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Review of Battery Electric Vehicle Propulsion Systems incorporating Flywheel Energy Storage

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Abstract

The development of battery electric vehicles (BEV) must continue since this can lead us towards a zero emission transport system. There has been an advent of the production BEVs in recent years; however their low range and high cost still remain the two important drawbacks. The battery is the element which strongly affects the cost and range of the BEV. The batteries offer either high specific power or high specific energy but not both. To provide the BEVs with the characteristic to compete with conventional vehicles it is beneficial to hybridize the energy storage combining a high energy battery with a high power source. This shields the battery from peak currents and improves its capacity and life. There are various devices which could qualify as a secondary storage system for the BEV such as high power battery, supercapacitor and high speed flywheel (FW). This paper aims to review a specific type of hybridisation of energy storage which combines batteries and high speed flywheels. The flywheel has been used as a secondary energy system in BEVs from the early 1970s when the oil crises triggered an interest in BEVs. Since the last decade the interest in flywheels has strengthened and their application in the kinetic energy recovery system (KERS) in Formula 1 has further bolstered the case for flywheels. With a number of automotive manufacturers getting involved in developing flywheels for road applications, the authors believe commercial flywheel based powertrains are likely to be seen in the near future. It is hence timely to produce a review of research and development in the area of flywheel assisted BEVs.

Keywords: Flywheel, Battery, Electric vehicle, Transmission, Motor-Generator

Introduction

The battery electric vehicle has been operating on the road since the very beginning. They were popular at the start of the 20th century when the internal combustion engine vehicles (ICEV) were less attractive. In the year 1900, 38 % of the total sales of automobiles in the US were BEVs as compared to 22% ICEVs with the rest being steam powered vehicles [1]. However with the rapid improvement in ICEV, the BEVs started losing their popularity and had almost vanished by the 1930s. They gained impetus periodically in the last century such as during the 1973 oil crises but were always stuck at the prototype stage or were produced in small numbers. The introduction of production hybrid electric vehicles (HEV) by Toyota in 1997 and subsequently by Honda in 1999 triggered a number of HEVs to be mass produced by other manufacturers in the 2000s. Since the last few years a small number of mass produced BEVs such as the Nissan Leaf, the Mitsubishi iMiEV and the Tesla Roadster have been introduced in the markets worldwide and many more are in the pipeline. However their high cost and limited range, relative to ICEVs, are still issues that impede their popularity [2].

Current batteries for BEVs

At present the most viable batteries for BEVs include the following:

1. Lead-acid batteries: These batteries are the oldest type of rechargeable batteries existing from as far back as the 1800s. They are low cost which make them attractive for various applications which are cost sensitive. They were the predominant batteries used for BEVs in the 1970s and 1980s, however their limited specific energy makes them unsuitable for modern long range BEVs. In addition to their limited energy, their cycle life is also limited which would warrant a change in batteries every 2-3 years. Lead-acid batteries commonly have specific energy of about 35 Wh/kg, specific power of about 150 W/kg and life of around 700 cycles.

2. Ni-MH batteries: Ni-MH batteries have been popular since 1990s and have been the choice in many HEVs and BEVs since they have relatively high cycle life and specific energy. Ni-MH batteries commonly have specific energies of about 70 Wh/kg, specific powers of more than 200 W/kg and life of around 1500 cycles. The main drawback is their high cost.

3. Li-Ion batteries: Li-Ion batteries were first announced in 1991 and are considered one of the most promising technologies for BEVs and HEVs. Their specific energy at around 130 Wh/kg is almost double than that of Ni-MH batteries but they suffer from higher cost. They have typically high specific power of around 250 W/kg and their life is around 1200 cycles which is lower. These are typically the batteries of choice for current production BEVs. Further details about batteries can be found in [1], [3], [4] and [5].

At present the most important bottleneck in BEVs is the battery itself, which strongly affects the range and cost of the BEV. The batteries offer either high specific power or high specific energy but not both. One of the ways of improving the BEVs is to hybridize the energy source. The usual strategy would be to combine a high energy battery with another high power source. This would shield the battery from peak currents and improve its capacity and life. The thermal requirements of the battery will also be reduced. The concept of hybridization is discussed in [6].

Flywheels have been used to store energy since many years. High speed flywheels have the characteristics of high specific power, high specific energy, long cycle life, high energy efficiency, quick recharge, low cost and environmental friendliness. They do not suffer from temperature dependence and their state of charge is most easily determined. Their attractive properties make them an excellent secondary storage device to be used in BEVs. Though the usual application of flywheel energy storage system (FESS) in a BEV would incorporate a high speed FW coupled with a transmission to the driveline, some authors have suggested using the dead weight of the battery in a FW, though its practicality is unknown [7-8]. The FW can also be used as the sole energy storage system to hybridize a conventional ICE vehicle. The paper [9] presented by the same authors deals with that application of FWs.

Following are the main benefits of incorporating FWs in BEVs:

- Improve energy efficiency of the battery by taking care of the peak loads, which would reduce losses in the battery and improve range of the BEV
- Increase life of the battery
- Allow the optimization of battery as pure energy source
- Solve thermal issues of the battery
- Allow the powertrain to achieve better brake regeneration efficiency by avoiding energy conversion
- Possible downsizing of the main electric machine in case the FW is connected via a mechanical transmission

Transmissions for Flywheels

The flywheel needs to be connected to the driveline in a manner that allows the flywheel to change its speed independently of the velocity of the vehicle. As the flywheel usually gains speed when the vehicle is slowing down and loses speed when the vehicle is accelerating, the transmission has to be continuously variable in nature. One main difference between the continuously variable transmissions (CVT) used in conventional vehicle as compared to the ones required for FESS is that they have to be bi-directional and highly efficient in both the directions. There have been a number of different types of transmissions which will be discussed below. Although changing the speed of the flywheel is the most usual method of varying its energy content, some authors have suggested using a variable inertia flywheel [10-12].

Hydrostatic transmissions

In case of hydrostatic transmissions there is a variable displacement pump which is connected to a hydraulic motor via hydraulic lines along with the other necessary components. The pump converts the mechanical power into hydraulic power which is reconverted at the motor. In the reverse direction the pump acts as a motor and the motor behaves like the pump. The hydrostatic transmission will usually be an infinitely variable transmission (IVT). The stroke of the pump can be reversed so the transmission can rotate in both directions. During the 1970s these transmissions were popular due to their wide availability [13]. They usually tend to be noisy and bulky which makes them less suitable for a passenger car.

Electrical transmissions

The electrical transmission consists of a two motor-generators (MG) which are electrically linked together and necessary power electronics needed. During power transmission one machine acts as generator to convert mechanical power into electrical power and the other as motor to do the reconversion. These have been widely used for FESS since the early days and usually employ magnetic bearings. They add flexibility to the system; however they tend to be expensive as firstly the machines are sized big, since the whole power has to be transmitted via them, and secondly these usually include a number of power inverters, and further have the disadvantage of energy conversion. The flywheel motor-generator assembly usually called flywheel battery (FWB) or electromechanical battery (EMB) is a popular choice for BEVs. There are three topologies defined for the FWB [14] and shown in Fig. 1.

1. Fully integrated: In this case the FW and the MG are one unit and usually but not always, the inside out configuration is used, which means that the FW forms part of the outer rotor with the stator inside. In this case the design is highly compact. Since the containment is under vacuum the only way to remove heat is via radiation, so machine cooling poses a technical challenge. Another advantage of such a structure is that it can be hermitically sealed and it needs only electrical connections.
2. Partially integrated: In this case usually the rotor is inside the containment and the stator is outside the containment. The problem of rotor cooling remains though it is improved by the stator being outside the containment. It has good design adaptability and the available MG technology can be used.
3. Non-integrated: The FW and the MG are separate units mounted on the same shafts. It is bigger and simpler than the other topologies. The problem of cooling is avoided, potential to maximize the use of available technology, but a mechanical seal is required.

There have been a number of FWBs constructed by various organisations such as the University of Texas - Austin [14], Technical University Eindhoven [15] and Lawrence Livermore Laboratory [16].

Traction transmissions

In the traction drive, power is transmitted between two loaded objects through adhesive friction. The speed ratio is changed by varying the point of action of forces. The two popular transmissions in this category are the belt drives and the rolling contact traction drives.

Belt drives

In this type power is transmitted over a belt, chain or band clamped between two pulleys. The speed ratio is varied by varying the axial clamping forces for the two halves of the pulleys thereby changing the rolling radii on the pulleys. The clamping forces are usually controlled via hydraulics. One of the common designs is the Van Doorne steel v-belt in which steel segments are held by a steel band, which was one of the first commercially successful CVTs. In this case the driver pulley usually pushes the driven pulley so it is a compression belt.

Rolling contact traction drives

The two popular designs are the toroidal traction drive and the roller cone traction drive. The power is transmitted between two rolling elements separated by lubricant film. In the toroidal drive the inclination of the roller disc in the toroidal cavity is changed to vary the ratio. The required system torque is set by applying a force to the roller hydraulically which allows the roller to follow the ratio automatically, thus the drive is torque controlled. The Perbury transmission in the Sussex propulsion system [13, 17] and the Flybrid-Torotrak system used in Formula 1 KERS employ such a toroidal transmission [18]. Current traction CVTs are deemed a mature, low-cost and fuel-efficient technology [19].

Planetary gear set

The planetary gear set (PGS) is a speed coupling device commonly used in automatic transmissions in conventional cars. It gives the advantage of having multiple ratios in a compact space. In the conventional AT case usually one of the arms of the PGS is brakes and the other two act as input and output. However to be used as a CVT it has to be used as a two degree of freedom device implying that all the branches should be free to rotate. As a speed coupling device it has the property that speeds of two branches can be independently controlled and the speed of the third one is dependent on the other two. In the BMW [20] and Szumanowski concepts [21], the single PGS is used as a CVT.

Power split CVT (PSCVT)

The PSCVT is used to avoid the low efficiency of the variator only transmission. For the sake of clarity the previously mentioned transmissions will be referred as variator. The idea of a PSCVT is that part of the power is transmitted through the highly efficient direct mechanical linkage and the rest is transmitted through variator. The common disadvantage is that the ratio range is usually smaller than that of the variator itself, which can be altered by various means. The common PSCVTs employed in FW hybrid vehicles (FWHV) are electromechanical, hydromechanical and various traction drive PSCVTs. The concept of PSCVT for flywheel in vehicular application has been explored by [66].

