	Plug-in HEV
Series-parallel			x	x
Series			x	x
Parallel	x	x	x	

B. Different Functions of the Various HEV Architectures

The previous HEV architectures provide different levels of functionality. These levels can be classified by the power ratio between the ICE and EMs.

1) *Micro Hybrid:* Micro hybrid vehicles use a limited-power EM as a starter alternator [30], and the ICE insures the propulsion of the vehicle. The EM helps the ICE to achieve better operations at startup. Because of the fast dynamics of EMs, micro hybrid HEVs employ a stop-and-go function, which means that the ICE can be stopped when the vehicle is at a standstill (e.g., at a traffic light). Fuel economy improvements are estimated to be in the range of 2%–10% for urban drive cycles.

2) *Mild Hybrid:* In addition to the stop-and-go function, mild hybrid vehicles have a boost function, which means that they use the EM to boost the ICE during acceleration or braking by applying a supplementary torque. The battery can also be recharged through regenerative braking. However, the electrical machine alone cannot propel the vehicle. Fuel economy improvements are estimated to be in the range of 10%–20%.

3) *Full Hybrid:* Full hybrid vehicles have a fully electric traction system, which means that the electric motor can insure the vehicle's propulsion. When such a vehicle uses this fully electric system, it becomes a "zero-emission vehicle" (ZEV). The ZEV mode can be used, for example, in urban centers. However, the propulsion of the vehicle can also be insured by the ICE or by the ICE and the EM together. Fuel economy improvements are estimated to be in the range of 20%–50%.

4) *Plug-in Hybrid:* Plug-in hybrid electric vehicles (P-HEVs) are able to externally charge the battery by plugging into the electrical grid. In some cases, the plug-in vehicle may simply be a BEV with a limited-power ICE. In other cases, the driving range can be extended by charging the batteries from the ICE to extend the EV autonomy. This type of P-HEV is also called "range extend EV." P-HEVs are promising in terms of fuel economy. For example, the fuel economy of P-HEVs can be improved by 100% if the ICE is not used to charge the battery (e.g., in urban drive cycles). Increasing the battery size allows ZEV operation for small trips and thus results in an important reduction in fuel consumption and greenhouse gas emissions. Many studies are being conducted about P-HEVs [5], [6]. Although the impact of P-HEVs on electrical grid loads needs to be examined, the initial studies have shown that P-HEVs could reduce peak demand without requiring more power plants [6].

HEV architectures have different levels of functionality. As shown in Table II, some architectures are dedicated to certain HEV functions. (BEVs and FCVs are not considered in this table, because they use only electric power, and all the functions are insured by electrical machines.)

III. MODELING BATTERY-POWERED ELECTRIC VEHICLES, HYBRID ELECTRIC VEHICLES, AND FUEL-CELL VEHICLES

Depending on the objective of the study, different methods can be used to model BEVs, HEVs, and FCVs: component design [31], [32], topology analysis [33]–[36], energy or pollution assessment [37], [38], or energy management [26], [39]–[44]. In this paper, only the energy management models are considered.

Two different methods are used to manage the energy of these new vehicles. The first method involves control strategies, based on a physical model of the system. The second method involves optimization strategies, which are often based on simulations of the studied system. In both cases, an appropriate model of the vehicle is required. In the first case, the model has to allow the correct analysis of power flows between the various subsystems to deduce control laws. In the second case, the model is used to develop the simulation, which will be used to assess the energy-management performance.

Modeling these systems is thus a fundamental step in proposing efficient energy management [12]. However, it is also quite complex due to the multiple interconnected physical subsystems and the multiple scales of the different dynamics [45]. A cybernetic approach is required to take the dynamic interaction between the multiphysical systems into account.

Section III is organized in two parts. The first part focuses on the different modeling methods. The second part focuses on the modeling of HEVs for energy management. Although the various modeling methods are considered in terms of HEVs, they can easily be extended to BEVs and FCVs, because these two kinds of vehicles can be considered as specific cases of HEVs, as shown in the previous section.

A. Different Modeling Methods

1) Definitions of Some Notions Used in Modeling: Since certain notions are often confused with others, we provide definitions of the most often confused notions to clarify our discussion of the modeling process.

