Control Problems in Electric and Hybrid Vehicles

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ABSTRACT: The new method of vehicle propulsion for hybrid and electric vehicles involves solving new problems with their control, primarily the control of electrical propulsion units. The new approach requires energy management for the hybrid vehicles. Specific control is necessary for battery management. Using electrical batteries in vehicles presents a multidisciplinary problem in cooperation of great amount of batteries and the electrical grid, the control vehicle to grid (V2G) systems.

KEY WORDS: electric vehicles, motor control, energy management, battery management, V2G (vehicle to grid systems).

1 INTRODUCTION

Electric propulsion systems in hybrid and electric vehicles utilize the majority of currently used control systems; on the other hand, it is necessary to use new, and often more sophisticated, methods for control.

- Fundamentally it is necessary to control the velocity and torque of electrical motors.
- Hybrid vehicles (HEV) need energy management systems which switch to the propulsion mode with the best efficiciency. (IC internal combustion engine, electric motor, both engines, recuperation).
- Electric vehicles (EV) need energy management, to distribute energy between the motor and the sources of electrical energy (batteries or hypercapacitors).
- A specific problem is the control of charging (and recharging during recuperation) of chemical batteries. It is necessary to accommodate the charging process to the different properties of the individual elements of a battery and to guarantee reliable functioning of the battery in the case of the malfunctioning of one or several elements.
- An additional adjacent problem for hybrid and electric vehicles (and a very critical one in the near future) is the cooperation of charging devices with electrical grids by means of “smart grids”, or by using “vehicle to grid” (V2G) technology.

2 ELECTRIC MOTOR CONTROL

The method used for motor control depends on the choice of the motor; the choice of the motor depends on the type of electrical vehicle (EV) or a hybrid vehicle (HEV). Having decided on the type of vehicle the appropriate motor may be selected. There are the following types of electric motors suitable for the propulsion of EV, HEV, and PHEV vehicles: the DC motor, the induction motor, the PM (with permanent magnets) synchronous or the PM brushless motor, and the switched reluctance motor.

DC motors have been prominent in electric propulsion due to their torque-speed characteristics suiting traction requirements well, along with their speed controls being simple. They have been used for electric railway traction for a long time. However, DC motor drives have a bulky construction, a small density of power on unit mass, low reliability and a high need for maintenance, due to the commutator and the brushes.

The most popular traction unit for medium and high power is the induction motor. An induction motor is usually controlled through variable frequency (VFD) by means of a pulse width modulation (PWM), created by different types of inverters. Due to the decreasing cost of semiconductor power and control elements, inverted output or multilevel pulse width modulation is used. Using of higher frequencies (and higher voltage) minimizing of the power density of the induction motors. A further advantage is the contactless transmission of energy between the stator and rotor. No maintenance of the commutator and brushes is necessary. On the other hand, control by means of variable frequency rather complicates the design of control loops for velocity and torque control. This means that the motor becomes nonlinear. Due to a different reactance of winding on different frequencies the current in individual coils varies, and, as a result, the magnetic flux and torque vary as well. For this reason it is necessary to control both frequency and voltage simultaneously.

Usually, there are two methods for this simultaneous control. They are called “scalar” or “vector” methods. A standard scalar drive puts out a PWM pattern designed to maintain a constant V/Hz pattern for the motor under ideal conditions. How the motor reacts to that PWM pattern is, to a great extent, dependent upon the load conditions. However, from this point of view, this is feed – forward control without any information on the real output torque of the motor. Problems associated with the scalar VFD’s inability to alter its output according to changes in the load increase as the speed reference decreases.

A vector drive uses the feedback of various variables to further modify the PWM pattern to maintain a more precise control of the desired operating parameter, be it speed or torque. Using a more powerful and faster microprocessor, it uses the feedback information to calculate the exact vector of voltage and frequency to attain the goal. In a true closed loop fashion, it goes on to constantly update that vector to maintain it. It tells the motor what to do, then checks to see if it did it, then changes its command to correct for any error.