System Layouts

The FW in a BEV can be incorporated in many ways using the transmissions described above. When using a pure electrical transmission, the layout is a standard one, shown in Fig. 2 and marked as layout 1, usually with a number of power converters depending on the type of electric machine used (The dashed line in the Fig. 2-4 represents an electric link and the solid line a mechanical link). The battery and the FWB are connected electrically to the main electric machine. For the mechanical/hydrostatic transmissions, the following two layouts as shown in Fig. 3 and Fig. 4 can be defined. In effect the layout 2 is just an electric machine with a bigger inertia. The layout 2 gives the possibility that the vehicle could be solely controlled by controlling the CVT, when using certain types of electric machines and no separate machine control is needed [22]. The disadvantage is that the power has to pass through the CVT all the time, which might not be desirable at lower efficiency points. Another is that the FW and MG speeds are always coupled together due to which the FW cannot be independently controlled. In the layout 3, the CVT is only linked to the FW and the MG is either directly linked on the drive shaft or via some fixed gearing. The advantage of this layout is that the FW can be independently controlled and it can be integrated easily on an existing system, however the machine needs to be controlled separately.

History of flywheel assisted BEV applications

Flywheels have been used in vehicular applications for many years. One of the first major applications was their use in the so called Gyrobus by Oerlikon in Switzerland in the 1950s [23]. This was a specially designed 35 seater bus which used a 1500 kg, 1.6 m diameter and 32 MJ FESS as the sole energy source. This bus ran in cities in Europe and Africa for 16 years before it was discontinued in 1969.

Whitelaw (1972) proposed probably one of the early concepts of a flywheel battery electric vehicle (FWBEV) [24]. According to the author the case for local duty vehicle (LDV) was strong as most journeys in cities of US were less than 50 miles. The local duty vehicle (LDV) would have an energy storage system (ESS), a range of 50 miles and maximum speed 50 mph. Since the BEV was very heavy and the ICEV would burn fuel, a flywheel electric LDV was proposed. A FWB with batteries and DC motor propulsion is shown in Fig. 5. The energy removal rate from FWB would be uniform while the batteries will provide for non-uniform power surges. FWB would be charged at home. The FWB would provide average power and batteries would provide peak power. The author says that such a vehicle was possible with technology of that period. According to the review authors, this is a rather unique case as the usual application of FW in BEV consists of the FW providing the power surges.

Kugler proposed a system in which the flywheel was integrated to reduce peak current in lead acid battery of BEV [25]. Fig. 6 shows the schematic. The goal was to provide an efficient powertrain for lead acid BEV to have the performance to co-exist with ICEVs safely on public roads. The FW was coupled to a continuous running electric motor which was designed for efficient operation in a narrow speed range. Once started the motor ran continuously even when the EV was stopped and during these phases it charged the FW which acted as a load leveller. The benefits were high power output, mechanical regenerative braking, extended battery life and avoidance of expensive motor controllers. The FW rotated at moderate speeds from 5000 to 10000 rpm and the transmission was hydromechanical, which was popular due to its commercial availability. The author mentions that if such a flywheel battery electric vehicle is not required to undergo a number of closely spaced consecutive accelerations it would be able to compete with ICEV on performance basis.

Locker [26] developed a FWBEV at the Scientific Research Foundation (SRF) in Jerusalem. The schematic of the vehicle, which would be an intra-city van or mini bus, is shown in Fig. 7. The FW supplies power for acceleration and regeneration and the lead acid battery and electric motor provide average power. Like the Kugler system, the FWBEV uses hydromechanical transmission. The author mentions that the hydromechanical CVT is efficient only in a narrow range and thus to improve efficiency the system uses a two regime operation. The maximum speed of the FW is 7200 rpm. The control strategy is explained. The principle of the constant total kinetic energy (KE) of the vehicle and FW is used and the battery makes up the losses. However this system has the disadvantage of history dependence and it does not take into account the other loads on the battery. To overcome this, a delay is introduced in the total KE control principle as long as the battery can provide for all other loads and then the KE of the FW would be changed. Vehicle speed is not varied by controlling voltage or current but by varying the transmission ratio depending on the difference between the demanded and actual power. Since the transmission is torque limiting the achievable regeneration has a limit. It mentions that the driver could select the city mode and the maximum FW speed would be reduced.

In 1977 Schwarz presented a comparison of three design approaches for BEV – series motor with chopper controller, separately excited motor with field control and FWBEV with v-belt CVT [27]. The range achieved on the SAE J227a schedule D drive cycle was highest for the FWBEV but none of the options were able to meet the Department of Energy (DOE) goals. There is not much information given in the paper.

In 1975 post the 1973 oil crises, DOE (which was the Energy Research and Development Administration (ERDA) at that time) organised the first flywheel technology symposium and declared its intention to develop flywheel technology [28]. This was after the Rockwell International Corporation conducted a technical and economic feasibility study of the flywheel as an ESS for utilities, transportation, and industry under DOE sponsorship. The findings were presented at the symposium [29]. It was concluded that advanced composite FESS can extend hybrid and all electric transportation application to smaller vehicles. A FWB could also be developed in the near term to be used in a BEV.

In 1976 the US congress enacted the Electric and Hybrid Vehicle Research, Development, and Demonstration Act which authorized a Federal program of research and development to promote electric and hybrid vehicle technologies. From 1976 to 1983 DOE and other federal agencies in the US sponsored many projects related to flywheels which are described below.

In 1976, a patent was filed by Garrett Corporation describing an electromechanical transmission for a FWBEV with lead acid batteries [30]. The project was DOE sponsored and was to contribute to the development of a near term electric vehicle [31]. The schematic of the system is shown in the Fig. 8. The flywheel is connected to the sun gear of a PGS and the MG1 is connected to its ring gear. The carrier is connected to the drive shaft on which MG2 is mounted either directly or with suitable gearing. During the acceleration period the flywheel provides power to the vehicle through the direct mechanical link and the MG1 acts as a generator and controls the speed of the flywheel. The MG2 acts as a motor. During Cruise period the MG1 acts as motor to charge the FW and the MG2 powers the vehicle. During deceleration part of the vehicle energy directly charges the flywheel and the rest is transferred to the FW via the MG1-MG2 circuit. Here the MG1 acts as the motor and MG2 as the generator. The controller modulated the MG1-MG2 circuit to maintain an essentially constant armature current differential between MG1 and MG2 which resulted in almost uniform battery current discharge rates [32]. Another variation of this particular transmission is the MG2 directly on the same shaft as the flywheel which is shown in few patents [33-34]. Stavropoulou (1981) developed a computer model of a similar powertrain for an electric bus [35].

In 1976 Lustenader from GE introduced the FWB to be used as a load levelling device for a BEV [36]. The concept was first proposed by GE to DOE in 1974 and later GE was contracted to develop the system. Fig. 9 shows the schematic of the proposed vehicle. The steel Flywheel and AC inductor type motor alternator was to be used as a single unit. The FWB was connected electrically to a bidirectional solid state inverter/rectifier. The DC motor is separately excited. Various modes of operation were considered and the load levelling mode in which the FWB would be charged by the battery during idling periods was chosen. During evaluation of the system it was apparent that it suffered from many drawbacks. The performance of the system was highly dependent on the drive cycle and was reduced when operated on low maximum speeds and low stop frequency cycles. This was due to the fact that the vehicle's kinetic energy was less and the parasitic losses in the system were high. It was concluded that the system was not suitable for practical implementation and improvements were required [37].

The US postal service and DOE jointly developed a flywheel battery electric postal jeep to improve range, stop-start capability and acceleration performance of existing electric postal vehicles [38]. Fig. 10 shows the schematic. The flywheel assists the electric motor in powering the vehicle thereby reducing the peak current on the lead acid batteries. The EM is used to drive the vehicle from stationary to 7 mph, reaching its top speed of 36,000 rpm and after that the fluid coupling is engaged. The flywheel is used to power the vehicle from 7 mph to 33 mph, which was its top speed, via the variable v-belt drive. The process is reversed during braking. The flywheel was 0.5 MJ, multiple disc type with a top speed of 36000 rpm. The flywheel was able to substantially improve the acceleration (0-30 mph in 12 s) and gradeability (10% @ 20 mph) as compared to the base vehicle's acceleration (0-30 mph in 24 s) and gradeability (10% @ 14 mph). The drawback of this arrangement was that the vehicle still had to be launched using EM.

Garrett Corporation was also involved in developing a FWB for vehicular use under a DOE contract [39]. The goal of the project was to find out the benefits of a light-weight, hermetically-sealed energy storage unit for vehicular applications. Fig. 11 shows the schematic. The composite flywheel had a speed range from 21000 - 42000 rpm. The MG was a squirrel cage induction type. The peak power was 45 KW and the energy capacity was 250 Wh [22]. The FWB was designed and partially evaluated before the project was discontinued due to electric machine failures and lack of funding [40].

In 1979 Raynard conducted a study on advanced electric propulsion system concept for electric vehicles [41]. In this study 17 EV propulsion concepts were evaluated. The systems included basic systems with and without transmissions and with and without flywheels. The evaluation was done through simulation on the SAE J227a schedule D drive cycle (Fig. 12) and considered improved state of the art (ISOA) lead acid and Ni-Zn batteries. For the cases with a flywheel a simple energy management was followed of keeping the total KE constant. Study showed that for driving range of 161 Km on successive SAE J227a schedule D drive cycles, the system with the flywheel would achieve the range with the lowest battery weight. Out of the 17 concepts two were selected for conceptual design. One of the two selected was a flywheel assisted design coupled with double cavity toroidal regenerative CVT.

In 1979 Younger conducted a study of advanced electric propulsion systems concept using flywheel for EV [42]. In the study 28 systems were analysed, all incorporating FESS and compassion without FESS was not evaluated. These included different types of components and arrangements and included DC/AC motors with or without multispeed transmissions. They could be grouped in 4 types and included both mechanical and electrical transmissions for the flywheel. Like in the previous study the targeted range was 161 km on the SAE J227a schedule D drive cycle. The batteries considered were mainly ISOA lead acid and some evaluation was carried out on Ni-Zn batteries. It also included an assessment of the technical advancements necessary to achieve the selected drivetrains. Various strategies of dividing power between battery and flywheel during acceleration and deceleration were studied. For the conceptual design stage two of the many analysed designs were selected. These were the AC induction motor with FWB and DC motor with Flywheel/CVT. The two conceptual designs could meet range and performance goals but not the energy consumption targets with lead acid batteries. From the evaluation the greatest technical developmental risk was for the CVT.

In 1979 Schwartz conducted a study to determine the effect of applying flywheels to EVs using advanced batteries [43]. When used with flywheels, the batteries are to have maximized specific energies at the expense of high power capability for optimal performance. The characteristics of FWBEVs are compared to BEVs having the same range and peak-power capability. Different combinations of vehicle power and range are considered and as in the previous studies, an SAE J227a schedule D drive cycle is used. Lead/acid, Ni/Fe, Ni/Zn, $ZnCl_2$, $LiAl/FeS_2$, Na/S (cer), and Na/S (glass) are the batteries that have been considered. It concluded that as the performance requirements of EVs increase the flywheels will be more effective in improving the vehicle's range.

