# TRANSMOTOR BASED ELECTRIC BICYCLE WITH INDEPENDENT PEDAL SPEED/TORQUE CONTROL

A Thesis

by

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# ABSTRACT

In this paper, an electric bicycle based on a dual mechanical port machine (also referred to as the 3-member transmotor), is proposed. By using the transmotor, the user is able to achieve independent control of torque and speed for pedaling and for bicycle propulsion. In other words, the user is able to pedal at the torque and speed of his/her own choosing, whilst maintaining complete and independent control of total bicycle propulsion. This is a feature that is not found in any of the e-bikes currently available in the market. A possible architecture for this model was looked at where a motor and generator were connected in series. An alternative and more integrated solution to this model was discussed in the form of the 3-member transmotor. A detailed description of the power balance equations for the transmotor and the various operating modes it offers is discussed. A study of the existing electric bicycle technologies and their shortcomings is given in this thesis, after which a model for an electric bicycle has been developed based on the transmotor and the series motor-generator models. The performance of the proposed systems and its comparisons with existing models is also presented after simulation in MATLAB.

# ACKNOWLEDGEMENTS

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# CONTRIBUTORS AND FUNDING SOURCES

## Contributors

This work was supervised by a thesis committee consisting of Professor Mehrdad Ehsani [advisor], Professor Shankar P. Bhattacharyya and Professor Laszlo Kish from the Department of Electrical and Computer Engineering, and Professor Won-Jong Kim from the Department of Mechanical Engineering.

The transmotor based electric bicycle was conceived by Professor Ehsani. The transmotor analyses depicted in Chapter 3 was derived in part from previous studies conducted at Texas A&M University and published in 2018.

All other work conducted for the was completed by the student independently.

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# NOMENCLATURE

| | |
|---|---|
| SMG | Series hybrid with Motor and Generator |
| P | Power |
| T | Torque |
| t | Time |
| $\omega$ | Angular/Electrical frequency (rad/s) |
| KERS | Kinetic Energy Recovery System |
| n | Number of pole pairs |
| PMSM | Permanent Magnet Synchronous Motor |
| BLDC | Brushless DC Motor |
| FOC | Field Oriented Control |

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# 1. INTRODUCTION AND LITERATURE REVIEW

## 1.1 Introduction

Electric bicycles have been around for decades. In places like Europe and China, they have already started becoming a way of life. In Europe, where electrification of road transport is a major milestone for 2020, e-bikes are the only form of transport that has already achieved the target. 8% of new bicycles in Europe are of Electric Power Assist type [1], and this push is only going to get bigger. Bicycles, being a lightweight, compact and inexpensive mode of transport provides the perfect avenue for engineers to design and experiment a possible solution for sustainable short-range transportation [2]. This thesis tries to develop a better alternative to existing e-bike models that aims to address their shortcomings and achieve independency of torque and speed at the pedal and bicycle wheels. Methods to achieve this will be discussed and a new type of electric machine – the transmotor- will be used to design an integrated model of this e-bike.

## 1.2 Literature Review

### 1.2.1 Existing E-bike Technologies

The traditional bicycles have been transformed into electric bicycles with the attachment of an electric motor in order to propel it. The major advantage of electric bicycles is that they provide an environmental and economical mode of transport in highly populated countries. The growth of electric bicycles surged due to that fact that they are one of the cheapest modes of transport when compared to a gasoline scooter or car [2]. There are many aspects favoring the use of bicycles like low energy cost per distance travelled, saving in other costs like parking, insurance, registration and the health benefit of the rider. These are also the fastest growing segments of the transport market. Improved batteries and motor technology, component modularity and more research studies in this sector have made e-bikes travel longer distance at a faster rate than ever. Over 31 million bikes were sold in 2012 [2] with China (Xincri) being the largest manufacturer of electric bicycles, exporting the majority of electric bicycles and also meeting the local demand. These electric bicycles have been making their way into the U.S market for about two decades.

If we date back to where everything began, we will notice that the emergence of electric bicycles began almost at the same time as traditional bicycles. The first patent for the electric bicycle was provided for a bicycle battery with six brush poles, a DC collector and a hub motor mounted on the rear wheel. Around 1920, a mass production for electric motors for bikes began in a German company. Then, several patents were granted for prototypes and the bicycles benefited from new inventions and technologies in the industry. Around 1992, a portable bicycle with a small electric motor to drive the rear wheel and with batteries built into its frame came into existence which was followed by Yamaha trying to spread the model of "bicilec" or "pedlec" which became a huge success [2]. Another major milestone was the emergence of lithium battery in 2000s which led to the reduction in the weight of the bicycle. In 2012, 854,000 e-bikes were sold in the EU27, in France, 134,000 e-bikes were sold in 2016, compared to 37,000 in 2011 and in Italy, more than 124,000 e-bikes were sold in 2016 [2]. Also, it was estimated that around 21 million electric bicycles were circulating in China which is more than the total number of cars in China. The large portion of the customers in China are the police and the postal service

There are a wide range of electric bicycles that are commercially available with this rapid growth in the industry. There is a spectrum of e-bikes with varied range of specifications and designs. The distinctions in the design are mostly related to performance, design and control modes such as throttle control and pedal assist. The major design domains are electrical, mechanical and system level [3]. The system level design could be in a serial or parallel way with parallel case being the most popular way of designing a bicycle. Moving on to the Electrical domain, the most common energy storage topology is chemical. The VRLA (valve regulated lead acid) battery is becoming popular in China while Li-ion (Lithium ion) battery is becoming standard in Europe. Also, the brushed dc motor, is being gradually replaced by the BLDC (mostly with trapezoidal back emf) for conversion kits or e-bikes to provide optimal power density, naturally smaller dimensions and reliability [4].

Moving on to the mechanical engineering domain, the main questions to be considered are: where to put the motor and whether it should have gears. The most predominant type of motor placement includes rear and front wheel hub motor placement as they are cheaper and they can be easily installed.

The front wheel hub motor provides the advantage of better weight distribution, easier maintenance, installation and better compatibility with the current installed bike drivetrain. Some of the drawbacks are that the traction could be a problem while using a high-powered motor or while using it in hilly region. With the rear hub motor placement, traction is better especially in hilly regions, but the bike can become highly unbalanced. The other drawbacks of rear hub motor include worse installation and maintenance when compared to front wheel drive. These mentioned options with various other classifications allow the designer of an electric bike or the customers to evaluate his choices before commencing the actual design or buying a particular model [3].

Like other transport modes, electric bicycle users are also diverse. Most of the e-bikers in the California region were older, better educated and had high incomes. In China, e-bikes are a motorization steppingstone as its economy grows. 93% of the global e-bike sales in

2012[1] was accounted by China and most of the e-bikes sold in China are exclusively throttle-controlled, which means that there is no pedaling effort on behalf of the rider. The growth in e-bikes sales in China occurred from the ban on petrol-powered scooters and mopeds in many cities. But the growth is not prominent in other developing Asian countries which mostly rely on Gasoline two wheelers. Germany and Netherlands are the two-leading e-bike markets if the European E-bike sales are considered. In terms of gross sales, the next closest countries in line are France, Italy and Austria. These countries have overcome infrastructure and safety barriers, and therefore they offer the most fertile market for the introduction of e-bike. It is difficult to track e-bikes in North America as the conventional bicycles are converted to e-bikes by just adding a battery, motor and controller kit, although a study estimated that around 2000000 e-bikes were brought in the USA in 2013 [1].

The major benefit seems to be the capability to maintain speed with less effort. Increased speed and reduced physical exertion are the motivating factors. Also, according to interviews taken in California, the owners seem to enjoy cycling with additional electrical assistance [1]. E-bikes have lot of potential to replace the motor vehicle use and it also suggests that the electric bicycles may reduce the number of trips taken by car.

We will be focusing on the pedelc models for this research. These models operate with the pedals connected in a parallel configuration with the electric motor, so that the motor is able to add torque to the users pedaling.

### 1.2.2 Coupling of Hybrid Electric Vehicles

Coupling modes of HEVs and various configurations have been discussed in detail in [5]. In summary, there are 2 main architectures of hybrid electric vehicles:

1. Series Hybrid
2. Parallel Hybrid

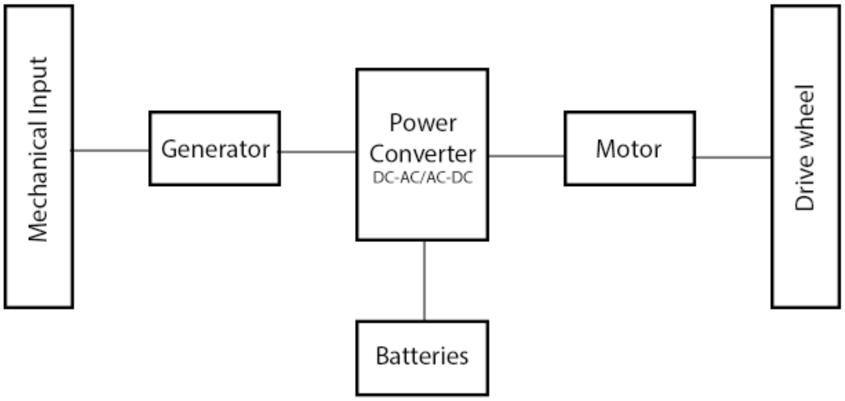

Figure 1.1: A series hybrid drivetrain

Figure 1.1 shows a series hybrid drivetrain. The key feature of this configuration is that two electric powers are added together in the power converter, which functions as an electric power coupler to control the power flows from the batteries and generator to the electric motor, or in the reverse direction from the electric motor to the batteries [5].

**Advantages**

- There is no mechanical connection between the mechanical input and the drive wheels. Consequently, the mechanical input has no constraints and can operate at its “sweet spot” throughout.

- The drivetrain may not need a multigear transmission. Therefore, the structure is greatly simplified and costs less. Using two motors can decouple the speed of the two wheels, removing the mechanical differential.
- The control strategy of the drivetrain may be simple compared to other configurations because of its fully mechanical decoupling between the mechanical port and wheels.

**Disadvantages**

- The energy from the mechanical port changes its form twice to reach its destination. (mechanical - electrical in the generator and electrical - mechanical in the motor). The losses from these power conversions add up.
- The additional generator adds a cost and weight element.
- The entire power for propulsion is provided by the traction motor and therefore, it needs to be sized accordingly to provide the necessary acceleration and gradeability.

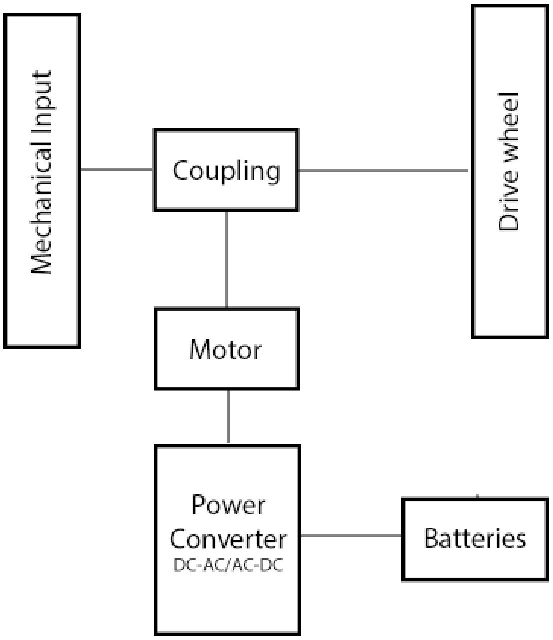

Figure 1.2: A Parallel hybrid drivetrain

Figure 1.2 shows a parallel hybrid drivetrain. The two mechanical powers are added together in a mechanical coupler. The power flows can be controlled only by the power plants—the mechanical input and the electric motor. [5]

**Advantages**

- Here, both the mechanical port and the motor are coupled to the drive wheels, and involves no energy conversion, so the energy loss may be less.
- The need for an additional generator is eliminated and the traction motor can be sized smaller than in a series configuration.
- Because the torque output is the sum from the two sources, the traction motor does not have to produce the entire power needed for propulsion.

