RESEARCH ON A REGENERATIVE BRAKING SYSTEM FOR A GOLF CART

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1 ABSTRACT

In the course of a senior design project at the University of Portland in Oregon, a golf cart powered by a traditional petrol engine has been converted into a battery powered electric vehicle (BEV). As a future project, the implementation of a regenerative braking system (RBS) is planned. However, various types of regenerative braking systems exist, which can initially lead to confusion and uncertainty about the right technology to follow. Thus, the aim of this research is to serve as an initial RBS guide, providing background information about regenerative braking, as well as a detailed investigation and comparison of existing regenerative braking systems. Then, based on the knowledge acquired, two solutions tailored to the relatively light golf cart are proposed. Finally, future improvements and developments for the suggested solutions are described.

As a conclusion, it was discovered that an electric regenerative braking system seems to offer the most promising technology for the cart. This is due to several reasons, including the beneficial functional properties determined in the RBS comparison, and senior design project constraints regarding scope and budget. An important point to be considered in the design of an RBS solution is that the golf cart is a rear axle powered vehicle. Thus, a smart blend of regenerative braking and friction braking is highly required. Since a DC series motor is propelling the cart once converted to a BEV, the first RBS solution proposed foresees keeping the existing components of the electric drivetrain. In contrary, the second solution is based on systems used in similar lightweight RBS applications, however expecting exchanged electric drivetrain components. A brushless DC motor including appropriate controller is suggested and would form a common RBS together with the battery pack. Eventually, as an improvement for any battery powered vehicle with an electric RBS, a combined energy storage comprising ultracapacitors and batteries is illustrated. This leads to an increased lifetime of the batteries and protects them against fast and sudden charge/recharge cycles.

2 INTRODUCTION

The University of Portland, Oregon, owns a golf cart, powered by a traditional petrol engine. Through the course of a project in the academic year 2015/16 this cart is converted into a battery powered electric vehicle (BEV). Since the cart already has an existing running gear, the project focusses on construction and successful implementation of an electric drivetrain by the end of the spring semester 2016. For a future project however, the addition of a regenerative braking system (RBS) is planned.

2.1 RELEVANCE OF THE TOPIC

Regenerative braking systems recover a part of the energy that is necessary to brake the vehicle. Instead of using friction to slow down, a regenerative braking system uses the moment of inertia of an actuator to decelerate, regenerating energy at the same time. In an electric regenerative braking system for example, the actuator is an electric motor, which is normally propelling the vehicle. However, it will be operated as a generator under regenerative braking. The energy regenerated can then be harnessed to recharge the energy storage of the vehicle [1].

With an increased demand for less consuming and less polluting vehicles, electric vehicles and hybrid vehicles have gained popularity. However, the limitation of driving mileage for electric drives is still an obstacle that has to be remediated. With an enlarged driving mileage per tankful, also the cost per mileage decreases, because the same amount of energy allows longer travel distances. Thus, existing solutions for this issue are a big topic for the future of transportation. One way of doing so is using an RBS [2]. Two studies in [3] and [4] indicate that a 1600 kg vehicle can experience theoretical fuel savings of up to 23% on a level road during urban driving, given the case that a regenerative braking system was supplemented. However, this saving is decreased as the weight of the vehicle decreases, resulting in theoretical savings of about 15% for a 1000 kg vehicle. Because a golf cart is even lighter, maximizing fuel savings is a demanding challenge. Thus, the selection of the most suitable regenerative braking technology is a key point to be researched.

2.2 TARGETS OF THIS RESEARCH

Since the implementation of an RBS would go beyond the scope of the conversion project mentioned, the research should facilitate students in the initial phase of a future RBS-project. To assist in the classification and evaluation of existing RBS technologies, detailed descriptions of the technologies available are included, followed by a general comparison of them in chapter 4.4. Based on the findings of the comparison and the specific case of the golf cart, an argumentation about the ideal RBS technology is presented. Two proposed RBS solutions using this technology are then tailored to the golf cart. In addition, recommendations for future actions to be carried out are given, in order to improve the proposed solutions. With this, the following scientific questions are answered:

- What are the different systems of regenerative braking that exist?
- Which regenerative braking system is most suitable for the golf cart belonging to the University of Portland?
- What will the final system look like and how will it be integrated in the rest of the yet to be developed electric drivetrain?
- Which developments and improvements will have to be done in following semesters?

To start off, background information about vehicle braking and regenerative braking in particular is given to assist the reader in understanding the underlying ideas and requirements of a regenerative braking system.

2.3 APPLIED METHODOLOGY

The methodology applied in this research to find answers to the scientific questions was a literature review. Mainly journal articles were considered, but also books and relevant internet sources. The most recent sources of information were preferred.

Key words used during the quest for appropriate, contemporary literature were regenerative braking, regenerative braking systems, regenerative braking systems AND EV, regenerative braking technology, and regenerative braking comparison. The search was executed on several databases, including University of Portland Library OPAC, University of Applied Sciences Upper Austria Library OPAC, IEEE Xplore and Mendeley Research Papers Database.

3 THEORETICAL BACKGROUND

This chapter gives theoretical background information on regenerative braking, which is crucial for understanding the function and need of a regenerative braking system (RBS). First, braking of vehicles and motors is presented. The braking theory gives insight into the optimal braking process of a vehicle. This is followed by introductions to electric braking technologies and hybrid braking systems. Then, typical driving cycles for testing an RBS are illustrated. The last part of the chapter investigates regenerative braking in general and gives information about the fields of application, the components, the working principle, common advantages and disadvantages, efficiency, design and regenerative braking control.

3.1 BRAKING OF VEHICLES

Although the conventional braking method in passenger vehicles is based on friction, braking of vehicles can be executed in other ways too. However, every braking technology follows a certain braking theory, which deals with the distribution of the braking forces on the wheels. This chapter gives insight into both the basic theory of braking, as well as electric and hybrid braking technologies.

3.1.1 Basic Theory of Vehicle Braking

The braking theory around conventional braking has been well established over time. It represents a solid model every type of braking should adhere to, in order to achieve the shortest braking distance possible and maintaining vehicle stability. The theory gives information about the optimal distribution of the total braking force on front and rear wheels [5].

A fully loaded passenger car mass of 1500 kg (1250 kg unloaded) is the basis for this braking theory. Ignoring rolling resistance and aerodynamic drag, the forces that impact on the vehicle can be split to W_f and W_r. Force W_f represents the normal force acting on the two front wheels of the car, while W_r is the force acting on the two rear wheels, as shown in Figure 3.1 [5]. They are expressed as:

$$W_f = \frac{Mg}{L}(b + \frac{j}{g}h_g)$$

$$W_r = \frac{Mg}{L}(a - \frac{j}{g}h_g)$$

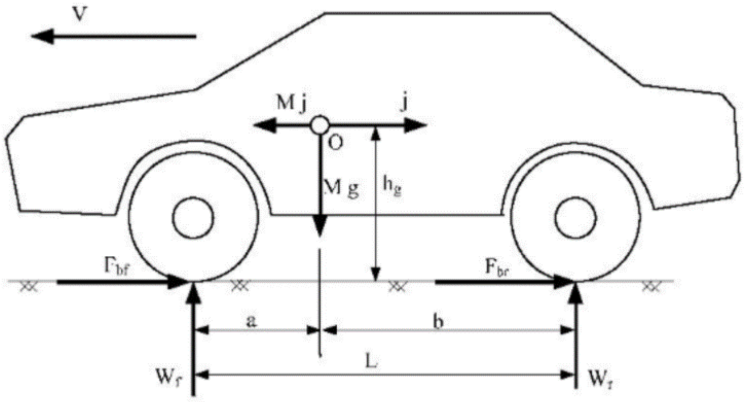


Figure 3.1 Forces acting on the car while braking [5]

In the two formulas given above, a and b are distances measured from the center of gravity of the car O. The vehicle deceleration j is given in m/s^2, and is derived from the relation of total braking force F_b divided by the total mass car M.

$$j = \frac{F_b}{M} = \frac{F_{bf} + F_{br}}{M}$$

On Figure 3.1, the force F_{bf} corresponds to the front braking force and force F_{br} corresponds to the rear braking force. At optimal braking performance, force F_{bf} should be proportional to the normal force W_f, and force F_{br} should be proportional to force W_r, as stated in the formula below:

$$\frac{F_{bf}}{F_{br}} = \frac{W_f}{W_r} = b + \frac{\left(\frac{j}{g} h_g\right)}{\left(a - \frac{j}{g} h_g\right)}$$

These conditions imply a simultaneous locking of both front and rear wheels. Because $j = g\mu$, the formula above can be taken further and results in [5] into:

$$\frac{F_{bf}}{F_{br}} = \frac{\left(b + \mu h_g\right)}{\left(a - \mu h_g\right)}$$

The adhesion coefficient μ equals the ratio between the tractive (braking) force and the normal load. It varies with the condition between tire and road, and the wheel slip [6]. In order to create a model that states the optimal braking force distribution for front and rear wheels at various adhesion coefficients, braking force curves have been established [7].

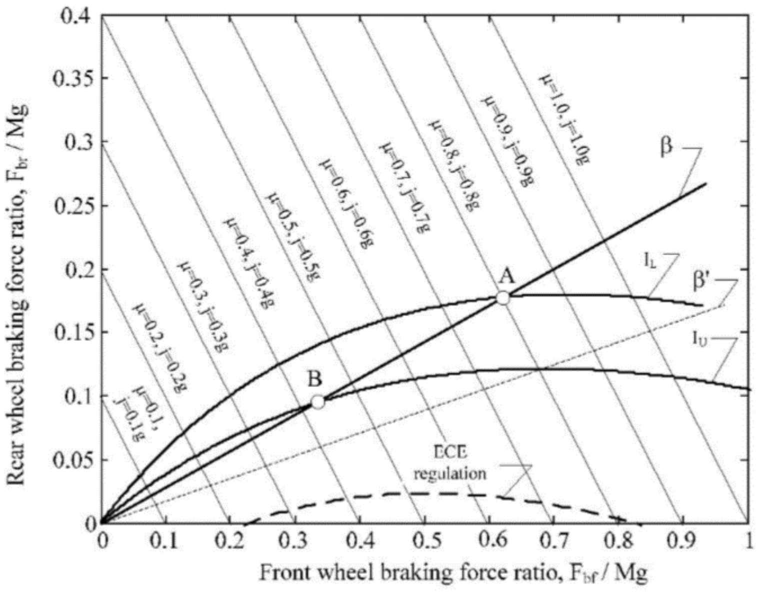


Figure 3.2 Ideal braking and real braking force on the front and rear wheels, and the minimum braking force on rear wheels with loaded condition (ECE-regulation) [5]

Figure 3.2 [5] depicts four braking force distribution curves. The curve labeled I_U is the ideal curve for the unloaded vehicle braking distribution, while I_L represents the ideal curve for loaded vehicle braking distribution. Both I_U and I_L are parabolic curves and embody a rather complex braking force distribution, however leading to maximum braking stability [8]. In contrast to the ideal braking force distributions, for conventional vehicles it is common to handle the braking force distribution by means of a linear function, depicted in Figure 3.2 as the straight line labeled β. For the fully loaded vehicle curve, only one intersection with the ideal curve for loaded vehicles can be found with point A (with μ=0.8). Here, both front and rear wheels are locked at the same time, which represents the desired case. In case the adhesion coefficient is less than 0.8, the front wheels are locked first, followed by the rear wheels. This situation signifies not an ideal, but still a good directional stability. However, with μ>0.8, it can be seen that the values for β exceed the ideal curve I_L. In this case, the rear wheels are locked first, resulting into potential vehicle instability. This situation must be avoided for a safe braking process. An unloaded vehicle shows an even higher instability tendency, as seen with point B, acting as the border to instability at lower μ than for point A. In reality, this case is bypassed by assuring that the rear wheels do never have the possibility to become locked. Thus, for the loaded vehicle, curve β’ is applied, ensuring a limited braking force for every possible value of the adhesion coefficient. The drawback of this convention is an unideal braking distribution, as the front wheels are locked too early. To produce relief, the ECE regulation was created, shown in Figure 3.2 with the curve labeled ECE-regulation [5]. The United Nations Economic Commission for Europe set this regulation, which full name is ECE13-R, to ensure braking safety. Figure 3.3 [8] summarizes the information given and displays the permitted area of braking distributions.

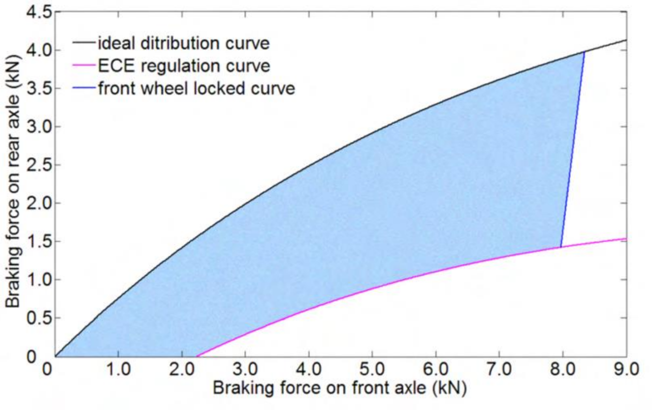


Figure 3.3 Permitted area of force distribution [8]

Today, sensors are able to exactly determine the vertical loads of front and rear wheels. Thus, braking forces can be applied precisely to follow the ideal braking distribution and to use the maximum adhesive capability between road and tire [7].

Summarizing the information included in this chapter, it is given that a vehicle must follow the braking force distribution curve described, in order to brake in the shortest distance and to avoid losing control. The braking force distribution diagrams help selecting the right curve and assure that the ECE- regulation is complied. At the same time, it is ensured that the maximum rear braking force is not exceeded. This point is significant, because blocked rear wheels lead to potential vehicle instability. Finally, recent sensor technology allows a precise determination of the braking forces on each wheel, thus improving the braking process.

3.1.2 Electric Braking of Motors

Electric braking is an alternative to mechanical braking and offers advantages such as high efficiency and a low maintenance. Three types of electric braking methods can generally be distinguished: dynamic, countercurrent and regenerative braking [9]. In order to understand the differences of dynamic and countercurrent braking to regenerative braking, they are presented in the following subchapters. Regenerative braking is explained in detail in chapter 3.2.4. Last in this chapter, an electric braking technology is presented, which can only be applied on a number of AC machines.

3.1.2.1 Dynamic Braking

This chapter illustrates the working principle, fields of application and the benefits of the first electric braking technology discussed: dynamic braking.

With the rotation of an electric motor, kinetic energy is saved in the turning mass. If no type of braking is employed, the kinetic energy is dissipated only because of friction and windage losses, which results in a slow motor stop [10]. In dynamic braking, the kinetic energy is converted into electrical energy and then dissipated in heat. In order to achieve this, the motor is detached from its power source and works as a generator. It is connected to resistive elements, which allow a braking current I_B flow. Thus, the dissipation of electrical energy is made possible, slowing down the machine. The braking time is directly proportional to the rate of energy dissipation, which increases with a higher braking current. As a result, the resistive elements should be designed small [9]. However, as the turning mass is slowed down, less kinetic energy is available for conversion. Thus, the current I_B is decreased and the energy dissipation lessens. As a result, the machine cannot be stopped by using the methodology of dynamic braking only [11].

A dynamic braking method is mostly used for emergency and safety braking. It shows various advantages for these applications. First, it is a simplistic braking method, using only the motor installed without requiring any external braking elements. This represents at the same time a safety factor, as no external sources of power are needed to perform the braking. Another big advantage is the usefulness of dynamic braking in situations in which the wheels are slipping while braking. Once the wheels are locked due to slipping, the dynamic braking force exerted decreases. Thus, the wheels start revolving again and a faster stop of the vehicle is attained, compared to a stop with locked wheels. As mentioned at the very beginning of this subchapter, the braking force is highest at high speeds of the vehicle. As a result, dynamic braking offers a rapid initial slowdown, which is beneficial for the prevention of accidents. Typically, dynamic braking is employed on high-speed drives, reducing their initial speed to a lower level. Then, other braking systems like frictional brakes are applied [11].

An exemplary field of use for dynamic braking systems are cranes, which can be stopped quickly in the case a power failure. Switches that trigger automatically once a certain speed limit is exceeded enable dynamic braking [11].

To summarize the information of this chapter, it can be said that dynamic braking converts kinetic energy into electrical energy to stop an electric machine. However, this energy is not stored, but immediately dissipated in heat. The braking force shows its peak at the high rotational speeds and is typically not able to stop the motor on its own. The fields of application are mainly emergency and safety braking and the technology can be found on cranes.

3.1.2.2 Countercurrent Braking

This chapter talks about countercurrent braking, including three subchapters. The basic principle is explained first, before separate descriptions for the application on DC and AC machines follow. Last, the method of antiplugging protection is touched.

Countercurrent braking is also known as “plugging”. It is executed by reversing the motor connections, in order to produce a counter torque in the motor. This counter torque operates as a retarding force and finally stops the shaft from turning. This braking method is not only used for rapid braking, but also for a prompt reversal of the rotational direction of the motor shaft. However, before countercurrent braking is operated, it has to be ensured that the machine is able to sustain occurring currents and that repeated countercurrent braking is not harming the machine [12].

Countercurrent braking is applied differently between DC and AC machines and the two approaches are further explained in the following two subchapters.

3.1.2.2.1 Countercurrent Braking for DC Machines

For DC machines, countercurrent braking is structured in two different methods, called plugging and terminal voltage reversal (TVR) [13].

Plugging is used for gravitational-type loads like elevators. To brake an elevator in upward motion using plugging, the initial terminal voltage V_1 is reduced to a lower voltage V_2. This voltage V_2 is too little to raise the elevator, however it should cause a certain current flow that results in a torque that equals the load torque. As a result, the elevator is first slowed down and then stopped. If the torque produced is even less than the load torque, the motor should be detached electrically, otherwise an acceleration in the reverse direction. Frictional brakes are needed then to keep the elevator in standstill [13].

TVR on the other hand is employed by reversing terminal voltage polarities [9]. A sudden change of the input voltage V_T polarity causes a current I_A flow in the reverse direction, producing a counter torque that stops the motor shaft. Since the armature current I_A is based on the voltages V_T and E_a, which in the starting case of TVR add up because they have the same polarity, an excessively large armature current flows. The protection of the machine against these dangerous currents is done by an altered schematic during the braking cycle [13].

3.1.2.2.2 Countercurrent Braking for AC Machines

In order to use countercurrent braking for AC machines, the phase sequence of the stator windings has to be reversed, therefore reversing the rotational direction of the stator magnetic field. A possible interchange is for example from stator winding sequence ABC to sequence ACB. Since the shaft is trying to follow the stator magnetic field, it is first slowed down and, if not stopped at zero speed, it starts turning in the opposite direction. Only if the power supply is detached at zero speed, the machine is stopped by countercurrent braking [9] .

3.1.2.2.3 Antiplugging Protection

Countercurrent braking is not always desired to actuate as the initial braking method of a motor. If the motor does not withstand a large counter torque, an antiplugging protection is installed to prevent the motor from doing so. A switch opening the control circuit of the countercurrent contactor is used to enable plugging as recently as the motor speed is lowered to a value that is acceptable [12].

3.1.2.2.4 Summary: Countercurrent Braking

Briefly described, countercurrent braking implies reversing the motor connections, in order to produce a counter torque in the motor. The retarding force that is the direct result stops the shaft from turning eventually. If not blocked, countercurrent braking can then reverse the rotational direction of the motor shaft.

For DC machines, plugging and terminal voltage reversal (TVR) are known. A countercurrent is established in electric machines by reversing terminal voltage polarity. For gravitational loads like elevators a stop is managed by reducing the supply voltage. AC machines by comparison require an exchange of two of the three stator windings.

Because the starting torque of countercurrent braking can become excessively large, an antiplugging protection was created. It comprises an automatic switch that enables this braking technique at appropriate circumstances.

3.1.2.3 Braking of AC Motors with DC Voltage

Another electric braking technology is described briefly in this chapter. It is applicable exclusively on a small number of AC machines.

This type of braking, classified as electric braking in [14], can be used for two different types of induction motors. It can either be applied on AC wound rotor motors or on AC squirrel cage motors and suggests the usage of DC voltage, which is fed by an all-electric braking controller. This controller can be supplemented to an existing starting controller and introduces direct current to one or all of the three phases of the stator. Thus, a stationary DC field is created, which forces the motor to stop quickly [14].

3.1.3 Hybrid Braking Systems

This chapter touches on the term hybrid braking systems and describes, why they have arisen.

The various braking systems available show individual advantages, but they also have downsides. A regenerative braking system alone is not guaranteed to always provide ample braking force. However, as safety represents the most important concern for the braking of vehicles, hybrid braking systems have been developed. These systems combine different types of braking systems and can be formed with brakes like mechanical, electric regenerative and hydraulic regenerative brakes for example [5].

A regenerative braking system is usually a hybrid braking system, further information is provided in chapter 3.3.

3.2 DRIVING CYCLES

A Driving cycle is an important tool that allows measurements between different vehicles and regenerative braking systems. This chapter first defines them and then talks about the common types of driving cycles. Then, the application of driving cycles for regenerative braking purposes is explained.

3.2.1 Definition

A driving cycle is a fixed schedule of vehicle operation. It allows the execution of various tests to be conducted under reproducible conditions. Some of the applications of driving cycles include emissions measurement, engine testing and drive train durability. Usually, driving cycles are set in terms of vehicle speed as a function of time. They are used in laboratories, as well as on test tracks. For tests, the vehicle speed has to follow the driving cycle speed given within stated tolerances, then measurements can be taken [15].

3.2.2 Cycle Types

Since the various tests require different testing parameters, numerous different driving cycles have been developed for cars, vans, busses, trucks and motorcycles. They can be divided into “steady state” cycles and “transient” cycles. Only latter ones are used for measurements of regenerative braking properties, as they include more or less continuously changing vehicle speed and engine load [15].

Only a few cycles have been used for the majority of tests. These cycles are mainly defined in legislation of the corresponding countries. Although they are highly stylized in general and do bear little relation to real driving patterns, they are used to approve new vehicle models. The New European Driving Cycle (NEDC) is one example for it. In contrast to that stand the real-world cycles, which are more transient than legislative cycles [15].

