Dr. Norbert Cheung's Series in Electrical Engineering

Level 5 Topic no: 21

Hybrid Electric Vehicles (HEV)

Contents

Reference:

C.C. Chan and K.T. Chau, Modern Electric Vehicle Technology, London: Oxford, University Press, 2001

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1. HEV Configurations

When incorporating both of the ICE and electric motor, the vehicle is usually known as the hybrid EV (HEV). This HEV is actually not a new idea. A patent by Pieper in 1905 delineated that a battery-powered electric motor was used to boost the acceleration of an ICEV (Wouk, 1995; Bates, 1995).

Due to the limitations of available energy sources, the EV cannot offer a compatible driving range to the ICEV. People may not buy an EV, no matter how clean, if their range between charges is only 100–200 km. The HEV, using an ICE and electric motor, has been introduced as an alternative solution before the full implementation of EVs when there is a breakthrough in EV energy sources. The definite advantage of the HEV is to greatly extend the original EV driving range by 2–4 times, and to offer rapid refuelling of liquid petrol or diesel. An important plus is that it requires only little changes in the energy supply infrastructure. The key drawbacks of the HEV are the loss of zero-emission concept and the increased complexity. Nevertheless, the HEV is vastly less polluting and has less fuel consumption than the ICEV while having the same range. These merits are due to the fact that the ICE of the HEV can always operate in its most efficient mode, yielding low emissions and low fuel consumption. Also, the HEV may be purposely operated as an EV in the zero-emission zone.

Traditionally, HEVs were classified into two basic kinds—series and parallel. Recently, with the introduction of some HEVs offering the features of both the series and parallel hybrids, the classification has been extended to three kinds—series, parallel and series–parallel. In the year 2000, it is interesting to note that some newly introduced HEVs cannot be classified into these three kinds. Hereby, HEVs are newly classified into four kinds:

- series hybrid
- parallel hybrid
- series–parallel hybrid and
- complex hybrid.

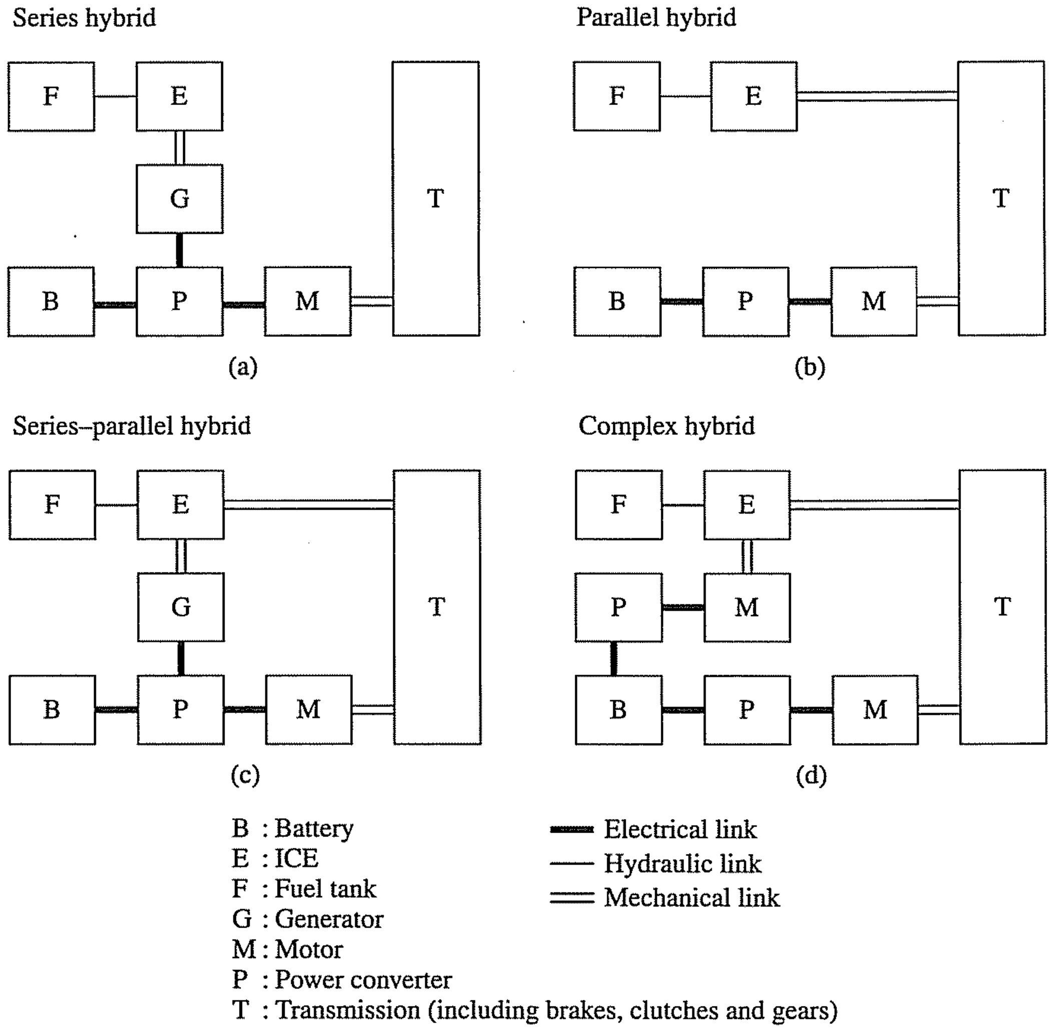


Fig. 4.1. Classification of HEVs.

4.1.1 SERIES HYBRID SYSTEM

The series hybrid is the simplest kind of HEV. Its ICE mechanical output is first converted into electricity using a generator. The converted electricity either charges the battery or can bypass the battery to propel the wheels via the same electric motor and mechanical transmission. Conceptually, it is an ICE-assisted EV which aims to extend the driving range comparable with that of the ICEV. Due to the absence of clutches throughout the mechanical link, it has the definite advantage of flexibility for locating the ICE-generator set. Although it has an added advantage of simplicity of its drivetrain, it needs three propulsion devices—the ICE, the generator and the electric motor. Another disadvantage is that all these propulsion devices need to be sized for the maximum sustained power if the series HEV is designed to climb a long grade. On the other hand, when it is only needed to serve such short trips as commuting to work and shopping, the corresponding ICE-generator set can adopt a lower rating.