1) *Model:* A model is a pattern, plan, representation, or description designed to show the main objectives or functions of an object, system, or concept. A model may be represented either by experimental data using lookup tables and efficiency maps or by mathematical equations. The same system can be represented using different models. Depending on the study's objective (e.g., design, analysis, implementation, or energy management), different levels of accuracy are required. The validity range of the various models depends on the simplification assumptions applied.

2) *Modeling:* Modeling is the act of creating a model that sufficiently accurately represents a target system to permit the study or simulation of those systems. When a cybernetics approach is adopted, the first step is to define

the boundary between the system studied and its environment. The next step consists of defining the study's objective (which must lead to the required granularity level) and determining the simplification assumptions. Creating the model is the last step.

3) *Modeling formalism:* A formalism is a way to organize ideas, concepts, or models according to specific rules and conventions. A modeling formalism is a way to organize a model. The same model can be described by different structured representations to highlight various properties. For example, the state-space representation organizes a model according to a specific mathematical system to highlight the model's dynamic properties. The more complex the system, the greater the number of ways that it can be described. Each modeling formalism has its own philosophy, representational notions, and organizational rules.

4) *Modeling software:* The modeling software provides an environment for simulation. Depending on the software constraints, models can be implemented in such environments. Models are the inputs for software development.

5) *Systemics:* Systemics is the science of the interactions between a system and its environment. The system is considered to be composed of subsystems engaged in dynamic interactions. Unlike the classic Cartesian approach, in a systemic approach, the system must be studied as a whole and cannot be studied as independent subsystems. This holistic property suggests that the interaction between two subsystems can make new system characteristics emerge and can cancel some local characteristics. Two different systemics approaches are usually used.

1) In *Cybernetic Systemics*, the system is studied without internal knowledge. For this reason, it is often called the black-box approach. Adopting a cybernetic approach would mean building a behavior model using specific identification tests. In this approach, the system control is mainly based on the closed-loop concept.

2) In *Cognitive Systemics*, the system is studied with prior knowledge. Adopting a cognitive approach would mean building a knowledge model based on the physical laws of devices. In this approach, the system control can be developed using an inversion-based methodology [46].

2) Description of the Various Kinds of Models:

1) *Steady-state, dynamic, and quasi-static models:* Steady-state models, which consider that all transient states are negligible, are based on experimental data in the form of lookup tables or on simplified dynamic models that require less computation time. Full-fledged dynamic models, on the other hand, take transient states into account. They are also more general, more accurate, and more complex than steady-state models, but they require more computation time. To obtain the benefits of both types of models, quasi-static models are sometimes developed. This kind of model consists of a steady-state model to which an equivalent dynamic model of the system is added [47]. For example, ICEs are often modeled using a map (steady-state model) associated with a first-order system (dynamic model). Depending on their interactions, vehicle subsystems can be modeled by both their steady-state relationships and their dynamic relationships [44].

2) *Structural and functional models:* A structural model represents the system through interconnected devices, according to its physical structure. This kind of model is easy to use, because it is only necessary to connect devices, as in the real system. Most of the new software packages for vehicle simulation are based on structural models: Component libraries are available, and users just have to "pick and place" the components to build the vehicle architecture. Structural models are generally focused on the design and analysis of the studied system, using powerful solvers to allow efficient simulation of complex systems. A functional model represents the system through interconnected mathematical functions [48], in which each function is associated to a physical device. For this reason, the system's physical structure is often lost, but the system analysis is made easier.

For complex systems, one of the problems to be solved when modeling is the association of the various system devices, thus applying the holistic property. In the case of structural software, a specific solver is required to solve the association problems. In fact, the quality of the simulation depends on the quality of the solver. The solution is often obvious. In the case of functional software, the user has to solve the association problems before implementation, meaning more physical knowledge is required. However, this functional approach highlights the holistic constraints.