**Disadvantages**

- Its major disadvantage is the mechanical coupling between the mechanical and electrical ports to the drive wheels. The mechanical port operating points cannot be fixed in a narrow speed and torque region and is constrained by the drive cycle.
- Another disadvantage may be the complex structure and control.
- The speed and torque at the mechanical port and the wheels are not decoupled

### 1.2.3 Transmotor Research

The team at the Advanced Power Electronics and Motor Drives lab at Texas A&M have been developing and working on the transmotor for several years. It is an electric machine with 2 rotating parts. It is a three-port device. It has two mechanical ports and one electrical port [6-7]. It is able to transfer mechanical power from one port to the other through magnetic coupling between the air gap. As the outer rotor is free to move, it experiences a torque equal in magnitude and opposite in direction to the torque of the inner rotor.

The topology has been introduced discussed in [5] and has been analyzed and studied with mathematical models in [8], [9] and [10]. Almost always, the focus of transmotor research has been with respect to its applications on HEVs. Transmotors have been discussed as an option to overcome shortcomings of conventional electric kinetic energy recovers systems (KERS) by using flywheels connected to the transmotor. [8] focused on electromagnetic gearing options offered by the transmotor on HEVs and [7] applied the concept of transmotors to reduce the battery size in EVs by utilizing flywheel energy storage.

## 1.3 Problem Definition

To develop an electric bicycle with independent speed/torque control at both the pedal side and the bicycle wheel side. The user should be able to control the speed of the bicycle on any given terrain independent of the torque/speed at which he/she is pedaling. In other words, the user is able to pedal at the torque and speed of his/her own choosing, whilst maintaining complete and independent control of total bicycle propulsion. This is a feature that is not found in any of the e-bikes currently available in the market.

This thesis proposes a possible architecture that achieves this level of control where a motor and generator were connected in series. An alternative and more integrated solution to this model was discussed in the form of the 3-member transmotor. A study of the existing electric bicycle technologies and their shortcomings is given in this thesis, after which a model for an electric bicycle has been developed based on the transmotor and the series motor-generator models.

# 2. ELECTRIC BICYLES

## 2.1 Introduction

A standard bicycle, although a compact and inexpensive mode of transport, has its share of problems. As anyone who has ridden more than a mile on a bicycle can attest, maneuvering through slopes can sometimes prove to require a herculean amount of effort, despite the best gearing that bicycle manufacturers can provide. In cities like San Francisco where the roads have steep slopes and grades of 25% and higher, riding a standard bicycle would be an impossible task for a normal person. The rider is limited by the amount of torque he can provide on the pedals. Gearing can reduce the torque the rider feels, but this comes at the expense of speed. Some riders prefer to feel the least amount of torque on their feet, and instead prefer to pedal at a faster rate in order to achieve the required propulsion. Some prefer having it the other way around. In an ideal world, torque and speed would not have to come at the expense of each other and the rider should be able to pedal at whatever speed or torque he or she wishes. A rider would be able to pedal at extremely low torques and still have the bicycle whizzing through the sidewalk, and maneuvering an uphill slope would feel no different from cycling down a straight path.

## 2.2 Electric Bicycle Model

An e-bike attempts to address all these shortcomings of a standard bicycle by assisting the rider with the help of an electric motor. The work required for propulsion is either done entirely by the motor, or is split between the rider and motor, acting as a sort of electric assist. Since there is an added source of power, the rider is no longer constrained by his physical limitations, and can achieve the level of propulsion required to maneuver any sort of terrain with little to no effort extended from his side. This is one the major reasons electric bicycles were hugely popular among people aged 40-60 in the initial days [1].

Online surveys from e-bike owners suggest the increased speed and reduced physical exertions are major motivations associated with commuting by electric bicycles. [1] A reemerging theme in social media and internet blogs is that the electrical assist has made bicycling fun again.

One of the biggest advantages of e-bikes is its role in replacing motor vehicles for short distance commute. While the author believes that we have a fair amount of time remaining before that shift ever truly occurs, it is hard to ignore the benefits that these devices offer. E-bikes, when compared to other modes of short distance transport include lower energy cost per distance traveled (Consumes less than 2% of the energy used by a car for the same distance). They also present advantages in other forms such as a lack of need for insurance, licenses, registration etc., whilst also providing the same benefits that a traditional bicycle gives such as ease of parking, storage and the health benefit for the rider. [4]

There are two major kinds of electric bicycles. The first is the fully electric model which offers the user no option to pedal the bike with his/her own power. These are basically electric scooters. This research focuses more on the second hybrid type of electric bicycle which uses both a pedal and electric motor in parallel and in this thesis, the term “electric bicycle” or “e-bike” is used to refer to these hybrid models only. This model uses both the rider input and battery power for propulsion. At present, electric bicycles offer 3 different modes of riding for a user to choose from:

- Pedal only
- Electric Assist
- Fully electric

The drive consists of controls for the power flow between battery, rider and electric motor. The power flow from the rider and the battery act in a parallel configuration to propel the bicycle. The 3 configurations are summarized as follows:

### 2.2.1 Pedal Only

This mode relies solely on the pedal power of the user, and will behave exactly like a traditional bicycle with no added assistance from the motor. Depending on the model you purchase, your bicycle will may or may not come with a particular set of gears ranging from 3 to 8 and sometimes more.

### 2.2.2 Electric Assist

In this mode, the motor acts as an electrical assist and adds on to the torque provided by the user at the pedals. The end results is that the bicycle is being propelled with a greater torque than is provided by the user. It makes cycling effortless and flattens out the hills.

An example of how it performs is given below:

Let us consider a case where Electrical-assist mode provides three different levels of assistance: Low (50%), Medium (100%) and High (300%). In the low setting, the motor adds an additional 50% of power to your pedaling, while at High it is quadrupled. A change in a dial, or twist of a throttle switches you through the different levels.

### 2.2.3 Electric Only

This mode of operation allows you to sit back and take a break, as you let the motor do the work. To use “electric only” mode, the user simply twists the throttle and will feel the motor kick in and propel the bicycle forward.

## 2.3 Performance Evaluation of Existing E-bikes

The following Table 2.1 categorizes the major performance characteristic of electric bicycles as they exist today.

Table 2.1: Performance characteristics of an electric bicycle

| | |
|---|---|
| Average speed | 19kmph |
| Maximum speed | 32kmph (according to U.S regulations) |
| Travel range | 50km - 150km |
| Motor power | 200W – 1000W |
| Battery power | Up to 500Wh |
| Gradeability | Up to 30% |
| Torque | Up to 100Nm |
| Bicycle weight | Less than 40kg |

The electric motor in an e-bike provides a battery powered electric assist to the users pedaling. The motor acts in a parallel configuration with the pedal which gives the bicycle more propulsion than is possible with pedal power alone. The motor is engaged when the user pedals and the assist level can be adjusted by twisting a dial, a throttle etc.

BLDCs are the most common motor type for e-bikes. It offers higher efficiencies and more power density albeit involving a more complex control mechanism. The motor placement may be of rear hub or mid hub type. Each has its own set of pros and cons. The rear hub drives are usually more versatile and less expensive and ae best for long, mostly flat road commuting. Mid hub drives are lighter and provides a greater torque, making it much better suited for offroading and steep grades. The centered position also makes for a much more balanced bike, and swapping out wheels becomes a much easier task when the entire motor assembly does not need to be detached.

Most e-bikes today use both torque and cadence sensors to determine the motor control.

## 2.4 Design and Specifications

### 2.4.1 Bicycle Design

Electric bicycles today work on a parallel configuration between the pedal and the motor, as shown in Figure 2.1. Torque from the motor is added to the pedal torque to assist the rider.

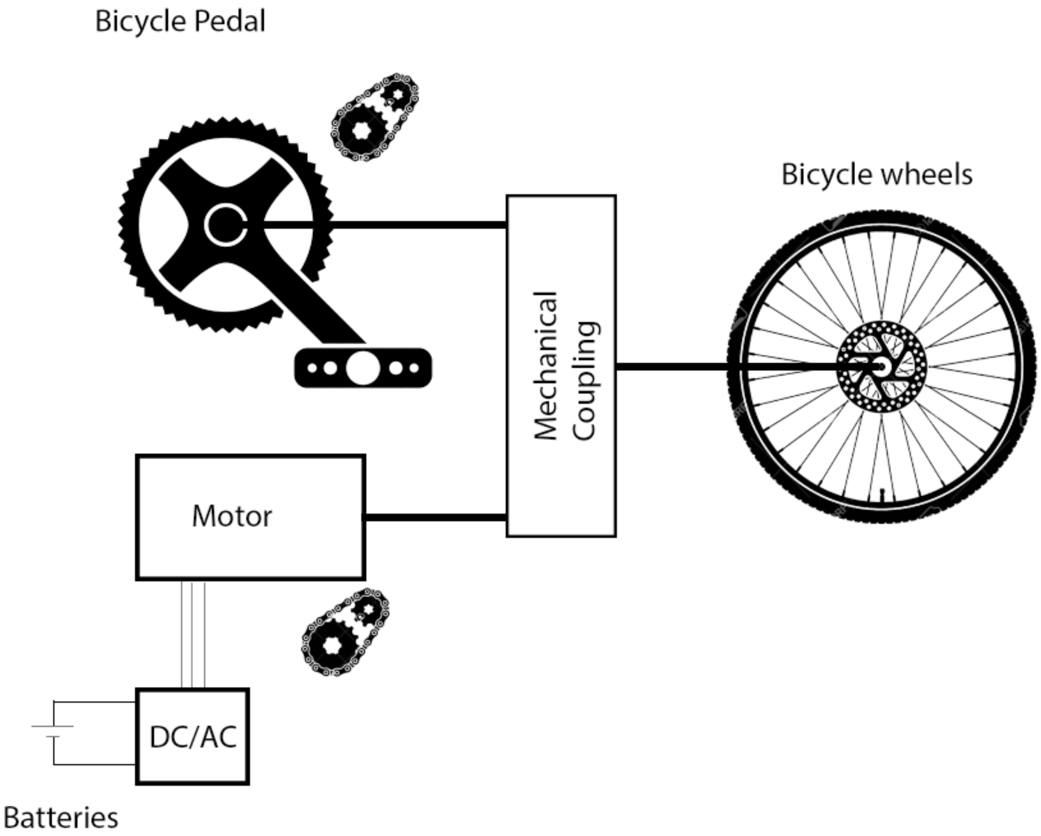

Figure 2.1: Pedelec architecture of e-bikes

The major element to be designed in an electric vehicle is the electric motor itself. Specifically, the rated power, torque and rated speed. For this we need to specify the requirements of the bicycle. From the data in the previous section, the requirements have been set for a fairly high-grade electric bicycle with a high maximum speed and gradeability, as shown in Table 2.2.

Table 2.2: Performance requirements for the e-bike

| | |
|---|---|
| Average speed | 20kmph |
| Maximum speed | 45kmph |
| Gradeability | 25% |
| Acceleration | 0-20kmph in 5s |

For any vehicle, the tractive effort needed for propulsion at a certain velocity, V, is comprised of 3 components – the tractive effort needed to overcome rolling friction, aerodynamic drag and the gravitational pull due to the grade. This is represented in the equations below.

$$\mathrm{T_{total} = T_{friction} + T_{aerodynamic} + T_{grade}}$$

$$\mathrm{T_{total} = Mgf_r + \frac{1}{2}\rho C_d A * V^2 + Mgi}$$

The power required from the motor is the product of the tractive effort and the velocity, divided by the efficiency of the transmission.

$$\mathrm{P_{motor} = \frac{V}{\eta}(Mgf_r + \frac{1}{2}\rho C_d A * V^2 + Mgi)}$$

According to riding conditions, three cases can be distinguished. [11] They can be described as follows:

1. Case 1: At low speeds (less than 3m/s), the majority of power is used to overcome the rolling friction.
2. Case 2: At speeds greater than 3m/s, the majority of the power is used to overcome the air drag
3. Case 3: As the grade increases, the power required for overcoming aerodynamic forces and rolling friction is overshadowed by the power required to overcome the slope.