3.2.3 Application for Regenerative Braking

For literature about regenerative braking systems, exemplary driving cycles used for measurements of regenerative braking properties are NEDC, ECE-driving cycle, Federal Test Procedure FTP75, Supplemental Federal Test Procedure (SFTP), New York City Cycle (NYCC), Urban Dynamometer Driving Schedule (UDDS) and the Chinese Urban Bus Driving Cycle [8], [5], [16].

Figure 3.4 [5] depicts a use case for the FTP75 urban driving cycle. Traction and braking energy consumption are measured along the speed dictated by the driving cycle.

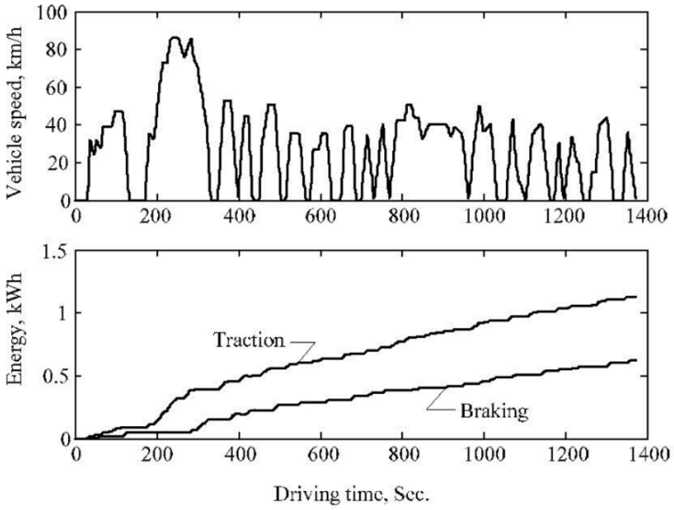


Figure 3.4 Traction and braking energy consumption in FTP75 urban driving cycle [5]

3.2.4 Summary: Driving Cycles

To summarize the information given above, a driving cycle is a fixed schedule of vehicle operation. Various tests can be conducted under reproducible conditions and are provided afterwards for comparisons of the vehicles. For regenerative braking applications, measurements of traction energy and braking energy can be carried out for example.

3.3 REGENERATIVE BRAKING

Braking theory, several electric braking systems and driving cycles were introduced in the chapters above. This chapter is a general introduction to regenerative braking. First, it is explained what a regenerative braking system is, what components it usually comprises, what the advantages, disadvantages and fields of application there are. Then, efficiency of regenerative braking and factors for a successful usage are illustrated. Moreover, regenerative braking design and the regenerative braking controller are presented.

3.3.1 What is Regenerative Braking?

This chapter introduces regenerative braking. It explains what regenerative braking is and outlines the advantage offered over conventional braking technologies.

Conventional braking technologies convert the potential and kinetic energy of a moving vehicle into thermal energy by means of friction [16]. This thermal energy is practically wasted, as it is carted off by airstreams [17]. In contrast to that, regenerative braking technologies do capture and store kinetic energy in a converted form while braking. They can either feed energy back to the motor while accelerating, or recharge the power supply [1]. The amount of energy, which is available for storage, depends on multiple factors, including drive train efficiency, drive cycle, inertia weight and the type of storage [17].

3.3.2 Importance of Regenerative Braking

The importance of regenerative braking is demonstrated in this chapter by explaining its main benefit. Figures and examples emphasize the importance.

With an increased demand for less consuming and less polluting vehicles, electric vehicles and hybrid vehicles have gained popularity. These vehicle types assure reduced operating costs and are also known as green vehicles [17]. However, even though vehicular control technology and integrative technology have been developed intensively, the limitation of driving mileage for electric drives is still an obstacle that has to be remediated. One way of doing so is using an RBS (regenerative braking system) [2].

In urban driving, about one third to one half of the entire energy necessary to operate the vehicle is used for braking [18]. Studies have presented that fuel economy for hybrid vehicles could be enhanced up to about 30% with regenerative braking [17], [19]. For fully electric vehicles on the other hand, an enlarged driving range of 8-26% could be expected if such a system was implemented [2], [20]. In [1], which discusses regenerative braking technologies for heavy goods vehicles, a comparison of various fuel reduction measures is depicted. It states regenerative braking with a 20% reduction potential, followed by stop-start hybrids, aerodynamic improvements and tire improvements with the relatively little amount of about 7%, respectively. Hence, a regenerative braking system is substantially improving the energy efficiency of vehicles [20], [21].

Briefly summed up it can be noted that regenerative braking systems significantly enlarge driving range and reduce emissions. Both is desired for recent fully- and hybrid electric vehicles, which are increasingly demanded by the market. Thus, regenerative braking systems possess an inherent importance for the future of transportation.

3.3.3 Fields of Application

Two significant fields of application could be identified in literature. They are mentioned in this chapter. The field of application relevant to this paper is further described with historical facts.

Important regenerative braking application areas that could be identified are the fields of transportation and cyclic working motions [22]. This paper focusses mainly on transportation, which embodies the origin of regenerative braking.

Arising first from trains in electrified railways, using the electric motor as a generator for braking, regenerative braking was then introduced to various metro systems [17]. Among them are systems in Vienna [23], Caracas [24] and Sao Paolo [25].

Since electric motors today cannot only be found in trains, but also in electric vehicles, regenerative braking expanded to vehicles like e.g. cars and heavy goods vehicles (HGVs) [11], [13]. However, many of the vehicles mentioned possess internal combustion engines (ICEs). These engines do not offer the same simplicity for implementing a regenerative braking system, because the energy conversion processes are irreversible. Thus, they require further equipment and become a hybrid system [26].

In plain language, regenerative braking systems for transportation purposes have emerged in electrified trains and expanded eventually to electric vehicles. For vehicles driven by an ICE, further equipment is necessary, leading to hybrid propulsion systems.

3.3.4 Components of a Regenerative Braking System

In this chapter, the common components of an RBS are listed. Furthermore, examples of them for several technologies are stated.

In order to not only capture, but also store energy, every regenerative braking system consists of an actuator and an energy storage device, respectively. In many cases found in literature, also a controlling unit is part of the RBS. In the case of a typical electric vehicle (EV), the actuator is an electric machine (motor/generator) and the energy is stored in the battery, the power source of the vehicle. Common actuators are electric machines, hydraulic pump-motors, CVTs (continuously variable transmissions) and air-powered motors. As energy storage devices are batteries, ultracapacitors, metal accumulators, flywheels and elastomer systems named [1].

The braking controller establishes the link between actuator and energy storage device. It controls the overall process of the actuator, monitoring wheel-speed, calculating braking torque and directing generated electricity during braking into the energy storage device. The braking controller receives information from the driver (usually through pedal position) and translates it to actual machine prompts [2].

To summarize the information given in this chapter, it can be said that any regenerative braking system includes an actuator and an energy storage device, respectively. Generally, also a controlling unit, called braking controller, is part of the RBS.

3.3.5 Classification of Regenerative Braking Systems

This chapter talks about the classification of the regenerative braking systems used in this paper.

Regenerative braking systems can be clustered in the different technologies they are based on. These include electric, kinetic, hydraulic and other technologies [1], [17]. All of them are presented in detail in chapter 4. Regenerative braking systems are generally supposed to be hybrids, because the actuators capture energy in one form, which usually has to be converted then into a different form to allow storage in the connected storage device. An electric machine generates electrical energy, which is then stored chemically in batteries for example [1].

3.3.6 Working Principle for Electric Energy Regeneration

The principle of energy regeneration is described in this chapter, presenting a simple regenerative braking system, the electric RBS.

Electric regenerative braking systems take the electric motor, which is normally used to propel the vehicle, and use it as a generator. Doing so, negative torque is supplied to the driven wheels. The rotation of the wheels represents kinetic energy, and part of it is converted to electrical energy by the generator, which acts as a resistive load. Subsequently, the electrical energy generated can be used for recharging or power supply purposes [20].

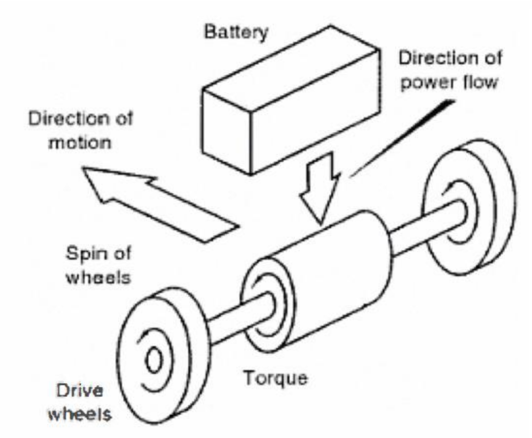


Figure 3.5 Normal forward driving condition as a motor [18]

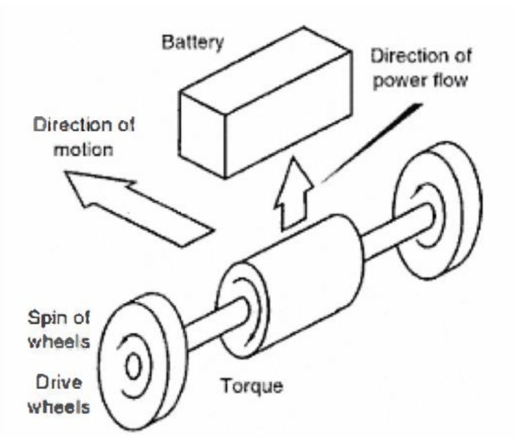


Figure 3.6 Regenerative action during braking [18]

In Figure 3.6 [18], the regenerative braking process for an electric RBS is illustrated. It can be compared to the normal forward driving condition in Figure 3.5 [18], in which the motor propels the vehicle and takes energy from the battery.

Briefly described, the electric energy regeneration is based on the electric machine. It operates as a generator during braking, acting as a resistive load. The battery stores the electrical energy and the process is reversed for acceleration.

3.3.7 Advantages

Next to advantages already mentioned, regenerative braking systems offer several important advantages over traditional braking systems, which are presented in this chapter.

In [27], [22], [28] and [2], the following advantages are summed up:

- Better fuel economy and driving range; conditioned inter alia by control strategy, powertrain design, duty cycle and efficiency of individual parts
- More control over braking
- Increased efficiency and effectiveness in stop-and-go driving
- Reduction of wear on mechanical brake system
- Prolonged lifespan of friction brakes and vehicle battery

For hybrid vehicles, a few advantages have to be added. First, a regenerative braking system is contributing to the reduction of emissions. At the same time, a reduction in engine wear is possible, e.g. through on/off strategy in stop-and-go driving. Using an RBS allows downsizing or even eliminating of existing components. An example for that is downsizing the fuel tank and thus compensating the weight of the regenerative braking components added. Last, regenerative braking for hybrid vehicles offers a comparable driving range to conventional vehicles already today.

Summarizing the general advantages of an RBS, one can deduce that better fuel economy and extended driving range are the most outstanding ones. Also an increased control over braking is possible and wear on the mechanical brake system is reduced. Thus, the lifespan of friction brakes and the battery are prolonged. Hybrid vehicles show extra benefits, like a reduction of emissions or downsizing of the engine.

3.3.8 Disadvantages

Regenerative braking offers many advantages. However, also potential disadvantages do exist, which are described in this chapter.

First, a regenerative braking system cannot fully replace friction brakes. Three main reasons are known for this, including the fact that the wheel torque capacity of electric motors is commonly less than the one for friction brakes. Additionally, the ability of regenerative braking to control the braking force distribution is limited [29] and the time response of charging systems is restricted [30].

Second, a size constraint is known for cars. Regenerative braking systems must be designed as small as possible, yet efficient enough [27].

Third, added extra components increase the weight of the vehicle. This is especially crucial for hybrid vehicles, as several parts must be complemented and fuel consumption is generally increased with the weight of the vehicle, offsetting the actual benefits of the RBS [27].

Fourth, as mass production is not yet standard for regenerative braking systems, significant expenses for planning, manufacturing and installation arise [31], [27].

Next, there is a safety concern with energy storage of high energy density, but which is desired for an efficient RBS. Passengers must be protected and the chance of dangerous failure must be minimized [27].

Sixth, also unwanted noise can occur, depending on the technology selected. Seventh, although regenerative braking systems reduce the wear on mechanical brake systems and therefore seem to reduce maintenance, they can imply maintenance efforts for the extra components added. This introduces the last disadvantage, which is an increased complexity of the braking system and its control system [27].

The downsides of regenerative braking systems can be summed up as follows: Regenerative braking systems cannot fully replace friction brakes, mainly because the braking torque is not sufficient for every situation. Next, size and weight of the system take away precious space and add weight to a vehicle. Since mass production of RBS is not standard yet, such a system require significant expenses. Other disadvantages include unwanted noise, maintenance efforts and increased complexity of the braking system.

3.3.9 Requirements for Successful Usage

Although regenerative braking systems can theoretically be applied to every type of vehicle, some requirements have to be fulfilled for a successful application and energy regeneration. Several requirements that were found in literature are presented in this chapter.

The total amount of energy that is possible to regenerate while braking depends to a big part on the driving condition. The more braking action involved in a driving cycle, the more braking energy is available for regeneration [2]. Urban driving conditions given in urban driving cycles are therefore an ideal area for regenerative braking systems, clearly preferred over highways. Because the inertia weight, based on vehicle weight, is also an important factor, prospective possibilities are offered to city busses, taxis, delivery vans etc. [17]. Figure 3.7 [32] gives insight into the effect of both vehicle mass and speed on the regeneration energy. It can be seen that latter increases non-linearly with increased mass and speed. Furthermore, it is also deduced that values for the regeneration energy can be expected to be less than maximum for high-load and low-speed conditions, while low-load operations result into the lowest values.

Since the efficiency of a propulsion system is improved with an RBS, the initial cost of implementation should be paid back with energy savings over a specified timespan. Otherwise, the system is not cost effective. Additionally, the system must be of compact size and capable of handling high power levels [17].

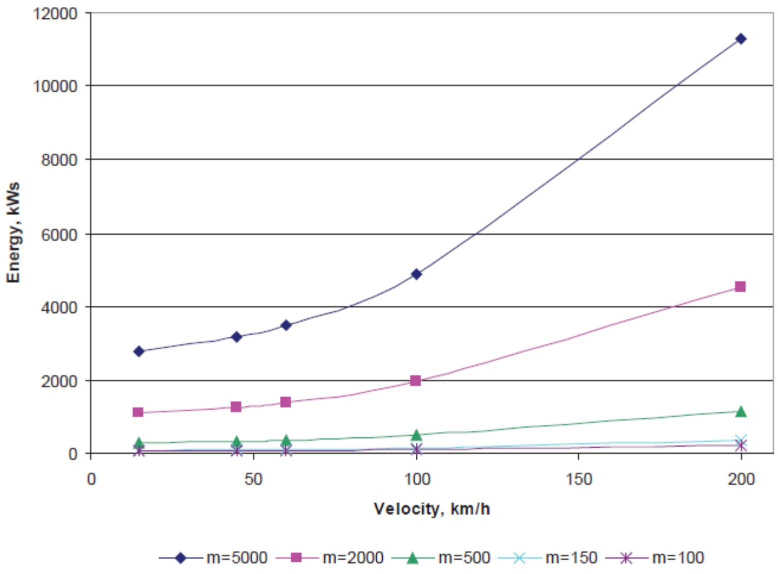


Figure 3.7 Energy with respect to the speed at different traction masses [32]

Further requirements are included in [33] and [32] as:

- High capacity per unit weight and volume energy storage systems
- Optimal braking control
- High power rating to allow large energy flows per time
- Braking energy absorption in direct proportion to braking
- Smooth power delivery from storage to actuator
- Proper drive tuning provided
- Efficient energy conversion

This chapter illustrated that urban driving conditions given in urban driving cycles are an ideal area for regenerative braking systems. Highways demand little braking action and are therefore not suitable. In addition, the vehicle inertia weight has a big impact, offering prospective possibilities to heavier vehicles like city busses, taxis or delivery vans. Further, the system must show a compact size and be able to handle high powers. Smooth power delivery to the actuator, adequate braking control and being cost effective are other important factors that influence a successful usage of an RBS.

3.3.10 Efficiency of an RBS

This chapter discusses the efficiency of a regenerative braking system, presenting a typical power distribution in a battery electric vehicle. The following subchapters describe various factors that influence the energy regeneration efficiency and effectiveness.

An efficient energy conversion is demanding little losses of energy per component. However, of the total power supplied, less power is actually used for braking due to losses. The same is valid for regenerative power, which is reduced again for a significant amount. Figure 3.8 [32] depicts the typical power distribution in battery powered electric vehicles. An input-output efficiency of energy source and drive train is stated in [34] as 70 to 80%, which is available at the wheels. The amount of regenerated power is no more than 20 to 50% of the wheel power, or 20-35% of the total traction power.

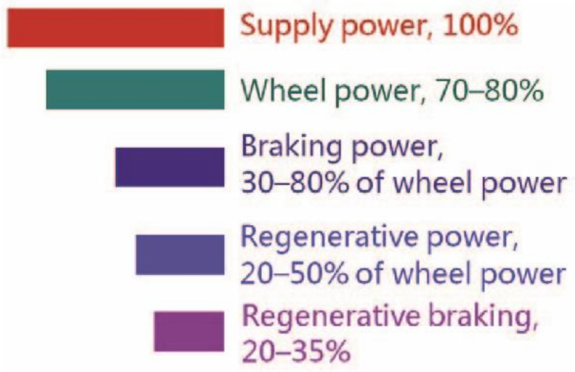


Figure 3.8 Power distribution in BEV [32]

This information is summarized as the regenerative braking efficiency and is accounted as follows:

$$\eta_b = \frac{W_{wb}}{W_w}$$

W_{wb}, the energy available at the wheels after regeneration, is put in relation with W_w, the energy captured from the wheels before regeneration [32].

3.3.10.1 Motor Speed

The recommended operating time of a regenerative braking system varies with the different technologies. However, it is also largely determined by the braking power available, which changes with the speed of a vehicle.

Figure 3.9 [5] shows the braking energy distribution on vehicle speed of a typical passenger car in the FTP 75 urban driving cycle. As can be seen, the braking energy applied in the low speed area is relatively small. The maximal energy that can be recovered by a regenerative braking system is based on the total braking energy applied. The more braking energy required, the

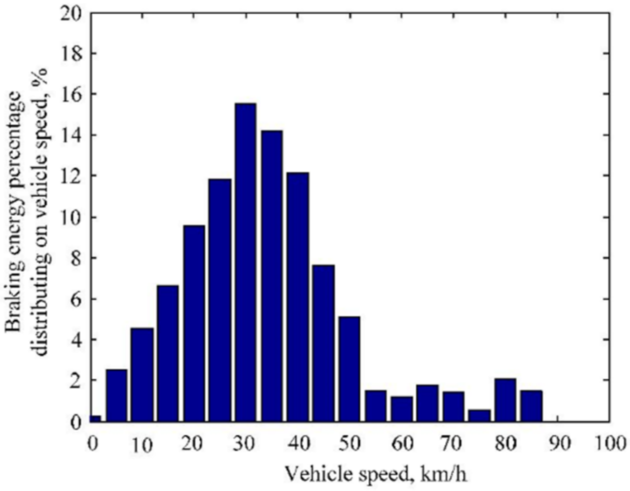


Figure 3.9 Braking energy distribution on vehicle speed in FTP 75 urban driving cycle [5]

more energy can be recovered. At the same time, the more braking energy recovered, the more effective the regenerative braking system. Thus, regenerative braking is not very common for speeds up to 15 km/h [5].

3.3.10.2 Battery Charge Power

If the energy storage device of the vehicle is a battery, the battery charge power is influencing the possibly regenerated power. The larger the charge power of a battery, the more power can be regenerated. This is illustrated in Figure 3.10 [8].

Charge power P_{ch} is the power available to recharge the batteries. It is calculated by taking P_{gen}, the electric power the electric motor generates, and subtracting the average power for any accessories P_{ac}.

$$P_{ch} = P_{gen} - P_{ac}$$

In case of charge, power P_{ch} is positive, while it is negative during discharge. To describe the charge process in a battery, an internal resistance battery model is adopted. Hence, the battery is characterized with a voltage source and an internal resistance. If current I is flowing into the battery, charge power can be described by the following formula.

$$P_{ch} = EI + I^2R$$

The open circuit voltage E, which changes with the battery state of charge (SOC), is multiplied with the charge current I, while the second part of the summation above is formed by the power transformed at the internal resistance R [8].

The battery SOC is an important parameter describing the residual capacity of the battery. It can be estimated through data about the collected voltage, current and temperature [35]. For lead-acid batteries, it can be computed roughly with the formula given below, where SOC_0 corresponds to the initial state of charge of the battery, δt to the sampling time and C_p to the Peukert discharge capacity [8].

$$SOC = SOC_0 + \frac{\delta t * I}{C_p}$$

The Peukert discharge capacity varies with the different chemistries of the batteries. However, researchers found that the Peukert constant values for lead-acid batteries should be interpreted very carefully, as a constant discharge current and a restricted temperature increase inside in the battery are required to deliver appropriate results [36].

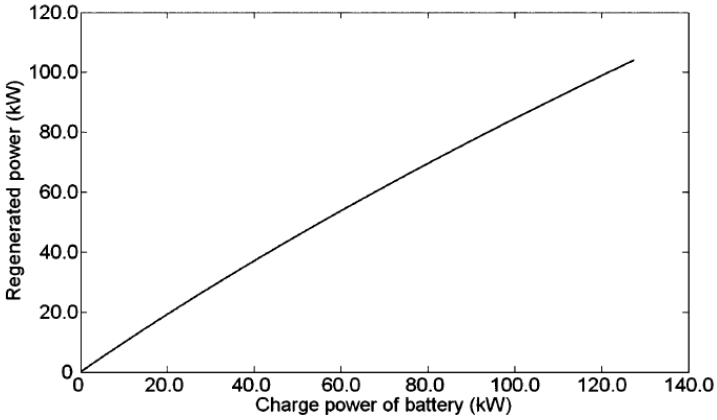


Figure 3.10 Relation between the regenerated power and the charge power of the battery [8]

For other battery chemistries like lithium iron phosphate (LFP), the SOC-model described above is not suitable, because they show a flat discharge characteristic and strongly variable working conditions. Hence, the Peukert relationship should be modified [37].