4.1.2 PARALLEL HYBRID SYSTEM

Differing from the series hybrid, the parallel HEV allows both the ICE and electric motor to deliver power in parallel to drive the wheels. Since both the ICE and electric motor are generally coupled to the drive shaft of the wheels via two clutches, the propulsion power may be supplied by the ICE alone, by the electric motor or by both. Conceptually, it is inherently an electric assisted ICEV for achieving lower emissions and fuel consumption. The electric motor can be used as a generator to charge the battery by regenerative braking or absorbing power from the ICE when its output is greater than that required to drive the wheels. Better than the series HEV, the parallel hybrid needs only two propulsion devices—the ICE and the electric motor. Another advantage over the series case is that a smaller ICE and a smaller electric motor can be used to get the same performance until the battery is depleted. Even for long-trip operation, only the ICE needs to be rated for the maximum sustained power while the electric motor may still be about a half.

4.1.3 SERIES–PARALLEL HYBRID SYSTEM

In the series–parallel hybrid, the configuration incorporates the features of both the series and parallel HEVs, but involving an additional mechanical link compared with the series hybrid, and also an additional generator compared with the parallel hybrid. Although possessing the advantageous features of both the series and parallel HEVs, the series–parallel HEV is relatively more complicated and costly. Nevertheless, with the advances in control and manufacturing technologies, some modern HEVs prefer to adopt this system.

4.1.4 COMPLEX HYBRID SYSTEM

As reflected by its name, this system involves a complex configuration which cannot be classified into the above three kinds. As shown in Fig. 4.1, the complex hybrid seems to be similar to the series–parallel hybrid, since the generator and electric motor are both electric machinery. However, the key difference is due to the bidirectional power flow of the electric motor in the complex hybrid and the unidirectional power flow of the generator in the series–parallel hybrid. This bidirectional power flow can allow for versatile operating modes, especially the three propulsion power (due to the ICE and two electric motors) operating mode which cannot be offered by the series–parallel hybrid. Similar to the series–parallel HEV, the complex hybrid suffers from higher complexity and costliness. Nevertheless, some newly introduced HEVs adopt this system for dual-axle propulsion.

2. Power Flow Control

The 4 key goals:

- maximum fuel economy
- minimum emissions
- minimum system costs and
- good driving performance.

Key Control Strategies for Power Flow Control:

- Optimal ICE operating point—The optimal operating point on the torque-speed plane of the ICE can be based on the maximization of fuel economy, the minimization of emissions, or even a compromise between fuel economy and emissions.
- Optimal ICE operating line—in case the ICE needs to deliver different power demands, the corresponding optimal operating points constitute an optimal operating line. Figure 4.3 shows a typical optimal operating line of an ICE, in which the optimization is based on the minimum fuel consumption which is equivalent to the maximum fuel economy.
- Optimal ICE operating region—the ICE has a preferred operating region on the torque-speed plane, in which the fuel efficiency remains optimum.
- Minimum ICE dynamics—the ICE operating speed needs to be regulated in such a way that any fast fluctuations are avoided, hence minimizing the ICE dynamics.
- Minimum ICE speed—when the ICE operates at low speeds, the fuel efficiency is very low. The ICE should be cut off when its speed is below a threshold value.
- Minimum ICE turn-on time—the ICE should not be turned on and off frequently; otherwise, it results in additional fuel consumption and emissions. A minimum turn-on time should be set to avoid such drawbacks.
- Proper battery capacity—the battery capacity needs to be kept at a proper level so that it can provide sufficient power for acceleration and can accept regenerative power during braking or downhill. When the battery capacity is too high, the ICE should be turned off or operated idly. When the capacity is too low, the ICE should increase its output to charge the battery as fast as possible.
- Safety battery voltage—the battery voltage may be significantly altered during discharging, generator charging or regenerative charging. This battery voltage should not be over-voltage or under-voltage; otherwise, the battery may be permanently damaged.
- Relative distribution—the distribution of power demand between the ICE and battery can be proportionally split up during the driving cycle.
- Geographical policy—in certain cities or areas, the HEV needs to be operated in the pure electric mode. The changeover should be controlled manually or automatically.

4.2.1 SERIES HYBRID CONTROL

In the series hybrid system, the power flow control can be illustrated by four operating modes shown in Fig. 4.4. During startup, normal driving or acceleration of the series HEV, both the ICE (via the generator) and battery deliver electrical energy to the power converter which then drives the electric motor and hence the wheels via the transmission. At light load, the ICE output is greater than that required to drive the wheels so that the generated electrical energy is also used to charge the battery until the battery capacity reaches a proper level. During braking or deceleration, the electric motor acts as a generator which transforms the kinetic energy of the wheels into electricity, hence charging the battery via the power converter. Also, the battery can be charged by the ICE via the generator and power converter, even when the vehicle comes to a complete stop.