To meet the requirements mentioned in Table 3-2, the electric motor chosen is a 1kW motor with a maximum speed of 3000rpm. A base speed of 1000 rpm has been chosen, which would give a speed ratio of 3 [5]. The plot of motor characteristics, showing the torque-speed and power-speed curves is shown in Figure 2.2 below.

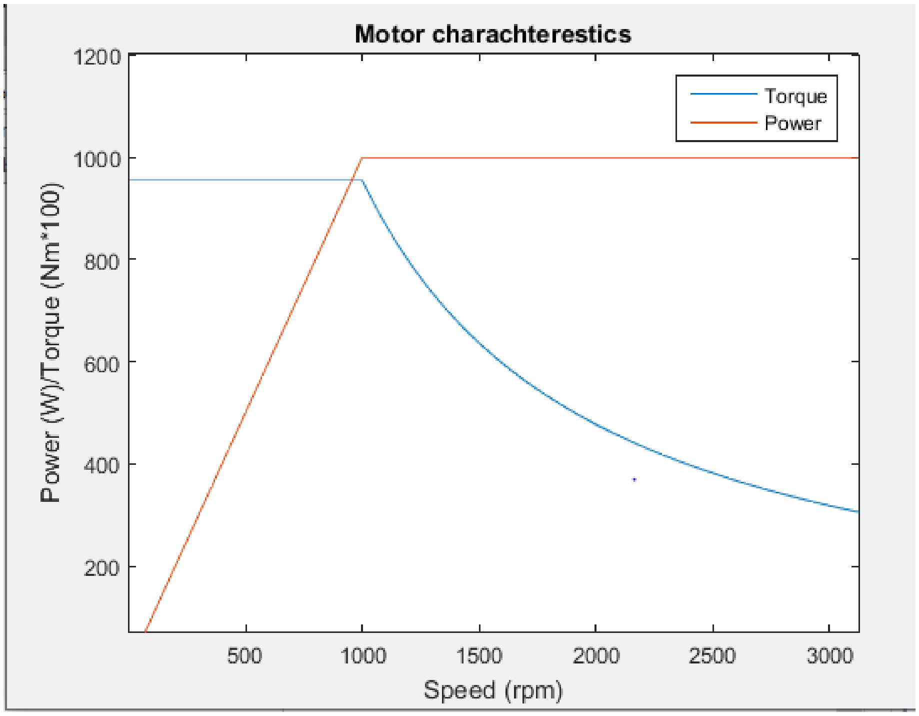

Figure 2.2: 1kW electric motor characteristics

We can see that this motor can provide a maximum constant torque of almost 9.5Nm. A gear ratio of 8 has been chosen so that at the bicycle wheel end, we have a maximum torque of around 76Nm and a maximum rated speed of 375rpm. The bicycle wheel radius has been chosen to be a standard value of 0.3m. A total weight of 100kg has been considered for the mass of the bicycle and the rider. The aforementioned design choices have been summarized in Table 2.3 and Table 2.4 below.

Table 2.3: Electric motor characteristics chosen

| | |
|---|---|
| Motor Power | 1000 W |
| Maximum speed | 3000 rpm |
| Base speed | 1000 rpm |
| Maximum constant torque | 9.5 Nm |

Table 2.4: Other design choices

| | |
|---|---|
| Gear ratio | 8 |
| Max torque | 76 Nm |
| Max speed | 375 rpm |
| Bicycle wheel radius | 0.3 m |
| Total mass of rider + bike | 100 kg |

### 2.4.2 Simulations

Using the motor and design considerations from the previous sections, the performance of the bicycle drives against various grades is shown in the plot below. We can see that the requirements stated in the previous section is met using this design.

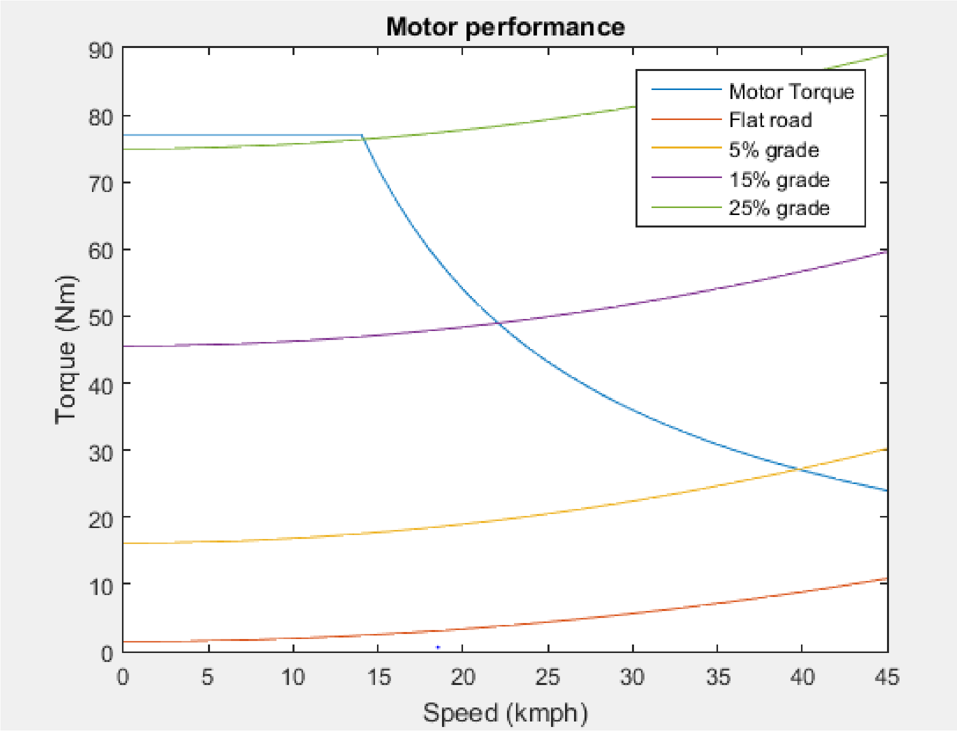

Figure 2.3: Motor performance over grade levels for the e-bike

From Figure 2.3, we can see that this design can easily achieve a maximum speed of 45kmph on a flat road and can traverse grades as steep as 25% with a speed of 15kmph. The acceleration performance of this bike is given in Figure 2.4.

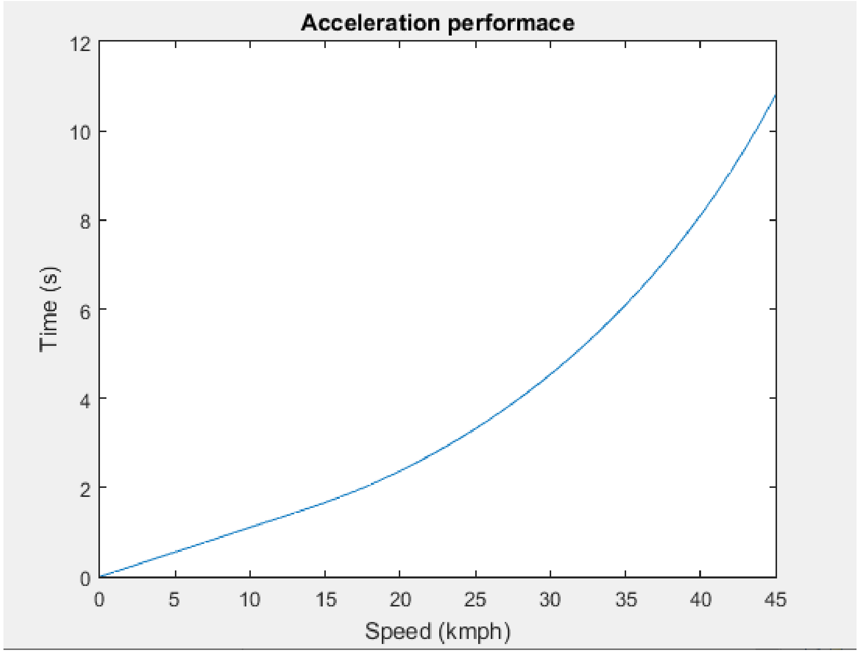

Figure 2.4: Acceleration performance for the e-bike

The e-bike can accelerate from 0 to 20kmph in 2.4s and can reach its maximum speed of 45kmph in under 11s. This performance evaluation goes on to highlight the advantages an e-bike has over regular bikes and even traditional scooters. Because of the high starting torque capabilities of an electric motor, we are able to achieve stellar acceleration times and are also able to traverse much higher grades without using complex and failure prone gearing mechanisms.

# 3. A SERIES HYBRID MODEL OF THE ELECTRIC BICYCLE

## 3.1 Introduction

There is no denying that the market for electric vehicles is growing. When compared to traditional bicycles, electric bicycles offer the rider a much more convenient and physically less-taxing experience. However, even with all their advantages, there is still a major disadvantage that all these bikes have. There is no independency of the torque and speed at the user end and the overall bicycle propulsion. In other words, the bicycles in the market at the moment do not offer an option where the user can pedal at whatever speed and torque, he or she chooses, whilst having complete and independent control of the bicycle propulsion. Such a product would offer the perfect bicycling experience and according to the author is much better architecture of an electric bicycle.

## 3.2 Shortcomings of Existing Models

The electric bicycles with throttle only mode of operation is limited in a multitude of ways. They are essentially plug-in electric scooters, and need to be recharged in order to be used. It makes no use of human pedal power during electric-mode. Some bikes that use this topology do allow pedaling, but it is possible only when the electric motor is decoupled. So, the user has to choose between cycling entirely with pedal power or entirely with the electric motor. There is no hybrid operation mode. The user cannot get an assist from the motor in difficult terrains he wants to pedal through, like uphill gradients, and needs to switch over entirely to the electric mode which utilizes the electric motor. The excess energy from the user cannot be converted and stored in to electric energy. Therefore, these are limited to only being plug-in vehicles. It goes without saying that the energy used by these bicycles is much higher than with a bicycle that is capable of a hybrid mode of operation. Although, these bicycles can be designed to take advantage of regenerative braking, it still lags behind the hybrid bicycles because the user input cannot be used to recharge the battery. In pedal-only mode, the entirety of pedal power goes towards bicycle propulsion. It also does not provide the range of riding options that the hybrid-electric bicycles provide.

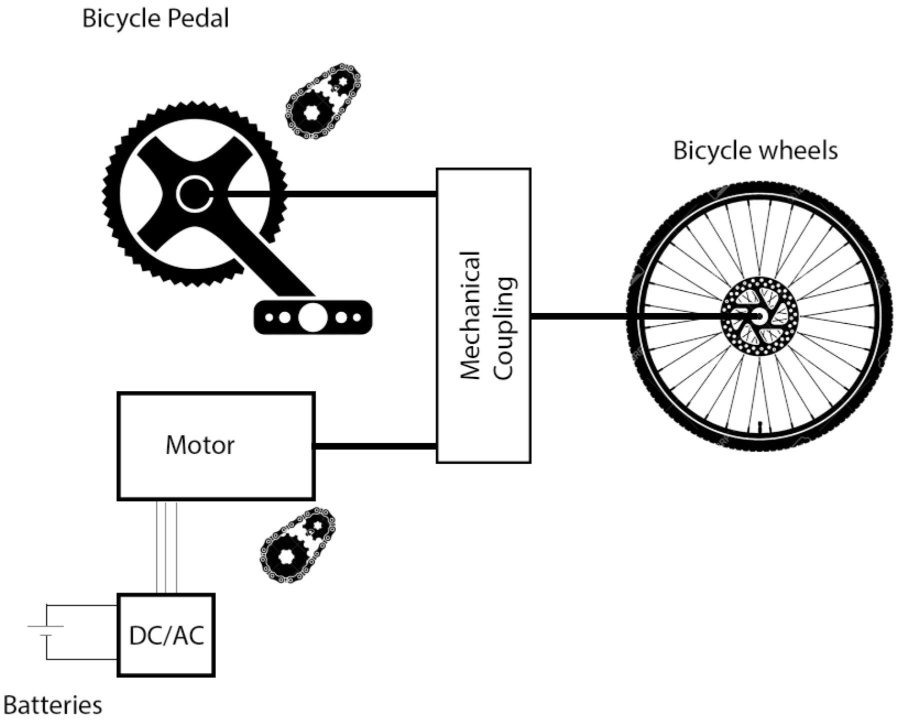

Figure 3.1: Existing e-bike architecture (Pedelec)

Pedelec models work by adding torque to the users pedaling using toque coupling in a parallel configuration as shown in Figure 3.1. The power balance equations can be written as:

$$P_{bicycle} = P_{pedal} + P_{motor}$$

$$T_{bicycle} = k_1 T_{pedal} + k_2 T_{motor}$$

$$\frac{\omega_{pedal}}{k_1} = \frac{\omega_{motor}}{k_2}$$

The motor provides a torque which is added to the user provided pedal torque. So, the user feels as though he is giving more power and achieves a faster acceleration. However, from the power balance equations, we can see that the torque addition can take place only if the pedal speed and motor rpm are equal. So, the speed of the bicycle is still dependent on the users pedaling. The independency of pedal speed/torque and bicycle speed/torque is missing here. As with the throttle-only bicycles, the pedelc models need to be plug-in vehicles. Since the bicycle speed is governed by the users pedaling, there is no possibility of the user being able to provide excess energy that can be used to recharge the batteries. Again, regenerative braking can be used to some extent. But without the option of being able to be recharged by pedal-power, this model is also far from ideal.