Finally, the regenerated power as illustrated in Figure 3.10 is calculated in [8] with:

$$P_{reg} = P_{ch} - I^2 R$$

Furthermore, for lithium ion batteries it is explained in [20] that a battery SOC lower than 10% implies a large inner resistance and is therefore unsuitable for large regenerative charging currents. The regenerative braking force should be kept low in this case. Battery SOCs between 10% and 90% are suitable for large regenerative charging currents and the regenerative braking force should be increased appropriately. However, with a battery SOC bigger than 90%, the regenerative charging current should be diminished again, because of the danger of deposit of undesirable substances.

3.3.10.3 Control Strategy

Various control strategies for electric vehicles exist and their heavy influence on braking efficiency is proven with simulations and experiments. In [32], the difference between two control strategies is demonstrated exemplarily with experimental results. The first one is a vector direct torque control (DTC), which uses the built-in current and speed sensors and shows adaptively tuned torque. It is the first technology to control torque and flux directly, reducing response time of the drive [38]. The second control strategy, called scalar open-ended voltage frequency control (VFC), uses no sensors and feedbacks.

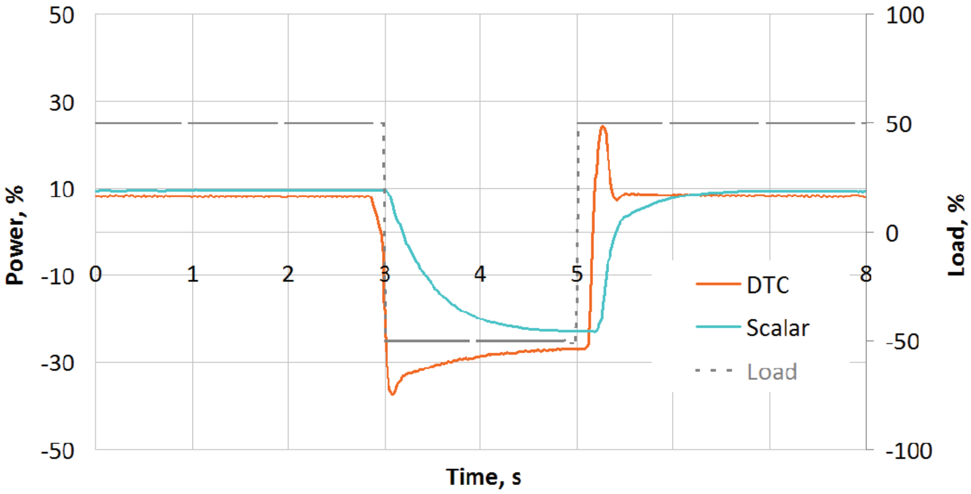


Figure 3.11 Experimental speed and power traces at downhill movement [32]

The difference in the regenerated power can be seen in the timeframe from 3 to 5 seconds in Figure 3.11, which shows an experimental imitation of a short-time downhill movement. The negative power in the timeframe mentioned implies a power flow towards the energy storage system. It is stated that the DTC control strategy regenerates a larger amount of energy, than the Scalar VFC does. Hence, the regenerative braking efficiency is influenced by the control strategy chosen. Further information about regenerative braking control strategies is provided in Chapter 3.3.12.

3.3.10.4 Summary: Efficiency of an RBS

The overall amount of regenerated power is no more than 20% to 35% of the total traction power of a battery powered vehicle. Influencing factors on the efficiency of an RBS are e.g. motor speed, battery charge power, battery temperature and the control strategy. Most braking energy is produced at speeds around 30 km/h and it can only be regenerated with batteries with large charge power. However, the battery charge power changes with the battery SOC, which depends on the composition of the batteries. Lastly, the choice of the control strategy also has a significant impact on the regenerated power: A vector direct torque control delivers higher energy regeneration than a voltage frequency control for example.

3.3.11 Regenerative Braking Design

This chapter talks about regenerative braking design topics, such as the legislative background, crucial design tasks, an exemplary structure of an RBS, braking strategy design and braking force distribution design.

As mentioned earlier, regenerative braking systems alone are hardly capable of providing high decelerations and cannot yet fully replicate the operability of mechanical friction brakes [29], [21]. Thus, it is common to combine regenerative braking with a mechanical braking system, called hybrid braking or multi-mode braking system then [39], [5]. In [21] and [7], it has been found that hybrid braking systems can be electronically controlled and that they are also known as brake-by-wire systems.

3.3.11.1 Legislative Background

EU brake regulations (ECE Regulations 13H and 13.11) on new vehicles braking systems divide the braking systems equipped with a regenerative braking mode into three different categories. Category A includes systems, which do not possess regenerative braking as part of the braking system. In fact, this category describes the regenerative braking mode, which is active when the throttle in a vehicle is released. Category B is split in “Phased-“ and “Non-Phased” braking systems and comprises the regenerative braking system as a part of the overall braking system. Category B - “Non-Phased” leads to a braking strategy called parallel braking. Regenerative braking torque starts being exerted simultaneously to or slightly after the braking torque of friction brakes. Category B - “Phased” on the other hand, implies a consecutive usage of regenerative and friction braking, also known as series braking strategy [40].

ECE regulations 13H and 13.11 also list two conditions for hybrid braking systems of category B to allow regenerative braking application. First, friction brakes must balance the intrinsic variations of the regenerative braking torque, such as battery SOC or motor thermal characteristics for example. Second, the system must act automatically on all wheels and guarantee that the braking demand of the driver is met for changing adhesion coefficients [40].

Additional requirements of the regulations stated above exist about the anti-lock brake system (ABS), which must have control over the torque provided by the regenerative braking [40].

3.3.11.2 Design Tasks

Two important problems must be faced while designing a braking system with RBS. The first one deals with the distribution of the total braking force between the regenerative brake and the mechanical brake, also known as braking strategy. Goal of this distribution is to maximize the braking energy regeneration. The second one refers to the braking theory, dealing with the distribution of the total braking force on the front and rear axles. Its goal is to ensure vehicle stability and braking performance [41], [7].

Another design decision necessary is to set the axle(s) on which the RBS is operating. Normally, a regenerative braking system is applied on the driven axle, because of the particularly increased effectiveness [41]. For passenger cars, the natural design might therefore be front wheel drive, while rear wheel drive is reported to be appropriate for busses and trucks [5].

3.3.11.3 Exemplary Structure of a Hybrid Braking System

An exemplary structure of a hybrid braking system is depicted in Figure 3.12 [7]. This braking system is electronically controlled and it is used on a front wheel drive vehicle. Two subsystems can be identified, including the electric regenerative braking system and the electronically controlled mechanical friction braking system. The former consists of electric motor drive, transmission and motor controller. Although no energy storage is depicted, it must be implemented for a complete electric regenerative braking system. Suitable choices for this case

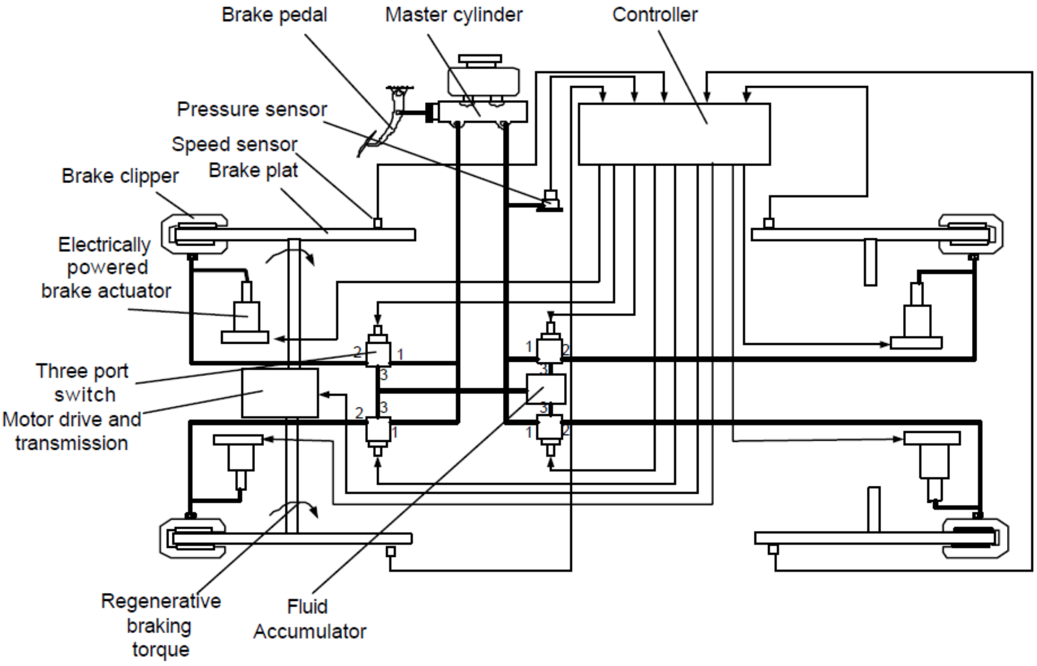


Figure 3.12 Structure of fully controllable hybrid braking system [7]

can be a battery or an ultracapacitor, further information is given in chapter 4.2.1. The electronically controlled mechanical friction braking system consists mainly of brake pedal, master cylinder, electrically powered and electronically controlled brake actuators, electronically controlled three-port switches, fluid accumulator, pressure sensor and the overall controller. The three-port switches show the following common status: port one and port three open, port two closed [7].

When the brake pedal is hit, the fluid accumulator is charged with braking fluid through the three-port switches and it emulates the braking pedal feeling for the driver. The pressure sensor identifies the pressure of the fluid and conveys it to the overall controller, which determines the braking torque of front and rear wheels, regenerative braking torque and mechanical torque, based on motor characteristics and the control rule. Then, the motor controller, which is not depicted on Figure 3.12, forwards the regenerative braking torque requested to the motor. The overall controller manages the braking actuators in order to establish the accurate mechanical braking torque for every wheel [7].

Furthermore, the braking actuators also serve as antilock braking system (ABS), preventing the wheels from being locked entirely. The three-port switches ensure braking performance, even in the case of failure of a braking actuator. In such a case, they close port three and open port two, which allows the braking fluid to flow directly to the wheel cylinder, creating braking torque [7].

3.3.11.4 Braking Strategy

In practical regenerative braking strategy design, either a parallel or a series braking strategy can be used [20].

The parallel braking strategy represents perhaps the simplest and closest strategy to the one pure frictional braking systems follow. It foresees the addition of an RBS to an (existing) frictional braking system and has the advantage of a comparably simple control. Both regenerative braking torque and mechanical braking torque are applied at the same time and increase with the braking force demand of the driver [41]. However, the key problem of the parallel strategy is that the braking forces cannot be allocated to the axles individually, therefore reducing overall energy regeneration potential [20].

Series braking strategy offers a higher potential of energy regeneration [8]. When the braking process starts with hitting the brake pedal, the regenerative system alone should be used. Only if the total braking force commanded by the driver is exceeding the maximal regenerative braking force producible, the mechanical braking system turns on and assists achieving the requested braking force [7]. Therefore, the series arrangement allows the regenerative braking system to maximize application time and energy regeneration. Due to the development of more advanced braking systems, it is possible today to control braking forces on each wheel independently and to apply regenerative braking torque up to the maximum road tire adhesion supported. Figure 3.12 constitutes an example for that, presenting a fully controllable hybrid brake system [7], [5].

3.3.11.5 Braking Force Distribution Strategy

Figure 3.13 Frame of a braking force distribution strategy [8] shows an exemplary frame for a braking force distribution strategy. Based on driving cycle and calculated braking torque limits, the braking torque is distributed to front axle friction brakes, rear axle friction brakes and the regenerative brake, in this case the motor [8]. The motor braking force acts on the driven axles and is not further specified in this frame.

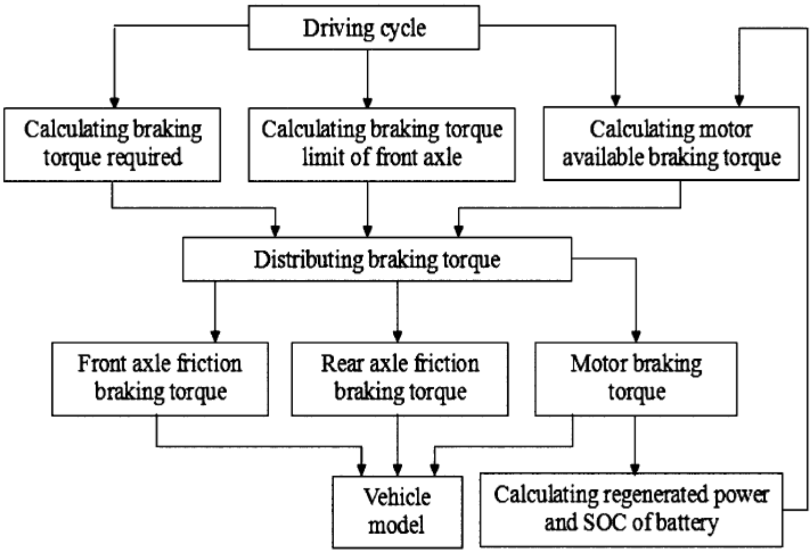


Figure 3.13 Frame of a braking force distribution strategy [8]

Since the ideal braking force distribution during braking is reached when front and rear braking forces are distributed according to the front and rear loads [16], a controlling unit takes care about the braking force distribution. Based on the control rule programmed on it, the braking process can take several forms. Figure 3.14 [16] shows four possible braking force distributions.

Curve I embodies the ideal braking force distribution, at which both front and rear axles will be locked at the same time when reaching the adhesive road tire limit. However, most vehicles are designed presently to follow curve β.

A regenerative braking force distribution strategy proposed in [16] suggests following the thick solid line. From points O to A, the regenerative braking force of the rear wheels is used, since it involves light braking operation only. Thus, vehicle stability is guaranteed. From points A to B, the total braking force requested is too large for the regenerative braking system only, therefore mechanical braking force is added on the front axle. Once point B is reached, the mechanical braking force of the front axle is at its peak. If the driver requests more braking torque, both front and rear axle mechanical braking forces are increased simultaneously. The distribution strategy follows curve β then.

As mentioned in chapter 3.1.1, the braking curve must not exceed the ideal braking force distribution curve I, otherwise the rear wheels will lock before the front wheels and lead to potential vehicle instability. Therefore, an antilock braking is installed to avoid that case, forcing the brake controller to decrease the braking forces on the wheels being locked, until they recover their rotation [16]. In [7], [42] it is described that an actively controlled regenerative braking system and mechanical braking actuators can easily assume this task. When the commanded braking force exceeds the maximal braking force that the ground supports, the actual braking force follows the maximum ground braking force. This electronically controlled brake system shows significant advantages over conventional ABS. While it is faster and more accurate, also the mechanical movement in the solenoid valve is eliminated.

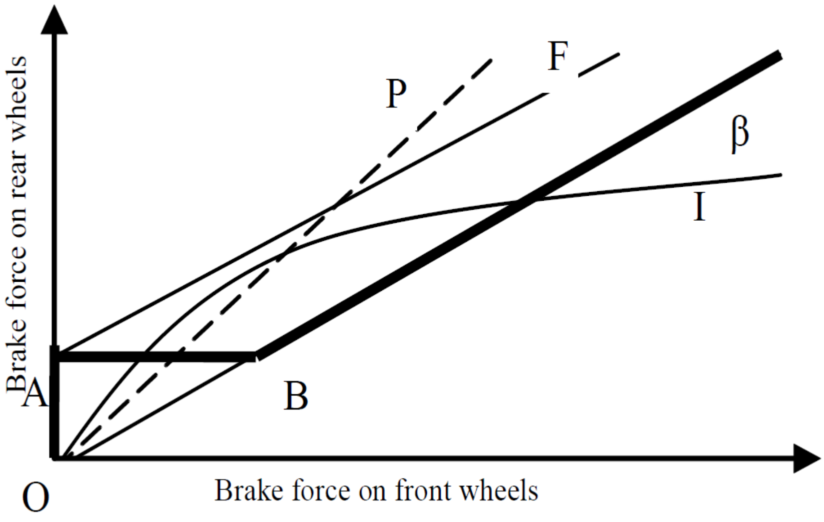


Figure 3.14 Various braking force distributions [16]

On Figure 3.14, two more strategies are depicted, both of parallel type. The first one is a classic parallel strategy, represented by the dashed line from O to P. The regenerative braking force is added to the mechanical braking force and both are increased constantly to meet the total braking force requested. The second one follows the points O – A – F and is a parallel strategy, which controls regenerative braking with the beginning pedal travel.

3.3.11.6 Summary: Regenerative Braking Design

According to EU brake regulations (ECE Regulations 13H and 13.11), new vehicle braking systems are divided into three different hybrid categories. Category A describes the regenerative braking mode only, which is active whenever the throttle in a vehicle is released. Category B is divided in “Phased-“ and “Non-Phased” braking systems. Latter leads to a parallel braking strategy, at which regenerative braking torque starts being exerted simultaneously to or slightly after the braking torque of friction brakes. Category B - “Phased” is a series braking strategy, implying a consecutive usage of regenerative and friction braking.

In the RBS design, two important problems must be faced. The first one is the braking strategy, distributing the total braking force between the regenerative brake and the mechanical brake. The second one deals with the distribution of the total braking force on the front and rear axles.

While the parallel braking strategy represents a simple solution, adding an RBS to an (existing) frictional braking system, a series arrangement allows the regenerative braking system to maximize application time and energy regeneration. In more advanced braking systems, it is possible to control braking forces on each wheel independently, maximizing the road tire adhesion for each wheel. The exemplary structure given shows an electronically controlled braking system, which is fully controllable. It includes two subsystems with the electric regenerative braking system and the electronically controlled mechanical friction braking system.

Figure 3.13 Frame of a braking force distribution strategy [8] shows how an exemplary programming frame for the distribution strategy. It can be understood that driving cycle and the calculated braking torque limits are used as input for distributing the braking torque to front axle friction brakes, rear axle friction brakes and the regenerative brake. Finally, four different braking force distribution curves are shown, matching to the RBS model used in the chapter.

3.3.12 Regenerative Braking Control

Since the braking process must be controlled to follow the braking strategy, this chapter talks about regenerative braking control.

The amount of energy that can be regenerated is influenced by various factors. While the safety and the vehicle stability during braking are key elements that have to be adhered to, also high energy regeneration effectiveness is desired. An optimal braking control is necessary to achieve these goals [32].

A regenerative braking control has the exercise to control the braking process. A braking controller as described in further chapters is programmed to do so, establishing the link between actuator and battery storage system. However, nonlinear parameter perturbation and serious external disturbances exert on an RBS and make it an uncertainty system [20]. In [20], a literature research about the various regenerative braking control attempts was executed and the findings have been classified in four categories: Rule based strategies, fuzzy control strategies, H_∞ control and neural network approaches.

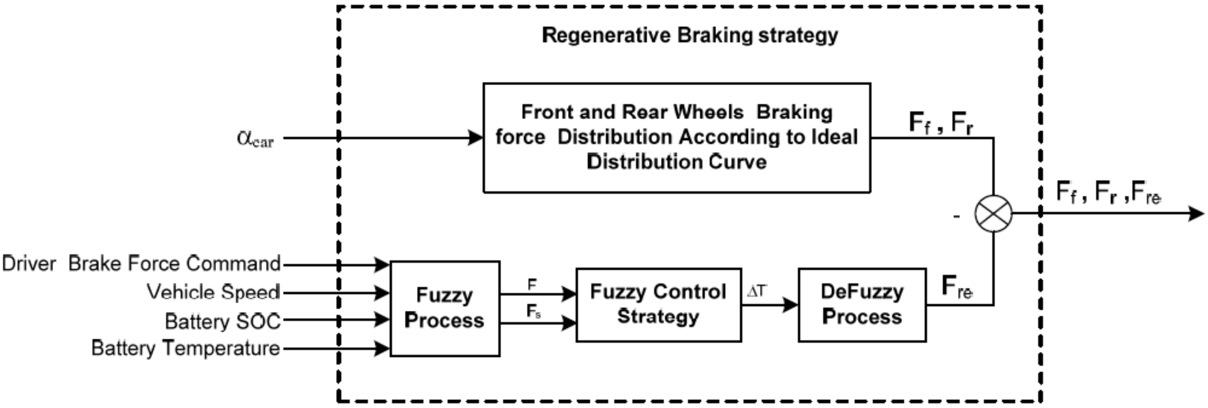


Figure 3.15 Structure of the control strategy system [20]

The fuzzy control strategy is used here to demonstrate the function of a regenerative braking control. Figure 3.15 shows an exemplary structure of such a fuzzy control logic based regenerative braking strategy. The four input parameters driver brake force command, vehicle speed, battery SOC and battery temperature are used and processed with the fuzzy control strategy. The output is a regenerative braking force F_{re}, which is paired with the front and rear braking forces F_f, F_r. Latter two forces are determined with the coded braking force distribution strategy and depend on the desired vehicle deceleration $\propto_{car}$ [20].

Summarizing it can be said that regenerative braking controllers can be classified in four categories: Rule based strategies, fuzzy control strategies, H_∞ control and neural network approaches. All of them have the exercise to process input data of the vehicle and to manage the regenerative braking process accordingly.

3.3.13Summary: Regenerative Braking

In this chapter regenerative braking is introduced. It is given that regenerative braking technologies do capture and store kinetic energy, either feeding it to the actuator while accelerating, or recharging the power supply. RBS are important for the future of vehicles, because they the significantly enlarge driving range and reduce emissions. In addition, they prolong the lifespan of friction brakes and the battery pack. However, also downsides of regenerative braking systems are known, such as the incapacity of fully replacing friction brakes, added size and weight to the vehicle, high cost and increased complexity of the braking system.

Any regenerative braking system includes an actuator and an energy storage device. Generally, a braking controller is also part of the RBS as a controlling unit. To explain the working principle of an RBS, electric energy regeneration can be used as an example. The electric machine, propelling the vehicle in motor mode, is operated as a generator during braking. Thus, it embodies a resistive load, slowing down the vehicle. The battery stores the electrical energy and the process is reversed for acceleration.