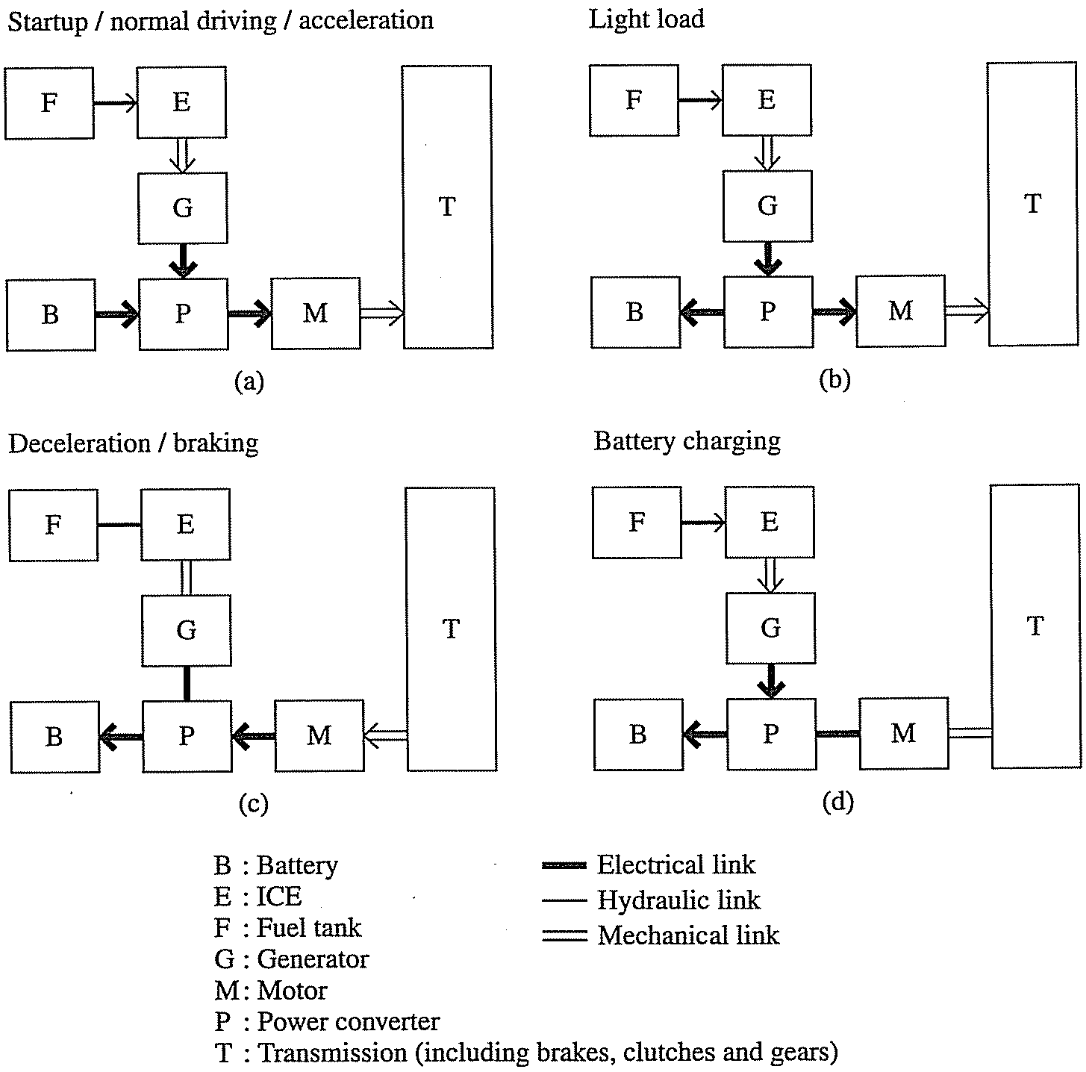


Fig. 4.4. Series hybrid operating modes.

4.2.2 PARALLEL HYBRID CONTROL

Figure 4.5 illustrates the four operating modes of the parallel HEV. During startup or full-throttle acceleration, both the ICE and electric motor proportionally share the required power to propel the vehicle. Typically, the relative distribution between the ICE and electric motor is 80–20%. During normal driving, the ICE solely supplies the necessary power to propel the vehicle while the electric motor remains in the off mode. During braking or deceleration, the electric motor acts as a generator to charge the battery via the power converter. Also, since both the ICE and electric motor are coupled to the same drive shaft, the battery can be charged by the ICE via the electric motor when the vehicle is at light load. Recently, the Honda Insight HEV has adopted similar power flow control.

