Overview of the Ways to Design an Electric Bicycle

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Abstract – **This paper reviews possible approaches to the design of an electric bicycle with an emphasis on three different domains – electrical, mechanical and system level design. It reviews the available solutions to a wide range of issues in each of the above mentioned domains. After grouping the solutions presented and classifying them on a domain basis the paper presents a classification on the ways to design an electric bike, so that a designer can easily obtain the required information in order to start their project.**

Keywords – **Electric bicycles, Electric Power-Assisted Cycles, Light Hybrid Vehicles**

I. INTRODUCTION

The deployment of electrified road transport in the range of 5-10% is one of milestones for the year 2020 in Europe [1]. However, the amount of electrified vehicles is not increasing as steadily as lawmakers would like them to-only 1.4% of the new vehicles were electric ones in 2017 [2]. There is one kind of electric transport, where the desired goal for electrification level is already reached. With 8% of the new bicycles being of the Electric Power-Assisted Cycles (EPACs) type, the electrification of this kind of transport is already in a very advanced state [3].

The EPAC are lighter, more compact and cheaper than electric cars and can be considered to be the forerunner of the impending electrification of road transport, which some envisioned as a way to achieve sustainable transport not dependent on fossil fuels [4]. Being cheaper to design, experiment and manufacture, this kind of transportation has stimulated the engineers and scientists to try different approaches to implement the overall system. This paper aims to summarize the possible approaches for designing such a vehicle by first separating the design phase into three different domains – electrical, mechanical and system level design. For each of them the paper tries to summarize the main problems and possible solutions that the designer must face in order to build the vehicle. Finally, on the basis of the presented information a classification is proposed that can be used as a general overview of possible ways to design an electric bicycle.

The paper is structured as follows: in Section 2 the three main design domains – electrical, mechanical and system level are presented, alongside questions for the engineer designing the vehicle. These issues need to be addressed during the design phase of the bicycle. The overview of the possible solutions in each different domain is the main topic of Section 3. There, each approach is first discussed, with its advantages and disadvantages, and emphasis is given to commercially available solutions. In the final section the proposed classification is presented. Finally, Section 4 concludes the paper.

II. MAIN METHODS

When choosing a concept for designing an EPAC, one needs to be aware of the different approaches that are possible. In order to be able to list them in some order the approach taken in this paper is to separate them into three main domains – Electrical Engineering Domain, Mechanical Engineering Domain and System Level Design Domain. The main questions in each domain are [5], [6]:

• Electrical Engineering Domain –What type of electric machine to use? What motor drive control algorithm to implement? , What power converters need to be designed? What will the primary energy storage be (possibly a hybrid one)? How to charge the battery or what type of BMS system to implement?

• Mechanical Domain – Where to place the electric motor? What gears should we use in order to combine human and machine torque?

• System Level Design – What kind of power topology to use? Should it assist only (pedelec) or can it be driven with pure electric power (ebike)? Should there be any energy regeneration in the bike?

The paper reviews the possible solutions to the above posed questions.

III. PROPOSED CLASSIFICATION

A. System Level Design

Looking at the system level EPACs are a light hybrid electric vehicle that combines human and electric power. There are two main ways to design such a vehicle - in a serial [7] or parallel way [5], [6], [8]. The parallel case shown in Figure 1 is the more popular way of designing such a vehicle. In this case, human torque is combined in the mechanical domain with the torque from the motor via gears [9]. In the serial configuration, shown in Figure 2 the human and electrical machine torque are coupled in the electrical domain. The double conversion of human power has the positive effect that optimal cadence can be achieved at all slopes, while lowering the overall efficiency. When implementing the serial hybrid approach, special care must be taken to ensure a natural feeling during cycling, minimizing the index of perceived exertion. The problem of optimal control for serial ebikes is the main topic in [10].

In this initial system level design phase one more question must be addressed – Should the system include regenerative braking? And should the bicycle be able to run on pure electric energy, without pedaling input from the cyclist (ebike) or the cyclist needs to apply power at all times in order to operate it (pedelec, PAS)?

Regarding the first question some theoretical considerations predict that around 35% of the energy can be recovered, in the case of an ideal recovery system in a certain hilly city test track [11]. Other studies argue that efficiency is less than 10% [12], while some real data showed that it is around 16% [13]. As the added cost to implement such a system is mostly a control algorithm that is a worthwhile investment from a design perspective [14].