In 1980 as part of the DOE's electric and hybrid vehicle development program 4 CVT concepts were evaluated by various sub-contractors for the flywheel application in EVs [44]. The basic schematic of the vehicle is shown in Fig. 13. The intended application was a 1700 kg vehicle with the flywheel speed varying from 14000 to 28000 rpm and CVT output speed from 0 to 5000 rpm. There was an option to have the minimum CVT output speed as 850 rpm with a slipping clutch to be used at the output in order to attain zero speed. The usual requirements of high efficiency, low cost and weight, high reliability, maintainability, ease of control and low noise were applicable.

The first of the designs studied was a steel v-belt CVT for the electric vehicle (EV) by Battelle Columbus Laboratories [45]. The Fig. 14 shows the schematic. The CVT included two steel v-belt elements in series with the necessary clutch and gears. The modulating clutch is used to produce the zero speed requirement on the output. The design of the CVT and the control is described. The belt is composed of a stack of solid cross-struts held together by a set of thin steel bands. It is a compression belt in which the v shaped driver pulley pushes rather than pulls the driven pulley. Since there is sliding movement between the bands over each other and over the struts when the belt moves proper lubrication is necessary. An electrohydraulic control system controls the belt shifting and regulates the axial clamping force between the pulleys. The vehicle operating modes are described including the start-up, normal operation and shutdown. It is suggested that vehicle controller would provide the driver with some way to set a nominal setpoint for the flywheel speed depending on the upcoming road conditions and the driving style.

The next design studied was a flat belt CVT concept by Kumm Industries [46]. The Fig. 15 shows the schematic. The belt is radially positioned between the guideways on the side of the two pulleys and the ratio change is achieved by changing the position of the belt along the guideways. The drive is used in conjunction with planetary gearing which allows the CVT to operate down to zero speed. There are two modes; a low speed and a high speed mode. The power is transmitted through both belt and the planetary gears in low speed mode in regenerative fashion and only through the belt in the high speed mode. The mode shift takes place by synchronous clutching. This design differs from the previous design in that the electric machine and flywheel are coupled together and all of their power passes through the CVT. The flywheel is coupled to the transmission via an electric clutch. The design of the belt CVT and the control is described. Both direct and differential arrangements for the CVT are examined and the arrangement having the least belt torque and power over the operating range is chosen. The technical requirements for the CVT included the high speed clutch and high speed DC motor which were unavailable at the time of the study.

The third design studied was a toroidal traction CVT by Garrett Corporation [47]. Fig. 16 shows the schematic. The study consisted of designing a preliminary concept for the CVT, identifying the required technical advancements for the development of such a CVT, and determining the suitability of the CVT for alternative applications. Firstly the geometry of the toroids and rollers was selected to achieve high efficiency, low hertz pressure and low energy dissipation. Then five CVT configurations featuring the toroidal traction design were evaluated on efficiency, cost, size, weight, reliability and control. The selected option was the dual cavity full toroidal design with regenerative gearing. The design of the toroidal CVT and the control is described. The CVT is controlled hydraulically by changing the position of the rollers which are clamped in between the toroids. A mechanical loading cam mechanism automatically ensures that there is enough clamping force between the rollers and toroids to prevent slip. Three areas of ratio control, fluid properties and evaluation of traction contact performance were identified to require further technical development.

The final design studied was a continuously variable roller cone traction CVT by Bales-McCoin Inc. [48]. Fig. 17 shows the schematic. The designed CVT consisted of traction cones and rollers in a regenerative path epicyclic gear differential. The variable ratio traction assembly is connected to output planetary differential through a set of idler gears. The flywheel is connected to the centre shaft through an input epicyclic reduction stage. A modulating clutch controls the ring gear of the input reduction unit. The clutch allows disconnecting of the flywheel at speeds less than 14000 rpm in order to decouple the flywheel when the output speed is below 850 rpm or in reverse mode. There is a central traction roller which is surrounded by four inclined cone rollers whose inner contact surfaces are parallel to axis of the roller. By changing the point of contact between the central roller and the cones the speed ratio is varied. The cones and the roller are loaded against each other hydraulically and the control system monitors the slip between them. The control system maintains optimum traction between the cones and the roller for all operating conditions via slip control feedback.

These 4 CVTs described above have been compared in [49]. The efficiencies of the CVTs are calculated and compared at nominal weighted averaged power of 16 kW and at an output speed of 3000 rpm for different flywheel speeds. The comparison is shown in Fig. 18. It seemed that the steel belt CVT was the most efficient under these conditions and in general the efficiencies seemed to differ little over the flywheel speeds.

In 1983 study Secunde discussed the progress in EV propulsion from 1976-1973 under the DOE electric and hybrid vehicle program [50]. Under this study 5 systems were compared having different levels of technology. The first System could have been built in 1976 which has DC motor, chopper and 3 speed auto transmission with torque converter. The second System was the same as the first one but with the latest available and more efficient components from 1982. The third was the DOE ETV-1 [51] which was built by GE and Chrysler. The fourth system was to take the best technology which included both off the shelf one as well as what could have been built at that time. The fifth and final system was a FESS with steel v-belt CVT incorporated in the EV. All the systems were simulated using the same lead acid battery. Results of the range calculations over the SAE J227a schedule D drive cycle showed that required battery energy density for a given range had been reduced by about 40 due to the propulsion system development. The acceleration performance of the flywheel assisted EV was by far the best. The report discusses the current situation, technology needs and the recommends that further development is needed to reduce cost.

In 1980 a flywheel assisted BEV was developed at Sussex University in the UK using the Perbury transmission [13, 17]. The Fig. 19 shows the schematic of the system. The DC compound wound motor is used and is connected to the flywheel via a reduction gear so the flywheel is just an additional inertia on the electric machine. The CVT is a dual cavity design with power recirculation and is similar to the toroidal traction CVT by Garrett described previously. Ratio change is affected by changing the rollers inclination. There is no external motor control and the only the CVT is torque controlled. The motor automatically produces power depending on the load it experiences after it is switched on. The system was developed for a 7.5 tonne urban delivery van. The peak torque of the transmission is 880 Nm and the battery is lead acid. The flywheel is 70 kg and runs at 13650 rpm.

During the development of FWBEVs in the 1970s, it was already evident by 1977 that in the near term even with the flywheel assistance the BEVs would not be able to match the ICEV in terms of performance. O'Connell suggested the solution as a quasi-electric drive which was a flywheel BEV augmented by a small ICE [52]. According to Burrows (1981), the BEVs could meet the standards set by the DOE though they could not meet the FUDC under which the ICEVs were tested [22]. A study by GM in 1982 [53] suggested that GM had postponed its BEV research programs as the BEVs were not competitive due to high cost of vehicle and battery replacement. Though with the FESS the performance and capacity of the BEV increases but so does the cost and complexity. It also gave the example of the test results of the ETV-2 FWBEV which showed poorer performance than predicted due to poor battery performance and drivetrain losses.

In 1990 Alcan International Limited, in collaboration with Unique Mobility Inc. and the University of Ottawa, had a program to develop an advanced EV utilizing FWB as a power surge unit for load levelling [54]. They used 0.5 kWh flywheel, 40 kW MG and 1000 kg lead acid batteries. The FWB was hermetically sealed, used magnetic bearings and a permanent magnet (PM) MG and had lower parasitic losses. The presented simulation optimization study showed that the FWBEV could meet the FUDC and that load levelling was accomplished by the FW.

In 1991 Braess presented the BMW EV development trends [20]. BMW built an EV with sodium sulphide (NaS) batteries in 1990. They proposed another concept to combine a high energy battery with a high power flywheel. The schematic is shown in Fig. 20. It utilized the PGS as a two degree of freedom device connected to a flywheel, the electric machine and the drive shaft with the necessary brakes and clutch to decouple the flywheel from the system during cruising. The speed and torque of the electric machine decided the power flow. At vehicle standstill, brake is applied and the MG charges the FW. Then FW accelerates the vehicle and MG acts as generator till zero speed and then reverses to become motor and gains positive speed and the MG and FW both power the vehicle. During cruising the FW is decoupled and the reverse happens during deceleration. The system showed improvement in energy consumption with lead acid batteries for the NEDC but not for the FTP cycle. However for the NaS batteries the advantage was less pronounced. The disadvantages of such a system are that it is less flexible; FW cannot be charged during vehicle cruising, clutch and brakes have to be controlled which causes loss of efficiency, the MG has to partly absorb braking energy and there are energy conversions.

In 1992 Szumanowski showed a system similar to the BMW system [21]. The schematic is shown in Fig. 21. The PGS is the CVT where the DC MG is connected to ring, FW to sun and carrier to wheels. During constant velocity driving FW is disconnected using an electromagnetic clutch. The MG is controlled using a DC/DC chopper. Simulations showed improvement in range over the BEV. It would have disadvantages similar to the BMW system as explained before.

In 1994 Schaible showed an electric drive system incorporating the FWB [55]. The system is shown in the Fig. 22. The FWB consisted of the flywheel coupled to a PMSM. There is an energy storage tank connected to the PMSM, which is a capacitor bank and acts as a temporary energy storage dump. The author suggests that due to the inertia of the FW, the FWB cannot meet the sudden demand in acceleration from the vehicle so the energy storage tank serves that purpose. The torque control of the system is shown.

In 1994 Anerdi showed a study supported by the European Commission (EC) evaluating FWB application in BEV [56]. Two cases were studied; one in which the FWB acted as the load leveller to the BEV and another where it was the sole energy source. From simulation results a 20% reduction of energy consumption on the UDC was shown possible by using FWB as a load levelling device compared to BEV. The FWB under the project was being designed at University of Sheffield [57].

A number of examples show the use of FWB in an EV. Saitoh (1999, 2004, 2005) studied FWB in an EV and proposed a so called super energy-efficient electric vehicle (SEEV) which consisted of a number of energy sources including Li-Ion batteries, photo voltaic cells and on board generator which could be fuel cell or ICE [58-60]. Xiong Xin Fu (2007, 2010) described the FWB design and control strategy of charging and discharging the FWB in a BEV [61-62]. Briat (2007) showed the application of FWB in a heavy duty EV with discontinuous mission profiles such as a refuse collector [63]. Lundin (2011) used a different design FWB (Fig. 23) in an EV as a secondary storage device [64]. The FWB has double stator windings and is placed between the battery and the drive motor. The low voltage side is connected to the batteries and the high voltage to the drive motor. This allows the FWB to charge or discharge both the drive motor and the batteries at two different voltage levels. A significant decrease in partial charge/discharge cycles, maximum current and battery resistive losses with the flywheel is shown in the results. However the design includes a number of power converters.