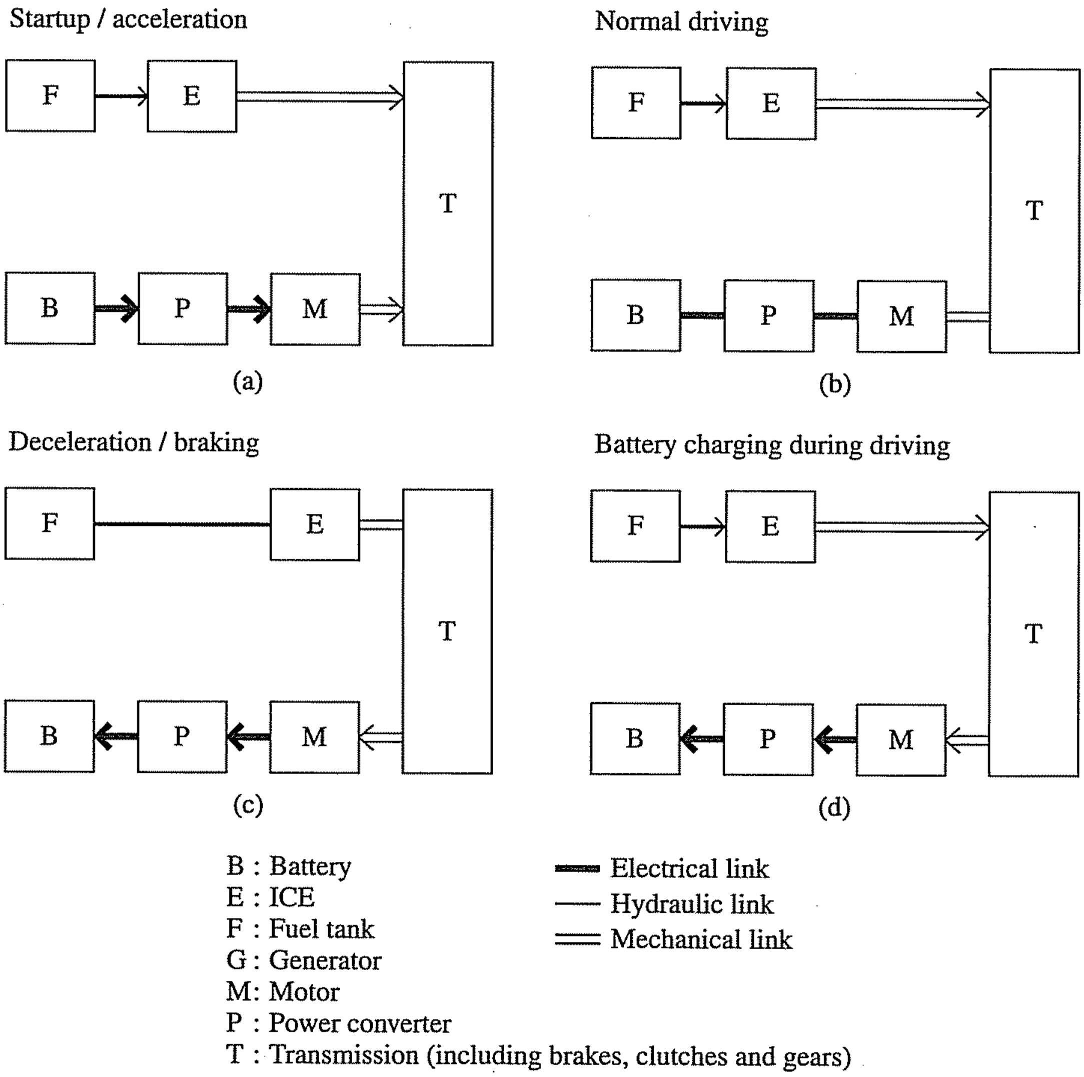


Fig. 4.5. Parallel hybrid operating modes.

4.2.3 SERIES–PARALLEL HYBRID CONTROL

Figure 4.6 shows an ICE-heavy series–parallel hybrid system, in which there are six operating modes. At startup, the battery solely provides the necessary power to propel the vehicle while the ICE is in the off mode. During full-throttle acceleration, both the ICE and electric motor proportionally share the required power to propel the vehicle. During normal driving, the ICE solely provides the necessary power to propel the vehicle while the electric motor remains in the off mode. During braking or deceleration, the electric motor acts as a generator to charge the battery via the power converter. For battery charging during driving, the ICE not only drives the vehicle but also the generator to charge the battery via the power converter. When the vehicle is at a standstill, the ICE can maintain driving the generator to charge the battery. Recently, a similar power flow control system has been applied to the Nissan Tino HEV (Inada, 2000).

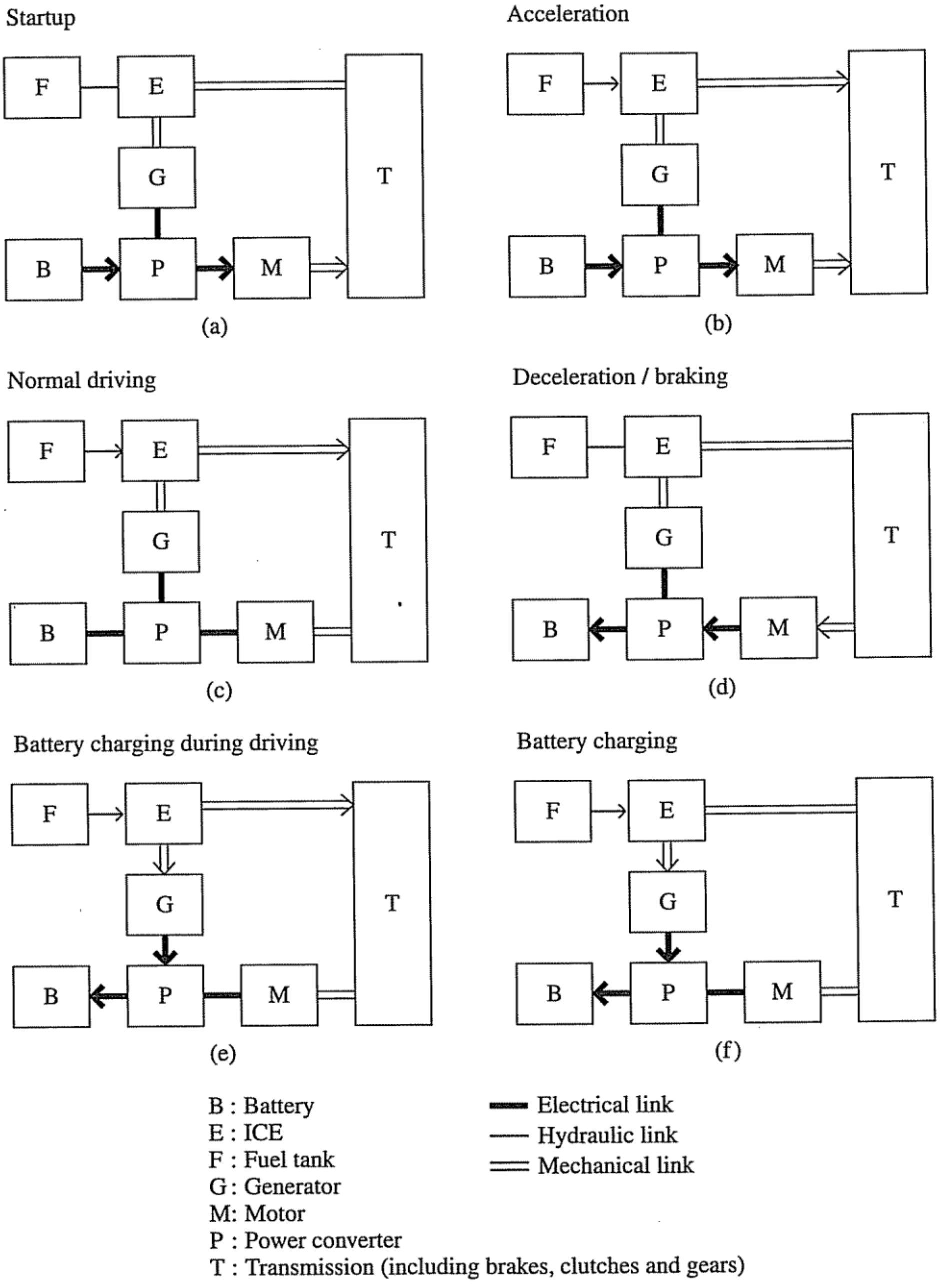


Fig. 4.6. ICE-heavy series–parallel hybrid operating modes.