1) *Forward and backward models:* Depending on the direction of calculation, vehicle models can be classified as forward or backward models [49]. The forward model approach is also called either the engine-to-wheel or the rear-to-front model. It begins with the ICE or another energy source and works "forward" using transmitted and reflected torque. Conversely, the backward model approach is called either the wheel-to-engine or the front-to-rear model. It starts with the required traction effort at the wheels and works "backward" toward the ICE or the primary energy source. Forward models better represent real system setup and are useful for testing control algorithms. This kind of approach requires some kind of "driver model," because a reproduction of speed profiles is not possible without a speed controller. One example of a forward model is the Powertrain System Analysis Toolkit [50]. Backward models may be faster than forward models, because they are often based on quasi-static models. Backward models require an imposed speed cycle to calculate the forces acting on the wheels, allowing power to be transmitted to the primary energy sources. Some approaches, such as ADVISOR, combine the two types of model [51].

2) *Causal and noncausal models:* A causal model is a model that uses the principle of cause and effect to describe the system's behavior. Physical causality is based on integral causality [52], [53]. In causal models, the output is always

an integral function of the input, which induces a time delay from input to output. In such models, some devices have fixed inputs and outputs, which leads to problems of association with other devices. In noncausal models, the inputs and outputs of the system devices are not fixed (i.e., floating inputs/outputs). The values of both can be chosen based on the association of the device with the other devices. For that reason, noncausal models are often used in structural software. If the potential problems of device association are not highlighted during the modeling process, they have to be taken into account by the software solver [54], [55].

B. Energy Management Models for HEVs

1) Models Appropriate for Energy Management: HEV energy management can be considered at two control levels. The first control level, i.e., local energy management, must be insured in real time in each subsystem; however, the second control level, i.e., global energy management, must be insured at the system level to coordinate the power flow of each subsystem. The final objective is managing all the energy in the entire system, which means controlling the subsystems and supervising the whole system. For this reason, understanding the function of each subsystem is essential, and thus, a functional model is more appropriate than a structural model. Because the objective is to manage energy, a causal model is more appropriate than a noncausal model since a misunderstanding of the physical causality can lead to a nonphysical energy management that cannot only reduce system efficiency but can also increase the risk of damage.

For local energy management, a real-time control of the power flows in the subsystems is required. Since forward models allow energy to be managed based on the physical power flow and dynamic models take transient states into account, a forward dynamic model is thus very useful for developing real-time algorithms for secure efficient management of fast and slow dynamics. Remember that transient states are associated with state variables, which represent energy.

For global energy management, a quasi-static model can be used with the aim of coordinating the energy flow from each subsystem. This supervision is necessarily slower than the local control. Since a more global model is sufficient, a backward model can be used to develop the control level associated with energy management.

2) Traditional Mathematical Formalisms and Newer Graphical Formalisms: Energy management can be described in many ways, but the functional and causal models are the most appropriate. The same model can be described in different ways to highlight different properties. Even though traditional formalisms have successfully been used for describing/modeling well-known monophysical systems, they suffer from limitations when faced with new multiphysical systems.

1) *Mathematical formalisms and block diagrams:* For complex systems, the well-known state-space formalism is often used. This formalism provides a functional description that portrays a specific organization of the mathematical relationships. In addition, because it expresses

the state variables as a consequence of the inputs, it also provides a causal description. This state-space representation is very useful for highlighting system properties, such as dynamics and observability. The advantage of such a representation is that the system is considered as a whole entity and that all couplings are taken into account. The drawback of this formalism is that the subsystems disappear. The high abstraction level masks the physical reality of the devices.

To better understand and visualize the system, block diagrams are often used. Transfer functions are derived from differential equations, and subsystem inputs and outputs are organized to couple the different subsystems. The advantage of block diagrams is that no restrictive rules are imposed, leaving users to organize the model based on their own ideas. The drawback is that no rule is defined to verify the coherence of the model with the system being modeled. Block diagrams are very useful for systems for which users have expertise. These types of descriptions were all designed for linear continuous and time-independent systems. For this reason, they are limited when the users need to take into account the nonlinearaities and other constraints that occur in complex multiphysical systems, such as HEVs.

2) *Graphical formalisms:* Graphical formalisms were developed to overcome the limitations previously mentioned to structure models of complex systems.