The structure of the scalar control of the drive is shown in fig. 1. It is necessary to detect the actual speed with the help of a sensor. We then have direct feedback control of the speed, but the torque is controlled indirectly through the velocity control.

The best independent control of the speed and torque is provided by a complete vector control of the IM according to fig. 2. (Caratolozo & Canseco, 2006). This method needs additional sensors for measuring the stator current. The three components of stator current are transformed into a two phase equivalent and then are transformed into rotating coordinates connected with the vector of rotor magnetic flux. Thus we obtain current carrying information on torque and current carrying information on magnetic flux.

They are used for an independent torque and flux control with torque and flux current regulators. Both currents are transformed to a 3 phase system and with the help of pulse width modulation (PWM) regulate the inverter supplying the motor.

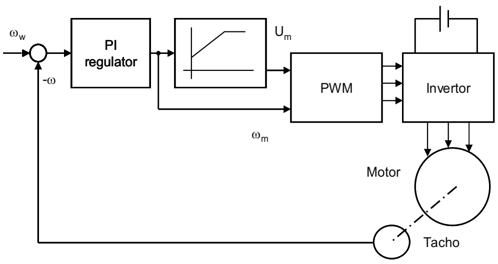

Figure 1: "Scalar" control of induction motor.

Vector control is more effective, and provides excellent dynamic properties for the motor, but is more expensive than a simple scalar control. To avoid the necessity of using the current and position or speed sensors, values of these variables are often estimated from other directly measurable variables with the help of estimation methods, such as observers, Kalman filters, etc.

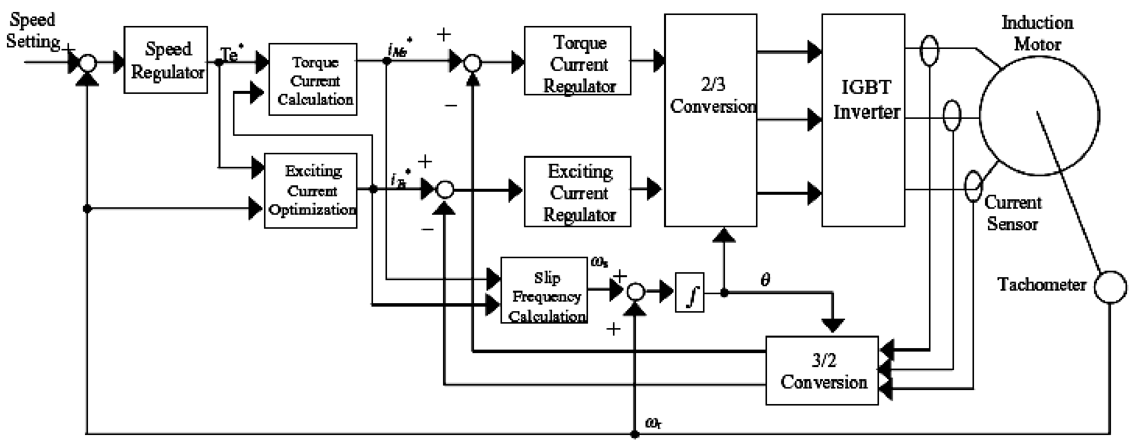

Figure 2: Vector control of induction motor.

Another motor utilized in the HV and EV is a permanent magnet synchronous motor (a brushless synchronous motor). Instead of the cage anchor, a synchronous motor has an anchor with strong permanent magnets. This leads to a rotation with a synchronous speed of a rotating magnetic field. These motors have a number of advantages. Firstly, higher power density, and secondly, better efficiency due to small eddy current loses in comparison with the squirrel-cage rotor, and an efficient dissipation of heat. On the other hand this motor has a short constant power region. However, a synchronous PM motor is the best motor provided that it is directly embedded in the vehicle's wheel. The necessary equipment for its control (the sensors, controllers, and semiconductor actuators) is the same as for the case of the induction motor.