4.2.3 SERIES–PARALLEL HYBRID CONTROL

Figure 4.7 shows a relatively electric-heavy series–parallel hybrid system, in which there are six operating modes. During startup and driving at light load, the battery solely feeds the electric motor to propel the vehicle while the ICE is in the off mode. For both full-throttle acceleration and normal driving, both the ICE and electric motor work together to propel the vehicle. The key difference is that the electrical energy used for full-throttle acceleration comes from both the generator and battery whereas that for normal driving is solely from the generator driven by the ICE. Notice that a planetary gear is usually employed to split up the ICE output, hence to propel the vehicle and to drive the generator. During braking or deceleration, the electric motor acts as a generator to charge the battery via the power converter. Also, for battery charging during driving, the ICE not only drives the vehicle but also the generator to charge the battery: When the vehicle is at a standstill, the ICE can maintain driving the generator to charge the battery. Recently, the Toyota Prius has adopted a similar power flow control system.

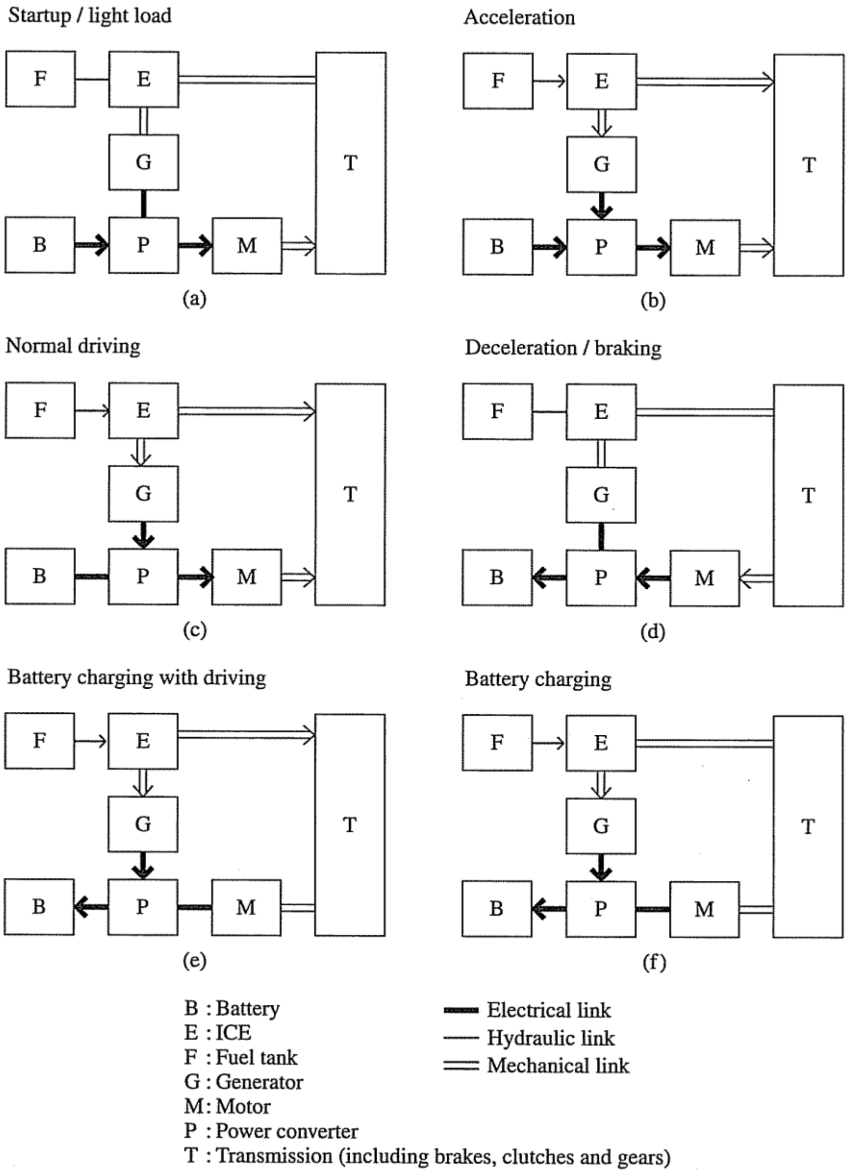


Fig. 4.7. Electric-heavy series–parallel hybrid operating modes.

4.2.4 COMPLEX HYBRID CONTROL

The development of complex hybrid control has been focused on the dual-axle propulsion system for HEVs. In this system, the front-wheel axle and rear-wheel axle are separately driven. There is no propeller shaft or transfer to connect the front and rear wheels, so it enables a more lightweight propulsion system and increases the vehicle packaging flexibility. Moreover, regenerative braking on all four wheels can significantly improve the vehicle fuel efficiency and hence the fuel economy.