### 3.3 Series Hybrid E-Bike with a Motor and Generator

One way of realizing the proposed electric bicycle model would be to have a motor and generator working in a series configuration, as in Figure 3.2. The generator converts the power from pedaling into electrical energy and stores it in the battery. The battery provides electrical power to the electric motor connected to the bicycle wheels in order to propel the bicycle. With such a configuration, we have effectively decoupled the power provided by the user and the output power to the bicycle. The user will be able to pedal at whatever torque and speed he or she is comfortable with and still be able to propel the bicycle as fast or as slow as desired.

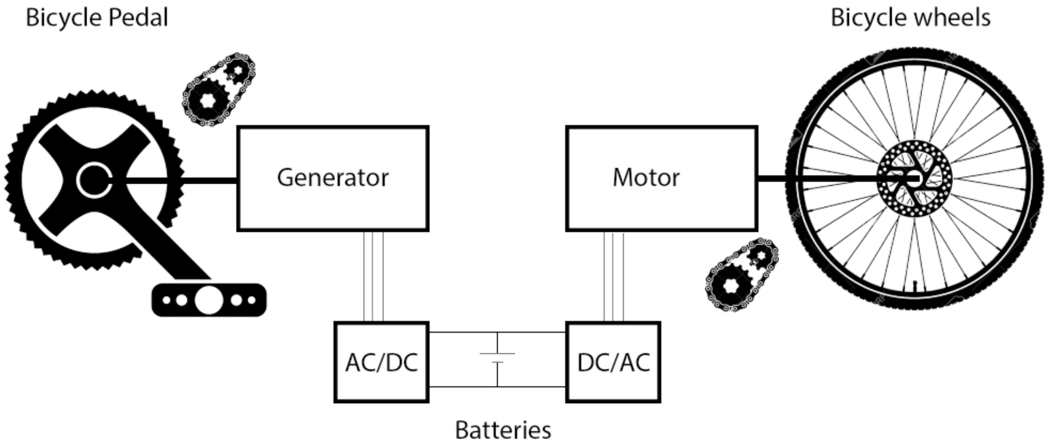

Figure 3.2: A series hybrid realization of the e-bike

### 3.4 Series Hybrid E-bike with Motor Generator Realization

The series hybrid e-bike, referred to as the SMG model from here on out, can be realized in several different ways. The most intuitive being one with the generator attached to the pedals and the motor attached to the back wheel as Figure 3.3.

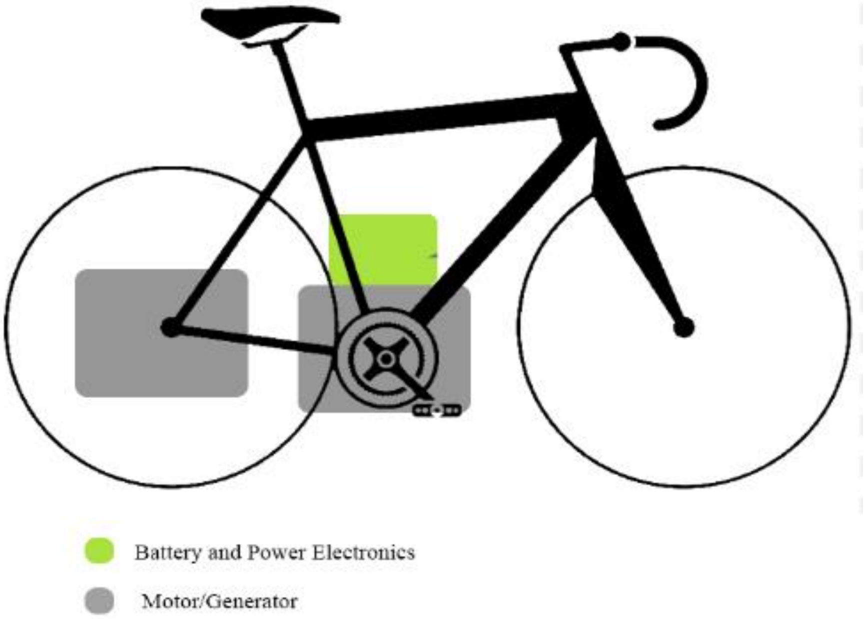

Figure 3.3: Realization of the series hybrid e-bike

The power from pedaling is converted in to electric power by the generator and stored in the batteries via the power electronic converters. The batteries supply power to the motor attached to the rear wheels which gives the propelling force. This is a simple modification to existing rear hub models, with the difference being the addition of the generator to the pedals. The user would also need two controls, one on each handlebar, in order to control the torque at the wheel and the pedals independently. By the authors envisioning this would be in the form of two individual throttles – a combination of what is found in conventional geared bicycles and conventional motorcycles, and is shown in Figure 3.4.

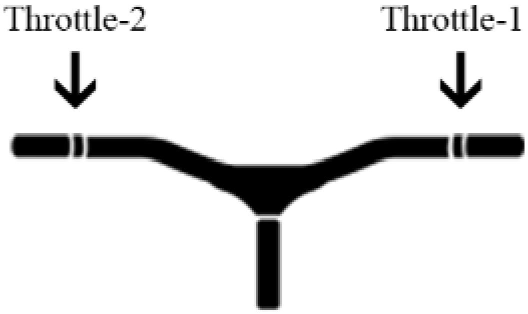

Figure 3.4: Independent control using two throttles

## 3.5 Shortcomings of the SMG model

However, having two electric machines working together in something as compact as a bicycle is not an ideal scenario. The power transfer from pedal to bicycle involves 3 power conversions. Mechanical – Electrical – Chemical – Mechanical. This will have a huge impact on efficiencies. Even with a high efficiency of 0.9 for all 3 processes, the total efficiency reduces to $0.9^3$, which is 0.729. And this is considering a best-case scenario. At low speeds, motor efficiencies drop further, and therefore the overall efficiency of the power conversion process will total up to a much less than ideal value.

### 3.6 An Integrated Solution to the SMG Model of the E-bike

The proposed model of the electric bicycle, one where the user has independent control of the pedal speed/torque whilst having independent control of bicycle propulsion, can be achieved using a better and more compact replacement for the motor generator combination. We will also see that this device reduces the sizing requirements and power electronics required for motor control. This device, being studied and developed by the group at the Advanced Motor Drives and Power Electronics lab is called the transmotor. The following chapter will explain the finer details of the functioning of the transmotor, and its power flow equations.

# 4. THE TRANSMOTOR

## 4.1 Introduction

A transmotor is an electromagnetic device which consists of two rotors. Both the windings and the permanent magnet rotor can rotate freely [5]. It can also be described as a motor with a floating stator configuration [12]. These devices obey the same electromagnetic principles that are applicable to conventional electric machines i.e. the interaction between the magnetic field and winding currents produce a torque in the rotor. According to Newton’s third law of motion, there is an equal and opposite torque felt by the stator. Whereas in conventional machines, the stator is fixed, in a transmotor, the floating stator (hereafter referred to as the outer rotor) is not anchored, and is free to react to this torque. The torque on both the inner and outer rotor is equal in magnitude but opposite in direction.

## 4.2 Two Member Transmotor

### 4.2.1 Power Balance Equations

A transmotor at a system level, is a three-port device. It has two mechanical ports and one electrical port [6-7]. It is able to transfer mechanical power from one port to the other through magnetic coupling between the air gap. As the outer rotor is free to move, it experiences a torque equal in magnitude and opposite in direction to the torque of the inner rotor. Effective magnetic coupling is achieved only if the electrical frequency in the windings is equal to the relative speed of the inner and outer rotors (multiplied by the number of pole pairs). By adjusting the winding frequency currents, we can control the amount of mechanical power transferred [6]. The transmotor cam act as either a motor or a generator depending on the relative speeds and the electrical connections. Let us consider a transmotor with a permanent magnet outer rotor and a power electronic converter connected to the windings of the inner rotor as shown in Figure 4.1 below.

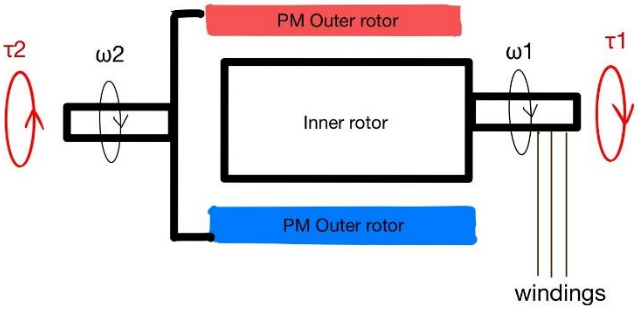

Figure 4.1: A 2-member transmotor

When the transmotor acts in motoring mode, transmotor takes electrical power from the power converter, whereas in generating mode, it provides electrical power. The magnitude of this power is the slip power between the mechanical ports. For an n pole transmotor, the speed, torque and power equations can be written as follows:

$$\mathrm{T_{electric}} = \mathrm{T_1}$$

$$\mathrm{T_1} = -\mathrm{T_2}$$

$$\omega_{\mathrm{electric}} = \mathrm{n}(\omega_1 - \omega_2)$$

$$\mathrm{P_{electric}} = \mathrm{P_1} - \mathrm{P_2}$$

For better understanding, let us consider an example case of a 2 pole (n =1) transmotor connected to a drive wheel and a pedal at each of its mechanical ports. The pedal is connected to the inner rotor and the drive wheel is connected to the outer rotor. Let us consider the case where both the mechanical ports are spinning in the same direction, as in Figure 4.2.