The following table 1 summarizes the above discussed systems into various characteristics including layout, transmission, application, capacity etc.

Table 1 Classification of various systems

System	Year	Layout	Transmission	Battery	Application	Capacity [Wh]	Maximum FW speed [rpm]
Whitelaw	1972	1	Electrical-fully integrated	Not specified	LDV	7850	38000
Kugler	1973	2	Hydromechanical	Lead acid	Not specified	119	12900
Locker	1976	2	Hydromechanical	Lead acid	Van	180	7200
Garrett	1976	3	Electromechanical	Not specified	Passenger car	750	25000
Lustenader	1977	1	Electrical-fully integrated	Lead acid	Van	105	20000
USPS	1977	2	Mechanical-belt	Not specified	Van	67	36000
Garrett	1978	1	Electrical-fully integrated	Lead acid	Passenger car	250	42000
Battelle Columbus	1980	3	Mechanical-belt	Not specified	Passenger car	500	28000
Kumm	1980	2	Mechanical-belt	Not specified	Passenger car	500	28000
Garrett	1980	3	Mechanical-toroidal	Not specified	Passenger car	500	28000
Bales-McCoin	1980	3	Mechanical-cone	Not specified	Passenger car	500	28000
Sussex	1980	2	Mechanical-toroidal	Lead acid	Van	530	3000
Alcan	1990	1	Electrical-fully integrated	Lead acid	Van	500	30000
BMW	1991	3	Mechanical-PGS	Lead acid/NaS	Passenger car	100	14000
Szumanowski	1992	3	Mechanical-PGS	Lead acid	Passenger car	Not specified	Not specified
Schaible	1994	1	Electrical	Not specified	Not specified	Not specified	Not specified
Anerdi	1994	1	Electrical-fully integrated	Not specified	Passenger car	250	Not specified
Saitoh	1999	1	Electrical-fully integrated	Li-ion	Passenger car	Not specified	Not specified
Xin Fu	2007	1	Electrical-fully integrated	Lead acid	Not specified	Not specified	Not specified
Briat	2007	1	Electrical-partially integrated	Lead acid	HDV	46	3000
Lundin	2011	1	Electrical-fully integrated	Lead acid	Passenger car	500	Not specified

Conclusions

BEV is an important mobility option which can reduce the dependence on fossil fuels. The fuel flexibility of the BEV has the greatest potential to utilize power from renewable or low emission sources to be used in the transport system. The greatest limitation of the BEV is the battery itself and hybridization of the energy sources of the BEV is one of the methods to improve the BEV. This paper deals with FW assisted BEV where the FW acts as a power source and battery as the energy source. The paper shows the history of flywheel based battery electric vehicles and reviews the various powertrain concepts in this field. The concept has been there since many decades and various organisations and researchers have presented different designs. With the advancements in FW technology, it can be said that their development has reached a point when there implementation in road vehicles might occur in the near future.

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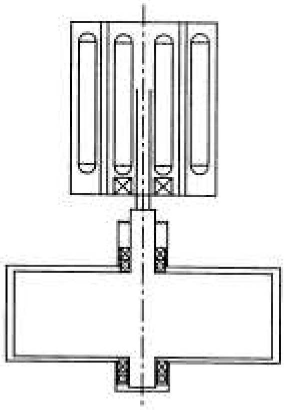
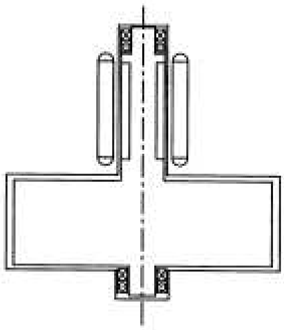
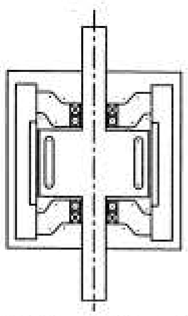
Figures



Non-integrated Topology



Partially Integrated Topology



Fully Integrated Topology (Inside-Out)