Regarding the second posed question, it should be noted that the law in some countries answers this question unilaterally [3], [5]. Most of the sold EPACs in Europe are of the pedelec type, and it seems to be the more popular choice [5].
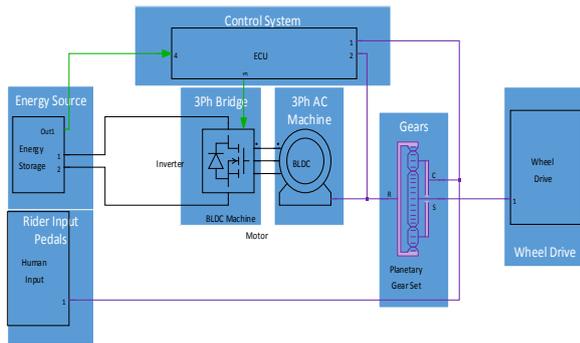

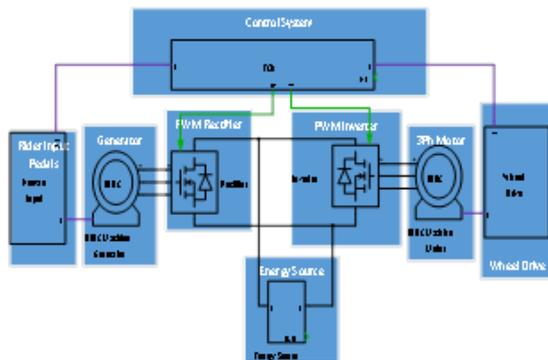Fig. 1. Parallel Configuration of an electric bicycle

Fig. 2. Serial Configuration of an electric bicycle

B. Electrical Engineering Domain

In Figure 1 and 2 it is assumed that the energy source is a chemical battery and the drive is achieved with a brushless dc motor – both of which could be changed with other alternatives and the choice lies in the electrical engineering domain.

The most common topology for the energy storage is a chemical energy source. The VRLA battery is the cheaper choice, popular in China [15]. The Li-Ion battery is becoming the standard when obtaining conversion kits or buying a new ebike in Europe [16]. There are some experiments about adding alternative energy sources, such as a fuel cell [17], [18] or a super capacitor to either replace the battery [19], or supplement it [20]. As the standard bike is not expected to achieve spectacular accelerations, and the energy pulses that need to be absorbed when implementing regenerative braking are not large, the benefit of adding a high specific power device, as the supercapacitor, seems counterintuitive [21]. On the other hand, using hydrogen can lower the range anxiety, offering greater ranges utilizing cheap fuel and rapid charging, which is not possible without swapping the batteries. There

are some commercially available fuel cell bikes from Pragma Industries in France and Linde H2 Bike in Germany.

The brushed dc motor, while very popular in early implementations of EPACs [8], has been gradually replaced by the BLDC (mostly with trapezoidal back emf) for almost all conversion kits or ebikes. The main reason for this is its optimal performance in terms of reliability, power density and naturally smaller dimensions [5]. The other types of ac motors, namely the induction machine, synchronous and switched reluctance motors have not yet gained popularity. The induction machine, although cheaper and more reliable, has the disadvantages of lower torque density and lower efficiency. Thus its application in small electric vehicles, such as an ebike, is not very popular. One example using IM is shown in [22]. The potential volatility in the price of rare earth magnets has spurred interest in the switched reluctance motor [23]. In its classical form it offers better fault tolerance, cost and easer sensorless control, while its disadvantages are lower efficiency, torque density, noise and larger torque ripple in comparison to the brushless motor. A more detailed comparison for advanced various types of motors and their applications for electric vehicles is shown in [24].

In order to correctly commutate the BLDC motor with trapezoidal back-emf the position of the rotor must be known. This can be done by deducing it from the measured back-emf or some other non-direct method (called sensorless control) [25]. The other available method is to measure it directly by a rotary sensor such as Hall sensors or an encoder [26]. The latter approach is more common in ebikes, with motors having adopted the integrated Hall sensor approach. When using Hall sensors there are two different switching control schemes - a two-phase 120° conduction or a three-phase 180° conduction scheme. The former achieves higher maximum torque, while the latter has the advantage of better operation in the constant power region. Both schemes can be improved by phase advancing the pulses, compared to the feedback signal from the hall sensors at higher speeds [27]. The main reason to use an encoder as the feedback mechanism is the possibility to implement more sophisticated control algorithm such as Direct Torque Control [28], [29]. The use of such control mechanisms allows for tighter control of the obtained torque or speed command, less ripple and better drive dynamics. Out of these reducing the ripple torque is the most important aspect as it directly relates to driving comfort.

C. Mechanical Engineering Domain

When considering the questions in the mechanical domain the main ones are: Where to put the motor? Should it have gears? How to couple the torque from the human and motor in case of a parallel hybrid configuration?

If only one motor is used its position – front or rear wheel hub motor or center mount motor- effects the traction, weight distribution and ease of maintenance and installation. For conversion kits the rear and front wheel hub motor placement is the most predominant type, because they are cheaper, can easily be installed by using a larger range of "of the shelf" motors and have less strain on the drivetrain. On the other hand, the central mounted motor with its weight distribution offers the best overall

performance as it also utilizes the existing gears (this can be seen as a weak point as it puts more strain on this drivetrain). Being more expensive it is offered from fewer manufactures like Bosch in Europe or Bafang in China.