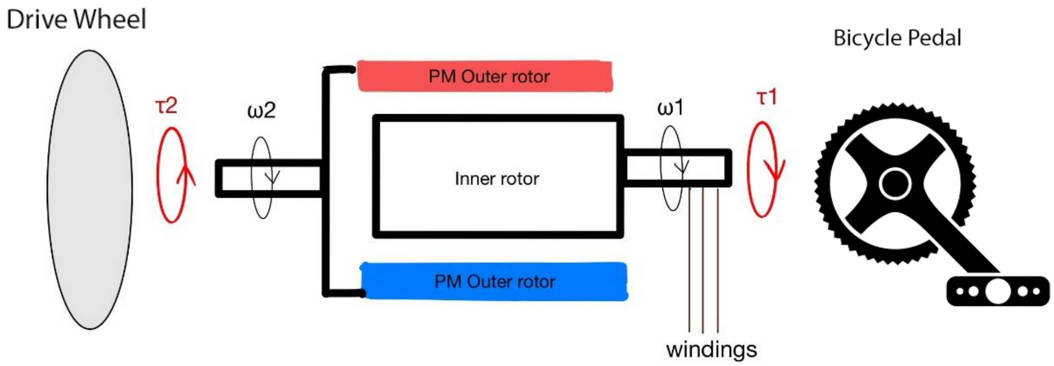

Figure 4.2: Transmotor power flow example

When positive torque is applied to the pedals to accelerate it, an equal and opposite torque acts on the drive wheel but in the opposite direction, decelerating it. The direction of Power flow is from drive wheel to pedals. The following 3 operating modes are possible:

1. When speed of drive wheel is greater than speed of the pedal, greater power is being generated by the deceleration of the drive wheel than is being drawn by the pedal. (Figure 4.3) This Power gets stored in the battery. The transmotor, at this point, is acting in the generating mode. This is because relative to the outer rotor, the inner rotor experiences a positive torque, but the speed is in the negative direction. Speed and torque are in opposite directions. From the four-quadrant operation of electric machines, we know that this is a case of the machine acting in generator mode.

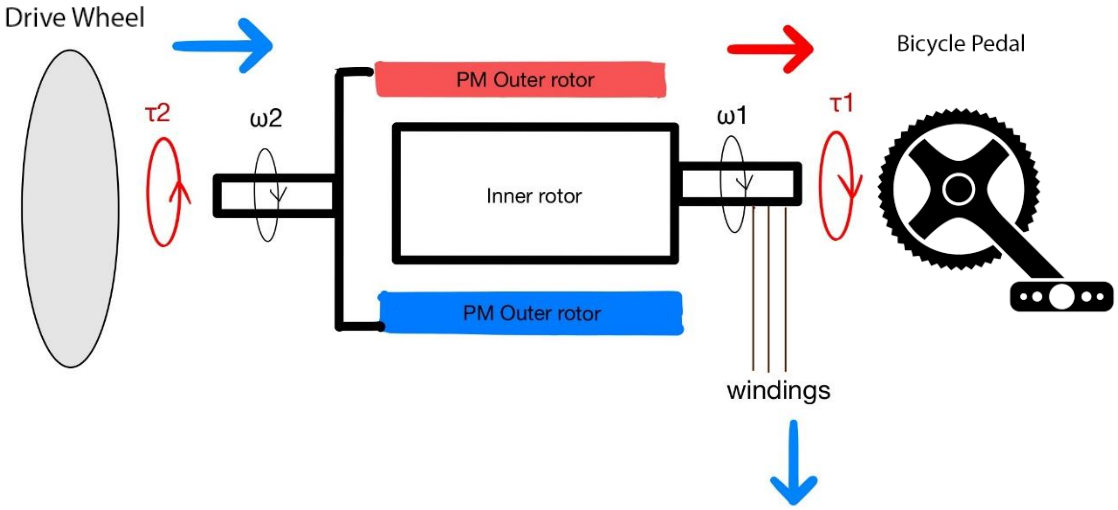

Figure 4.3: Power flow when ω2>ω1

2. When the speeds are equal, the power generated from the deceleration of the drive wheel flows to the pedal. (Figure 4.4) The battery does not supply or recharge power.

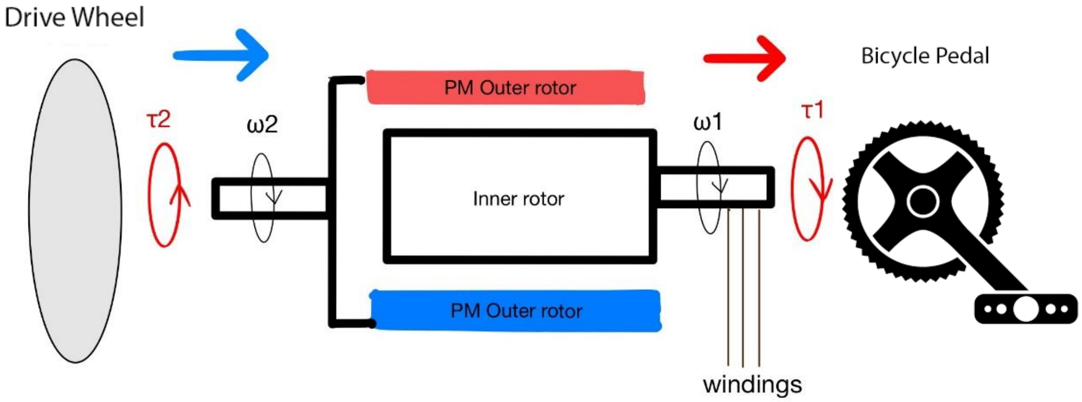

Figure 4.4: Power flow when ω2 = ω1

3. When the speed of the drive wheel is less than that of the pedal, the power generated from the deceleration of the drive wheel is not sufficient to manage the power drawn by the pedal (Figure 4.5). This excess power is provided by the battery. The transmotor, at this point, is acting in the motoring mode.

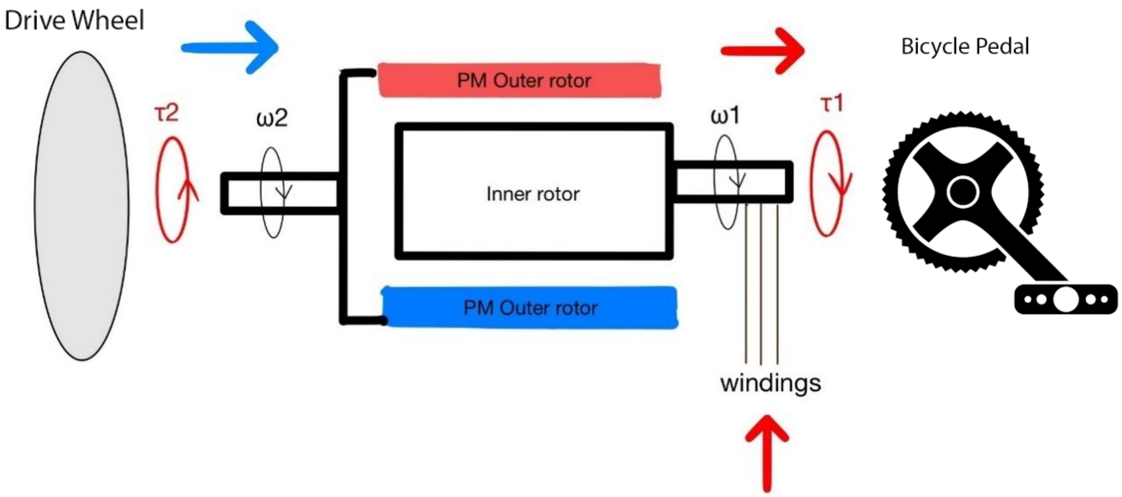

Figure 4.5: Power flow when ω1 > ω2

When negative torque is applied to the pedal, in order to decelerate it, an equal and opposite torque acts on the drive wheel accelerating it. Now, the power flow is from the pedal to the drive wheel. With the transmotor, the act of decelerating the pedal in this case, is equivalent to accelerating the pedal. All the previous cases hold true if we simply consider the case where negative torque is applied to the pedal, as a case where we are trying to accelerate the drive wheel. The 3 operating modes become:

1. When speed of the drive wheel is greater than speed of the pedal, greater power is required to accelerate the drive wheel than is being provided by the deceleration of the pedal (Figure 4.6). The excess power is provided by the battery and the transmotor is acting in motoring mode.

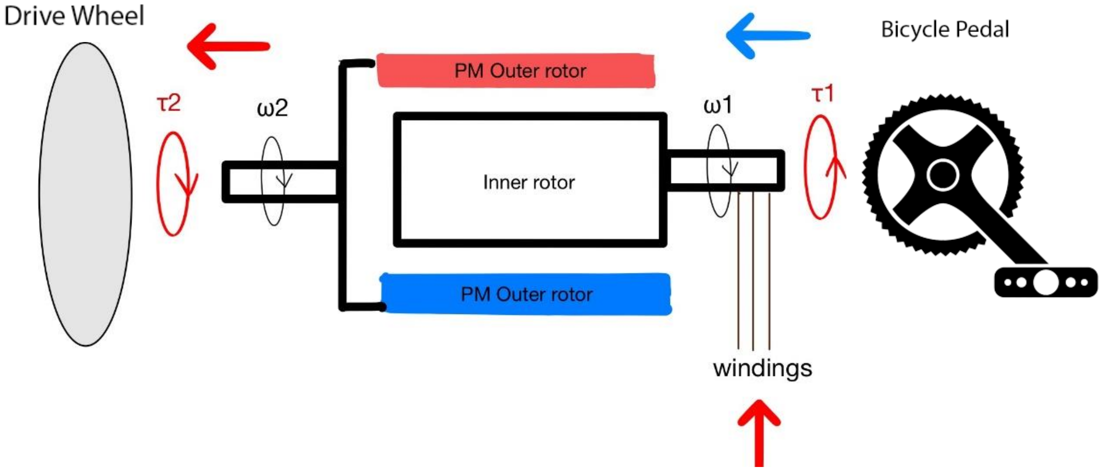

Figure 4.6: Power flow when torque is reversed and ω2 > ω1

2. When the speeds are equal, the power generated from the deceleration of the pedal flows to the drive wheel (Figure 4.7). The battery does not supply or recharge power.

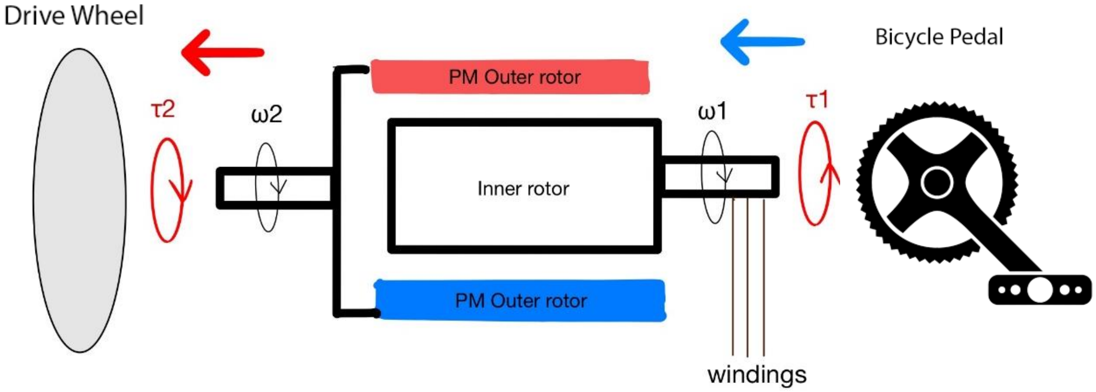

Figure 4.7: Power flow when torque is reversed and ω2 = ω1

3. When the speed of the drive wheel is less than that of the pedal, the power generated from the deceleration of the drive wheel is greater than the power drawn by the pedal (Figure 4.8). This excess power is stored the battery. The transmotor, at this point, is acting in the generating mode.

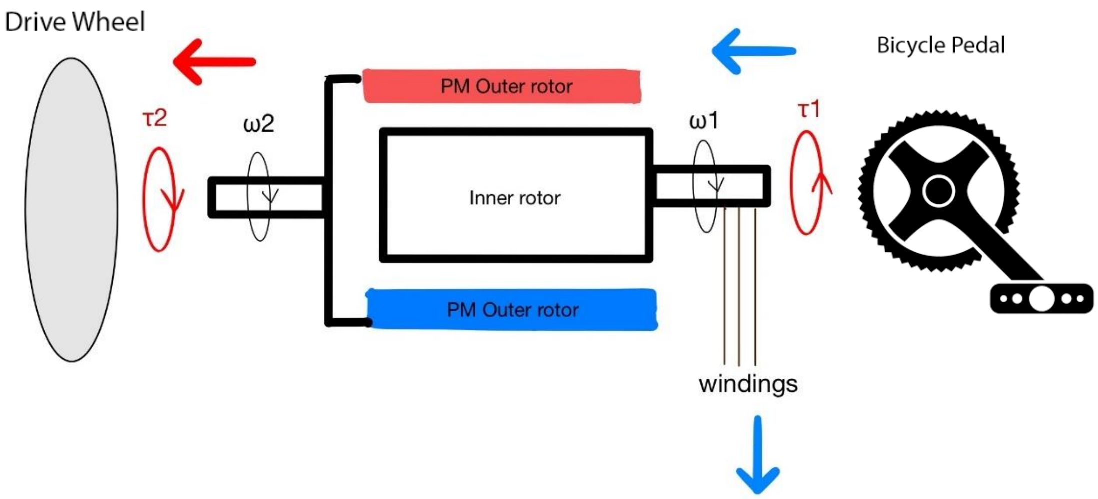

Figure 4.8: Power flow when torque is reversed and ω1 > ω2

Now let us consider the case where both the mechanical ports are spinning in opposite directions. In this case the electrical frequency is the sum of the magnitude of the speeds of the inner and outer rotor.