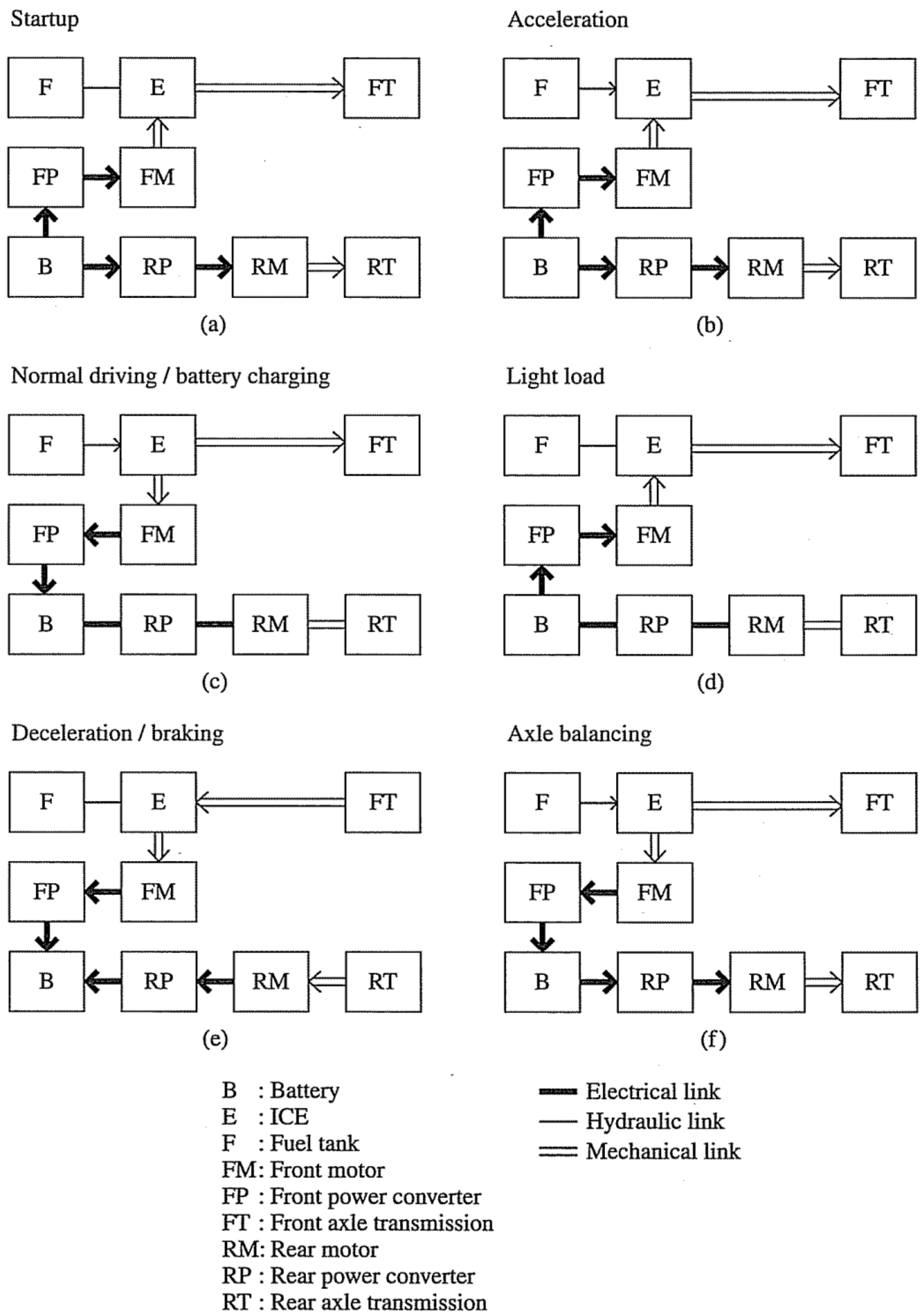
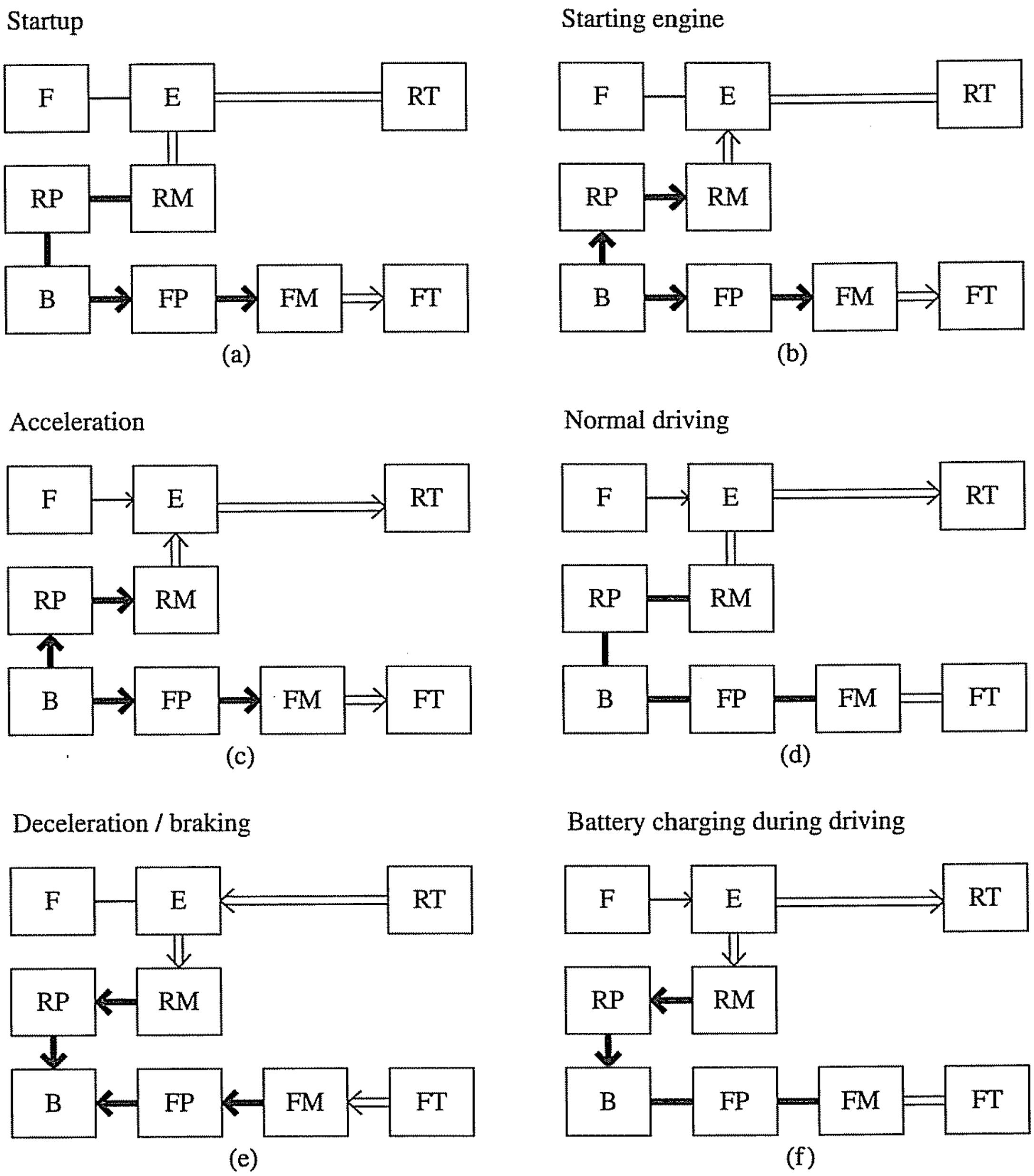


Fig. 4.8. Dual-axle (front-hybrid rear-electric) complex hybrid operating modes.