The last type available for EV and HV propulsion is a switched reluctance motor. The reluctance motor is an electric motor in which torque is produced by the tendency of its moveable part to move to a position (due to Thomson's principle of minimum energy) where the inductance of the excited winding is maximized. This means that the reluctance of the magnetic circuit is minimized. The reluctance motor is a type of synchronous machine. It has the wound field coils of a DC motor for its stator windings, but there are no coils or magnets on its rotor. These motors have definite advantages, such as simple and durable construction, fault-tolerant operation, simple control, and outstanding torque–speed characteristics. Its disadvantages are strong acoustic noise, torque and current ripple and specific structure of the actuator, specifically.

Now some remarks on control algorithms. For simple applications, conventional linear regulators, e.g., the PI (PS in digital form) are used. For more sophisticated control problems "bifurcation" can be seen in two main branches. One branch, which can be called "analytic", is based on the correct analytical description of the system (state control, optimal control, robust control, predictive control, etc.).

The second branch, which can be called "rule based", often utilizes simple algorithms which do not need a correct formal mathematical description of the system. These are methods ranging from the simplest lookup table control, through fuzzy control, as far as sophisticated adaptive methods and neural nets control. Ordinarily we can say that the first approach is mainly used within the area of academic research. However, for the real production of EV and HEV, the second approach is mainly utilized, e.g., (Salmasi, 2007; Li & Liu, 2009). This approach is also successfully applied in the design of auxiliary and assistive systems.

3 ENERGY MANAGEMENT

One of the HEV and PHEV specific control problems is energy management. HEV have both an IC engine and electric motor and two or three sources of energy (oil in the tank, and an electric charge in the battery or in the ultracapacitor). One advantage of the HEV is the possibility of combining these sources and drives to obtain the best resultant efficiency. This requires however sophisticated energy management. There are six possible different operation modes in both series and parallel HEV:

1. The battery alone mode: the engine is off; the vehicle is powered by the battery only
2. The engine alone mode: powered by the ICE/G (the engine and the generator)
3. Combined mode: both the ICE/G set and the battery provide power for the traction motor
4. Power split mode: the ICE/G power split to drive the vehicle and charge the battery
5. Stationary charging mode
6. Regenerative braking mode

The control problem is how to distribute power between different sources and different drives to obtain maximal efficiency. Usually we have a set of empirically measured points which allows the construction of approximate efficiency "maps". Examples of efficiency maps for an ICE engine and an electrical motor according to (Schouten et al., 2003) are shown in fig. 3. and fig. 4. The lines in angular velocity and torque coordinates are not torque characteristics, but are contour lines connecting points with the same effectiveness. For ICE the efficiency is indirectly proportional to fuel consumption. The thick line connects the local extremes and the arrows are directed to the global extreme, corresponding to maximum efficiency and minimum fuel consumption. A similar efficiency map can be created for the battery, in coordinates, the state of the battery (SOC) in [%] and power, as is depicted in fig. 6. (The grey area shows the highest efficiency).

Optimal control is difficult to apply because appropriate characteristics are not available in a formal mathematical form. The optimal distribution of power between sources (the ICE engine and electrical motor/generator and energy accumulators (batteries or ultracapacitor) is not merely an optimization problem but a decision problem as well. It is usually possible to formulate simple rules in the form of logical implications.

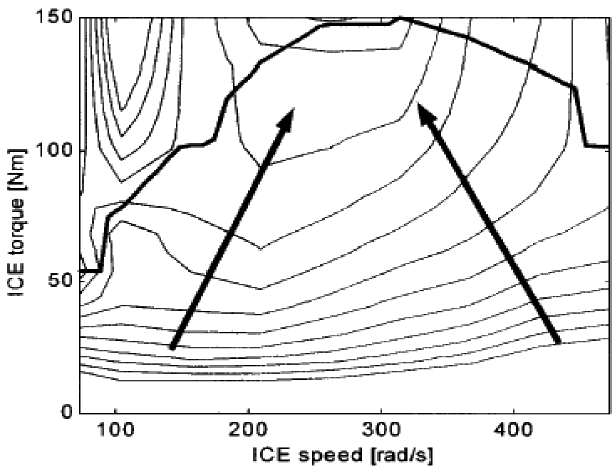

Figure 3: Efficiency map for IC engine.