Figure 1 FWB Topologies

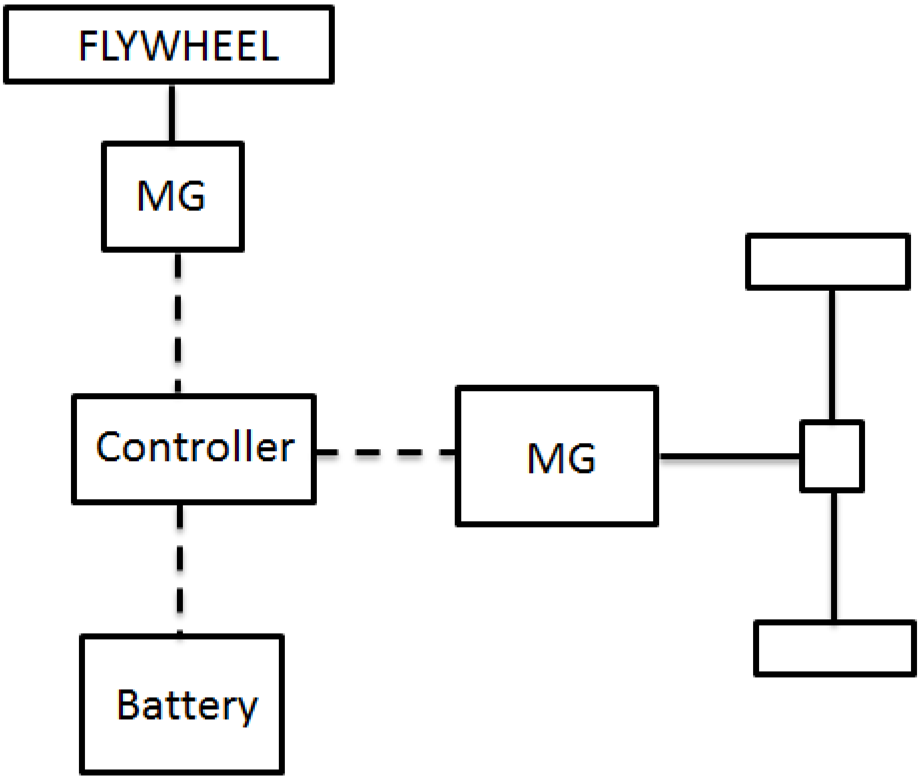


Figure 2 Layout 1

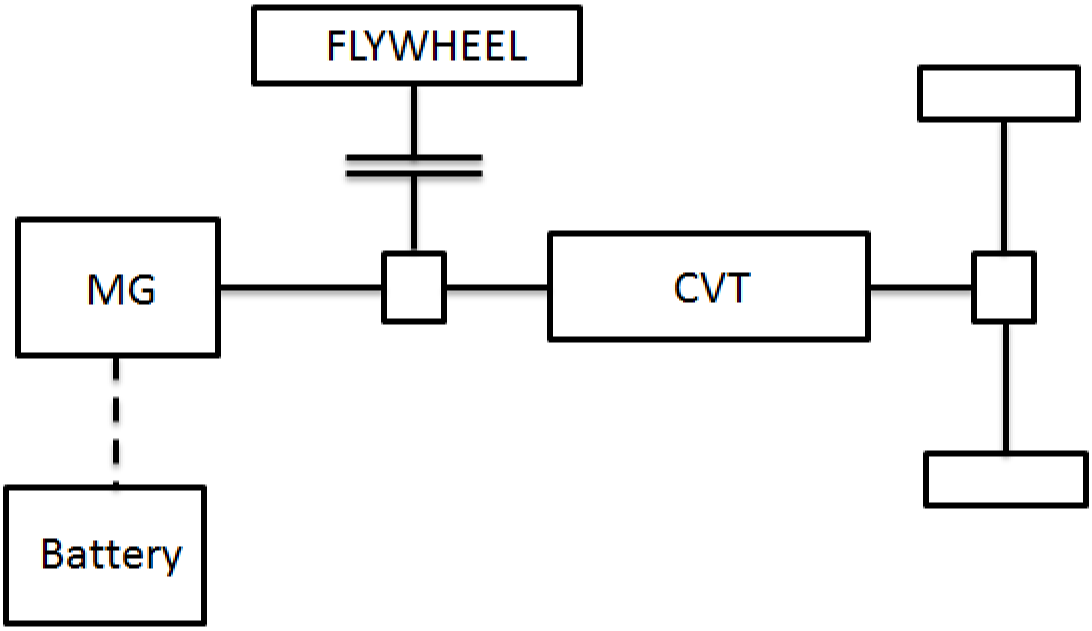


Figure 3 Layout 2

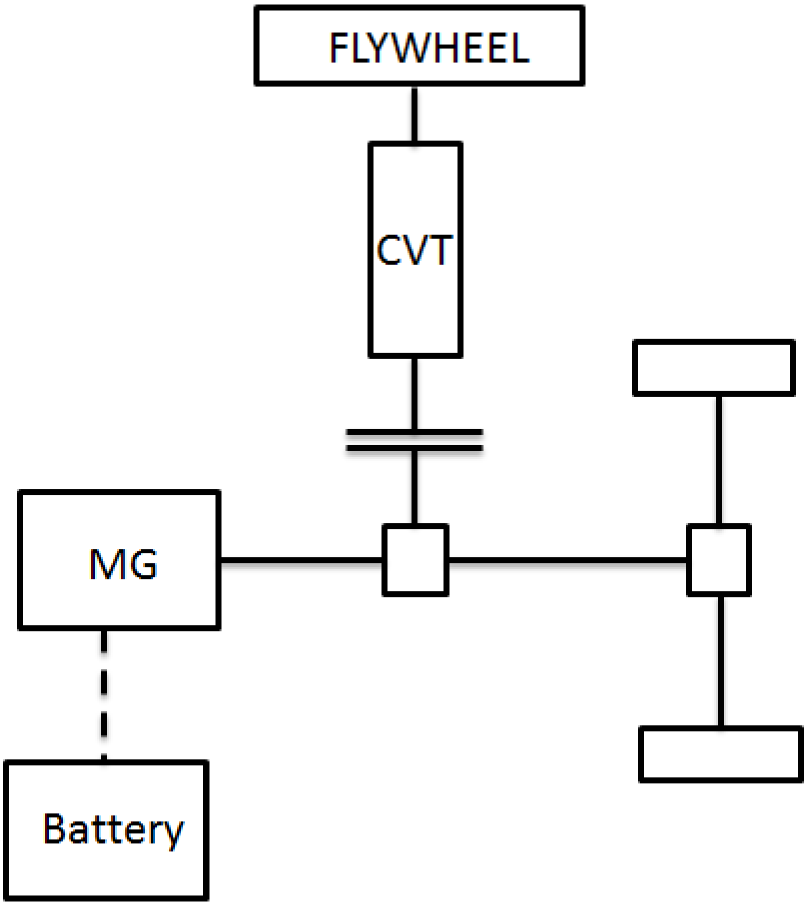


Figure 4 Layout 3

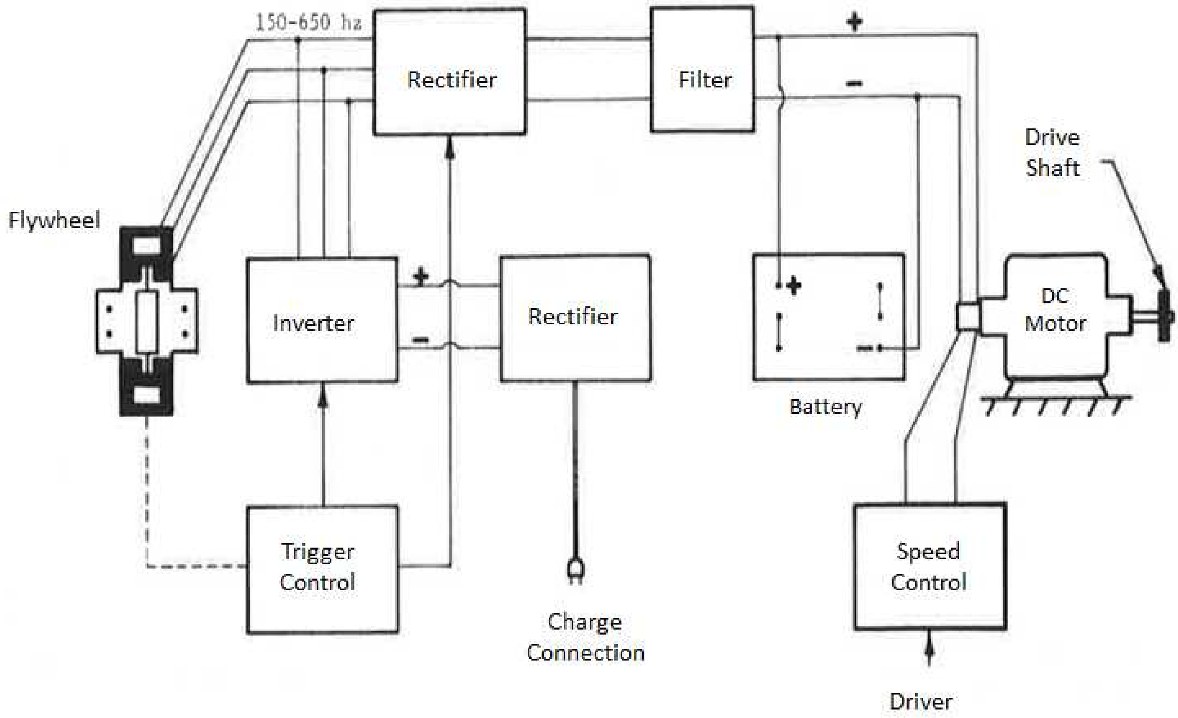


Figure 5 Whitelaw concept

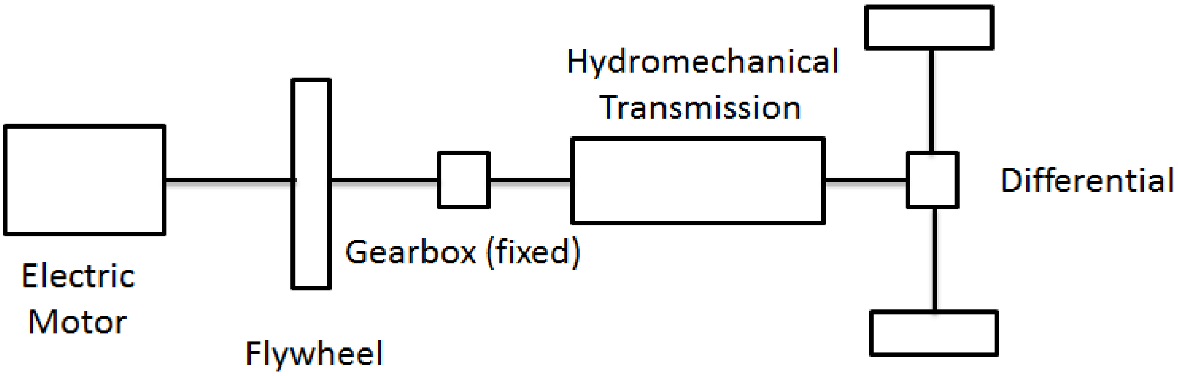


Figure 6 Kugler concept

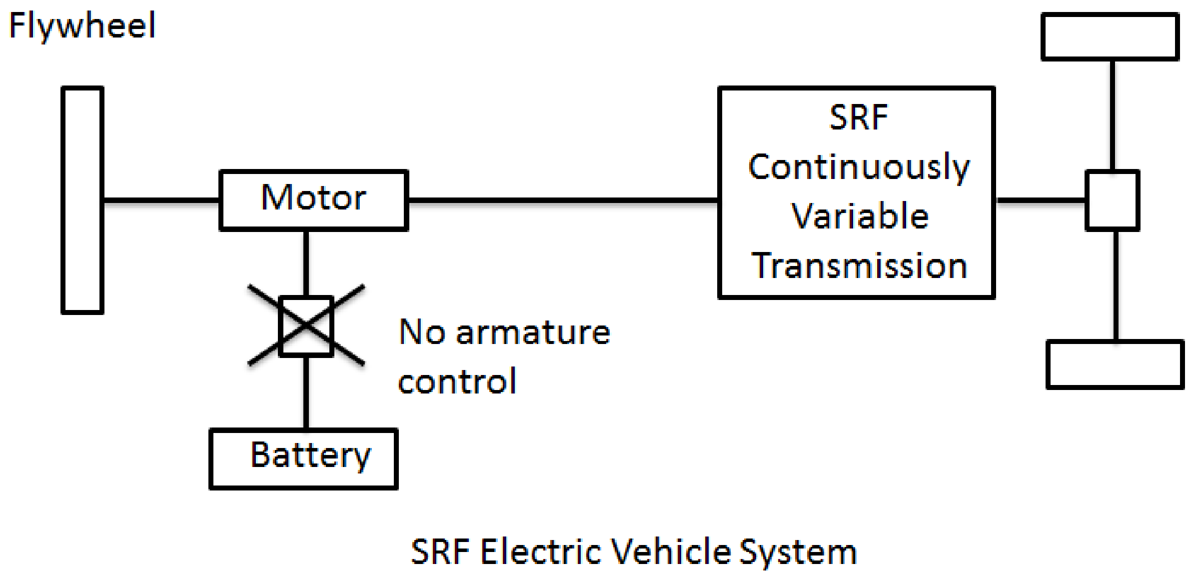


Figure 7 Locker concept

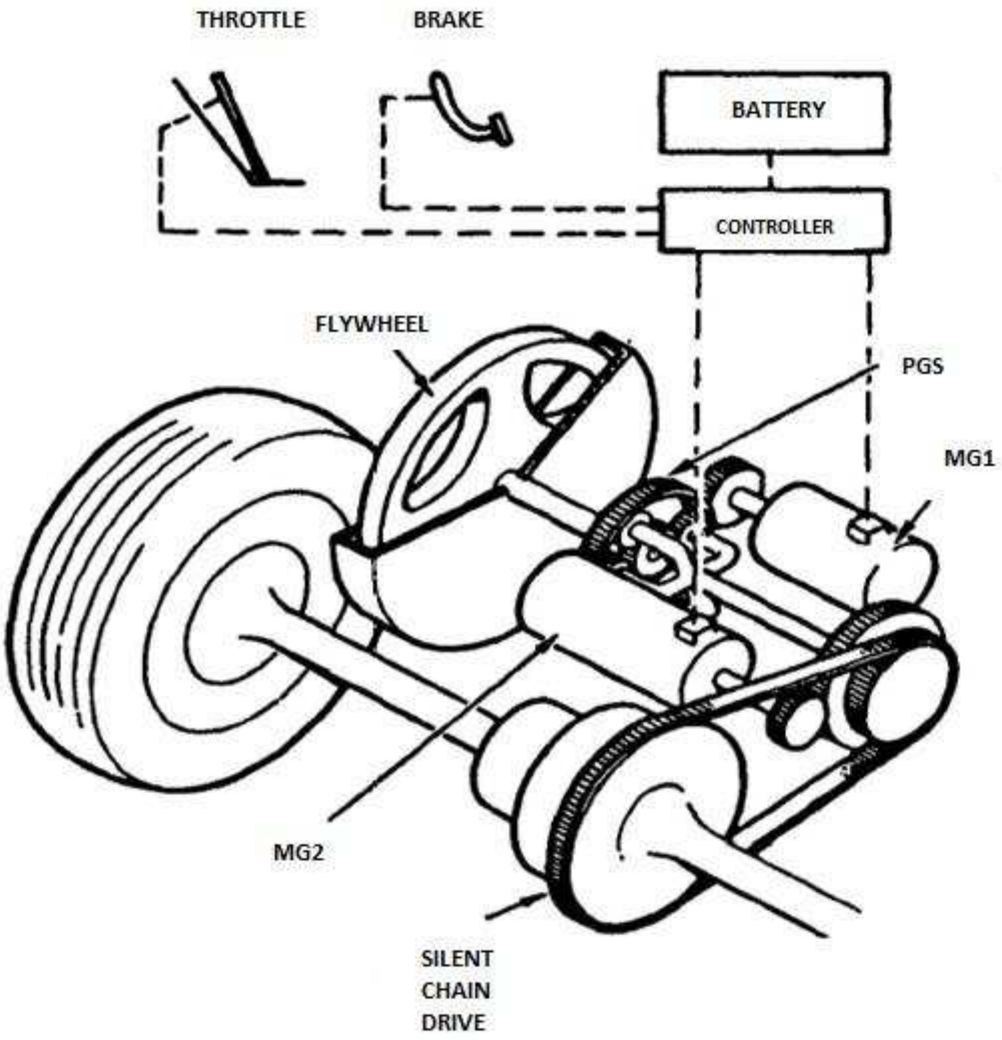


Figure 8 Electromechanical transmission