Bond graphs were developed in the 1960s to organize the power flow of energy systems [56], [57]. A bond graph is a powerful and unified formalism for describing multiphysical systems [58]. It is often used for design and analysis. It is composed of dissipative (R), accumulative (L and C), and conversion elements (TF and GY). The system structure is described using junctions (0 and 1) to connect elements. All the elements are linked by bonds, which support exchanged variables (flow and effort). A type of causality is defined for each element, but physical/integral causality is not mandatory. Using this graphical formalism, the power flow can be highlighted, and many physical properties can be derived. A global mathematical system model can be derived from the bond graph for control purposes. Fig. 7 shows an HEV described using the bond graph [59].

Power-oriented graphs (POGs), which were derived from bond graphs, were developed in the 1990s. POGs can be considered as a transcription of the bond graph using block diagrams [60]. The flux and effort are separated, and two main blocks (i.e., the elaboration and conversion elements) are defined to simplify the modeling process and the simulation. POG has been used to simulate electrical machines [60] and automotive systems [61].

Power flow diagrams (PFDs), which were also derived from bond graphs, were developed in 2004 [62]. PFDs involve splitting the bond to differentiate flow and effort variables to better interpret the system. New pictograms are defined to highlight the different elements in the system. PFDs have been used to study electric drives and traction systems [63].
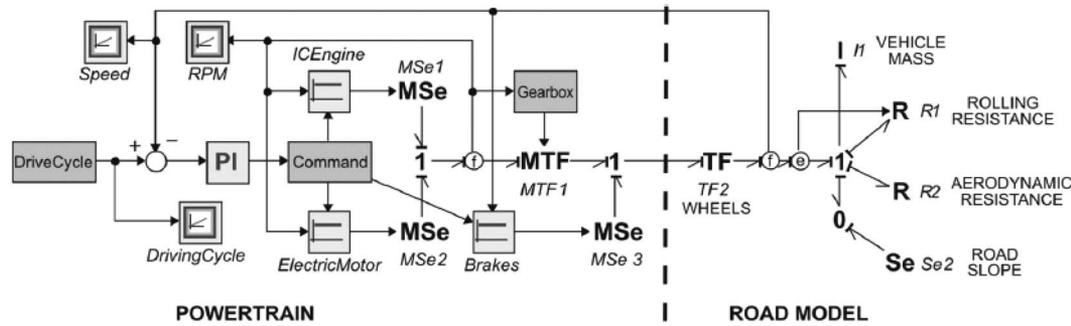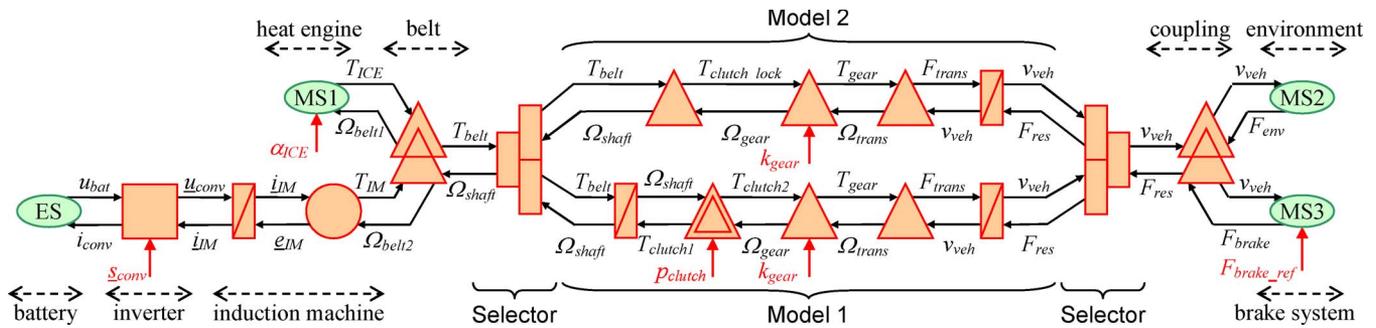
Fig. 7. Bond graph model of a parallel HEV [59].

Fig. 8. EMR of a parallel HEV using a clutch [72].

Causal ordering graphs (COGs) were developed in the 1990s [64], [65]. COGs structure inversion-based control [46]. Two elements (i.e., causal and rigid elements) are defined to highlight device inputs and outputs. The variables are the flow (i.e., kinetic) and the effort (i.e., potential). The only accepted causality is physical causality (i.e., integral causality) [52], [53], [64]. Due to this exclusive causality, control schemes can systematically be deduced from the process graph. COGs have already been used to study different types of electromechanical system control [46], [66].