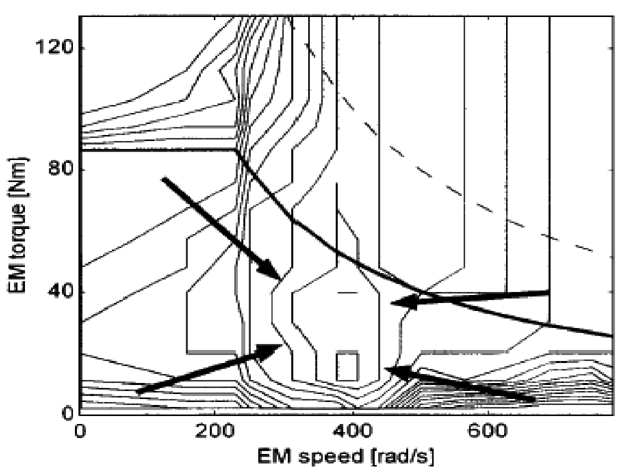

Figure 4: Efficiency map for electrical motor.

These rules may be utilized as a rule base for a fuzzy controller, such as Mamdani's or Sugeno's fuzzy controllers (Li & Liu, 2009; Schouten et al., 2003).

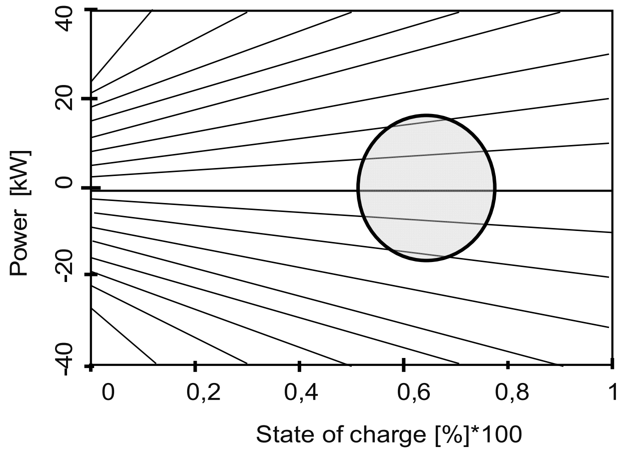

Figure 5: Efficiency map for battery.

4 BATTERY MANAGEMENT

The most expensive part of any EV or HEV is the battery. It is therefore necessary to control the charging and discharging process to attain its maximal service life. This is the main task of the battery management system. However, this system has many other significant functions (Conte, 2006). Any element of a battery is monitored (the charging or discharging current, the voltage and/or the temperature are measured). These data are necessary for a qualified protection from out of tolerance operating conditions. The EV or the full HEV battery usually consists of many serially connected elements in order to reach a higher voltage. The same current flows through all elements during the charging. From this point of view it is necessary to balance the voltage on any element to equalize the charge on all cells in the chain, thus extending the battery life. However, individual elements may have the same tolerances but different source resistance. This leads to different voltage on individual elements and their possible damage. If an element is damaged the balancing system is able to inactivate it (e.g., by shunting) to keep the whole battery in operation.

The state of charge (SOC) and the state of health (SOH) of the whole battery is computed from the measured data and stored. Parameters, such as the number of cycles, the maximum and minimum voltages and temperatures and maximum charging and discharging currents, can be recorded for subsequent evaluation. The fundamental function of the battery management system is control when charging it. The charge control strongly depends on the type of battery. Some types enable quick charging with heavy current, while other types may be damaged by such charging. For these reasons the battery management system must be able to communicate with the charging station or the test equipment.

Communications interfaces are also needed to enable the user the access to the battery for modifying the BMS control parameters or for diagnostics and tests. The structure of the battery management system is in Figure 6.