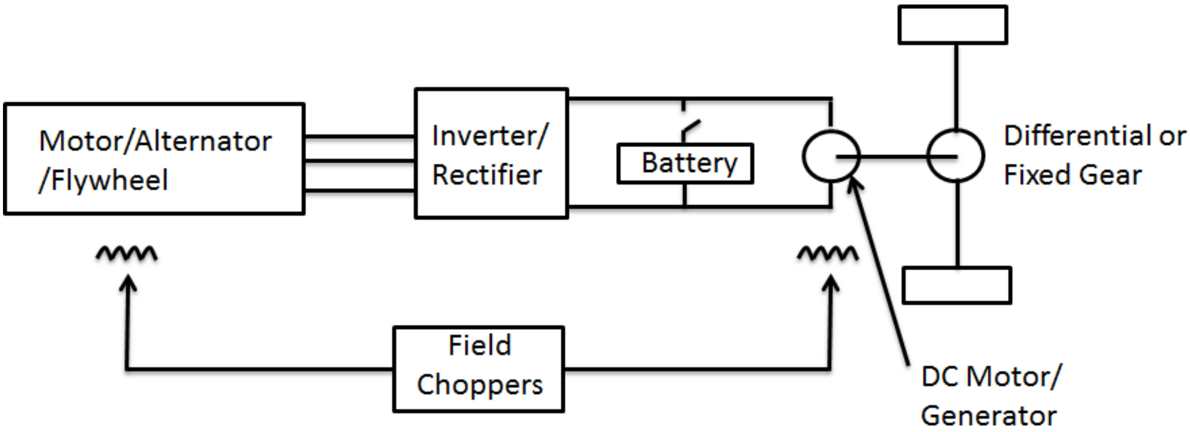


Figure 9 GE concept

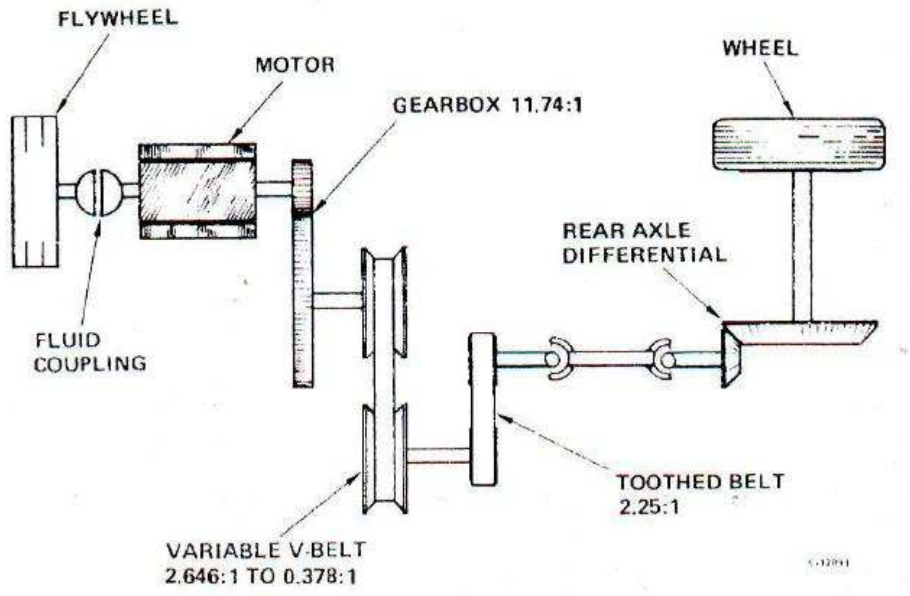


Figure 10 USPS vehicle concept

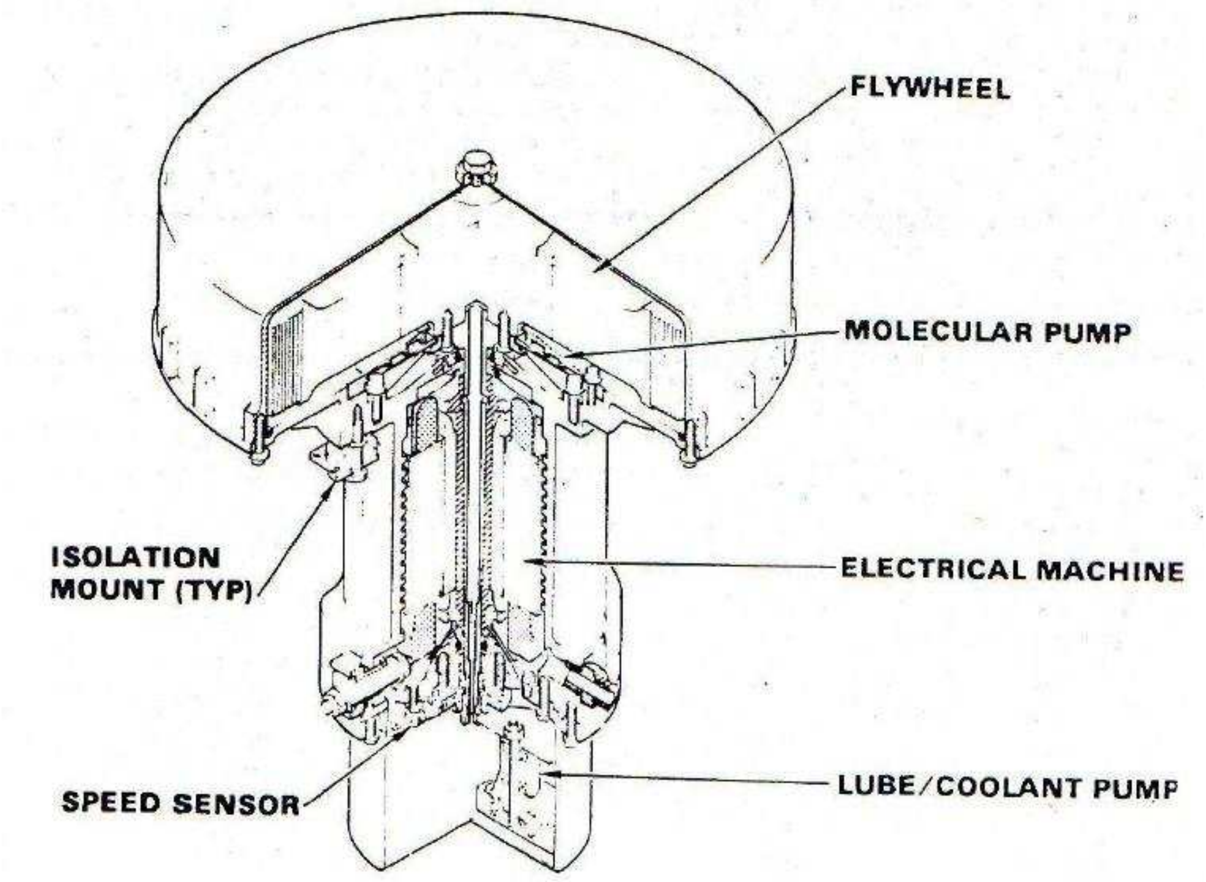
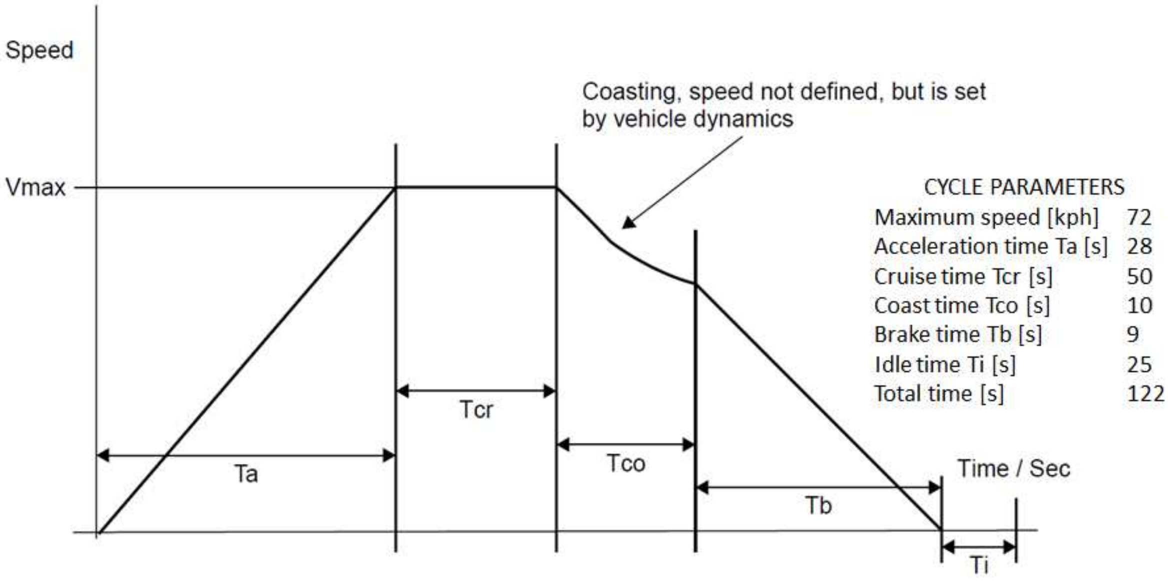


Figure 11 Garrett FWB concept [22]



CYCLE PARAMETERS

Maximum speed [kph]	72
Acceleration time Ta [s]	28
Cruise time Tcr [s]	50
Coast time Tco [s]	10
Brake time Tb [s]	9
Idle time Ti [s]	25
Total time [s]	122

Figure 12 SAE J227a schedule D drive cycle [65]