Urban driving conditions are proven to be the ideal area for high energy regeneration, because they demand much braking action. Since also the vehicle inertia weight has a big impact on the amount of energy that can be regenerated, prospective possibilities are offered to city busses, taxis or delivery vans.

The amount of regenerated power in a BEV varies between 20% and 35% of the total traction power. The efficiency is influenced by many factors, of which motor speed, battery charge power and the control strategy are mentioned.

In the RBS design, two important problems must be faced. The first one is the braking strategy, which is occupied with distributing the total braking force between the regenerative brake and the mechanical brake. The second one deals with the distribution of the total braking force on the front and rear axles. Two braking strategies are commonly used, called parallel braking strategy and series braking strategy. Former adds an RBS to an (existing) frictional braking system and represents a simple solution. A series arrangement allows the regenerative braking system to maximize application time and energy regeneration.

The exemplary structure of an RBS that is given shows an electronically controlled braking system, including two subsystems: The electric regenerative braking system and the electronically controlled mechanical friction braking system. From the frame for the distribution strategy can be understood, that driving cycle and the calculated braking torque limits are used as input for distributing the braking torque to front axle friction brakes, rear axle friction brakes and the regenerative brake. The result can be seen with four different braking force distribution curves.

Lastly, regenerative braking controllers are touched. They can be classified in four categories: Rule based strategies, fuzzy control strategies, H_∞ control and neural network approaches. Their task is to process input data of the vehicle to manage the regenerative braking process accordingly.

4 INVESTIGATION OF EXISTING RBS TECHNOLOGIES

Mechanical friction brakes exert mechanical resistance to the rotating wheels, which results into a deceleration and a standstill of the vehicle eventually. It was stated above that regenerative braking technologies do brake vehicles by building up different resistances; however, no detailed information has been given so far. This chapter gives insight into the existing technologies for regenerative braking systems, their components, and advantages and disadvantages. First, an overview about the different technologies is given. Second, the basic regenerative braking technologies are presented in detail. Then, few mixed regenerative braking technologies are mentioned. Last, a comparison of the most common regenerative braking technologies is carried out.

4.1 OVERVIEW OF REGENERATIVE BRAKING TECHNOLOGIES

This chapter gives a brief overview of the regenerative braking technologies presented in this paper. At the same time, the RBS classification used in the following chapters is shown.

The technologies were classified in the first place as either basic or mixed technologies. The names derive mostly from the type of energy that is primarily used for the functioning of every technology. Accordingly, mixed technologies include both energy types in their names.

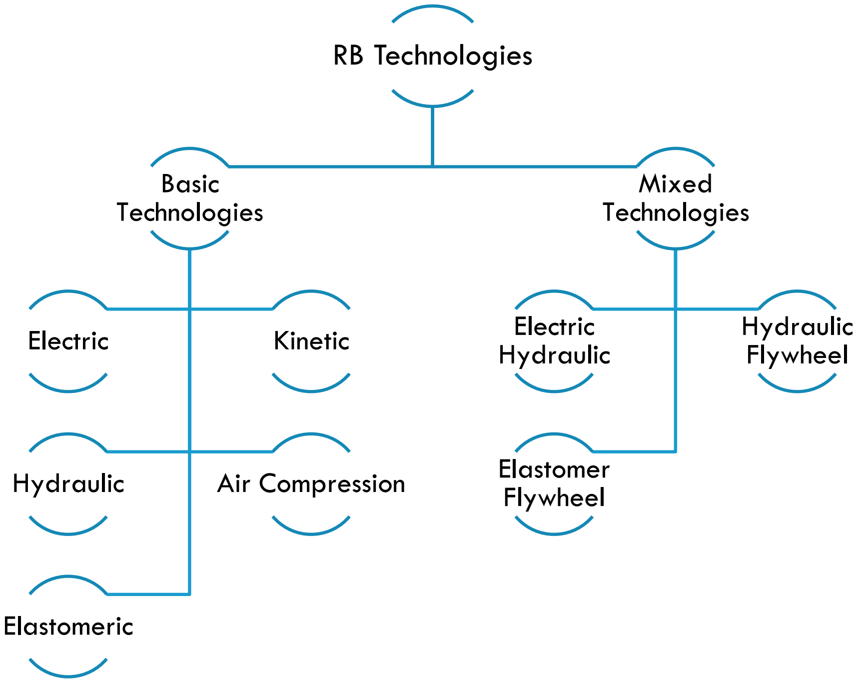


Figure 4.1 Overview of the regenerative braking technologies

4.2 BASIC REGENERATIVE BRAKING TECHNOLOGIES

This chapter presents five basic regenerative braking technologies, which were found to be the most common ones in the literature. Initially, the electric regenerative braking system is explained. Then, the Flywheel as kinetic RBS, hydraulic RBS and regenerative compression braking is described. Last, the elastomeric system is explained.

4.2.1 Electric Regenerative Braking System

In this chapter, electric regenerative braking systems are presented. The main distinctions between the various electric regenerative braking systems are found in their storage devices and the control circuits. Thus, this chapter focuses on presenting the differences among them.

Electric regenerative braking systems consist normally of an electric machine as an actuator, a control circuit, a controlling unit and one or more storage devices [2]. The working principle of energy regeneration for such systems is described in chapter 3.3.6.

In fully electric vehicles, actuators for RBS are electric machines, which are also propelling vehicles in motor mode. A general differentiation between actuators can be made with DC and AC machines. Both have been applied on electric vehicles for propulsion purposes and both offer possibilities for regenerative braking [10], [13]. DC machines are further explained in chapter 0 as they are of particular interest for the project.

Storage devices either include batteries, ultracapacitors, or a combination of both [15], [2]. In the following chapters, a system with batteries only is presented first. Then, a system with additional ultracapacitors is described.

4.2.1.1 System with Batteries

This chapter presents electric regenerative braking systems that use an electrochemical battery as storage device. A basic control circuit for a brushless DC motor is shown and batteries used are illustrated more in detail. After advantages and disadvantages of electric RBS, the energy recovery system of a Formula 1 vehicle is presented.

4.2.1.1.1 Basic Theory

An RBS with batteries as energy storage devices represents the basic electric hybrid regenerative braking system. In commercial hybrid and fully electric vehicles, many small single-cell batteries form the battery pack. A Tesla Roadster counts about 6800 Li-ion battery cells, each of the size of 18mm diameter by 65mm length. It is beneficial having many small cells, because a failure has expectedly less effect than a failure in bigger and fewer cells. The total mass of the entire battery pack is about 450kg and it requires cooling and heating to maintain an optimal operational temperature. Furthermore, complex battery inter-cell energy management is needed, adding mass to the electric regenerative braking system [43].

Batteries store energy chemically and tend to have high energy densities (or specific energies). Latter means that they are able to store large quantities of electrical energy [1]. Often, batteries are operated in a narrow bandwidth of the total state of charge range, because ideal charging and discharging efficiencies cannot be achieved for the border areas. Moreover, an enlarged battery lifetime can be reached [44]–[46]. In [1] it is reported that the academic methods of managing the SOC of the batteries vary widely, with values between 10% and a range of up to 60% of the full battery state of charge.

4.2.1.1.2 Components & Structure

As mentioned above, an electric regenerative braking system comprises typically an electric machine as an actuator, a control circuit, a controlling unit and one or more storage devices. This chapter focuses on the control circuit and its structure, since the overall structure is presented in chapter 3.3.11.3 and on Figure 4.4.

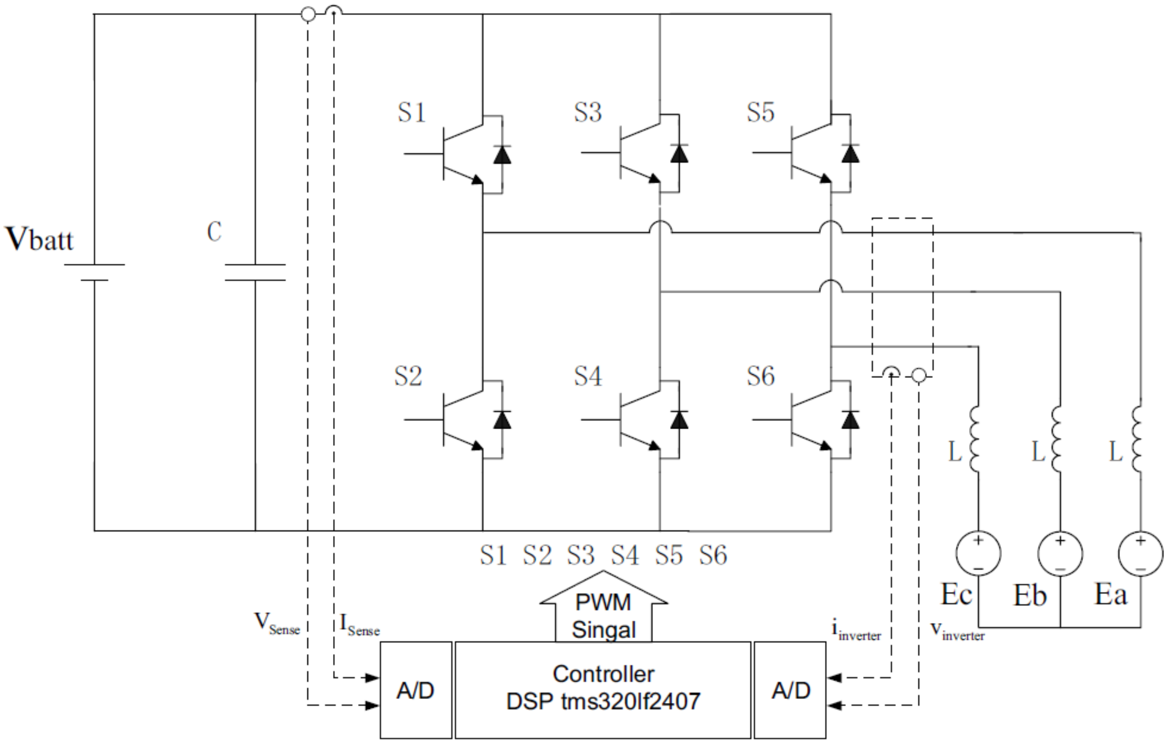


Figure 4.2 Equivalent circuit of an inverter driven three-phase PM BLDC motor [47]

An equivalent control circuit is shown on Figure 4.2 [47], connecting the electric machine with the terminals of the battery. The electric machine in this case is a permanent magnet brushless DC motor. It should be noted at this point, that brushless DC motors are formally classified as AC motors, since the DC voltage applied to the terminals is electronically switched on and off at the different stator windings in order to let the rotor rotate. This is resulting in an AC voltage with a square-wave shape or trapezoidal shape [48]. The motor is shown with three inductances labeled with L and the three back electromagnetic forces (EMFs) E_a, E_b, E_c on the right side of Figure 4.2. Switches S_1 to S_6 are the switching devices and diodes D_1 to D_6 are freewheeling diodes, connected in antiparallel to the switches. Capacitor C is a DC-link capacitor, which maintains the DC-link voltage V_{batt}. The circuit is also known as an inverter circuit, because it inverts the DC voltage delivered by the battery with a controlled switching sequence of the switches S_1 to S_6 [49]. The switching sequences can be viewed on Figure 4.3 [50] and are split in six sequences, depending on the position of the rotor. The figure also gives insight into the sinusoidal back EMF, the Hall sensor output and the energy regenerative mode switching signals. The Hall sensor is necessary to give feedback about the rotor position, which is crucial for correct switching sequences and therefore a smooth rotation of the rotor [48].

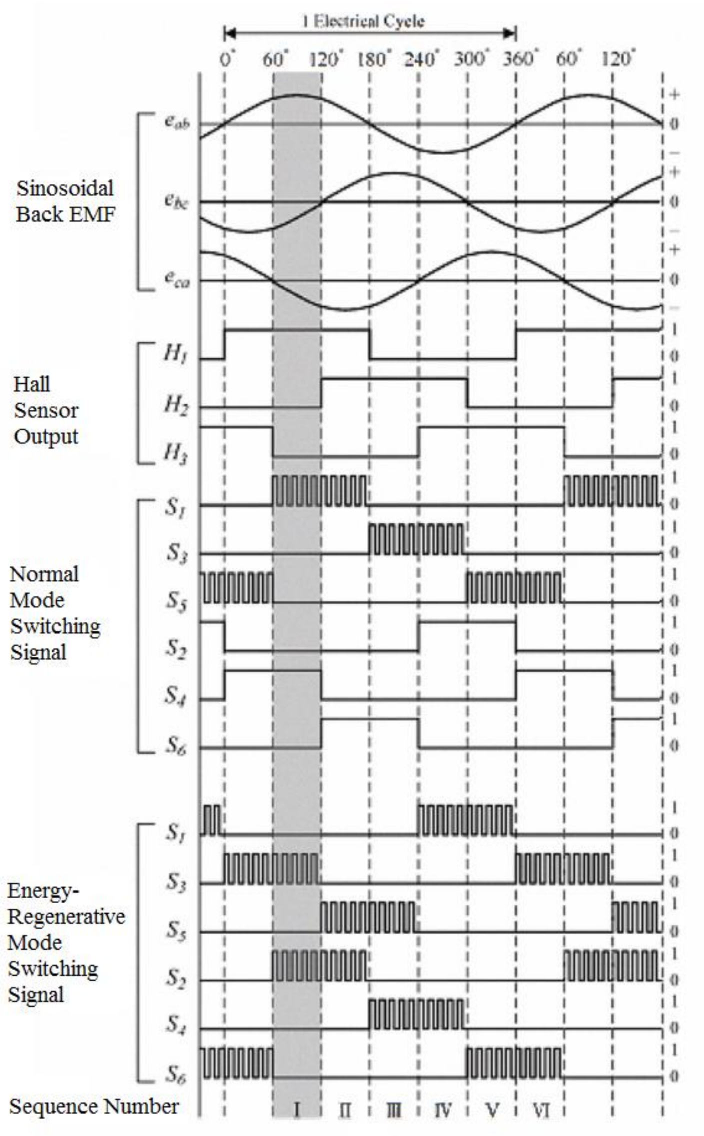


Figure 4.3 The characteristics of Hall sensor signals, back EMFs, and switching signal sequences of normal and energy-regenerative modes [50]

During motor mode (called normal mode on Figure 4.3), the high side switches S_1, S_3 and S_5 are operated in pulse width modulation (PWM) switching mode, while the low side switches S_2, S_4 and S_6 are operated in standard high/low switching mode. PWM allows controlling the torque developed by the motor [49]. As sequence number I shows that S_1 and S_4 are both switched on, a current i_{ab} can flow. The current flow changed since the last sequence number and an induction voltage e_{ab} must withstand the variation of the magnetic field according to Lenz's Law. Thus, the machine is turning [50].

The theory about braking energy regeneration for electric RBS implies that the electric machine is used as a generator and a back EMF (voltage) is induced. However, it cannot be expected that this back EMF is larger than the voltage of the battery. In order to charge the battery, the back EMF induced must be boosted. This can be done by a DC-DC converter [51] or with the control circuit presented in this chapter. Latter case can be explained as follows: The switching mode is changed to the energy-regenerative mode on Figure 4.3. This mode is triggered once a braking signal from the driver is sent to the controller. In the regenerative braking mode, every switch from S_1 to S_6 is operated in PWM switching mode [50]. Because of the PWM signal, which is continuously switching the switches on and off, it must be distinguished from now on between ON and OFF PWM condition. Still observing sequence number I, for ON PWM condition, the switches S_3 and S_2 are switched on. Voltage is supplied from the battery to the winding L, which is energized. Compared to the motor mode, the current changes its flow of direction through the electric machine and can be named i_{ba}. The total voltage v_L at the winding L amounts to the sum of $V_{batt} + e_{AB}$. However, no energy is yet being delivered to the battery. To accomplish this, switches S_3 and S_2 are switched off, changing to the OFF PWM condition. In that case the voltage v_L causes a current i_{off} to flow through the freewheeling diodes D_1 and D_4 to the battery. Thus, energy is supplied to the battery [47],[49].

4.2.1.1.3 Advantages & Disadvantages

A big advantage of a system like the one presented is that no additional hardware or complex software algorithms are needed [49].

Compared to ultracapacitors however, batteries show lower power densities (or specific powers). For acceleration and deceleration of vehicles, high power densities are required [31]. The charge and discharge times thus can be much faster than tolerated by batteries, especially during regenerative braking. Recharge times can be of the order of seconds, while discharge ratings of batteries are commonly done with hours [1]. This is one of the reasons, why electric regenerative braking systems sometimes combine batteries and ultracapacitors. Doing so, the advantages of both systems can be harnessed [51].

4.2.1.1.4 Energy Recovery System of Formula 1 Vehicles

This chapter presents the energy recovery system (known as ERS) of a Formula 1 car and explains, which electrochemical storage device is used.

A Formula 1 vehicle includes energy regeneration from braking energy as well as from heat energy of the exhaust gases. The braking energy regeneration is based on the electric regenerative braking principle and thus, this energy recovery system is mentioned here.

Since the championship of 2014, a Formula 1 car possesses a drivetrain, which is called Power Unit. This term replaces the traditional term “engine”, because the Power Unit is a hybrid system. It includes an internal combustion engine, a turbocharger and the ERS. Latter was employed for creating more than 20% of the total power in 2014 [52], [53].

The energy recovery system includes two motor generator units, called MGU-K and MGU-H, an energy store (ES) and control electronics. MGU-K is the kinetic motor generator unit, which represents the actual regenerative braking unit of the system. It converts some of the kinetic energy generated during braking into electrical energy and stores it in the energy store, which is a Lithium-Ion battery solution of 20 to 25 kg. Up to 120 kW of power can later be used for accelerations. However, the MGU-K unit releases all its power on the rear wheels of the car. MGU-H on the other hand is a unit that recovers heat energy. It is driven by the exhaust gases of the ICE and also feeds electrical energy to the energy store [52], [53], [54].

4.2.1.1.5 Summary: Electric RBS with Batteries

Electric regenerative braking systems with batteries as storage devices embody a simple RBS, which can be a neatly implemented in vehicles powered by an electric motor. However, batteries show significant disadvantages in terms of specific power. To improve the energy savings of such an RBS, ultracapacitors could be added.

4.2.1.2 System with Ultracapacitors

This chapter talks about electric regenerative systems, which use ultracapacitors as an additional storage device to batteries. The basic theory, components and structure, and advantages and disadvantages are included.

4.2.1.2.1 Basic Theory

Ultracapacitors are electric double layer capacitors and they store energy through charge separation. Compared to traditional electrolytic capacitors, they are able to store 20 times more energy [51].

The application of ultracapacitors during acceleration looks like the following: In principle, the battery provides the electric machine with the current required. If latter exceeds an instantaneous limit established by the controller, the ultracapacitor delivers the residual energy. For regenerative braking, the application of the ultracapacitors is similar. If the current flowing from the electric machine to the batteries is too large, the DC/DC converter feeds the excessive energy to the ultracapacitors [51]. But not only do ultracapacitors store regenerated energy during braking, they also store extra power generated by the power plant of the vehicle [1].

4.2.1.2.2 Components & Structure

For electric vehicles, the typical structure of such an integrated system is depicted on Figure 4.4 Regenerative braking system for use on an electric vehicle [30]. An electric motor is connected via a numeric motor controller and a control circuit to a battery pack. In parallel, a DC/DC converter and an ultracapacitor bank can be found.

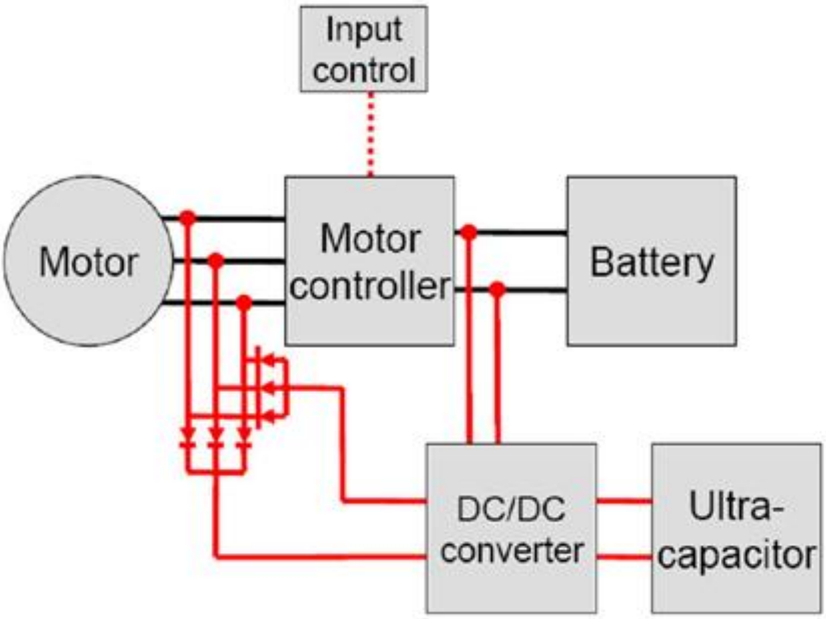


Figure 4.4 Regenerative braking system for use on an electric vehicle [30]

The DC/DC converter is needed to vary the voltage of both the ultracapacitor and the electric machine. Moreover, it has the task to control the state of charge of the ultracapacitor together with the control system [31]. The DC/DC converter consists of a buck-boost circuit. Thus, its operations can be split into buck- and boost operation. While latter is used for acceleration of the vehicle, buck is used for deceleration, assisting in the charging process of the capacitor.

4.2.1.2.3 Advantages & Disadvantages

Ultracapacitors have been identified in [31] to be a suitable energy storage medium for regenerative braking systems because of two reasons: The charge/discharge period is much faster than for flywheels e.g. and furthermore, ultracapacitors are cheaper for energy storage requirements.

Other advantages include an improved transient performance, innumerable charge and discharge cycles without performance decrease, increased lifetime of the batteries and their protection against fast and sudden charge/recharge and the possibility of saving regenerated energy even when batteries are fully loaded [51].

However, also ultracapacitors show SOC concerns similar to batteries. This is mainly due to the difficulty of extracting energy at low voltages [1].