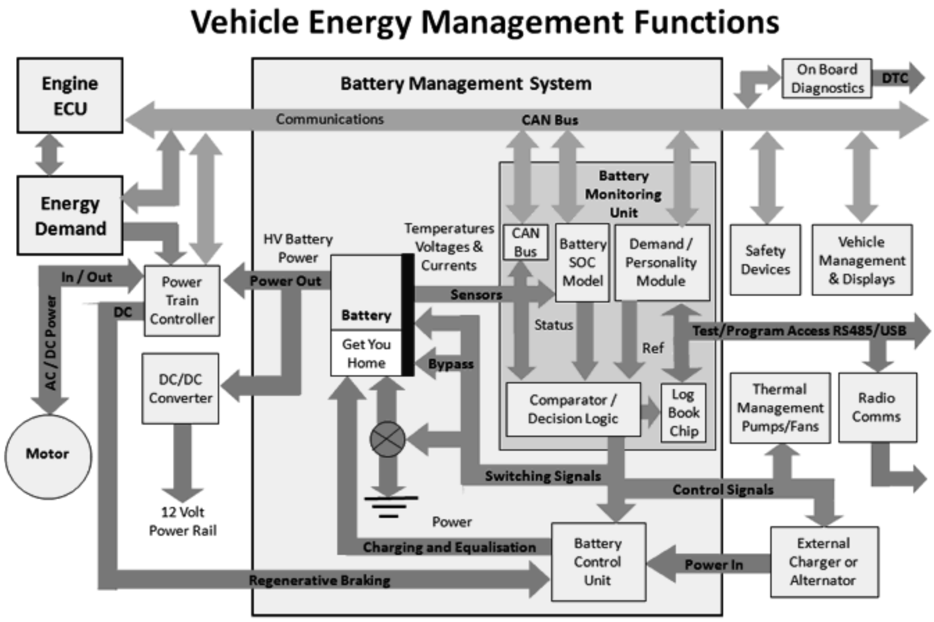

Figure 6: Structure of battery management system.

It seems, when excluding the charging control, that the battery management system is a type of measuring and communicating system. However, for its correct functioning, many control approaches are necessary. For example, the SOH is not directly measurable from the accessible data. It must be estimated from the measured currents, voltages and temperatures. The extended Kalman filters or neural nets are usually used as estimators.

5 VEHICLE TO GRID (V2G TECHNOLOGY)

Sophisticated control for the cooperation of the battery management system with “smart grids” is quite a challenging issue. A growing number of electric and plug-in hybrid vehicles need non negligible electrical power for charging their batteries. At first sight this requires the building of new power plants and a net reconstruction. However, due to sophisticated control and utilizing “smart nets” it is possible to charge them generally with existing power plants and nets, and, moreover, the batteries may also help increase the stability of the existing nets. This idea is called a vehicle-to-grid (V2G) system.

The PHEVs and EVs are mainly used for commuting. A typical or average commuting distance is about 50 km and the average commuting time is 50 minutes. This means that the typical vehicle is idle an average of 22 hours a day. The average commuting distance is smaller than the potential range of theses cars (which is 80–100km) but not all the energy stored in the battery is consumed for commuting. The typical time necessary for charging a battery (at home) is 5h, and usually less.

It follows from this fact that the battery is not utilized by the vehicle for a minimum of 17 hours, and thus can be utilized by another user, such as by a grid system operator.

The storage capability of the battery is from 1 to 60 kWh (from PHV to EV). The battery as a source has a very fast response, in the order of ms. The available power from the battery is in the 0.2–6kW range. On the other hand it is necessary to take into account some limitations. Of critical importance is the state of the charge (SOC) as a percentage of a fully charged battery. The best efficiency of a battery is around of 60%, but there are a lot of further constraints required in the charging – discharging process making the life of the battery longer. Tens of thousands and more aggregated vehicles may have a significant impact. From this follows the necessity to establish a new link between the producer and the consumer of energy, a link called an aggregator. The Aggregator will aggregate the demand of energy (power), for charging the batteries of individual vehicles, and withdraw it from the provider at the appropriate time according to the requirements of the grid operator. In contrast, the aggregated power may be utilized as a prompt power for overlay peaks of energy demand.