1. When positive torque is applied to either of the ports, an equal and opposite torque acts on the other one (Figure 4.9). Since both the ports are spinning in opposite directions both the pedal and drive wheel get accelerated. The power required for this acceleration is provided by the battery.

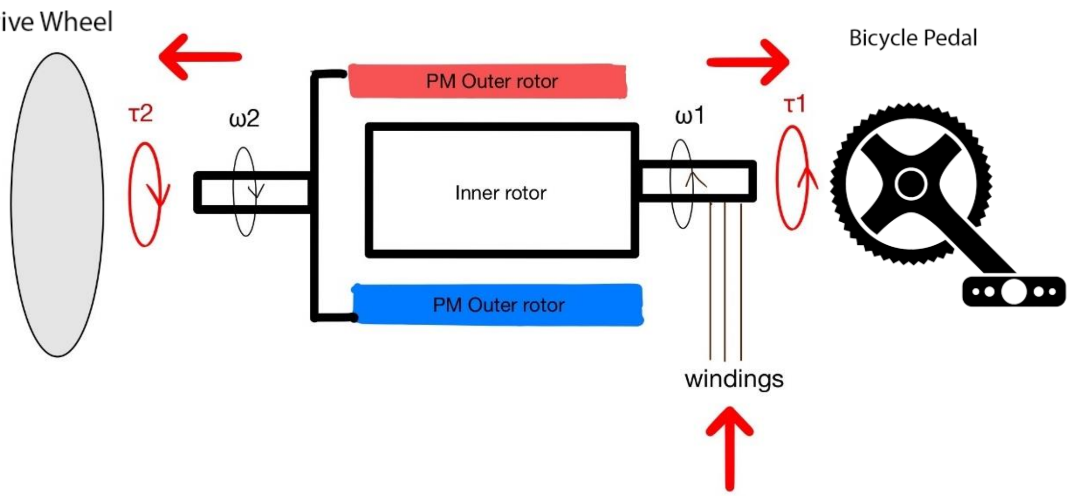

Figure 4.9: Power flow when ports are spinning in opposite directions and T1 is positive

2. Similarly, application of negative torque, decelerates both the pedal and the drive wheel and the power generated from both flows in to the battery (Figure 4.10)

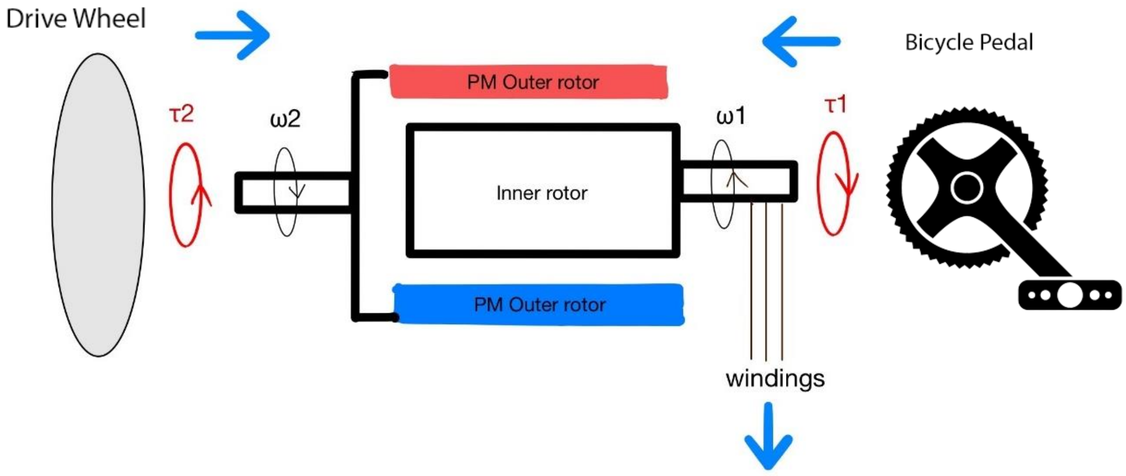

Figure 4.10: Power flow when ports are spinning in opposite directions and T1 is negative

We can clearly see that the transmotor allows much greater levels of freedom for power flow between the ports than with conventional machines. More details on the various transmotor operating modes can be found in [4] and [5].

### 4.2.2 Mathematical Model

The permanent magnet transmotor described, inherently being an electric machine has a mathematical model similar to that of a common PM synchronous machine. The only difference is the fact that we have to take in to account the movement of the stator. The electrical frequency, $\omega_e$ is determined by the slip between $\omega_{ir}$ and $\omega_{or}$. If we consider a reference frame with respect to the outer rotor, we can use the same PM synchronous machine equations by simply replacing the angular speed and position terms with their relative values with respect to the outer rotor [13].

$$\omega_e = n(\omega_{ir} - \omega_{or})$$

Note that the model is representing the equations for the transmotor in the dq reference frame, employing the Clarke and Park transforms.

Using this value of the electrical frequency, we can write the mathematical model as follows.

$$v_q = R_{ir} i_q + \frac{d\psi_q}{dt} + n(\omega_{ir} - \omega_{or})\psi_d$$

$$v_d = R_{ir} i_d + \frac{d\psi_d}{dt} - n(\omega_{ir} - \omega_{or})\psi_q$$

$$\psi_q = L_q i_q$$

$$\psi_d = \psi_m + L_d i_d$$

$$T_{ir} = \frac{3}{2} n\left(i_q \psi_m + \left(L_d - L_q\right) i_d i_q\right)$$

$$T_{ir} = -T_{or}$$

In surface PM machines, the contribution of reluctance torque is minimal due to the symmetry of flux paths and torque is directly controlled by the quadrature current $i_q$.

$$T_{ir} = \frac{3}{2} n i_q \psi_m$$

For field-oriented control techniques, the magnetizing current reference ($i_d$) is set to 0 for operations that do not involve field weakening. Torque control is achieved by controlling the quadrature current $i_q$. A block diagram for field-oriented control for transmotors is shown in the Figure 4.11.

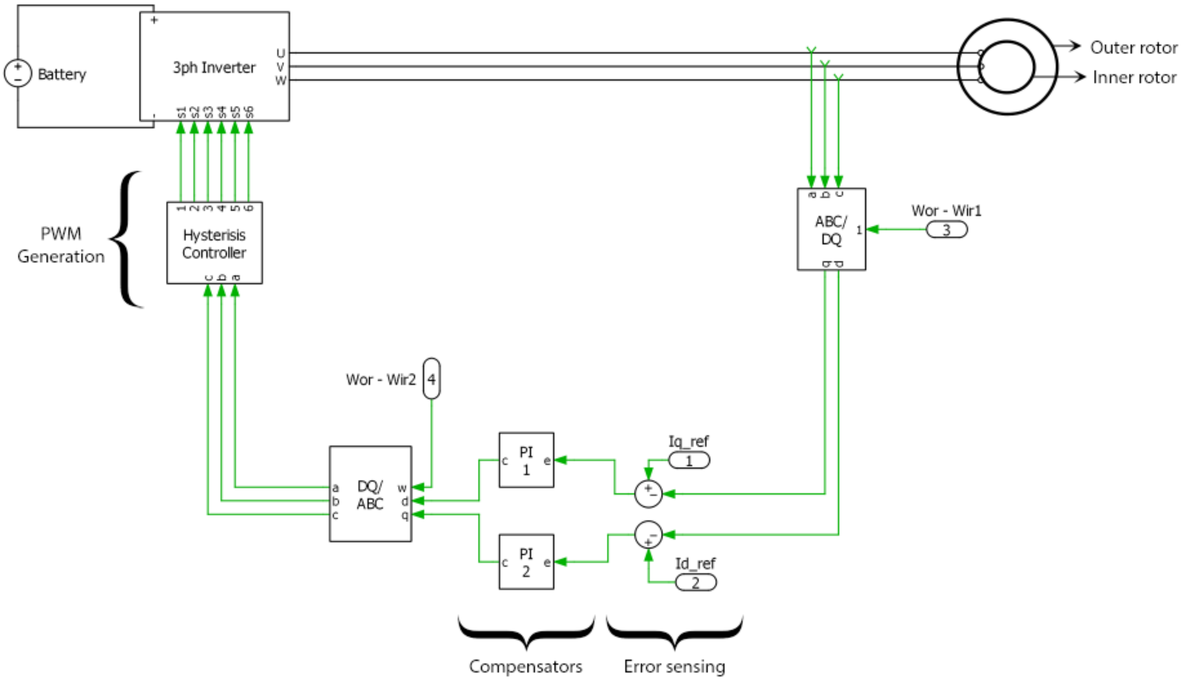

Figure 4.11: FOC block diagram for 2-member transmotor

### 4.2.3 Advantages

The transmotor can deliver greater mechanical power than its electrical power rating. As long as slip power is smaller than or equal to the transmotor's electrical rated power, the transferred mechanical power can be anything

## 4.3 Three Member Transmotor

The Three Member Transmotor, also known as the Dual-Mechanical-Port Machine, or a Dual-Rotor-Machine was first developed by Longya Xu, back in 2005. He proposed a machine with 3 basic parts separated by air gaps, out of which 2 parts have the freedom to rotate mechanically [9-10]. The torque acting on the central part will be the sum of the electromagnetic torques provided by the outer and inner air gaps. The stationary part needs to have electrical terminals as does one of the moving mechanical parts in order to balance the energy flow. This essentially describes a 4-port machine, with 2 mechanical ports and 2 electrical ports (Figure 4.12). The two mechanical movable parts can be assigned arbitrary among the three although

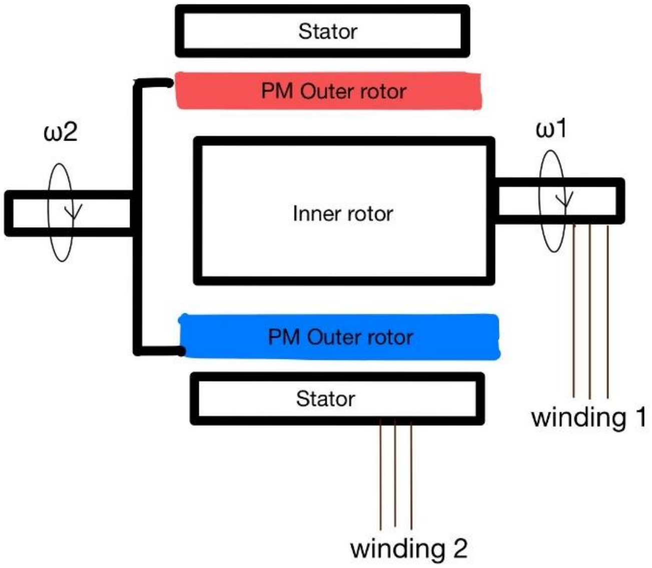

Figure 4.12: The 3-member transmotor

certain assignments may be more favorable than the others in terms of construction, controlling and application [9]. For this paper, the model referred to be will be one where the outer part is stationary (stator), with two rotating inner parts (inner and outer rotor) (Figure 4.13). The inner rotor and the stator have electrical windings powered by power-electronic converters and we have a permanent magnet outer rotor.