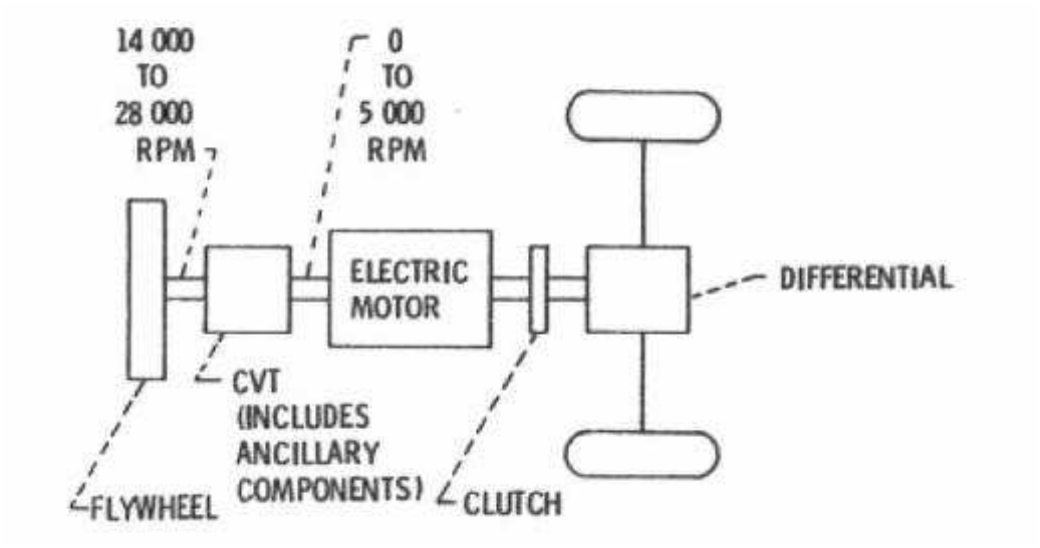


Figure 13 DOE concept

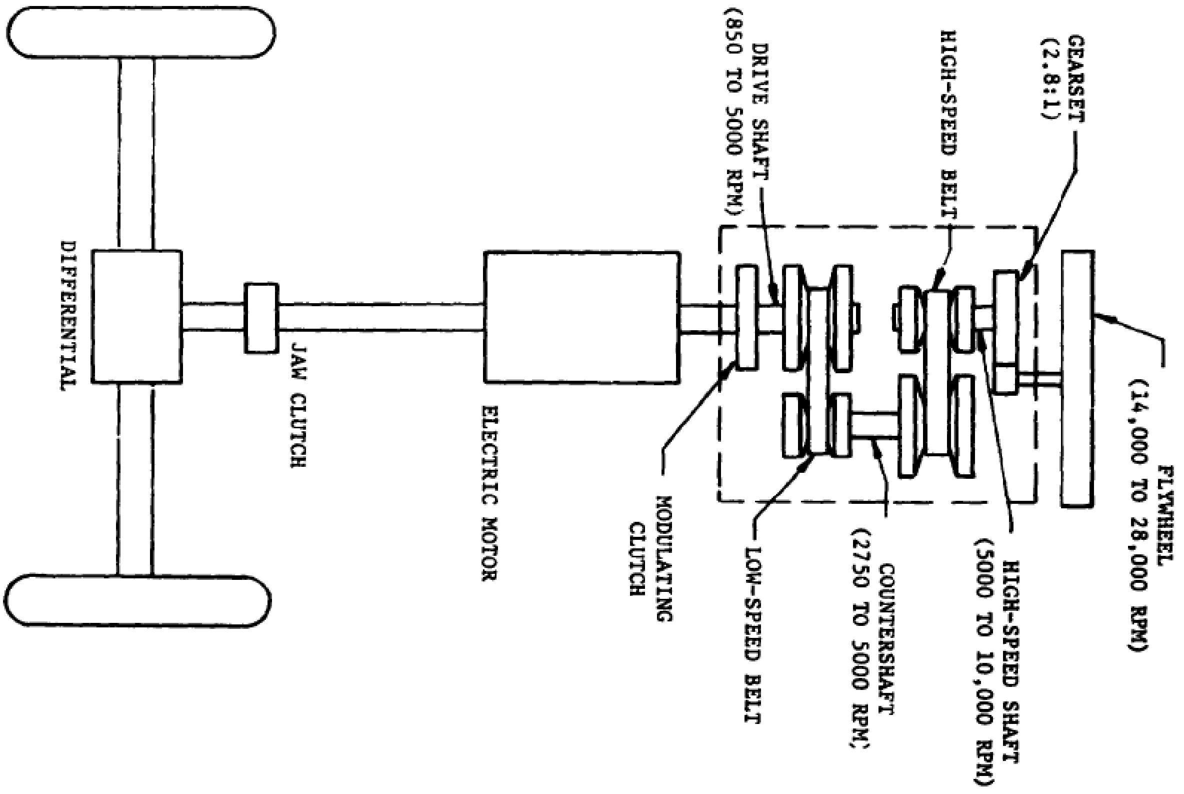


Figure 14 Battelle Columbus Laboratories concept

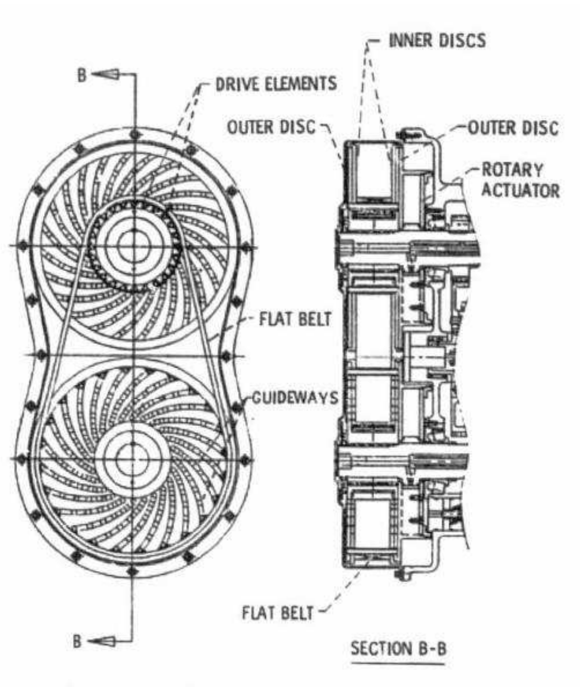


Figure 15 Kumm concept

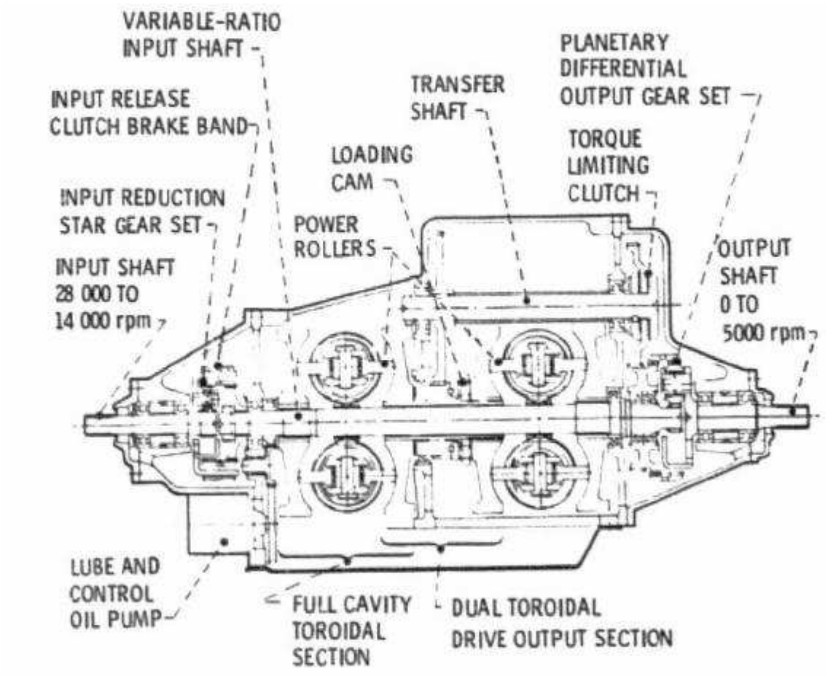


Figure 16 Garrett Concept

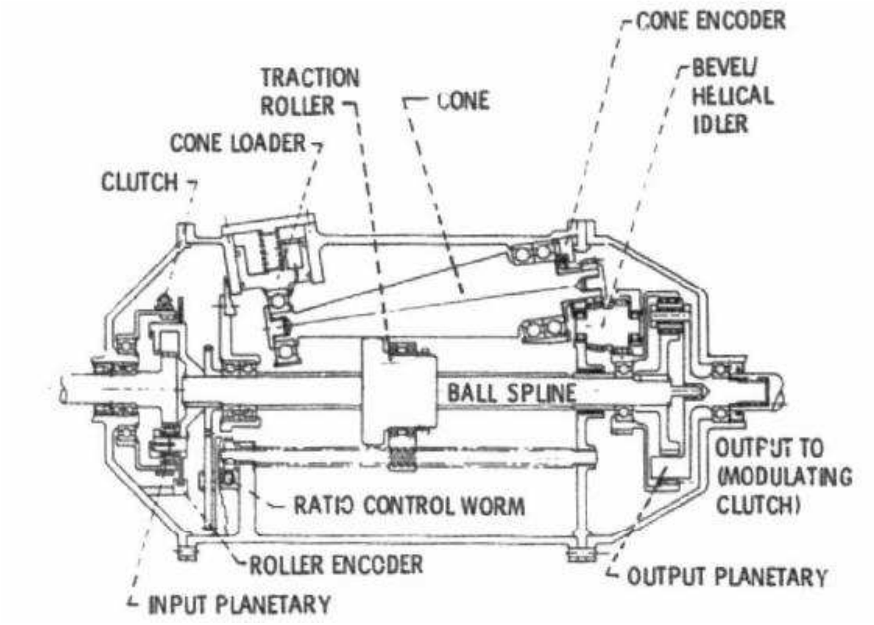


Figure 17 Bales-McCoin Inc. concept

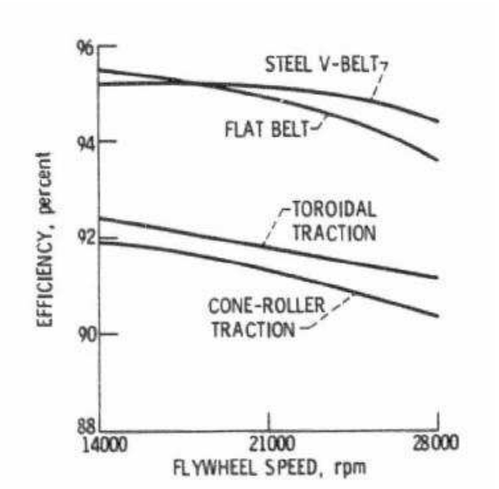