For example, let us take into account 12500 aggregated vehicles. Let us consider the capacity of an individual battery as 20kW and with 5h charging. This is a 50MW load, which may be connected in off-peak conditions. The shifting load phase into the night off-peak conditions may be deployed to levelize the load. On the other hand, the aggregated batteries may serve as a source of standby power for the peaks. This power may be connected to the grid in milliseconds. The functioning of the aggregator is depicted in fig. 7. (Guille & Gross, 2009).

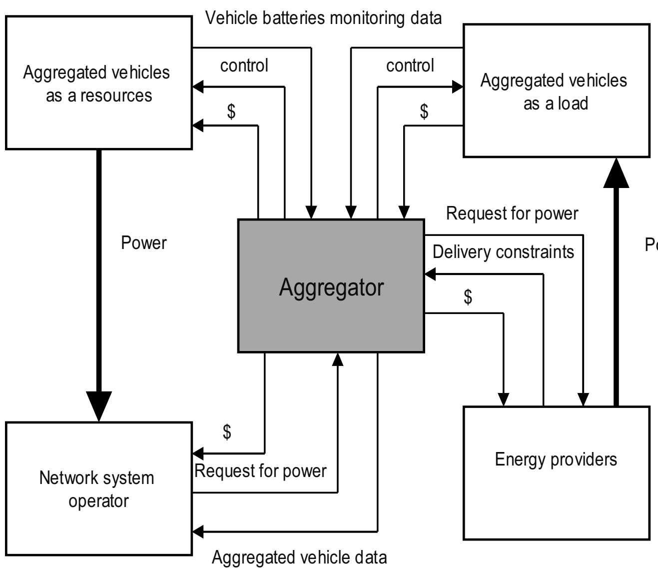

Figure 7: Supposed function of V2G system.

The aggregator is connected through a communication link with the aggregated vehicles. Any vehicle is capable of operating as a consumer or source of electrical energy. The individual batteries are monitored and the aggregator obtains information on the state of charge and other parameters of any battery. The Aggregator is capable of switching the vehicle into a charging phase or discharging phase. Any owner of the vehicle has an individual agreement with the aggregator specifying the conditions of charging and discharging the battery. The aggregator is connected with the electrical energy provider and negotiates with him about the time and the amount of energy delivered to the individual vehicles according to the provider's possibilities. The aggregator is also connected with the grid operator, optionally informs on the state of the stored energy and, on the operator's request, is also capable of providing peak power from batteries if necessary.

The information and energy (power) flows are accompanied by money flows. Prices of energy strongly depend on the time of day and on the origin of the energy (primary energy from a power plant or stored energy from batteries). Any battery owner pays to the aggregator for energy delivered to the battery. The aggregator pays for all delivered energy to the provider. On the other hand, the aggregator pays to the individual owners of cars for the stored energy utilized during peak hours, and obtains money for this service from the grid system operator. The approach described above seems to be a very attractive method of energy management. It enables more efficient exploitation of conventional and especially nuclear power plants. It also may solve many problems with renewable sources of energy, such as photovoltaic energy and wind turbines. However, V2G technology is at present a mere concept. It is a very complicated C3S (Computer, Communication and Control system) and it will need great effort in order to realize it in practice.

6 CONCLUSION

The main control problems connected with the utilization of electric and hybrid vehicles are discussed in the paper. Propulsion control by means of electric motors is solvable through common methods. A similar situation can be seen more or less in energy management and battery management. However, the cooperation of vehicle batteries with electrical grids is a great challenge for the near future. V2G systems need a multidisciplinary approach in order to utilize the possibility of controlling the distribution of electrical power from current sources.

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