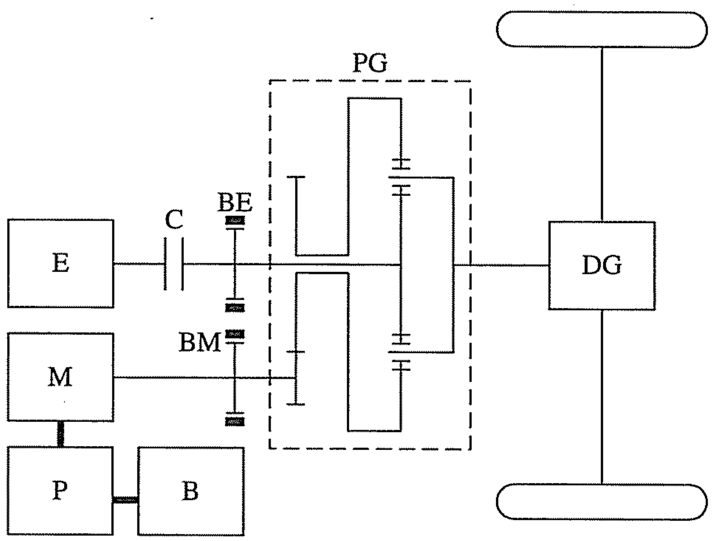
B : Battery
E : ICE
F : Fuel tank
FM : Front motor
FP : Front power converter
FT : Front axle transmission
RM : Rear motor
RP : Rear power converter
RT : Rear axle transmission

Electrical link
Hydraulic link
Mechanical link

Fig. 4.9. Dual-axle (front-electric rear-hybrid) complex hybrid operating modes.

3.   Example of HEV System Performance

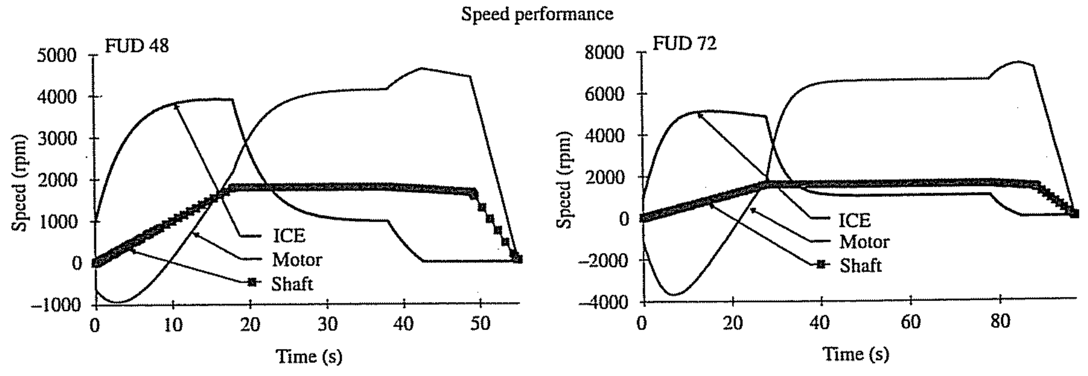
Figure 4.10 shows a new parallel hybrid HEV system (Szumanowski, 2000). This HEV system not only possesses the features of the parallel hybrid, but



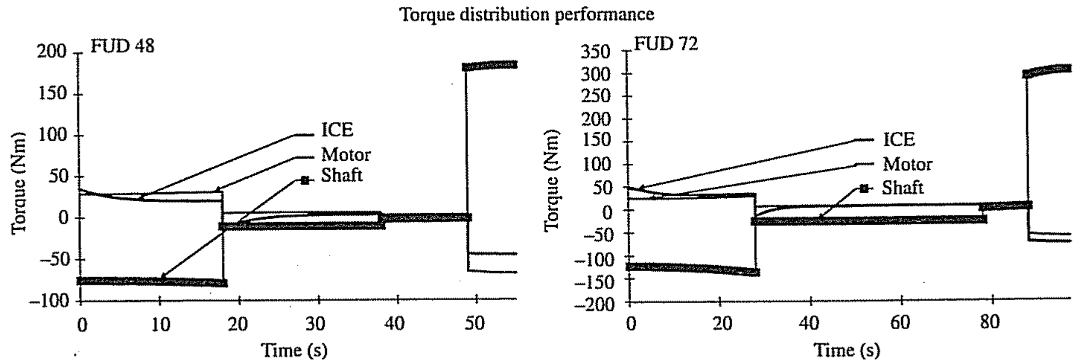
B : Battery
BE : Brake of engine shaft
BM: Brake of motor shaft
C : Clutch
E : ICE
DG : Differential gear
M : Motor
P : Power converter
PG : Planetary gear

Electrical link
Mechanical link

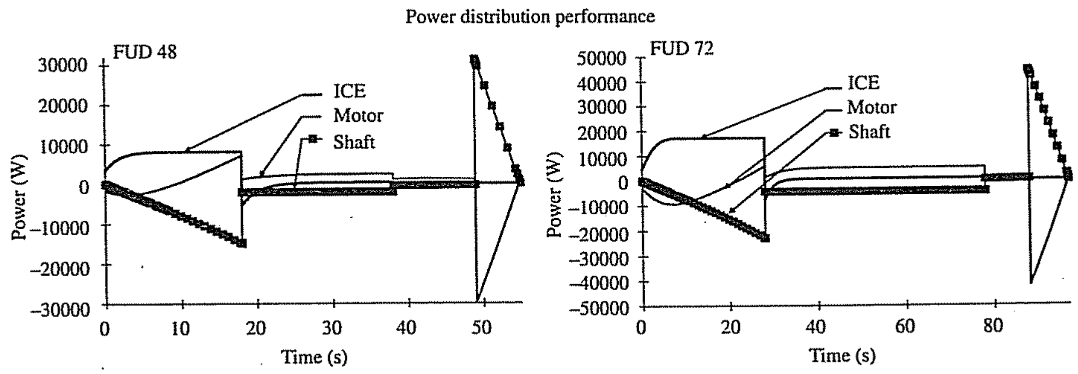
Fig. 4.10. New HEV system with planetary gearing. (Courtesy of A. Szumanowski.)