Using a hub motor that is mounted on the front wheel provides the advantage of better weight distribution, all-wheel drive with the human powering the rear wheel and finally easer installation, maintenance (especially when changing a flat tire) and better compatibility with the current installed bike drivetrain. The main drawbacks of the front wheel motor are that traction can be a problem in hilly regions or when using a higher powered motor. Also improper installation can be more dangerous. If the motor is put on the rear wheel the traction is better, especially in hilly regions and off-road, but the bike can become unbalanced, especially if the battery is also installed at the back. The installation and maintenance are worse compared to the front wheel drive [5]. Finally, there are some experiments with dual motors for the front and rear wheel that should also be mentioned [30]. They offer better performance as ATV compared to other alternative and there are some commercially sold such as Motorino MTgX2.

When installing the motor on the front or rear wheel two main alternatives exist – should the motor directly drive the wheel, or should it be a gear motor? The latter case leads to smaller motors that are more efficient, as they work at higher rpm. This ultimately means less weight, but adds some reliability issues with the gears. The heavier direct drive design, which is more popular in commercially sold conversion kits, can give more torque. Also due to its larger volume the motor can cool more efficiently. [16]. In Europe for BLDC geared motors can be obtained from Heinzman, Sanyo and Panasonic, while Crystalyte makes direct drive motors.

The central mounting of the motor provides the best overall performance, as it uses the available drivetrain to optimally adjust the gear ratio. However, this means that the cyclist must exercise greater care to the proper gear change, if he needs to operate the ebike optimally. In this configuration the motor and the pedals do not have the inherent uncoupling, as in the hub motor case [31]. Automatic gear changing can be a valuable option [32].

The type of gear system is the last important thing to take into consideration, with the options being the derailleur type, hub gear or the newer continuously variable transmission.

The predominantly used derailleur system is very light, cheap, has excellent efficiency and can achieve very large gear ratios [33], [34]. As it is a very sensitive mechanism its main drawbacks are the required maintenance and associated reliability issues, especially for offroad trips. An additional drawback is that gears cannot be changed while stationary or a gear ratio cannot be skipped. Additional problems are the efficient use of the available gear ratios and the step size between various gears [35].

An alternative approach is the gear hub approach with a single sprocket, which dramatically reduces maintenance and increases reliability, while at the same time having the advantage of linear distance between adjacent gear ratios and on spot gear shifting. Commercially available are usually with 8 gear ratios (with the exception of such as

Rohloff Speedhub with 14). They are more expensive and heavy compared to the derailleur mechanism, but offer very high gear ratios. Their main drawback is that they cannot achieve a finite number of transmissions, so still cannot utilize the full potential of the electric motor or the human cyclist.

Finally, continuously variable transmissions are becoming interesting for use in bicycles [35], [36], [37]. The NuVinci series of CVT have more than twice the weight of a derailleur system, and also the maximum ratio range of 380% is noticeably lower than the SpeedHub or the best derailleur systems. However, the possibility of electronic control and continuous adjustment of the gear ratio for torque control can lead to efficient operational conditions for both the motor and human [38]. It should be noted that the neatest way to implement an e- CVT is when the bicycle is based on a serial hybrid topology, because the system needs two motor/generators in order to control the output torque and bring about the constant cyclist input speed to varying wheel speed [37].

D. Proposed Classification

Figure 3 shows the proposed classification of electric bicycles by summing all the presented information and categorizing it according to the specific domain that it is applicable to.
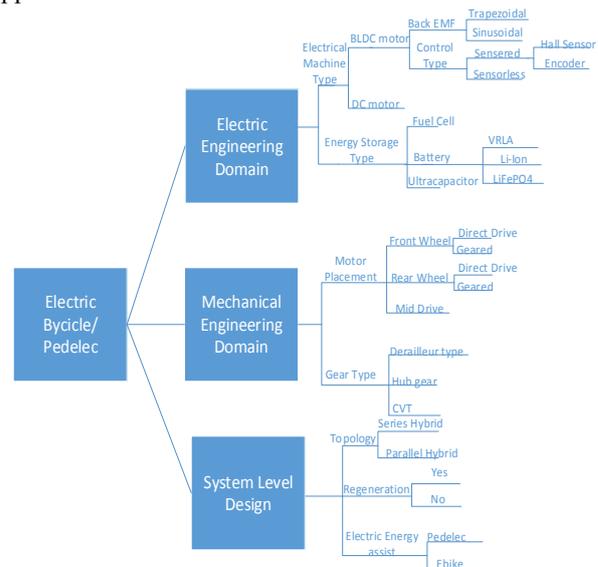

Fig. 3. Proposed Classification

The proposed classification allows the designer of an electric bike to quickly evaluate his options and look for additional information before commencing the actual design.

IV. CONCLUSION

The primary aim of this paper was to present the various approaches that have been accumulated in the scientific literature to design an electric bicycle.

In order to group them in some manner a new classification is proposed that groups the various issues that the designer is faced in three broad categories – system level domain design, electrical engineering domain design and mechanical engineering domain design. For each of the three domain the main issues are presented alongside the most popular ways to solve them. The advantages and disadvantages in choosing a particular solution are also discussed.

The goal of the paper is to help a designer of an electric bike choose an architecture, and also be aware of the various issues that he must address.

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