4.2.1.2.4 Summary: Electric RBS with Ultracapacitors

Ultracapacitors show desirable properties for an RBS regarding power absorption. However, they are seldom used as the only storage device, because they cannot keep energy stored on a long term. An electric regenerative braking system with batteries and ultracapacitors constitute a state of the art system of that kind.

4.2.1.3 Summary: Electric RBS

Electric regenerative braking systems offer a simple and effective technology. Actuators are electric machines, while storage devices include either batteries, ultracapacitors, or a combination of both. A system works best if both batteries and ultracapacitors are used, because the former can store high amounts of energy and is discharged slowly, while the latter is taking care of energy delivery for sudden braking and accelerating.

4.2.2 Kinetic Regenerative Braking System

The kinetic hybrid system presented in this paper is a flywheel system. The working principle, components, structure, advantages and disadvantages of flywheels are discussed in this chapter.

4.2.2.1 Basic Theory

A flywheel kinetic hybrid system stores energy in the form of mechanical (kinetic) energy, causing a disk or rotor to spin [55]. As an actuator, electric machines like a permanent magnet motor can be used. Generally however, flywheels need transmissions like CVTs to release their stored energy, so the transmission is seen as actuator for the RBS. Flywheel systems are also known as inertia storage devices, electromechanical batteries, flywheel batteries or as an FBESS (flywheel based energy storage system) [1], [2], [56].

When a vehicle is braking, the kinetic energy is used to accelerate the flywheel. In order to reduce windage losses, it is supported by magnetic bearings. Furthermore, the flywheel is operated in vacuum. At a later time, when energy is desired to be extracted from the flywheel, an electric generator is utilized. This generator provides the electric motor of the drivetrain with the power necessary to accelerate [17].

FBESS are briefly described suitable for interchanging medium and high powers (kW to MW) within a few seconds [56]. Additionally, they offer an energy efficiency of more than 85% [57]. The kinetic energy E_f, which is stored in the flywheel, is described in [1], [56] as:

$$E_f = \frac{1}{2} I \omega^2$$

Thus, E_f is highly effected by the rotational speed ω of the flywheel. In addition, the moment of inertia I is influencing the amount of energy to be stored. To store the maximum amount of energy, the flywheel is desired to spin at high rotational speeds. However, the top speed is limited by material properties. Once the maximum tensile strength is reached, the flywheel begins to disintegrate. The disk/rotor must thus exhibit high energy density, high mechanical strength and dynamics properties [58]. Another approach to increase E_f is to increase inertia I. This can be accomplished by increasing volume (so radius and height) and the mass m [56].

The rotational speed ω classifies flywheels in two types: low speed FBESS (up to 6000 rpm) and high speed FBESS (10^4 to 10^5 rpm) [59]. Former are generally cheaper and the technology used is conventional, while latter show better performance and advanced technologies at increased cost. In high speed FBESS, the flywheel and the electric machine are combined in a single compact element. This is typically not the case for low speed FBESS [56].

The ideal field of application of flywheels is described in [28] to be in cities where the distance between stops is less than half a kilometer. Especially busses can profit from them, since energy decays rapidly.

4.2.2.2 Components & Structure

A flywheel system basically includes a flywheel disc/rotor, magnetic bearings, a generator/motor, an enclosed vacuum chamber and a power conversion system [58]. Figure 4.5 Components that form an FBESS [56] shows the structure of such a system. The bidirectional converter is harnessed to transform the frequency of the generator to a different frequency desired by the operator. The output of the bidirectional converter can be connected to the drivetrain of the vehicle for example.

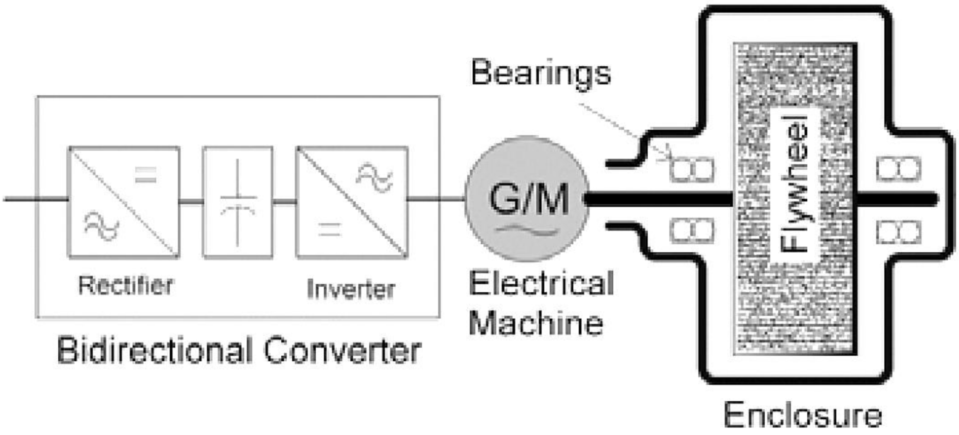


Figure 4.5 Components that form an FBESS [56]

4.2.2.3 Advantages & Disadvantages

Flywheels show some significant advantages, described in [60], [17] as follows. First, they show high energy density and assure a high rate of power extraction. Second, they are purely mechanical devices without external power input. Therefore, there is no ongoing chemical reaction like in traditional electrochemical batteries and the disposal of flywheels is unproblematic and green. Third, they show high efficiencies and practically unlimited life cycles, despite fast charging processes. Furthermore, a long maintenance period is provided, reducing maintenance costs at the same time. Last, flywheel systems are flexible in design and operation.

However, FBESS are demonstrating high complexity. They are not capable of storing energy for a longer time. Additionally, heaviness and high cost of the control hardware are mentioned as disadvantages.

4.2.2.4 Summary: Kinetic RBS

Kinetic hybrid energy systems are a good solution for storing braking energy and using it soon after for acceleration. A disc/rotor is speeded up, slowing down a vehicle and conserving kinetic energy, which is later converted to electrical energy by a generator and delivered to the drivetrain.

4.2.3 Hydraulic Regenerative Braking System

This chapter presents hydraulic regenerative braking systems, which use hydraulic accumulators to store and reuse braking energy. Some systems use hydraulic actuators as well and can therefore be classified as fully hydraulic regenerative braking systems, while other technologies form hybrid hydraulic systems.

Actuators vary depending on the technology used, however electric in-wheel motors, constant displacement hydrostatic pumps/motors and hydraulic radial piston ring cam motors are mentioned exemplarily [61], [62].

4.2.3.1 Basic Theory

The hydraulic accumulator is used to store energy in the form of compressed gas. The gas used is usually nitrogen and a hydraulic fluid compresses it. Several approaches exist to separate the hydraulic fluid from the gas, including a bladder, a piston or a diaphragm (membrane). However, hydraulic hybrid vehicles always use two different hydraulic accumulators. The first one is a high pressure (HP) accumulator and the second one is a low pressure reservoir (LP) [63], [1]. In the model shown on Figure 4.6 Hydraulic schematic diagram of the regenerative braking system [63], both accumulators are connected to a pair of in-wheel hydraulic pump motors via a valve block. These pump motors drive two of the wheels of the vehicle. The valve is depicted in its middle position, not allowing a fluid flow. In this case, the pump motors are

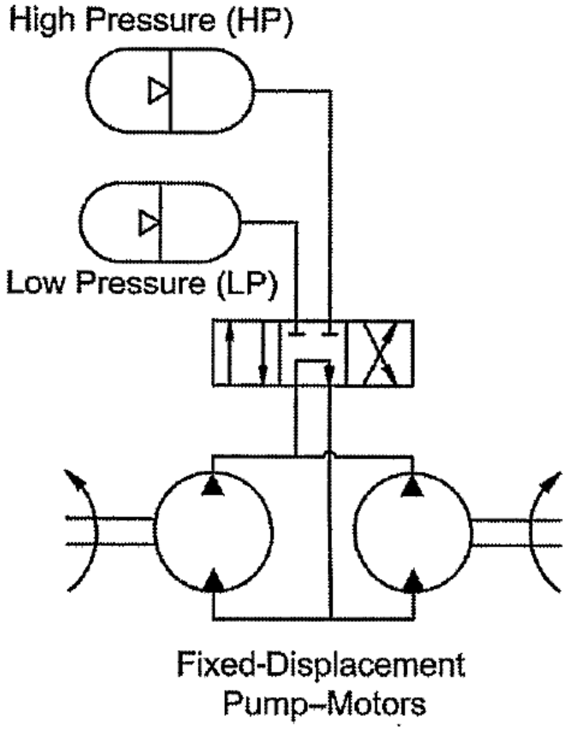


Figure 4.6 Hydraulic schematic diagram of the regenerative braking system [63]

idling. For braking action, the valve is switched to the right position. Doing so, the rotating wheels or the drivetrain power the fixed-displacement pump motors to pump fluid from the LP reservoir to the HP accumulator. Thus, a braking torque is provided, slowing down the vehicle. However, if the braking torque needed exceeds the maximum braking torque provided by the hydraulic regenerative braking system, mechanical friction brakes assist the braking process. Furthermore, if ABS is enabled, the regenerative braking action is blocked to guarantee braking safety [63].

Once the vehicle is restarting and accelerating, the position of the valve is changed to the left. In that case, the fluid can flow from the HP accumulator to the LP reservoir and it drives the pump motors at the wheels [63].

The efficiency of a hydraulic regenerative braking system was predicted in [64] to vary between 61% and 89%. Experiments to gather these numbers were executed on simple start-stop tests.

In [1] a comparison of various hybrid hydraulic regenerative braking systems is presented. A conclusion that can be drawn from it is that the systems have little impact on smaller vehicles, but few prospective fields of application for heavier vehicles like trucks, delivery vans or sedans are given.

4.2.3.2 Components & Structure

The structure of a hybrid hydraulic system is presented on Figure 4.6 [61]. In this case, two internal combustion engines are used to drive a constant displacement pump, respectively, but also electric machines could be used at their places. This double power plant system has the advantage that the ICEs can work at their most efficient point of operation. However, the combustion engines are not driving the wheels, but establishing and maintaining a present minimum pressure level in the system: The power is exclusively supplied to the common pressure rail (CPR). It is distinguished between low pressure CPR and high pressure CPR. Latter provides the wheels with power and the used flow is then lead into the low pressure rail to close the cycle. This architecture shows similarities to a typical electricity grid. However, the heart of the system are the hydraulic transformers, which convert and control the power flow. In addition, they make energy regeneration possible, reversing the acceleration process and amplifying pressures. This so called Hydrid system can substitute the mechanical drivetrain completely [61], [65].

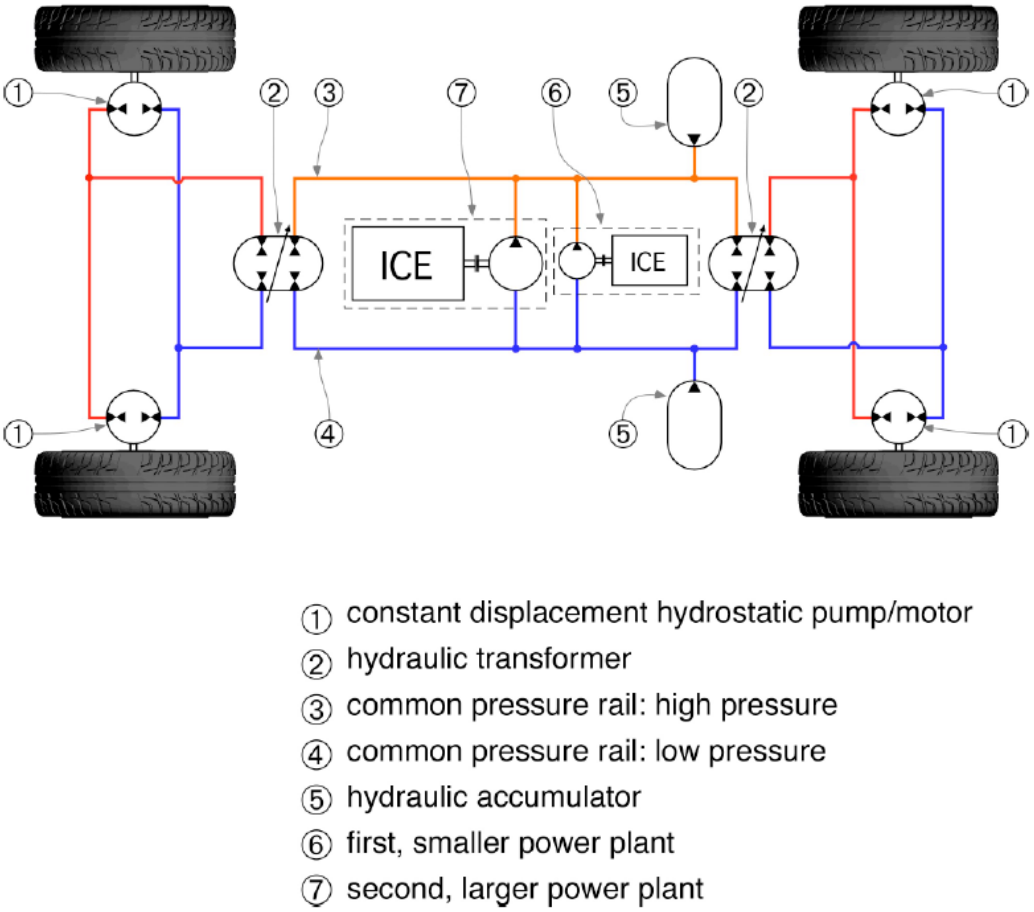


Figure 4.7 Hydraulic circuit of the hydraulic hybrid ('Hydrid') [61]

4.2.3.3 Advantages & Disadvantages

An advantage of hydraulic hybrid systems is that they can be easily implemented into existing vehicle systems. They enhance fuel economy of vehicles in many ways, including an elimination of idle losses, an optimal operation of the engine(s) around their sweet spot, a minimization of throttle losses for hydraulic cylinder control and a maximized energy regeneration [61].

The hydraulic accumulators are a simple and robust way of storing peak energies, demonstrating a high power density. Due to the fact that the hydraulic machine always operates under high pressure, it can be more efficient than electrochemical batteries [61].

However, it is stated in [66] that the fuel savings for small road vehicles are yet not high. Another disadvantage that was found in literature is that the regenerative braking system adds weight to the vehicle [63]. The specific energy of hydraulic systems is strongly influenced by the mass of the accumulators. Conventional steel accumulators are therefore being replaced by accumulators of composite materials, which are more expensive [1].

4.2.3.4 Summary: Hydraulic RBS

Hydraulic regenerative braking systems generally include hydraulic actuators and hydraulic storage devices. The common pressure rail allows an optimal use of the engine and the hydraulic RBS is able to store peak braking energies in short timeframes. However, the amount of power to be stored is depending on the mass of the overall system, which can be reduced with comparatively expensive accumulators of composite materials.

4.2.4 Regenerative Compression Braking

This chapter presents regenerative compression braking briefly. Next to the working principle, also components and structure, and few advantages and disadvantages are illustrated.

4.2.4.1 Basic Theory

The principle of regenerative compression braking is similar to hydraulic regenerative braking. A vehicle ICE is used as a compressor, pumping air into an air-tank. Later, the energy stored with compressed air is released, driving the cylinders and accelerating the vehicle [67].

This regenerative braking system offers a “round-trip” efficiency of 60% to 65%, including braking energy absorption and regeneration. It is described as a viable low-cost alternative to electric regenerative braking, because no electric motors and batteries are needed [67].

4.2.4.2 Components & Structure

In order to allow regenerative compression braking in a vehicle, the engine cylinders must be periodically connected to an on-board air-tank. This is accomplished by engaging three types of valves per cylinder: an intake, an exhaust, and a charging valve. Every valve is electronically controlled by the ECU (electronic control unit), which is continuously collecting data about the drivers braking demands and operational conditions of the vehicle. The basic structure of such a system can be seen on Figure 4.8 [67].

In the case of a braking action, the exhaust valves are disabled and the fuel injection in the cylinders is stopped. In fact, the cylinders only pump air into the air tank and thus kinetic energy is converted into energy of compressed air. The pressure in the air-tank is increased gradually, however the braking force should be kept constant. Thus, the timing of the valves is modified, resulting in a conservation of the indicated mean effective pressure (IMEP) [67].

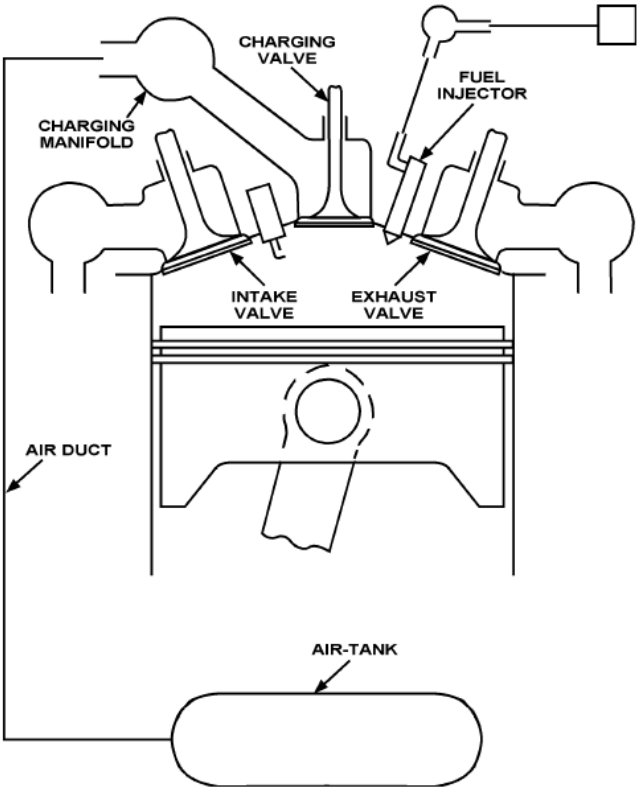


Figure 4.8 Engine system under regenerative compression braking [67]

4.2.4.3 Advantages & Disadvantages

While electric hybrid vehicles require additional electric equipment, this is not needed for a regenerative compression braking system in a vehicle powered by an ICE. Because both mentioned systems show similar efficiencies, a cost benefit can be noticed for regenerative compression braking systems. At the same time, a significant fuel reduction is given. In fact, a reduction neither in engine size, nor in vehicle weight is needed to achieve this fuel reduction. Another advantage is the high braking torque that can be reached under certain conditions, with a braking power exceeding the level of the engine driving power. Furthermore, a regenerative compression braking system takes away the need for engine idling [67].

Although the system presented can be refitted to an ICE, it is not mentioned in [67] that other actuators like electric motors work as well. In addition, no proof is given that this technology can stop a vehicle on its own. Thus, friction brakes are still required, providing extra braking torque if necessary.

4.2.4.4 Summary: Regenerative Compression Braking

Regenerative compression braking is a simple method of improving fuel consumption for vehicles using an internal combustion engine. An air-tank is connected to the charging valves of the cylinders and is compressing air during braking, which can later be reused for accelerating.

4.2.5 Elastomeric Regenerative Braking System

This chapter discusses the working principle, components and structure, and advantages and disadvantages of elastomeric regenerative braking systems.

4.2.5.1 Basic Theory

An elastomeric regenerative braking system, also known as ERBS, uses the kinetic energy of a vehicle in motion to stress elastomers. In doing so, braking energy is stored in the elastomeric storage device. This process is reversible, as elastomers tend to return to their relaxed condition [17], [68].

Various methodologies exist about stressing of the elastomers. However, the basic schemes are based on either tension, shear, compression, or torsion. The two most promising stressing schemes after different sources [69], [68], [17] are predicted to be tension and torsion. Most research efforts were carried out in the late 20st century, but a more recent study from 2011 reports that no working prototype has ever been built and implemented in a vehicle [70].

Cycling tests are reported in [17] to demonstrate energy efficiencies of the elastomers of 90% to 96.3%. These tests further indicated a lifetime of about 10^5 cycles. Additionally, study [68] found that approximately 45 liters of natural rubber will be enough to regenerate the braking energy of a car traveling at 30 MPH.

4.2.5.2 Components & Structure

The patent of an initial concept by Jayner [71] describes components and structure of an elastomeric regenerative braking system, entitled “launch assist device”. Figure 4.9 shows the drawing included in this patent. It has to be outlined however, that this system cannot give and take braking energy in every driving mode. Rather, the system charges energy in an elastomer when the vehicle is decelerated to standstill. Afterwards, this energy is used to assist the launch of the vehicle.

The launch assist device comprises gears, clutches, an elastomeric rubber element, and shafting. Latter is linked to the shaft connected to the wheels and captures kinetic energy from it. The braking process looks like the following: Depending on the direction of rotation, one of the two clutches 10 and 22 is engaged, while the other one is idling. Cable spool 4 is caused to turn, and as a result cable 3 is stretching the elastomeric rubber element 2. Latter is connected to the chassis of the vehicle at its other end.

Natural rubber was found to be the ideal elastomeric material for this application, regardless of the stressing schemes. Even though it may not be as resistive against external influences as synthetic rubbers, it showed superior characteristics regarding stressing efficiency, energy storage volume and the percentage of extension [68].