Speed performance
FUD 48
FUD 72
Speed (rpm)
Time (s)
ICE
Motor
Shaft

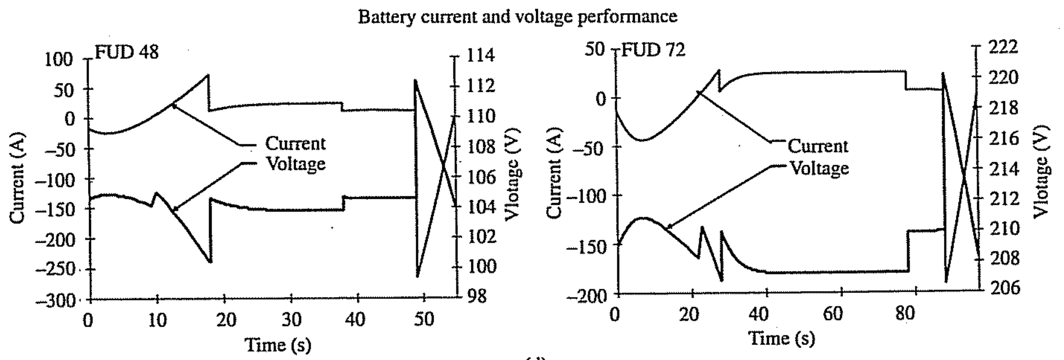
(a)


Torque distribution performance
FUD 48
FUD 72
Torque (Nm)
Time (s)
ICE
Motor
Shaft

(b)


Power distribution performance
FUD 48
FUD 72
Power (W)
Time (s)
ICE
Motor
Shaft

(c)


Battery current and voltage performance
FUD 48
FUD 72
Current (A)
Vlotage (V)
Time (s)
Current
Voltage

(d)

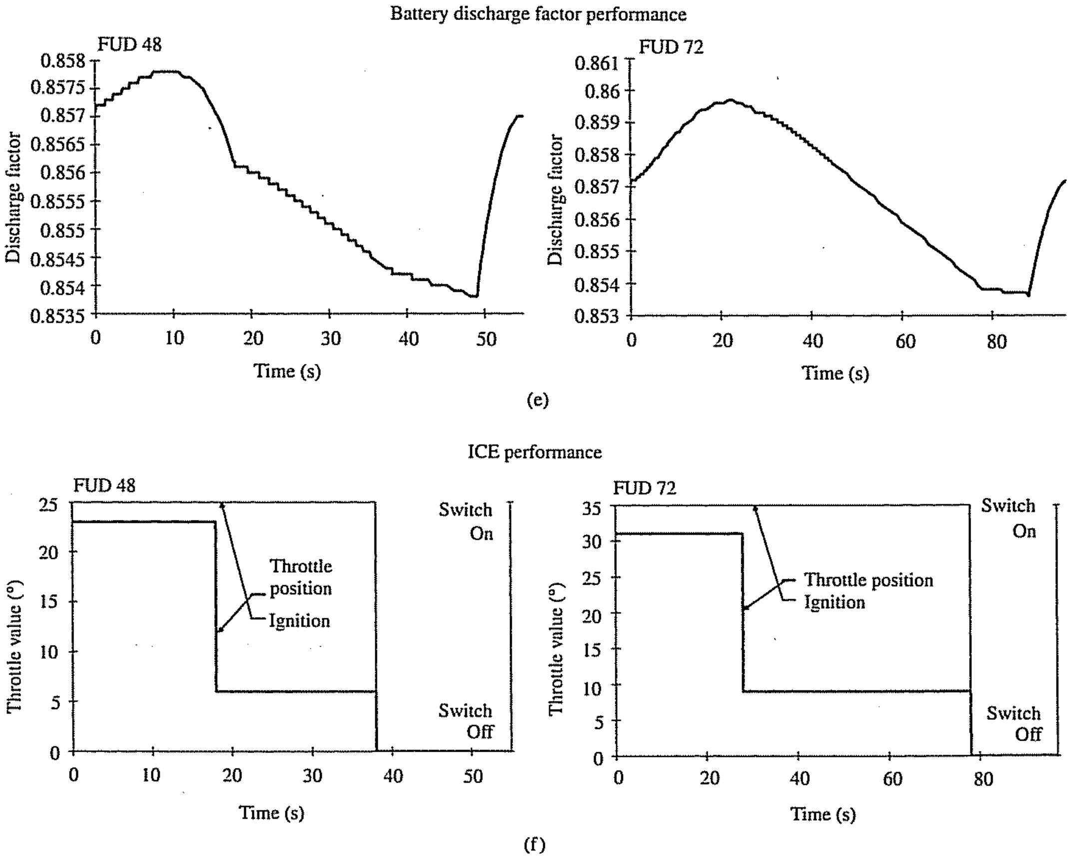


Fig. 4.11. Performances of a new HEV system. (Courtesy of A. Szumanowski.)

also incorporates a unique advantage of the series hybrid (namely the ICE can independently operate at the mode of minimum fuel consumption). The key is to employ a planetary gear which offers two degrees of freedom for mechanical transmission. In fact, A. Szumanowski and C.C. Chan have applied a patent on a similar HEV system with planetary gearing.

In city driving, the HEV system is characterized by the features of a parallel hybrid and the advantage of a series hybrid. When the vehicle is at full-throttle acceleration, the power is simultaneously delivered by the ICE and electric motor. While the vehicle is at normal driving (steady speed operation), the power is collaboratively fed by the ICE and electric motor via the planetary gear with two degrees of freedom in such a way that the fuel consumption of the ICE is minimum. This means that the ICE operates at minimum torque and power, and the majority of power is supplied by the electric motor.

During regenerative braking, the planetary gear operation is reduced to one degree of freedom by disconnecting the clutch and braking the sun gear shaft. Thus, the kinetic energy is converted to electrical energy and hence recharges the battery while the electric motor operates as a generator.

During suburb driving, the HEV operates as an ICEV. In this case, the electric motor is switched off and the ring gear shaft is braked, which means that the planetary gear operation is also reduced to one degree of freedom.

5-21 Hybrid Electric Vehicles (last updated: Oct 2023)

Toyota Prius parallel hybrid (plug-in version range:15 miles)

Chevrolet Volt, Series Hybrid with electric range of 50 miles

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