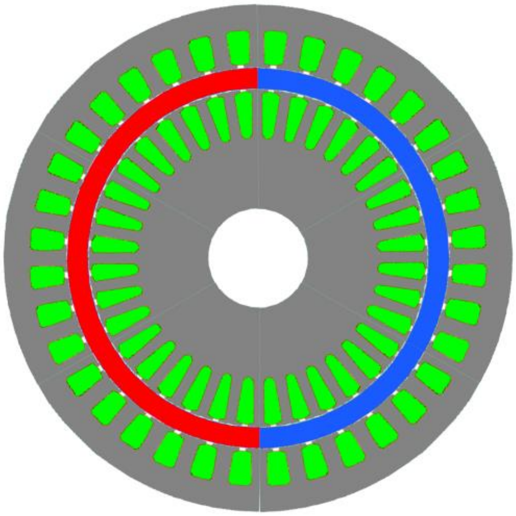

Figure 4.13: Cross section of a 3-member transmotor

When the speeds of the rotors are identical, the transmotor behaves as a conventional machine with 2 shafts. When there is a speed difference between the rotors, the energy flow and operating modes become diverse. For a detailed operation of the transmotor as applied to an HEV drivetrain see [10].

### 4.3.1 Analogy with 2-member Transmotor in Series with a PMSM

For ease of understanding, we can think of the 3-member as a transmotor with the outer rotor connected to a PMSM. In this series combination, there are two torques acting on the outer rotor. The equal and opposite force dictated by Newton's law which arises from the inner rotor torque through the air gap, and the torque provided by the stator. As before there is a speed coupling between the inner and outer rotors and the output mechanical speed is the sum of the electrical frequency and the input mechanical speed. For meaningful torque interaction between the PMSM and the outer rotor, the PMSM must be spinning at the same speed as the outer rotor.

In the 3 member, the stator performs the role of the PMSM described above. The torque is provided through the air gap between the stator and the outer rotor. The electrical frequency of the stator currents must be the same as the outer rotor mechanical speed in order to ensure effective torque coupling. From here on, the term transmotor will be used to refer solely to its 3-member form.

### 4.3.2 Power Balance Equations

The transmotor is a four-port device with 2 mechanical ports and 2 electrical ports, as shown in Figure 4.14. For this research, let us consider a machine with a stationary outer part, and two rotating parts on the inside. The inner rotor and the stator have electrical windings powered by power-electronic converters and the outer rotor sandwiched by the air gaps of the stator and inner rotor, is a permanent magnet rotor. The mechanical ports are the two rotating shafts connected to the inner and outer rotor and the two electrical ports are the windings on the stator and the inner rotor. We have also considered 2 pole machines such that n =1. (Electrical frequency = Mechanical frequency).

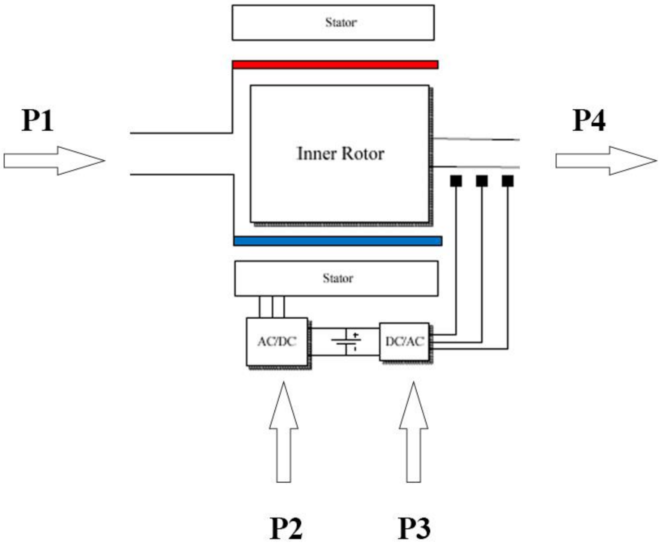

Figure 4.14: A 4 port device

Assuming a lossless system, P1 + P2 + P3 + P4 = 0, for this four port device. The two mechanical ports can be represented by

$$P_4 = T_{m1} * \omega_{m1}$$

$$P_1 = T_{m2} * \omega_{m2}$$

In an electric machine, the voltage equations are given by:

$$V = I*R + \varepsilon$$

Where ε is the back emf. Multiplying equation # by the current, I:

$$V*I = I^2 *R + \varepsilon*I$$

$$P_e = P_{loss} + \varepsilon*I$$

For an electric motor with motor constant k, $\varepsilon = k* \omega$ and torque $T = k*I$. Therefore, the equation becomes

$$P_e = P_{loss} + T^* \omega$$

$$P_e = P_{loss} + P_{em}$$

For this case, we have assumed negligible losses and when we refer to the electric power, we refer to the electromechanical power $P_{em}$ given by

$$P_{em} = T^* \omega$$

Therefore, for the two electric ports, the power equations van be written as:

$$P_3 = T_{e1} * \omega_{e1}$$

$$P_2 = T_{e2} * \omega_{e2}$$

From the previous discussions, we have established certain constraints for the transmotor. They can be summarized as follows:

1. The electrical torque of the inner rotor is equal to the mechanical torque at the inner rotor shaft.
2. The torque acting on the outer rotor is the sum of the torques provided by the stator and the inner rotor. The torque provided by the inner rotor on the outer rotor is equal and opposite to the mechanical torque provided by the inner rotor.
3. The electrical frequency of the stator currents must be equal to the frequency of rotation of the outer rotor for meaningful torque interaction.
4. The speed of inner rotor is the sum of the speeds of the outer rotor and the inner rotor winding current frequency (when the number of pole pairs, n=1).

$$T_{m1} = T_{e1}$$

$$T_{m2} = T_{e2} - T_{e1}$$

$$\omega_{m2} = \omega_{e2}$$

$$\omega_{m1} = \omega_{e1} + \omega_{e2}$$

From these constraints, we can see that there are essentially 2 magnitudes of torque and 2 magnitudes for speed throughout the system. The following substitutions are made to give a cleaner form for the power balance equations:

$$T_{e2} = T_2$$

$$T_{m1} = T_{e1} = T_1$$

$$\omega_{m2} = \omega_{e2} = \omega_2$$

$$\omega_{e2} = \omega_1$$

Substituting this in the power balance equations gives us:

$$P_1 = (T_2 - T_1) * \omega_2$$

$$P_2 = T_2 * \omega_2$$

$$P_3 = T_1 * \omega_1$$

$$P_4 = T_1 * (\omega_1 + \omega_2)$$

As with the example provided for the two-member transmotor, let us consider an example case of a 2 pole (n =1) transmotor connected to a pedal and a drive wheel at each of its mechanical ports. The pedal is connected to the inner rotor and the drive wheel is connected to the outer rotor as shown in Figure 4.15.

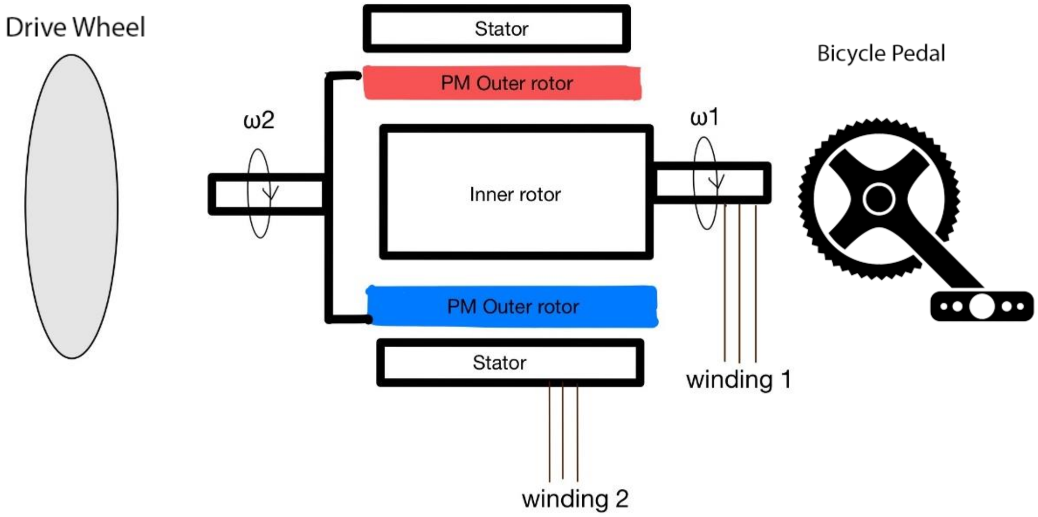

Figure 4.15: Power flow example for the transmotor

- Let us consider the case where both the mechanical ports are spinning in the same direction. When a positive torque is applied to the pedal to accelerate it, an equal and opposite torque acts on the outer rotor. The torque acting on the drive wheel will be a combination of this torque and the torque provided by the stator air gap.
  1. If the torque provided by the stator is in the same direction as the direction of rotation of the drive wheel, the stator side is acting in motoring mode and power will be drawn from the battery (Figure 4.16).

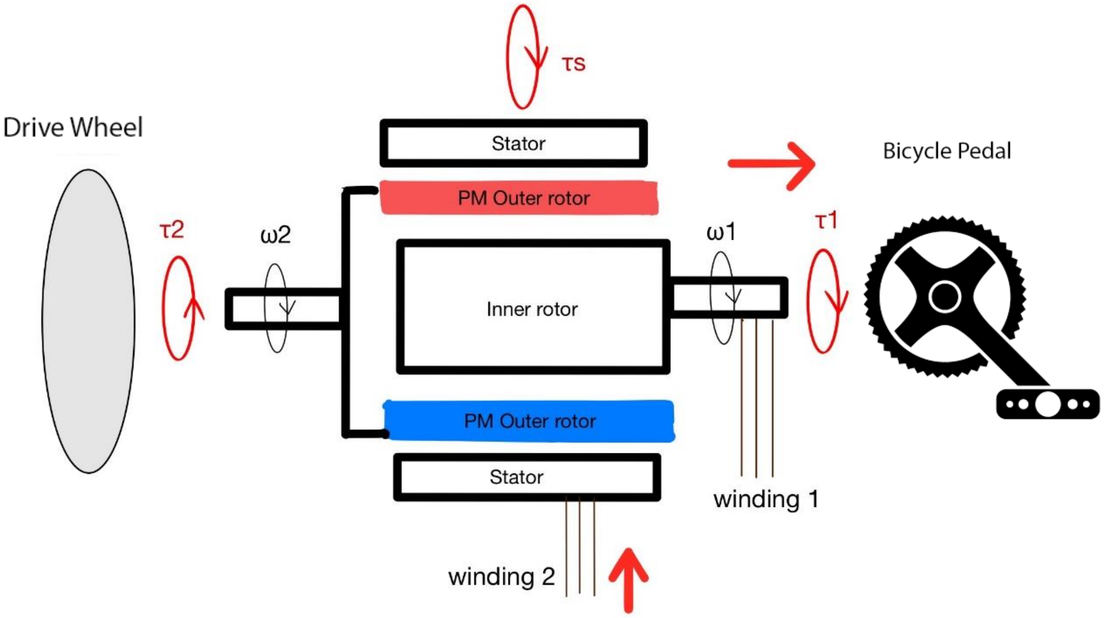

Figure 4.16: Power flow when Ts is positive

2. If the stator provides torque in a direction opposite to the direction of rotation of the drive wheel, the stator is acting in generating mode and power will be delivered to the battery (Figure 4.17).