Energetic macroscopic representation (EMR) was developed in 2000 [48]. It can be considered as an extension of the COG for complex systems. Macro pictograms are defined to highlight the energy properties of the system (e.g., energy source, accumulation, conversion, and distribution). All elements are connected according to the action–reaction principle. The result of the action and the reaction always yields power. Because EMR, like the COG, respects an exclusive physical causality, control schemes can systematically be deduced from this description. In addition, the energy management's degrees of freedom are highlighted during the inversion process [67]. EMR has successfully been used to model and control wind energy-conversion systems [68], railway-traction systems [69], BEVs [70], and HEVs [71]–[73]. Fig. 8 shows an EMR model of a parallel HEV with a clutch.

3) *Usefulness of graphical formalisms:* Some of these graphical formalisms have been compared to model an electric vehicle [74], [75]. Other such formalisms have been used for modeling, e.g., the gyrator-based equivalent circuits in HEVs [76]. These graphical formalisms are powerful descriptions that propose a unified description of multiphysical systems. The advantage of such graphical representations is that modeling rules help users to respect physical properties. The drawback of these representations is that they require prior knowledge about vocabulary, semantics, and graphics. They are often denigrated, because they require an additional step in the modeling process, meaning additional work, which is not always necessary when the user is an expert. However, this additional step is very important in a Systemics approach to HEVs, because these graphical formalisms provide a global perspective of the system and the interactions between its subsystems.

C. Summary of Vehicle System Modeling

Depending on the objective of the study, different models can be used to model the same vehicle. For the energy management of new vehicles, models have been developed for two different uses: 1) local control of the subsystems and 2) supervision of the entire vehicle. For local control, forward functional dynamic causal models are the most appropriate. Forward functional models allow easy implementation in real time. Dynamic causal models respect the physical power flow and the different transient states, which leads to efficient energy management, as well as avoidance of system damage. For global supervision of the vehicle, backward functional quasi-static causal models are the most appropriate. Such a model allows the main interactions between subsystems to be summarized to manage all the energy in the vehicle. A causal model yields the same inputs and outputs as a dynamic causal model and, thus, insures good interaction between the local control and the global supervision processes. Because BEVs, HEVs, and FCVs are complex

multiphysical systems, graphical formalisms are the most suitable for organizing the subsystem models and highlighting the main energy properties of the traction system.

IV. Conclusion

In a world where environmental protection and energy conservation are growing concerns, the development of electric, hybrid, and fuel-cell vehicles has been accelerated. The dream of having commercially viable electric and hybrid vehicles is currently becoming a reality since these vehicles are now available on the market. This paper has provided a timely review of the state of the art of BEVs, HEVs, and FCVs, with a focus on architectures and energy-management models.

Three issues are important in the development of these vehicles: 1) system architecture; 2) energy management; and 3) commercial concerns.

1) *System architecture:* There are three types of system architectures used in hybrid vehicles, i.e., series, parallel, and series–parallel. In light of its advantages and disadvantages, the series hybrid configuration is mostly used in heavy vehicles, such as military vehicles and buses. The parallel and series–parallel hybrid configurations are mostly used in small and medium automobiles, such as passenger cars and some smaller buses.

2) *Energy management:* Even if a good architecture is chosen, hybrid vehicles cannot yield satisfactory performance without efficient system control. A powerful model is essential for good energy management. We think that a real Systemics approach is necessary to take subsystem interaction into account. Different models and modeling methods have been presented. Graphical formalisms, e.g., EMR, are interesting tools, allowing a global overview of the system while taking into account the main physical properties.

3) *Commercial concerns:* Good hardware architectures and robust controls cannot ensure market success. Thus, it is essential to have an appropriate commercialization road map that aims to reduce costs and improve performance. Commercialization roadmaps generally include strategic plans, sufficient funding, innovative core technology, an understanding of the market demand, as well as the required infrastructure and services. Support from all the stakeholders involved is critical to the success of HEV development. (Interested readers can consult Chan *et al.* [77] for more information about commercial roadmaps.)

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