Figure 18 Comparison of the four concepts

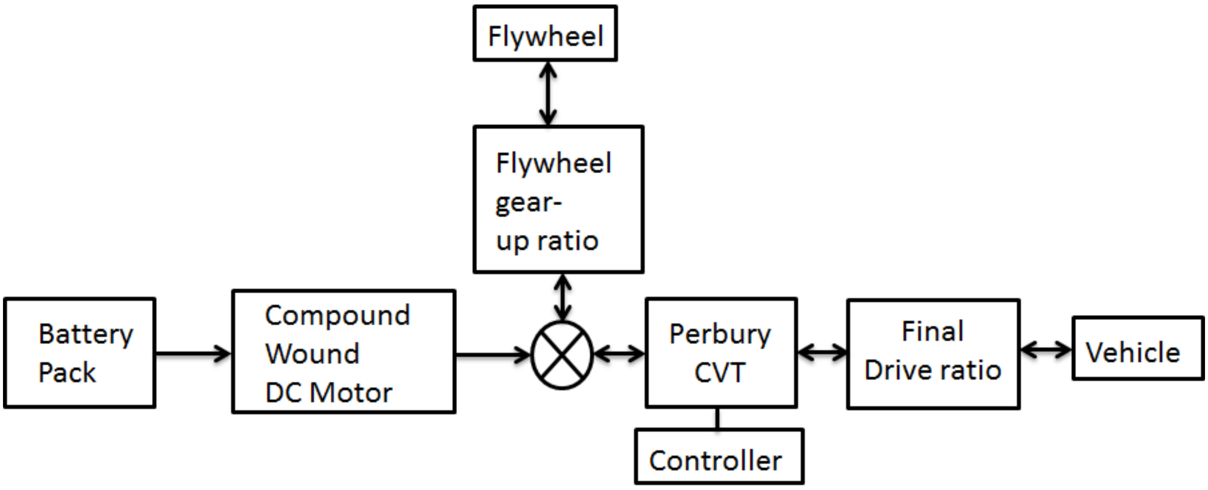


Figure 19 Sussex system

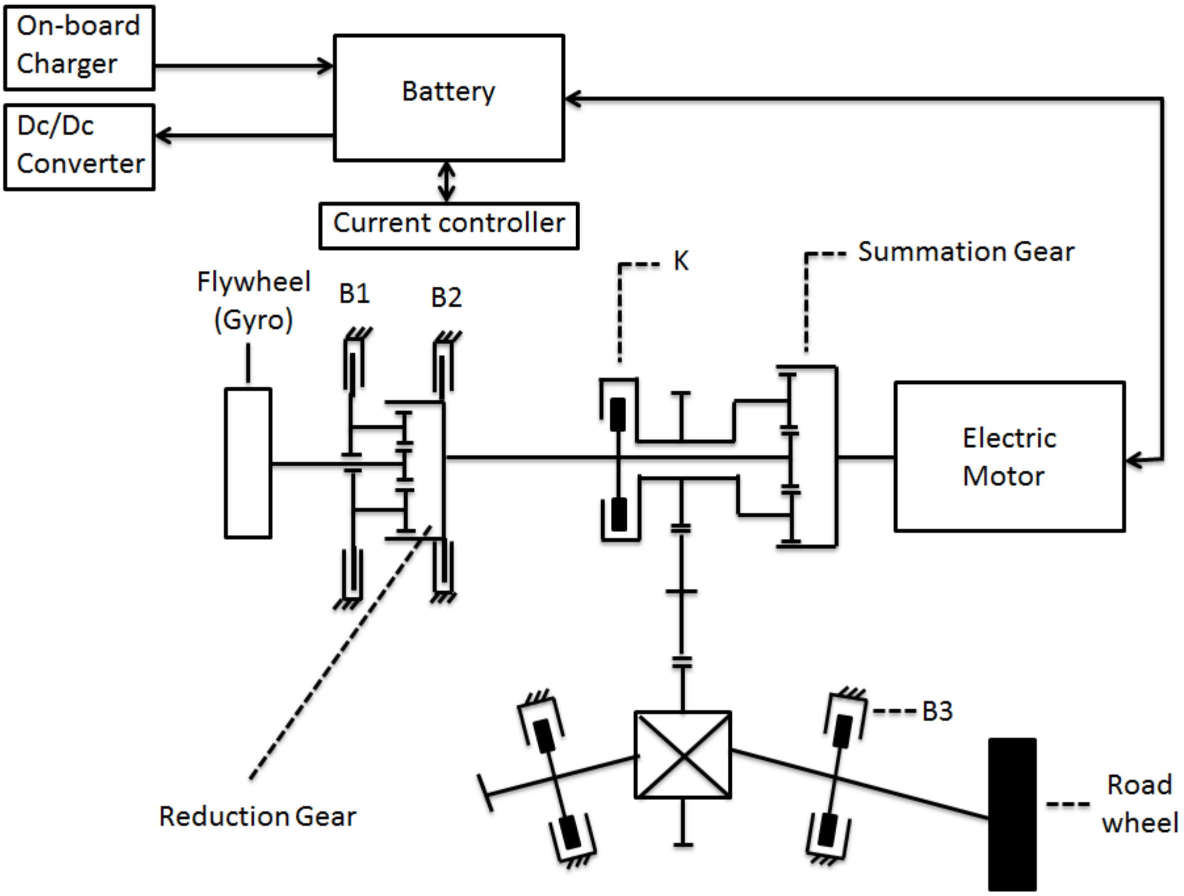


Figure 20 BMW concept

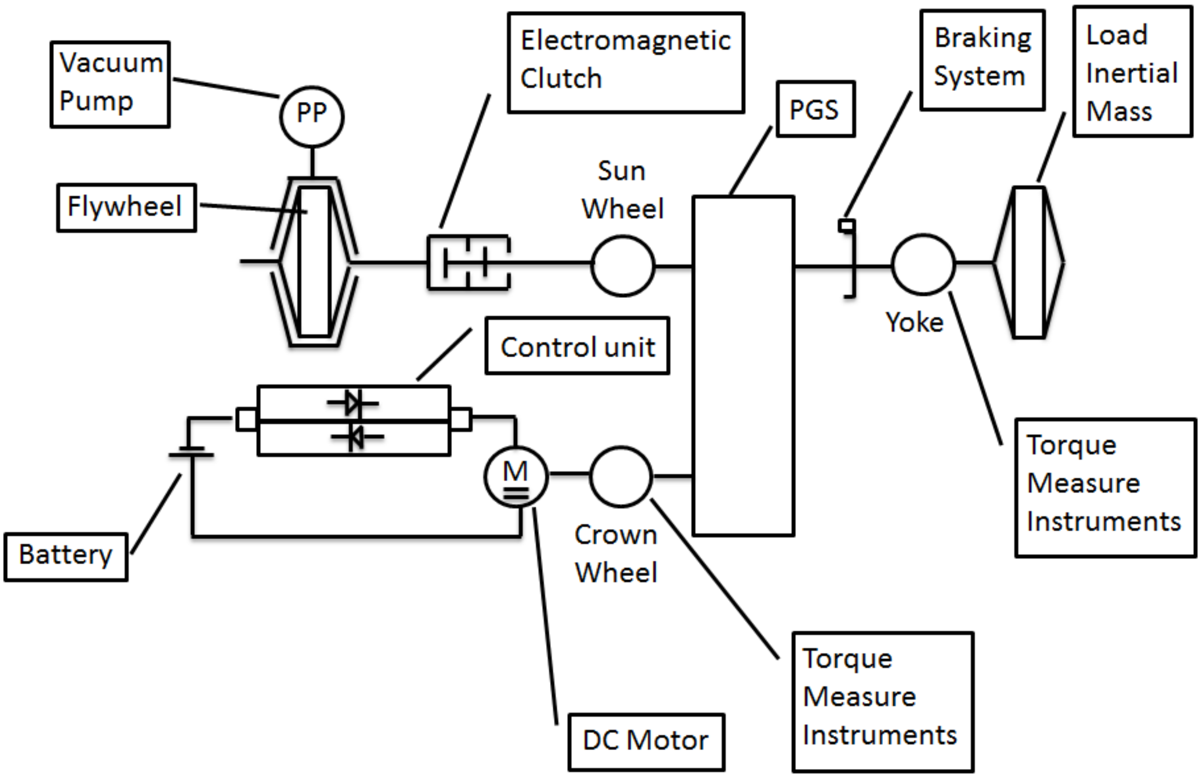


Figure 21 Szumanowski concept

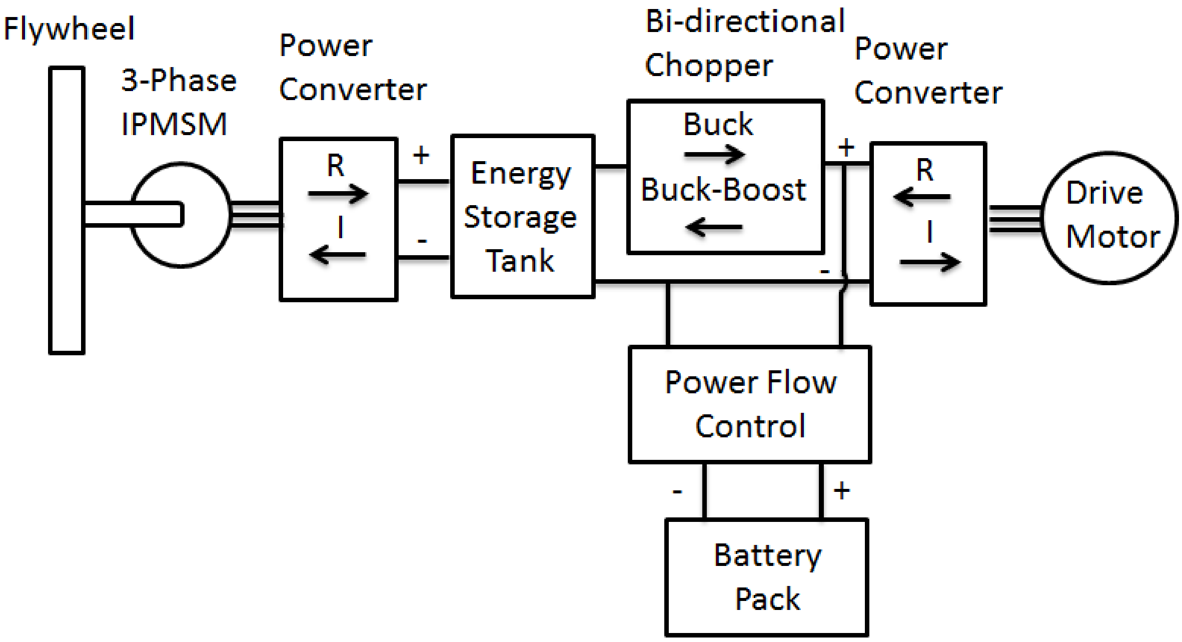


Figure 22 Schaible concept

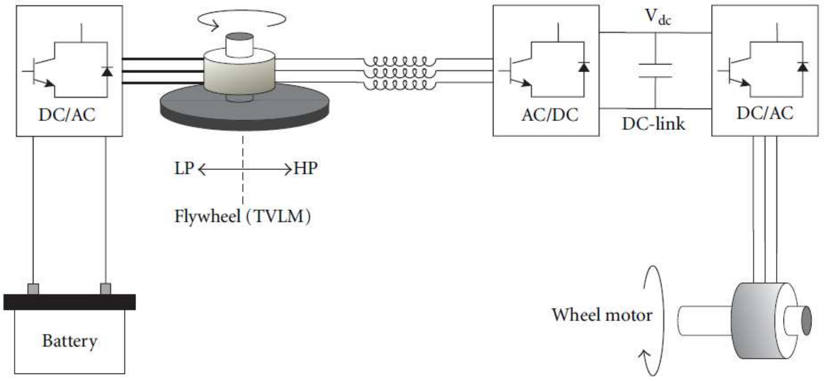


Figure 23 Lundin concept