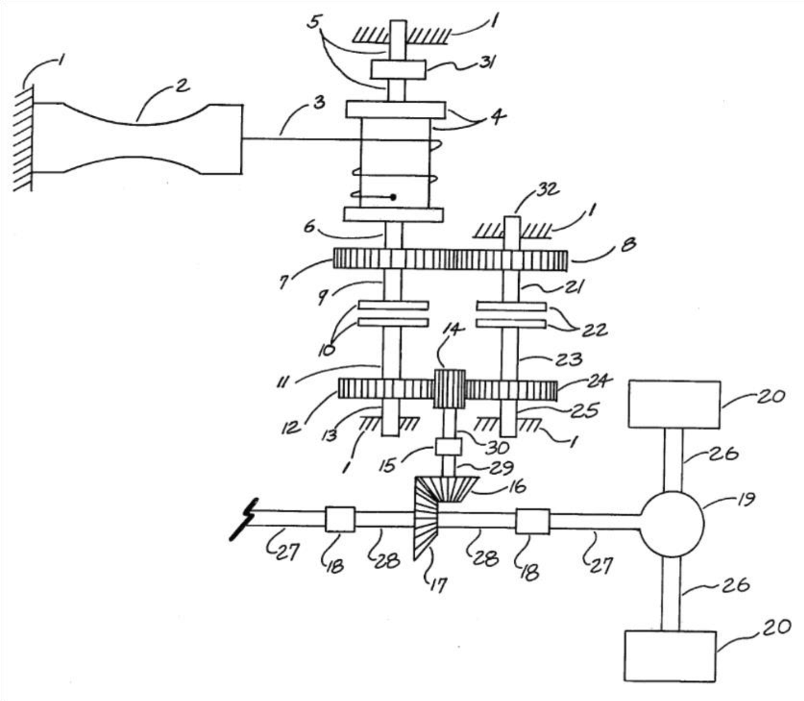


Figure 4.9 Patented launch assist device of Jayner [71]

4.2.5.3 Advantages & Disadvantages

The elastomeric regenerative braking technology presented has a significant advantage over the other technologies mentioned in this paper: It demonstrates an inherent simplicity. Next, a system with an elastomeric energy storage and a clutch shows an acceleration and deceleration characteristics similar to actual start-stop characteristics of a vehicle [69], [17].

Various problems have to be overcome to design such a system and represent therefore disadvantages of the technology. These problems mostly arise because of the characteristics of the materials used. Energy loss, called hysteresis loss, is the most outstanding issue. It heats the elastomers, resulting into reduced efficiency and possibly poor reliability and expensive running costs. Depending on the system, also abrasion and surface tears can have a negative influence on the lifetime of the elastomer. Scalability and a higher energy density of such a system are other problems that still have to be solved [17].

4.2.5.4 Summary: Elastomeric RBS

Elastomeric regenerative braking systems do store braking energy via tensioning an elastomer. Although the principle is inherently simple, no design has been realized yet. There are many factors constraining this type of RBS. Above all, the hysteresis effect, which is reducing the efficiency of the elastomers, and size constraints must be mentioned.

4.3 MIXED REGENERATIVE BRAKING TECHNOLOGIES

This chapter provides information about three alternative regenerative braking technologies, which combine elements from various basic technologies mentioned above. It is not the focus to present them in detail, but to give an idea about their working principle and their advantages. Included are the TwinTorq Electric Hydraulic motor, the Hydraulic Flywheel (HFW) and the Elastomer Flywheel.

4.3.1 Electric Hydraulic Hybrid Regenerative Braking Technology

A company from Oregon, called KersTech Vehicle Systems, integrates electric and hydraulic technology in one motor, called the TwinTorq motor. This electric hydraulic hybrid is a combination of an electric ring motor and a hydraulic radial piston ring cam motor. The hydraulic unit is used for acceleration from standstill and braking energy regeneration at low speeds, since it is thrice as efficient as the electric unit for that speed category. For acceleration and deceleration over a speed of 15 mph, the electric unit takes over, powered by a battery. A controller renders the transition from one technology to the other as smooth as possible. This system increases the overall motor efficiency significantly, as shown in Figure 4.10 [62].

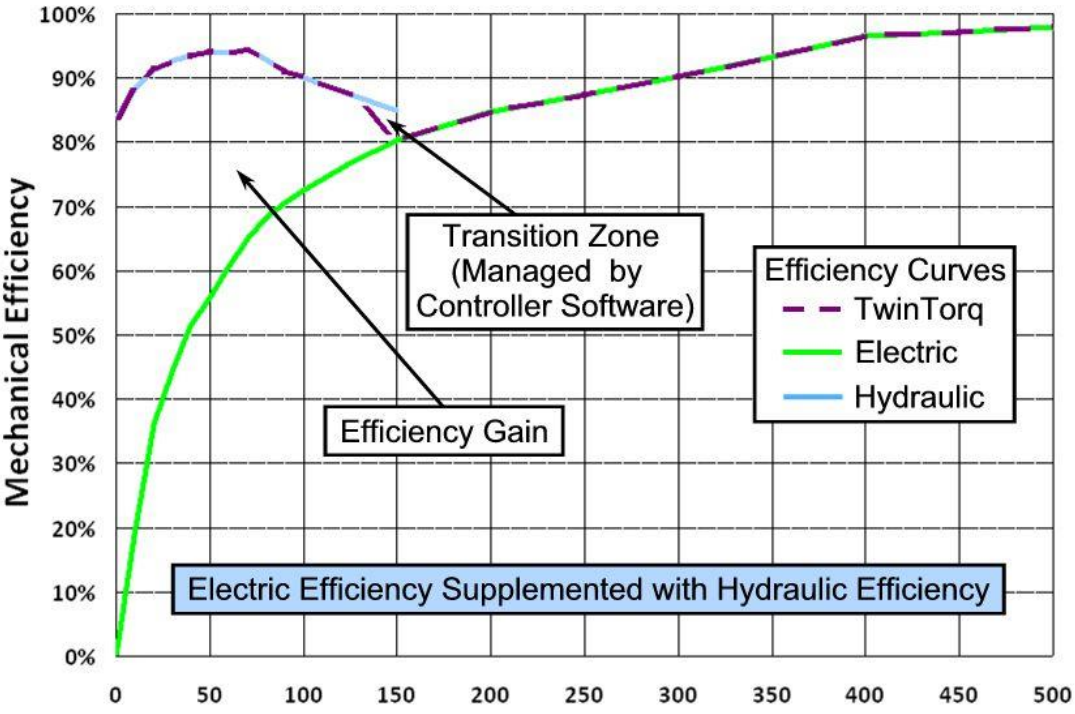


Figure 4.10 TwinTorq Efficiency Gain for EVs [62]

4.3.2 Hydraulic Flywheel Braking Technology

Bosch Rexroth created a Hydraulic Flywheel, called HFW [64]. This device is part of a hydraulic system that can be used in mobile machinery for hydrostatic travel drive and for hydraulic work functions. In order to compare this system to the others presented, this paper focuses on the hydrostatic travel drive.

The main task of the HFW in hydrostatic travel drive is almost identical to the one of a mechanical flywheel. It is about capturing and storing the kinetic energy released during braking. However, this system also shows many similarities to a typical hydraulic regenerative braking system. Indeed, it can also be retrofitted to an existing hydraulic system powered by an ICE. A distinctive point is that the HFW system does not feed the braking energy back to the cyclical high/low pressure system used in traditional hydraulic systems. Rather, it supplies it to an own HFW accumulator, which is filled with oil and thus charged. In order to allow a reuse of the energy stored, a bidirectional oil flow must be assured. For this reason a special hydraulic pump is engaged, which can switch between pump and motor mode [64].

Customer benefits for this system are given in [22] and comprise downsizing of the ICE because of the substantial power savings due to the HFW. At the same time, cost-intensive implementation of exhaust gas after-treatment systems can be avoided. Another advantage of the HFW is that power fluctuations of the ICE are balanced out. Finally, the system is based on a modular concept. This means that every component is corresponding to a certain standard, which has shown to be reliable.

4.3.3 Elastomer Flywheel

This concept of an elastomer flywheel profits from the nonlinear expansion and the inherent variable moment of inertia of an elastomer ring [72].

Compared to a conventional flywheel that suffers a speed loss of 50%, this technology makes it possible to extract around 80% of the energy stored in the flywheel at a speed change of only a few percent. This is possible due to the mix of elastic and centrifugal energy. Furthermore, the elastomer flywheel is operated at low angular velocity, which brings the advantage of direct coupling to an alternator. Another beneficial point is the low cost of the material, seeming to be a chance for the technology [72].

A downside of the technology is that a conventional flywheel has a higher energy density. Furthermore, because of the high degree of expansion, an elastomer flywheel requires more space than a metallic flywheel [72].

4.3.4 Summary Mixed Regenerative Braking Technologies

The electric hydraulic RBS offers the advantage of using both actuators for their ideal working points at an improved overall efficiency. The hydraulic flywheel is an alteration of the typical hydraulic RBS, storing braking energy in its own HFW accumulator. Finally, elastomer flywheels show a beneficial combination of the properties of both technologies, resulting in a comparably constant rotational speed of the flywheel, even for large energy extraction.

4.4 COMPARISON OF EXISTING TECHNOLOGIES

This chapter compares some of the regenerative braking technologies described above. First, energy storage systems are compared. Second, entire regenerative braking systems are compared. The main comparison parameters are chosen to be specific energy (or energy density) and specific power (or power density), as they give insight on functional properties needed for an RBS.

Every regenerative braking system is constructed of a combination of different components. Because these components and their properties vary broadly depending on the technology used, a comparison between systems must focus on specific, collective factors. In [1], two factors are chosen, namely specific energy and specific power. Consequently, a diagram was established, categorizing electrochemical batteries, ultracapacitors, mechanical flywheels, and two types of hydraulic accumulators (composite and steel accumulators). Because the research is based on data sheets of various manufacturers, the data point for elastomeric systems is estimated, since no design has been realized yet. From the examples given, it can be seen that composite accumulators show desirable properties for storage devices, as they have both a comparatively high energy density and a high power density. Therefore, compared to other systems of the same weight, they do not only store more braking energy, they can also absorb and release it more quickly. Other comparison metrics can be volumetric energy and volumetric power for

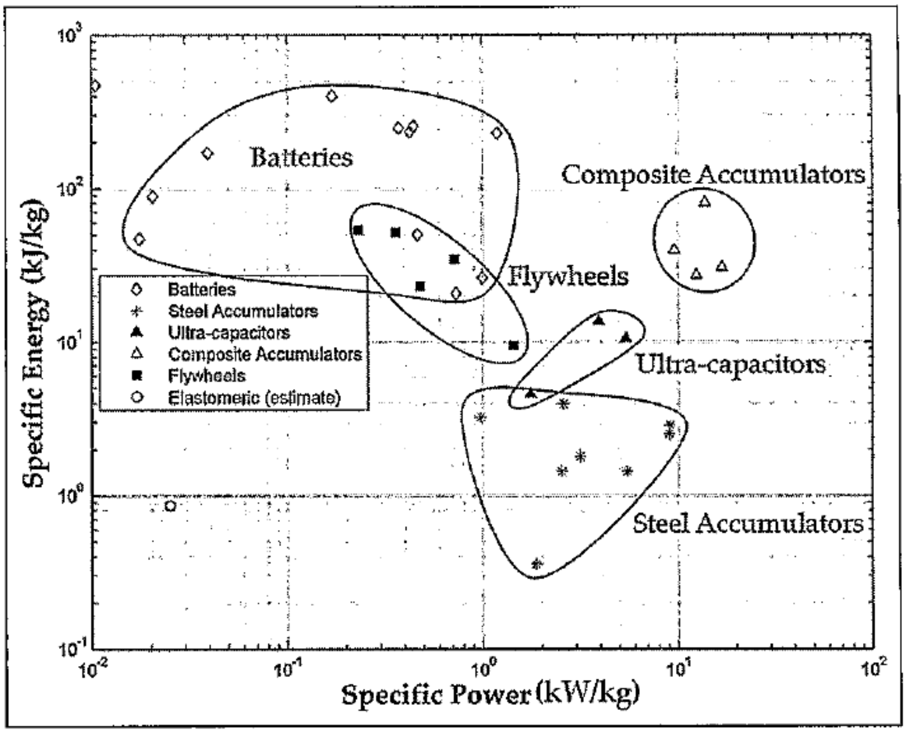


Figure 4.11 Storage device comparison [1]

example. Instead of the mass, these metrics give insight on the amount of space needed for storages devices, in order to deal with certain energy or power levels. A similar pattern could be found in [56], which compared different energy storage systems like flywheels, batteries and ultracapacitors. While batteries are the only group classified with a high energy density (10^2 kW/m^3), they show medium power density (10 kW/m^3). High-speed flywheels, low-speed flywheels and ultracapacitors show medium energy density (10 kW/m^3), but high power density (10^2 kW/m^3). Furthermore, it is stated that batteries show the lowest efficiency with 80% to 85%. Flywheels vary between 90% and 95% and ultracapacitors are claimed to be at least 95% efficient.

Since a complete regenerative braking system includes further components, a method called "power matching" [1] can be applied to find a suitable combination of storage device and actuator. It implies that any prospective storage device must show the ability of absorbing the amount of braking energy that is delivered by the actuator. In addition, it must guarantee enough power to meet the request of the actuator during acceleration. Mathematically, the power of the storage device is equaled to the power of the actuator as follows:

$$\dot{E}_S = \dot{E}_A$$

$$\dot{e}_S m_S = \dot{e}_A m_A$$

The variable $\dot{E}_S$ corresponds to the power of the storage device, while $\dot{E}_A$ is the power of the actuator. Further, $\dot{e}_S$ is the specific power of the storage device, m_S its mass, $\dot{e}_A$ the specific power of the actuator and m_A its mass. To show possible power-matched components, a matrix was established using Matlab [1]. The results are systems that are formed by one actuator and one storage device and are either completely hydraulic, completely electric or completely kinetic. Figure 4.12 shows these power-matched components along specific energy and specific power. These metrics are the same as used in Figure 4.11. The ovals show rough technology clusters, including electrical systems, flywheel-CVT systems and hydraulic systems with either steel or composite accumulators.

Electrical systems possess an electric machine as actuator and can add either batteries, ultracapacitors or both as a storage device. For the latter case, when batteries and ultracapacitors are combined, the black curves symbolize the effect of the ultracapacitors on the overall system performance. Since the axes are logarithmic, especially the curves on the upper right of the diagram it is visible that the specific power of the system can be increased. However, this leads to a reduction in specific energy [1].

The kinetic and elastomeric energy storage devices use a continuously variable transmission (CVT) as actuator, since they cannot deliver the power to the wheels directly [1].

Selection lines are included to assist the selection of the ideal system. Following them, it is assured that the mass of the system, which is needed to absorb the power, is the same as the mass needed to store the energy. The calculations were done for several decelerations from 0.1g to 0.5g, each for stopping a vehicle with an initial speed of 30 MPH. Since it is desirable to realize an RBS that is as light as possible, the optimal combinations according to the system selection chart on Figure 4.12 System selection chart [1] can be found following the selection lines to the upper right corner. Few optimal choices are depicted, with hydraulic systems made of composite materials forming the largest group with the most desirable characteristics. Few electrical systems and kinetic systems can be found as well, but hydraulic systems are up to 33% smaller and 20% lighter than the closest electrical solution. It must be added at this point however, that other factors like cost, complexity or maintenance effort of the RBS are excluded in this model [1].

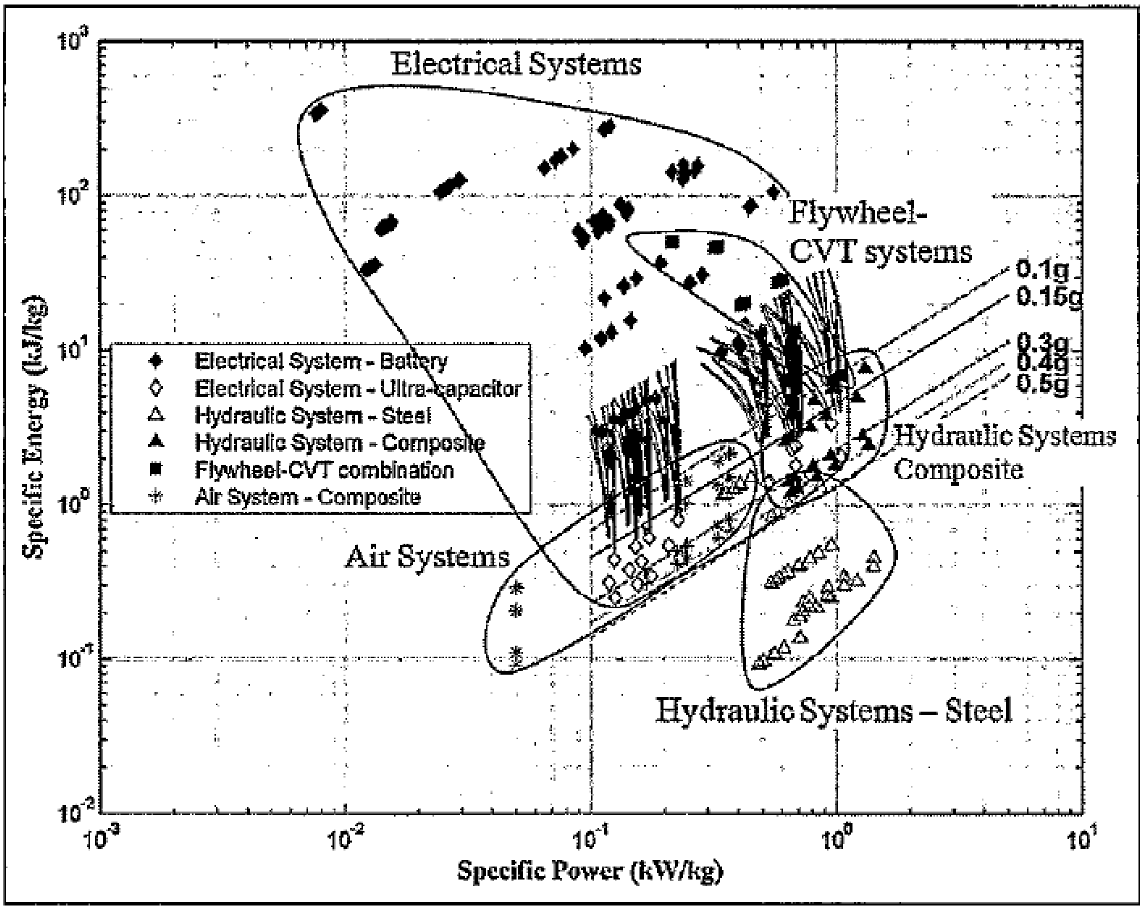


Figure 4.12 System selection chart [1]

Cost is an important factor for choosing the RBS components. It is reported that hydraulic systems are cheaper than electric or kinetic solutions because of their inherent simplicity and the little amount of components. Furthermore, wear is low if standard precautions regarding the hydraulic fluid are observed. Even though electric systems may be more durable, they presuppose regular replacement of the battery pack, which is costly. Additionally, the disposal of batteries involves environmental concerns. Ultracapacitors show less concerns, involving slight environmental issues. Kinetic systems show maintenance efforts because of their high rotational speeds, which cause wear in the bearings. However, flywheels are environmentally slightly concerning [1], [56].

Summarizing the findings from this chapter, one can deduce that a hydraulic regenerative braking system shows ideal functional properties for an RBS. It demonstrates high specific energies and high specific powers at comparably low weight. However, for the selection of an RBS also other factors like cost and maintenance effort should be included.

5 DEVELOPMENT OF AN RBS TAILORED TO THE GOLF CART

Since several scientific questions to be answered with this paper concern a regenerative braking system for the golf cart of the University of Portland, this chapter is taking care of these specific topics. First, the golf cart conversion project is illustrated, explaining which developments have been done by the time this paper was finished. Then, the potential energy savings of an RBS in a golf cart are investigated, followed by an introduction to regenerative braking for a golf cart. Simultaneously, it is explained which regenerative braking technology was chosen to be ideal for the cart and what the developments in this chapter cover. Two chapters including proposed regenerative braking systems are presented afterwards. The first solution deals with an RBS for the cart with the current drivetrain components. The second talks about an RBS with exchanged drivetrain components. Both solutions have the need for a braking control strategy, which is discussed in an own chapter. Last, developments and improvements for upcoming semesters are mentioned.

5.1 THE CONVERSION FROM COMBUSTION ENGINE TO ELECTRIC ENGINE

In order to illustrate significant issues that are encountered during the conversion of an ICE driven vehicle to a battery powered electric vehicle (BEV), the conversion project of the golf cart belonging to the University of Portland in Oregon, USA, is presented. In this chapter, information about both the golf cart and the project are given.

5.1.1 The Conversion Project

This chapter introduces the conversion project of the golf cart. It describes scope, purpose, initial situation, key design topics and limitations of the project as of January 2016.

The University of Portland Electric Vehicle (UPeV) team has been working in the 2015-2016 academic year on the conversion of a golf cart, which was provided by technician supervisor Allen Hansen. The conversion has been taking place in the Shiley Shop on campus, allowing using shop tools for the work. The main scope was set to be the successful creation of an electric cart by the end of spring semester 2016. The cart must also ensure that the technicians of the University of Portland can easily transport welding tanks and materials across campus. Other goals include a charge distance of 3 to 5 miles, limited battery damage and the capability of climbing the Shiley hill on campus.

Since this project is the initial step only, the cart is planned to be used for many future engineering projects. Suggestions of the UPeV team are an on board monitoring system, range optimizations and, to be emphasized, a regenerative braking system.

At the starting point of the project, the frame of the golf cart was in structurally sound condition and steering, tires, brakes and suspension were working. The inspection revealed however, that the Suzuki internal combustion engine was broken. Thus, the work of the project team was centered on the removal of the ICE and the construction of an electric drivetrain consecutively. Next to an electric motor, further components to be installed were battery pack, motor controller and battery charger. Important tasks have thus been the dimensioning of a motor to meet the capabilities of the cart, the identification of an optimal battery – motor combination, the determination of size and location of the battery mounts and the interfacing of the batteries with the system. Further tasks include the determination of an apt gear ratio for achieving enough torque at the wheels and the creation of the transmission from mechanical to electric power where the pedal meets the potentiometer.

The team has also found several limitations for the project. Identified were for example the weight limitation of the vehicle, estimated around 800 lbs. (363 kg), and safety aspects. These include speed limitations and battery maintenance. The top speed will be limited at 15 MPH, since that corresponds to the speed limit on campus. Battery maintenance issues are further explained below. Last, the size of motor cavity forces the team to place components in a compact way.

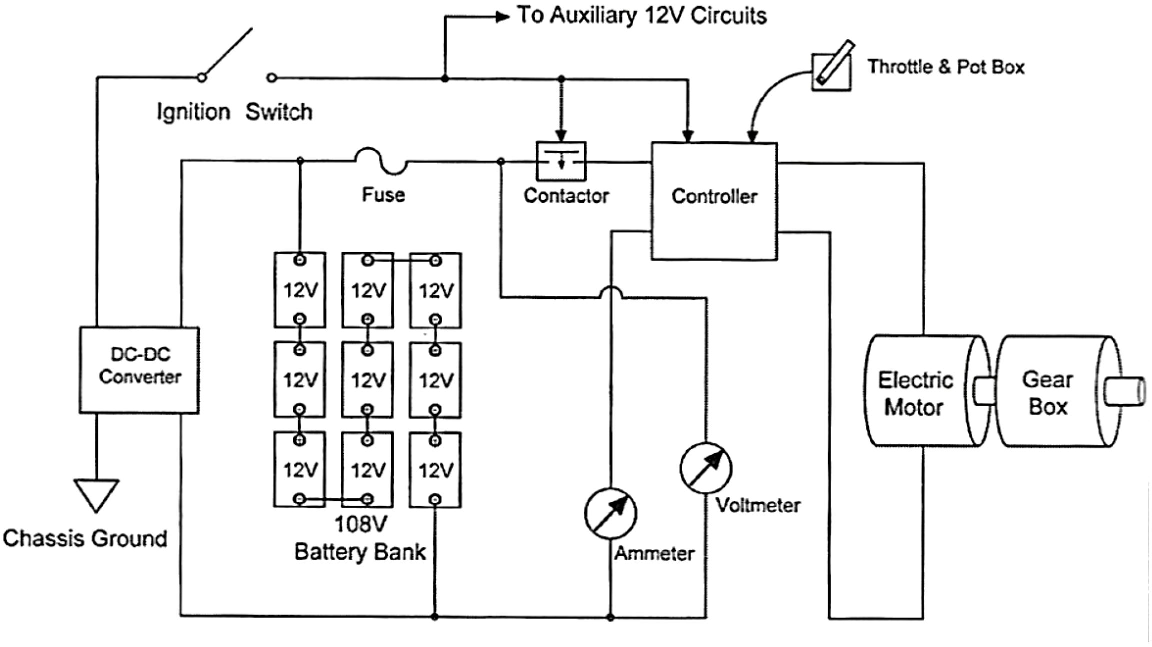


Figure 5.1 Cart Electric Drivetrain Schematic [73]

Based on the initial analysis, planning of the electric drivetrain was executed. The schematic selected as a template for the drivetrain is depicted on Figure 5.1 [73]. However, the drivetrain the team intends to design shows two slight differences. The final battery system will likely feature four to six 12V batteries in some combination of series and parallel arrangements. The second difference are the auxiliary 12V circuits, which are not considered to be implemented. However, they could be pondered in future to power onboard DC electronics such as a stereo or a heater.

Briefly summed up, the conversion project deals with the successful creation of a battery electric golf cart by the end of spring semester 2016. The cart must be tolerable of climbing the Shiley hill and show a charge distance of 3 to 5 miles. Future projects can then focus on the implementation of an RBS for example. So far, an initial analysis and the planning of the components has been executed. Emphasis is put on the selection of motor, battery pack, motor controller and battery charger. Limitations of the project are the maximum weight the vehicle supports (estimated around 800 lbs. or 363 kg), and safety aspects. The speed is limited to the campus speed limit of 15 MPH.

5.1.2 Components of the BEV Golf Cart

This chapter summarizes the three main components selected for the cart, which will be implemented in the spring semester 2016. First, the electric motor is described, followed by the battery pack and the motor controller eventually.

In order to calculate the required power for the motor to operate the cart on campus, two cases were investigated. The first foresees driving the cart on flat ground, while the second deals with the vehicle climbing the hill behind Shiley hall. The calculations were executed in Matlab, including various speeds and acceleration ranges. As a result, a motor power of about six horsepower was considered to be ideal. Between an AC or a DC motor, the choice was the direct current type eventually. This decision was based on reduced cost and complexity of the system and its components, since no conversion in AC is necessary. Thus, the motor selected is a 4.8/6.1 HP series wound model, which can be operated at 36/48V and a current of 130/125A.

The ideal battery composition for this project was chosen to be flooded lead acid. Even though lithium iron phosphate (LiFePo) batteries are lighter and show a higher energy density, they were unsuitable because of their high cost and complexity. Flooded lead acid batteries convince with the comparatively low price, the capability of storing enough energy and the ability to operate without a battery management system. NMHG (Nacco Material Handling Group) donated 11 heavy-duty lead acid batteries to the project, which are currently in test phase to see if they are able to retain charge. If the tests confirm usability, two arrangements can be envisaged. The first is a series connection of four of the 12V batteries, while the second intends to create two parallel strings, each including three 12V batteries. As of January 2016, the first arrangement is more probable to be realized, providing 48V to the motor controller, which is discussed next.

Figure 5.2 The cart with the batteries supplied by NMHG

The motor controller was ordered as part of a kit for series wound DC motors. It is able to command 144V of voltage and up to 500A of current. This controller will be connected to the potentiometer in the throttle pedal, controlling the power being delivered to the motor. Furthermore, it will protect the batteries from damage caused by overcharging or complete discharge.

To outline the content of this chapter, a series wound electric DC motor with 4.8/6.1 HP was selected to propel the cart in future. Its electric power will be supplied by the battery pack, consisting most likely of four 12V batteries in series arrangement. In order to vary speed of the golf cart, a suitable motor controller was ordered, able to command 144V and 500A. The throttle pedal will be linked to it, assimilating the typical speed control of a vehicle.

5.2 FROM A BATTERY POWERED EV TO A BEV WITH REGENERATIVE BRAKING

This chapter focusses on the transition from the BEV to a BEV with regenerative braking system. It is first explained, which energy regeneration potential can be expected for a golf cart. This is followed by a derivation of the ideal RBS technology, based on findings of the comparison in chapter 4.4 and the specific case of the golf cart explained in chapter 5.1. Consequently, two RBS solutions tailored to the golf cart are introduced and common design considerations are mentioned at the end of the chapter.

First, it is important to have an idea about the energy regeneration potential for a golf cart. Due to the low speeds of the cart, braking energy and the amount of energy that can be regenerated is predicted to be quite poor. However, as given in [32], a higher transmission ratio could transform the shaft rotational speed into a higher transmission output speed, yielding to higher braking efficiency. Additionally, it is mentioned that the lowest braking energy is found at low-load operations. Since the mass of the cart is comparatively light (700lbf or 320kg), also the braking load is comparatively low. Two studies in [3] and [4] indicate that a 1600 kg vehicle can experience theoretical fuel savings of up to 23% on a level road during urban driving, given the case that a regenerative braking system was supplemented. However, this saving is decreased as the weight of the vehicles decreases, resulting in theoretical savings of about 15% for a 1000 kg vehicle. In fact, a project with emphasis on the creation of an RBS controller for a golf cart showed at least 12% enlarged driving range [74]. Estimated that the UP golf cart is similar to the cart mentioned, an enlarged driving range of about 12% could represent a potential target for the RBS project. Two potential ways of achieving this target are the RBS solutions proposed, which are introduced in the following paragraphs.

As mentioned in chapter 5.1, the conversion project represents the beginning of a series of projects around the golf cart. Its aim is to provide the cart with an electric drivetrain by the end of spring semester 2016 and the order of appropriate components was the last milestone in fall semester 2015. Since the implementation of an RBS would go beyond the scope of the conversion project, this research should facilitate students in the initial phase of a future RBS-project. To assist in the classification and evaluation of existing RBS technologies, the research includes a general comparison of RBS technologies in chapter 4.4. Based on the findings of the comparison and the specific case of the golf cart, an argumentation about the ideal RBS technology is presented in this upcoming section, followed by specific introductions to the two proposed RBS.

Although hydraulic regenerative braking systems convince with ideal functional characteristics for an RBS, the two proposed RBS solutions are based on electric technology. This is due to several reasons. First, the electric drivetrain components are brand new and should not be rejected after few semesters. Rather, a solution within the same technology space should be found, since the implementation of a hydraulic propulsion system including regenerative braking would presumably exceed the scope of a single senior design project year. Furthermore, the projects on the golf cart are meant to build one on another, instead of restarting from scratch again. The scope of the first RBS project could thus include a successful implementation of an RBS and experiments about tuning of the overall braking system. Since the project teams have a budget constraint, this is another reason for a solution within the existing technology space. Although the comparison in chapter 4.4 concludes that hydraulic RBS show cost advantages if a complete system has to be implemented, in this case many parts of the existing electric drivetrain can be harnessed. Since some kinetic RBS also show desirable functional properties, their exclusion for the golf cart should be reviewed as well. A flywheel is an additional component that takes away significant space in the motor cavity. Since the residual space is very limited in the cart, this technology seems to be inappropriate. In addition, it is reported to be a very complex technology. Thus, an electric RBS seems to be the most promising system for the UP golf cart.

The first design solution given foresees keeping the existing components of the electric drivetrain, i.e. DC series motor, batteries and the DC motor controller. In contrary, the second solution is based on systems used in similar lightweight RBS applications, however expecting exchanged electric drivetrain components. Based on the reasons stated in the last paragraph, the first solution can be stated as the optimal RBS for the UP golf cart, because it reduces rejection of existing parts, adheres to the electric drivetrain technology and minimizes cost, building on existing components. Neither the first, nor the second solution does present final designs; they rather give insight into the crucial fundamentals for the realization of such systems and illustrate potential schematics. Practically, the scope of this paper is giving an initial guideline for the realization of an RBS tailored to the golf cart.

Although the solutions show inherent differences that are explained in the upcoming chapters, few common points to be considered in their designs are noticeable. The first is that the golf cart is a rear axle powered vehicle. As a critical case, the low friction scenario for rear axle regenerative braking was investigated in [75] and [29]. According to these sources, excessive regenerative braking can induce yaw instability, because the rear wheels become locked. Especially for this case, a smart blend of regenerative braking and friction braking should be envisaged to exactly deliver requested braking force while preserving vehicle stability. By saying this, another mutual design point is mentioned and confirmed in [74]: The electrical regenerative braking system of the golf cart EV cannot handle the total braking power alone and must be paired with a mechanical friction braking system. For both the proposed systems, the overall drivetrain schematic stays almost unchanged; solely alterations of individual components are detectable. Therefore, they are presented in the following chapters.

Summarizing the information of this chapter, it can be mentioned the following: Based on similar projects found in literature, an enlarged driving range of about 12% could represent a potential target for a future RBS project involving the UP golf cart. Based on the technology comparison given and the specific case of the cart, the most promising system seems to be an electric RBS. This is due to several reasons, including senior design project constraints regarding scope and budget, the usage of existing drivetrain components and the space available in the motor cavity. Thus, hydraulic RBS and kinetic RBS are excluded, although showing desirable functional properties as well. Since the implementation of an RBS would go beyond the scope of the recent conversion project, this research should facilitate students in the beginning phase of a future RBS-project, giving an initial guideline for the realization of an RBS tailored to the golf cart. For this, it was decided to propose two RBS design solutions. The first design solution foresees keeping the existing components of the electric drivetrain, i.e. DC series motor, batteries and the DC motor controller. In contrary, the second solution is based on systems used in similar lightweight RBS applications, however expecting exchanged electric drivetrain components. An important point to be considered in the design of both solutions is that the golf cart is a rear axle powered vehicle. Thus, a smart blend of regenerative braking and friction braking is required.

5.3 A PROPOSED RBS DESIGN WITH EXISTING COMPONENTS

This chapter presents a proposed regenerative braking system for the golf cart, which foresees keeping the existing components of the electric drivetrain. First of all, an analysis of the existing drivetrain components is given, since few of them must be modified for an RBS. Then, a prospective design is described.

5.3.1 Analysis of existing Components

At the end of spring semester 2016, the golf cart of the University of Portland will have a 4.8/6.1 HP series wound motor, 12V heavy-duty lead acid batteries and a matching motor controller for series wound motors. This chapter gives first insight into obstacles that have to be overcome to use the motor mentioned above for an RBS. Then, it is explained why the current controller is unsuitable for regenerative braking and how this problem can be remediated.

5.3.1.1 DC Series Motor

Since there is a difficulty in using series wound motors for regenerative braking, information about the issue and a method of overcoming are described in this subchapter.

DC motors are typical machines used for drive applications, mainly because of the large starting torque they provide, but also because of their simple operation and control [76]. The electrical interconnection of both armature and field winding decide on the type of machine, showing different speed-torque characteristics. The series motor shows a large starting torque at low speeds; however, the speed becomes excessively high at light loads. Hence, light loads are highly dangerous for series machines and must be avoided. Per definition however, regenerative braking begins with the transgression of the no-load speed (at zero torque), since that implies a back EMF voltage higher than the terminal voltage. Thus, in order to be used as a generator, the interconnection of the windings has to be altered during this phase. A possible solution is given with Figure 5.3 [13]. The field winding is provided with electrical energy by a separate voltage source V_f. It can be seen that the winding R_f is decoupled from its original circuit with the switches S_1 and S_3, and connected to V_f with switch S_2. During transition, it is important to guarantee an uninterrupted current flow in the field circuit, which is accomplished by

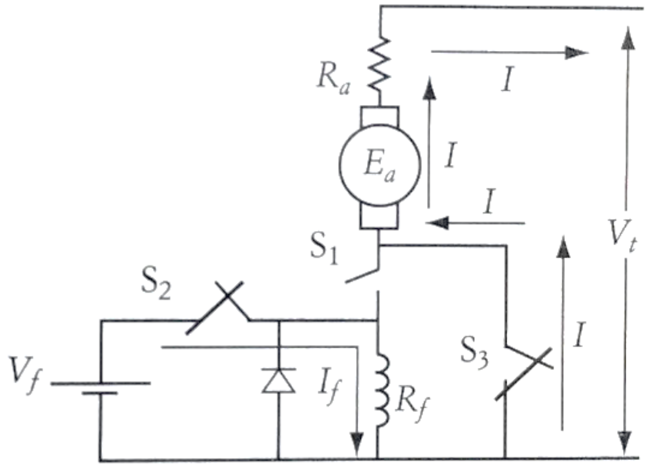


Figure 5.3 A regenerative braking circuit for DC series machines [13]

implementing a freewheeling diode parallel to R_f. This diode keeps the current continuous, until switch S_2 is closed [13]. The voltage generated can be obtained at the terminals as V_t, while the voltage V_f can be obtained as a fraction of the battery voltage for example.

Since the DC series motor shows excessive speeds at light loads, this situation must be avoided changing from motor to generator mode. Thus, an alteration of the circuit is performed, switching to a separate voltage source for the field circuit.

5.3.1.2 Motor Controller

Even though the DC series motor can be used under given circumstances, the motor controller is not compatible with regenerative braking in its original state. It is an Open Revolt 144 V 500 A DC Electric Motor Controller [77] and has simple software, not allowing regenerative braking control including one PWM signal and a simple control strategy. One of the first tasks for future projects could thus be the investigation of the controller hardware and the software code. For energy regeneration, it is important that a reversed current flow from the electric machine to the battery is possible. The switches and the circuits of the controller must allow this. However, the current flow must be controlled to have the braking process under control and thus an appropriate software code must be added, taking care of the switching sequence for example. Another option instead of altering the existing controller is buying a new DC series motor controller kit, which is compatible with regenerative braking. Since there is no such a DC series motor controller kit offered on [77], other sellers must be contacted.

The analysis of the motor controller leads to the certainty that it cannot be used for regenerative braking in its original state. Thus, an alteration of controller software and (if needed) hardware have to be taken into consideration for an RBS usage.

5.3.2 Design of the System

This chapter talks about key points of the design of an apt electric regenerative braking system, which includes existing motor and motor controller. Since the structure of the overall drivetrain schematic depicted on Figure 5.1 stays the same, the design of the motor controller is focused.

For a system with existing components of the electric drivetrain, the DC series motor and the motor controller have to be modified. A design suggestion for the circuitry of the DC series motor is given on Figure 5.3. However, the switches S_1, S_2 and S_3 must be operated to amend the interconnection of the windings. The motor controller could execute this task, comprising it as a piece of code at the beginning of the regenerative braking action.

In [39], an electric regenerative braking system applied on the rear wheels of a Tata Ace EV is presented. This small commercial vehicle uses a 5.2 kW or 7 HP (continuous) DC separately excited motor, which is connected to the rear axle differential. A transistorized traction controller provided by FSIP (Flight Systems Industrial Products) controls it. The proprietary software includes two functions that adjust the level of regenerative braking. One is “Armature Regen Amps” and can be adjusted within 32 A to 382 A. The larger the armature current, the shorter the stopping distance. In succession, the second function makes it possible to adjust “Field Regen Amps” and can be set from zero A to 50 A. These values could be helpful for the controller design, because the DC series motor field winding is also excited by a separate voltage during the regenerative braking mode. Further information about the controller and important design points for the regenerative braking strategy are given in chapter 0.

Summarizing this chapter it can be pointed out that the motor controller must take care of the transition of the DC series machine from motor to generator mode. This task can expectedly be executed with a software program. To have an idea, the field current in a similar project for a 7 HP motor is reported to range between zero A and 50 A, while the armature regenerative current varies within 32 A and 382 A. The larger the armature current, the shorter the stopping distance.

5.4 A PROPOSED RBS DESIGN WITH EXCHANGED COMPONENTS

This chapter illustrates an electric RBS design, which uses exchanged motor and motor controller. It is proposed, because several lightweight RBS projects use this common configuration. According to this, a BLDC machine is used as actuator, controlled by a fuzzy logic based controller.

In the first RBS proposed it is noticeable that the alterations of motor circuitry and motor controller represent main barriers for a successful implementation. Several lightweight EVs presented in literature use different components in their place. Applications range from electric bicycles [47] to LUV trucks [51] and represent a quite common scenario for the realization of regenerative braking. These systems comprise a brushless DC motor fed by an inverter, exactly as presented in chapter 4.2.1.1. These motors are an optimal choice for EVs, since they offer high power densities, good speed-torque characteristics, high efficiency, wide speed ranges, and low maintenance [78], [79]. BLDC motors are also known as electronically commutative motors (ECMs), while DC series motors are mechanically commutative brushed motors. The speed of BLDC motors is depending on the frequency of the PWM signal switching inverter switches. This stays in contrast to the speed regulation of brushed DC motors, which is depending on the amount of voltage supplied.

Because the motors possess inductances in their windings, these windings can work as part of a boost circuit, enlarging the generated voltage to allow battery recharge. The energy regenerative mode of a BLDC with inverter circuit is presented in detail in chapter 4.2.1.1 and could be considered as a guiding schematic.

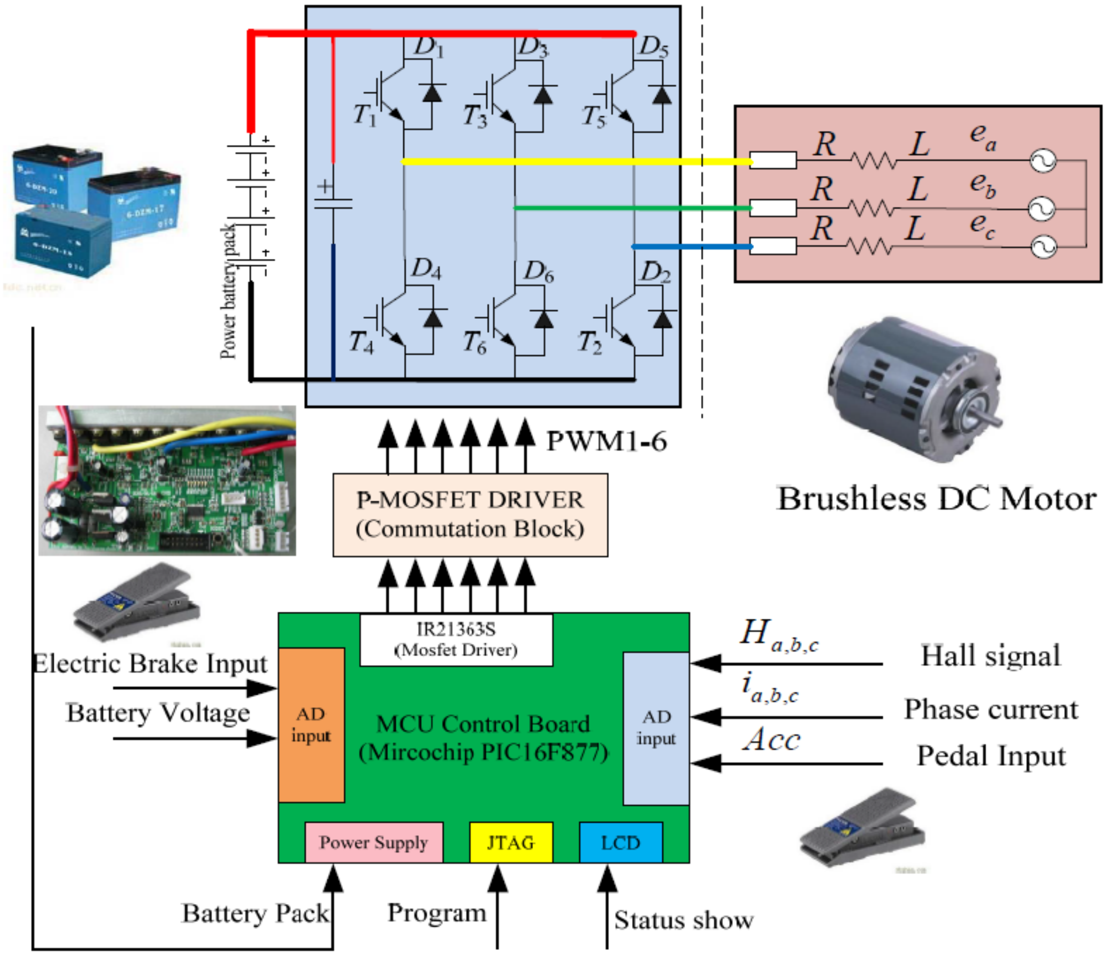


Figure 5.4 EV system configuration using a BLDC motor [74]

To maintain the overview of the altered electric drivetrain with these components, an EV system configuration is depicted on Figure 5.4. This system comprises a battery pack, an (inverter) control circuit, a permanent magnet BLDC, and a PIC16F877 microcontroller as core controller. Additional equipment includes various sensors (Hall sensors, phase current sensors), a programming interface, an LCD status show panel, a MOSFET driver IC, and two pedals (one for accelerations, one for brake control). The brake pedal integrates electric regenerative braking and friction braking in one pedal. In the case presented in [74], regenerative braking is executed when the pedal experiences angles ranging from 5° to 18°. Once 18° are exceeded, the system realizes that an emergent braking is necessary and activates the friction brakes. The transition from motor to generator mode can be executed by changing switching mode in the controller. No physical change of the circuit is needed, clearly representing an advantage over the proposed series motor energy regeneration process.

In a nutshell it can be said that this RBS design is very common, because its control is simple and does not require any additional components or circuit alterations. The structure of such a system is given on Figure 5.4 and includes a BLDC motor, batteries, sensors and a microcontroller-based motor control. Two pedals are used to control the vehicle motion. One constitutes the brake pedal, integrating electric regenerative braking and friction braking.

5.5 BRAKING CONTROL STRATEGY

If the RBS project includes the development of a motor controller instead of buying one, this chapter gives crucial information about the development of a braking control strategy.

A braking control strategy has to be carried out for both proposed solutions and is thus said to be a commonly needed development. The problem it addresses is the following: In order to translate the brake pedal information into a regenerative braking force, a regenerative braking strategy based on fuzzy control logic can be applied and saved on the microcontroller as a program. The structure of a suggested braking control strategy can be obtained from Figure 3.15 [20]. Based on the fuzzy control rules that have to be established, the regenerative braking force is calculated and output as Mf, a ratio of the total braking force. According to this, Mf0 foresees 0% regenerative braking force usage, while Mf5 foresees that 50% of the total braking force comes from regenerative braking. The classes include Mf0, Mf1, Mf2, Mf3, Mf4, Mf5, Mf6, Mf7, Mf8, Mf9 and Mf10.

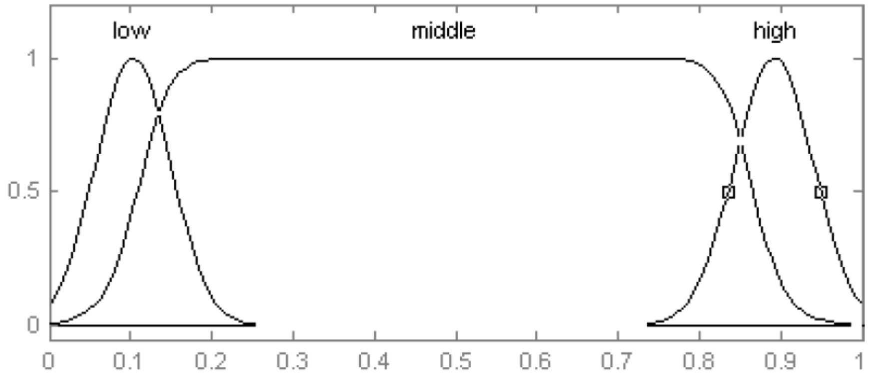
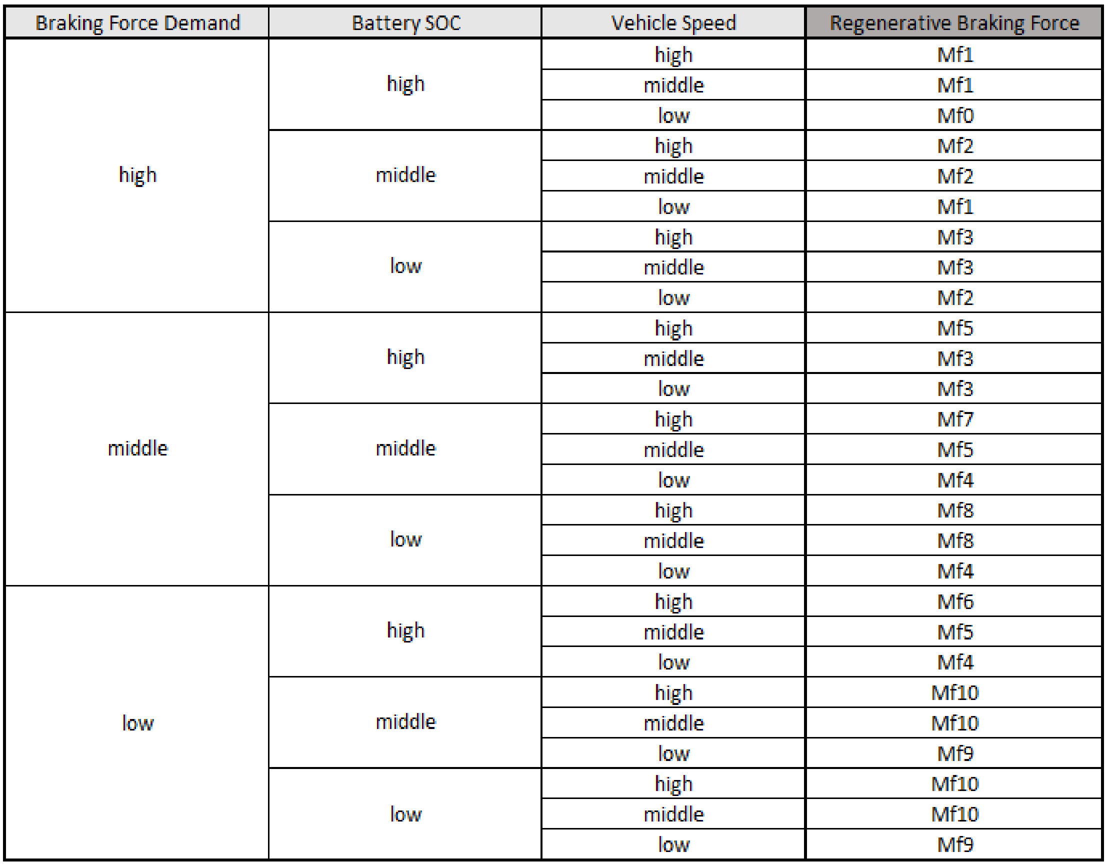


Figure 5.5 Relationship of RB force and vehicle speed [20]

In addition to the brake force demand and the battery voltage SOC stated on Figure 5.4, also vehicle speed is sensed. The relationships of these three factors and the regenerative braking force are established as follows: Each factor shows three ranges, within which the regenerative braking force can be clustered. It can be of low, middle or high level and an example is given with Figure 5.5. It states that for low speeds, regenerative braking force should also be low, assuring safety regulations. For medium speeds, the regenerative braking force can be increased to the middle level, while high speeds suggest high regenerative braking forces. This model is applied on all the three factors and finally a fuzzy rules base is established, summing up all the possible conditions and the resulting output regenerative braking force. Table 5.1 presents the fuzzy rules base, which could serve as a guideline for the control strategy design in an RBS project. In [20], a 16-bit microcontroller unit was used as vehicle control unit (VCU), executing the fuzzy regenerative braking strategy. The computational speed was set at a maximum frequency of 50MHz.

The braking force distribution strategy could generally follow the bold line presented on Figure 3.14. This corresponds to a series braking strategy with regenerative braking applied on the rear wheels only. At low braking force demand, regenerative braking is used to a large proportion. According to the fuzzy logic, there might happen some deviations from the bold line for specific



Braking Force Demand	Battery SOC	Vehicle Speed	Regenerative Braking Force
high	high	high	Mf1
		middle	Mf1
		low	Mf0
	middle	high	Mf2
		middle	Mf2
		low	Mf1
	low	high	Mf3
		middle	Mf3
		low	Mf2
middle	high	high	Mf5
		middle	Mf3
		low	Mf3
	middle	high	Mf7
		middle	Mf5
		low	Mf4
	low	high	Mf8
		middle	Mf8
		low	Mf4
low	high	high	Mf6
		middle	Mf5
		low	Mf4
	middle	high	Mf10
		middle	Mf10
		low	Mf9
	low	high	Mf10
		middle	Mf10
		low	Mf9

Table 5.1 Fuzzy rules base [19]

cases. An example are high battery SOCs, for which medium regenerative braking forces are suggested by the fuzzy logic. Thus, the line section O – A should receive a share of (front wheel) friction braking, resulting in a projected move of A along the x-axis. Although the bold curve does initially exceed the ideal braking force distribution, this is tolerable because it deals with low braking force demand and increases energy regeneration potential.

An important point for every regenerative braking system is the braking control strategy it follows. In order to translate the brake pedal information into a regenerative braking force, a strategy based on fuzzy control logic can be applied being programmed on the microcontroller. The regenerative braking force is calculated based on three levels (low, medium, high) of each of the three influencing factors. These are selected to be the braking force demand, the battery voltage SOC and the vehicle speed. A fuzzy rules base summarizes every possible condition and allocates appropriate regenerative braking force proportions. The result is a strategy, which follows (with slight exemptions) the bold line on Figure 3.14.

5.6 SUMMARIZED FINDINGS AND DISCUSSION

This chapter summarizes the findings of the fifth chapter and discusses them, emphasizing crucial design aspects for an RBS tailored to the UP golf cart. The findings should facilitate students in the beginning phase of a future RBS-project, giving an initial guideline for the realization of an RBS.

5.6.1 Summarized Findings

The conversion project of the UP golf cart deals with the successful creation of a battery electric golf cart by the end of spring semester 2016. A series wound electric DC motor with 4.8/6.1 HP was selected to propel the cart. Its electric power will be supplied by the battery pack, consisting most likely of four 12 V batteries in series arrangement. In order to vary speed of the golf cart, a suitable motor controller able to command 144 V and 500 A was ordered. Future projects can focus on the implementation of an RBS and based on similar projects, an enlarged driving range of about 12% could represent a potential RBS target. The technology comparison of the fourth chapter and the specific case of the cart yield to the assumption that the most promising system is an electric RBS. This is due to several reasons, including senior design project constraints regarding scope and budget, the priority in using existing drivetrain components and the space available in the motor cavity. Thus, hydraulic RBS and kinetic RBS are excluded, although showing desirable functional properties as well.

Two RBS design solutions are proposed. An important point to be considered in the design of both solutions is that the golf cart is a rear axle powered vehicle. Thus, a smart blend of regenerative braking and friction braking is required. The first solution foresees keeping the existing components of the electric drivetrain, i.e. DC series motor, batteries and the DC motor controller. Since the DC series motor shows excessive speeds at light loads, this situation must be avoided changing from motor to generator mode. Thus, an alteration of the circuit is performed, switching to a separate voltage source for the field circuit during regenerative braking. Since the original state of the Open Revolt Controller does not support regenerative braking control, also an alteration of controller software and (if needed) hardware have to be taken into consideration. To have an idea, the field current in a similar project for a 7 HP motor is reported to range between zero A and 50 A, while the armature regenerative current varies within 32 A and 382 A. The larger the armature current, the shorter the stopping distance.

In contrary, the second solution is based on systems used in similar lightweight RBS applications, however expecting exchanged electric drivetrain components. This type of RBS is very common, because its control is simple and it does not require any additional components or circuit alterations. Included are a BLDC motor, batteries, sensors and a microcontroller-based motor control. A brake pedal integrates electric regenerative braking and friction braking.

An important point for every regenerative braking system is the braking control strategy it follows. In order to translate the brake pedal information into a regenerative braking force, a strategy based on fuzzy control logic can be applied being programmed on the microcontroller. The influencing factors suggested are the braking force demand, the battery voltage SOC and the vehicle speed. A fuzzy rules base summarizes every possible condition and allocates appropriate regenerative braking force proportions. The result is a strategy, which follows (with slight exemptions) the bold line on Figure 3.14.

5.6.2 Discussion of the Findings

Although hydraulic regenerative braking systems convince most with ideal functional characteristics for an RBS, the two proposed RBS solutions are based on electric technology. This choice is discussed at this point.

The first reason promoting an electric RBS is that the electric drivetrain components are brand new and should not be rejected after few semesters. Therefore, a solution within the same technology space is prioritized. The implementation of a hydraulic propulsion system including regenerative braking would presumably exceed the scope of a single senior design project year, because all the existing components would have to be replaced. Another related reason is that the projects on the golf cart are meant to build one on another, instead of restarting from scratch again. Since the project teams have a budget constraint, this is another reason for a solution within the existing technology space. Although the comparison in chapter 4.4 concludes that hydraulic RBS show cost advantages if a complete system has to be implemented, in this case many parts of the existing electric drivetrain can be harnessed. Since some kinetic RBS also show desirable functional properties, their exclusion for the golf cart should be reviewed as well. A flywheel is an additional component that takes away significant space in the motor cavity. Since the residual space is very limited in the cart, this technology seems to be inappropriate. In addition, it is reported to be a very complex technology. Thus, an electric RBS seems to be the most promising system for the UP golf cart.

5.7 FUTURE DEVELOPMENTS AND IMPROVEMENTS OF CART AND RBS

This chapter includes information about the upcoming tasks of the golf cart conversion project and mentions potential improvements of the proposed RBS systems. It is talking about the addition of ultracapacitors to the batteries. Last, an alternative braking system for future projects is described briefly.

5.7.1 Upcoming Tasks of the Conversion Project

This chapter talks briefly about the upcoming tasks of the golf cart conversion project. Focus of the spring semester 2016 is going to be the implementation of the components mentioned.

The first step to be addressed in the spring semester is the completion of the battery case design and the motor mount. As mentioned before, the motor cavity offers little space, demanding an optimal arrangement of the elements to be placed. The 3D model of the golf carts rear end shown on Figure 5.6 illustrates the motor cavity and gives an idea about the planned placement of the battery pack. Furthermore, the existing driving gear housing is depicted, which represents the join to the rear wheels. After exploring appropriate gear ratios, the electric motor will be installed and coupled to the existing driving gears in the end.

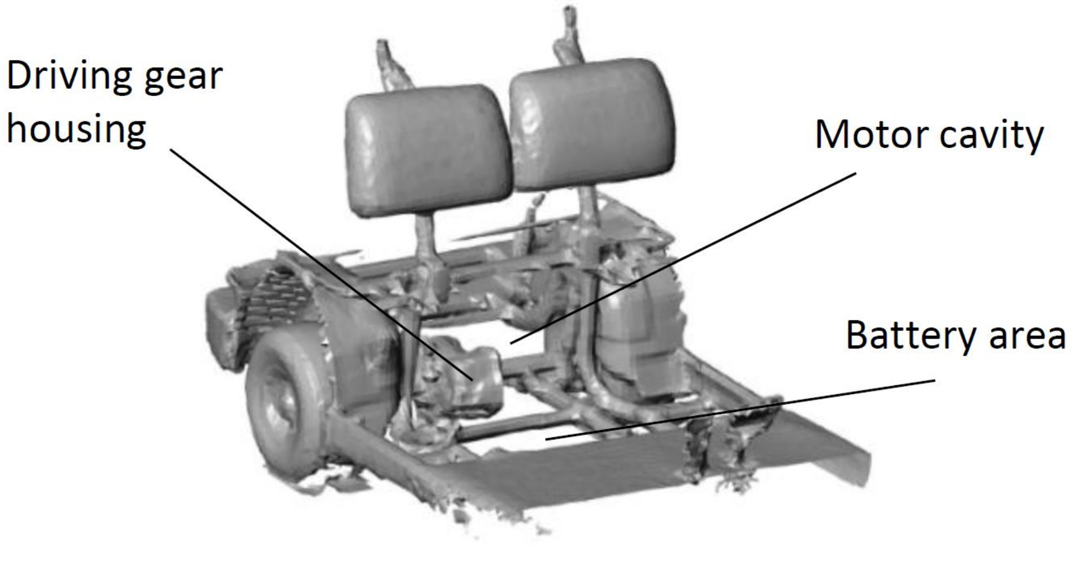


Figure 5.6 The 3D model of the golf carts rear end

The last steps for the project will be installation of batteries, motor controller and all residual electronics. After the final checks of mechanics, the cart will be handed over to shop technician supervisor Allen Hansen.

In a nutshell, the upcoming developments concern battery case and motor mount. Then, the motor, batteries, motor controller and the electronics will be installed. Finally, after passing the tests, the conversion project will end with a converted golf cart.

5.7.2 Addition of Ultracapacitors to the RBS

Chapter 4.2.1 concludes with the statement that an electric regenerative braking system works best if batteries are combined with ultracapacitors to store the braking energy. Therefore, this chapter presents such a combined energy storage system, which could be implemented in both the proposed RBS solutions as a follow up action.

A schematic presented on Figure 5.7 shows components and structure of an energy storage device consisting of batteries and ultracapacitors. Since it is designed for a double cabin Chevrolet LUV (light utility vehicle) truck with a gross weight of 1920 kg, the battery pack shows a significantly higher voltage than the prospective one of the UP golf cart. Thus, the values of the elements depicted have to be recalculated. The system consists of ultracapacitor bank, bidirectional DC-DC converter with a buck and a boost circuit, and a smoothing inductor L_S. When the vehicle accelerates, the capacitor voltage is discharged to one third of its nominal voltage. This allows harnessing power from the ultracapacitors for about 20 seconds. In order to do this, the system executes the boost operation, discharging the capacitor. Thus, the IGBT T1 is switched on and off alternately. During its ON mode, energy is extracted from the capacitor and stored in the inductor L_S. In the OFF mode, the energy is brought through D2 to the capacitor C. From there it is finally delivered to the batteries. The reversed action of transferring energy from the battery to the ultracapacitor is called buck. Analogous to boost, however using T2 and D1 instead of T1 and D2, the energy delivery takes place. It is further explained in [51] how the system is controlled. A digital signal processor (microprocessor) is used. Its software code shows two levels: A primary control responsible for the current reference I_{ref} flowing to the ultracapacitor and a secondary control responsible for the PWM signals addressed to the power converter. Primary control can also be described as charge control and keeps an appropriate level of energy in the capacitors, computed from the EV speed and the battery SOC. The charge in the ultracapacitors is high, when the vehicle speed and/or the battery SOC are low. It has to be mentioned at this point however, that the motor control including the actual regenerative braking control are executed in this example on a separate motor controller. Since the motor used in [51] is a brushless direct current (BLDC) motor, structure and motor control as depicted on Figure 4.2 can be imagined. The ultracapacitor bank includes 132 ultracapacitors, put in five different aluminum boxes. The capacitors per box are connected in series. Based on the slight differences in capacity, a tendency to charge unevenly can be noticed. Thus, voltage cell balancing (VCB) is required, remedying dangerous voltage overloads. The inductor L_S is designed for sustaining 100 A under steady state and 200 A for two minutes. Being made from aluminum and weighing about 20kg, this inductor shows 1.6 mH inductance and 0.03 Ω resistance.

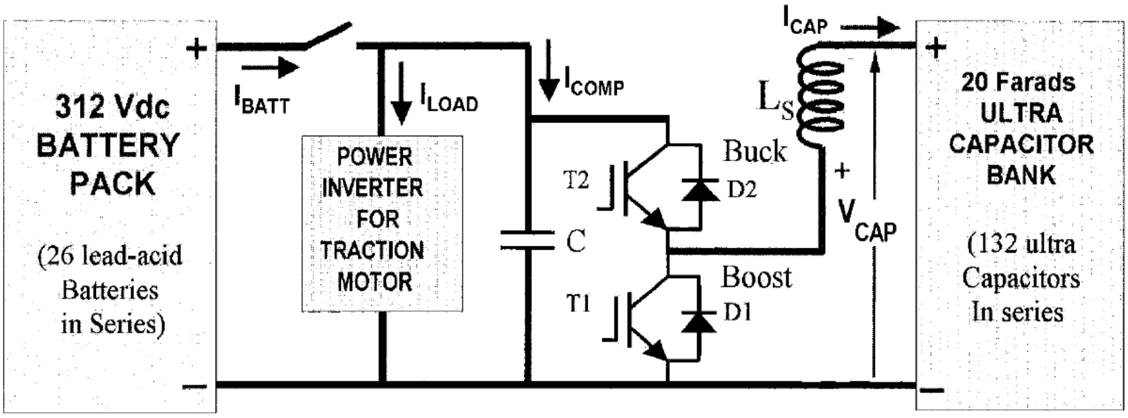


Figure 5.7 Ultracapacitor system [51]

Briefly said, electric regenerative braking system works best if batteries are combined with ultracapacitors to store the braking energy. Such a system could be implemented in both the proposed RBS solutions. Components and structure are presented on Figure 5.7 and the energy transfer is executed via a buck and boost circuit. A microprocessor controls the system on two levels: primary control takes care of an apt charge level depending on EV speed and battery SOC, while secondary control generates the PWM signals for the power inverter (for a BLDC motor). To construct an ultracapacitor bank, several series arrangements should be considered. A concern is uneven charge in the single capacitors, but it can be remediated with a voltage cell balancing system.

5.7.3 Alternative Braking System for the Golf Cart

This chapter introduces a future alternative to the hybrid braking systems suggested above.

An alternative to the hybrid braking system presented is a fully electric braking system. An example for a vehicle powered with in-wheel motors is given in [80]. A system without any mechanical brake is investigated. Rather, an electric regenerative braking system is paired with a countercurrent technique. Once the regenerative braking system cannot deliver enough braking torque, extra voltage is applied to the motors. This system shows various advantages like quicker response time, more precise braking torque measurement and a simplified control.

However, electric energy must provided at all time to stop the vehicle, which is a significant drawback. Nevertheless, such a fully electric braking system could be a project succeeding the initial RBS implementation.

5.7.4 Summary: Future Developments and Improvements

Upcoming developments to conclude the conversion from combustion engine to battery powered electric engine concern battery case and motor mount. Then, the DC series motor, batteries, motor controller and the electronics will be installed. Finally, after passing the tests, the conversion project will end with a converted golf cart.

An improvement for any electric RBS is a combined energy storage, comprising ultracapacitors and batteries. The energy transfer is executed via a buck and boost circuit and a microprocessor controls the system on two levels: primary control takes care of an apt charge level depending on EV speed and battery SOC, while secondary control generates the PWM signals for the power inverter (for a BLDC motor). To construct an ultracapacitor bank, several series arrangements should be considered. A concern is uneven charge in the single capacitors, but it can be remediated with a voltage cell balancing system. Another future development could be a fully electric braking system, excluding mechanical friction braking. According to this, an electric regenerative braking system is paired with a countercurrent technique. Once the regenerative braking system cannot deliver enough braking torque, extra voltage is applied to the motors. Although this system shows quicker response time and a simplified control, it must be supplied with electric energy at all time to stop the vehicle.

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