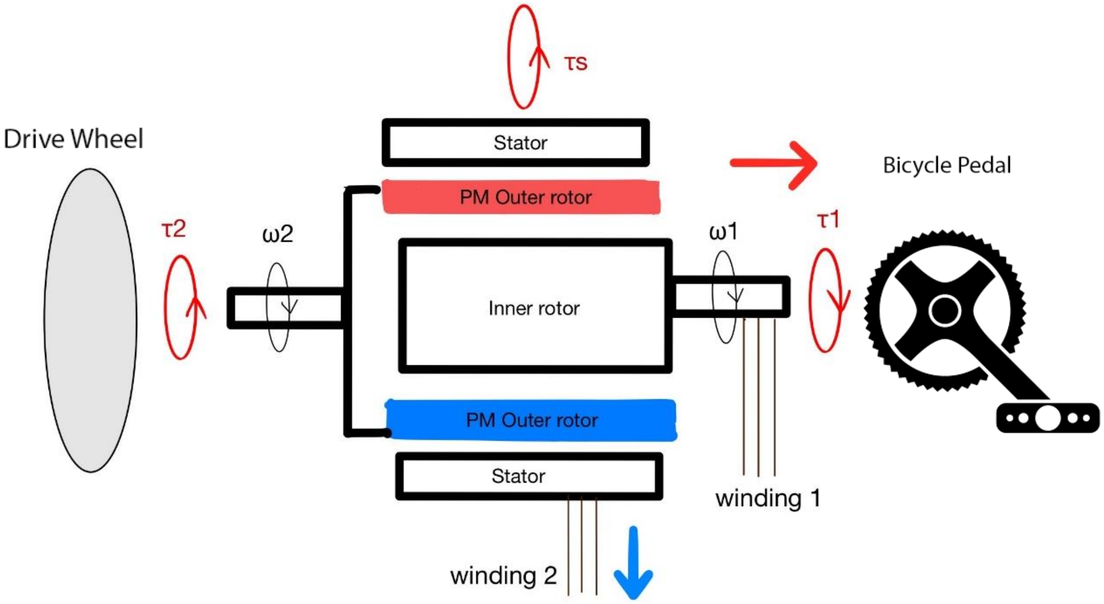

Figure 4.17: Power flow when Ts is negative

3. The torque acting on the outer rotor is equal to the sum of the torques provided by the inner rotor and the stator. The direction of the torque will correspond to whichever port is providing the torque with greater magnitude. However, direction of power flow is independent of the direction of the total torque.
4. If the speed of the drive wheel is greater than that of the pedal, with respect to the outer rotor, the inner rotor is spinning in a negative direction with a magnitude equal to the slip between the two rotors. Speed and torque are in opposite directions because an accelerating (positive) torque is being applied. Therefore, the inner rotor will be acting in generating mode and power will be delivered to the battery (Figure 4.18).

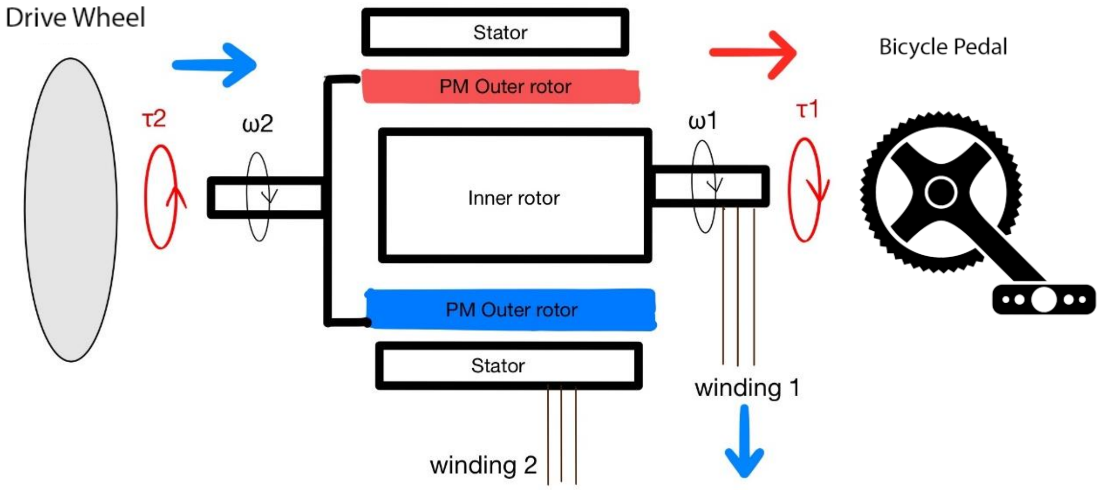

Figure 4.18: Power flow when ω2 > ω1

5. If the speed of the drive wheel is lesser than that of the pedal, then the inner rotor is spinning in a positive direction with respect to the outer rotor, with a magnitude equal to the slip between the 2 rotors. Speed and torque are both acting in the positive

direction; therefore, the machine is acting in motoring mode and power is being drawn from the battery (Figure 4.19).

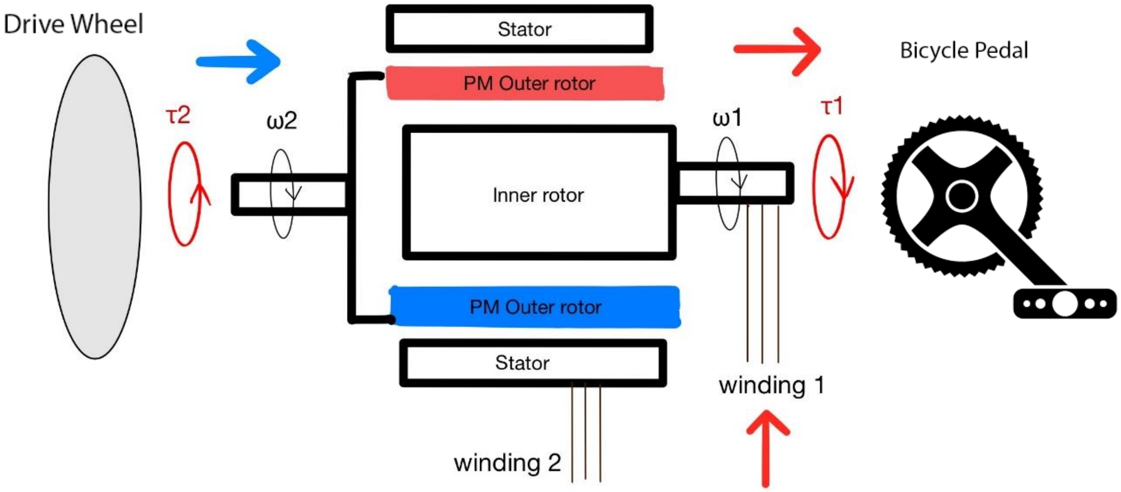

Figure 4.19: Power flow when ω1 > ω2

6. The magnitudes of the power generated or the power drawn will depend on the individual magnitudes of the torque and speeds of the different transmotor parts, as given in the equations stated above.

- The same scenarios are applicable when a negative torque is applied to the pedal. The flywheel is decelerated, and causes and equal and opposite accelerating torque on the outer rotor. The torque on the drive wheel will be a combination of this torque and the torque provided by the stator air gap.
    1. If the torque provided by the stator is in the same direction as the direction of rotation of the drive wheel, the stator side is acting in motoring mode and power will be drawn from the battery (Figure 4.20).

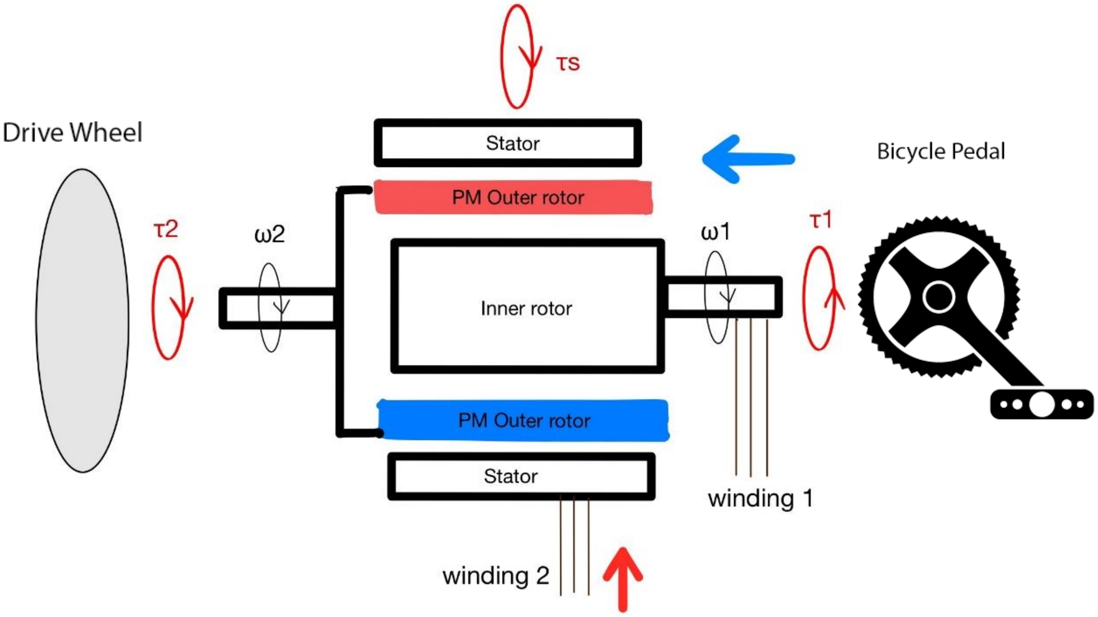

Figure 4.20: Power flow with negative T1 and positive Ts

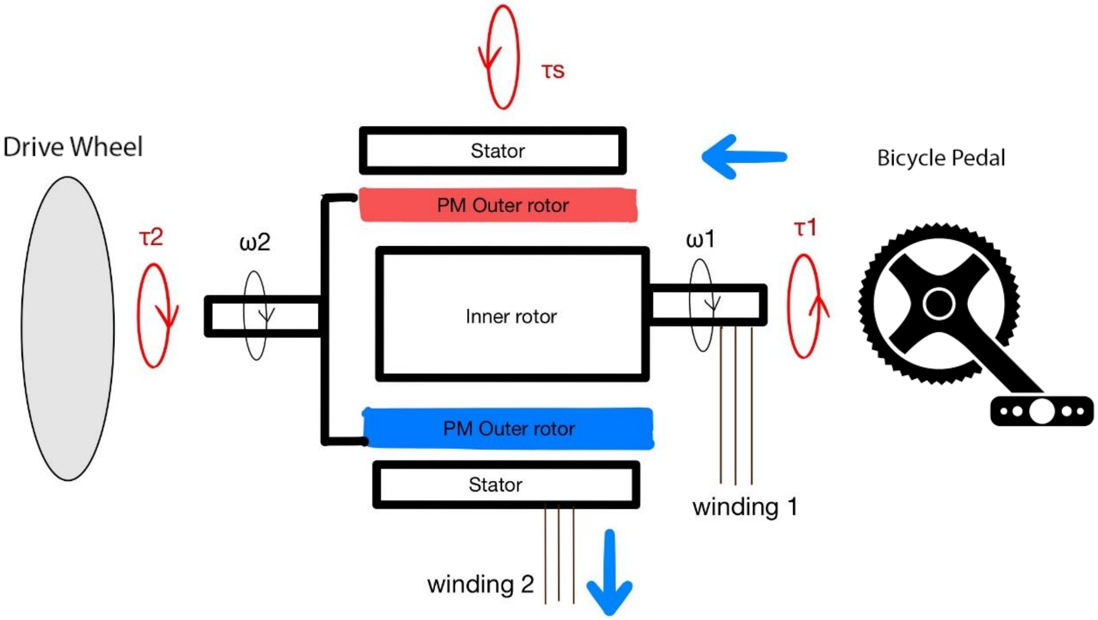

Figure 4.21: Power flow with negative T1 and negative Ts

2. If the stator provides torque in a direction opposite to the direction of rotation of the drive wheel, the stator is acting in generating mode and power will be delivered to the battery (Figure 4.21
3. If the speed of the drive wheel is greater than that of the pedal, with respect to the outer rotor, the inner rotor is spinning in a negative direction with a magnitude equal to the slip between the two rotors. Speed and torque are in the same direction because a decelerating (negative) torque is being applied. Therefore, the inner rotor will be acting in motoring mode and power will be delivered from the battery (Figure 4.22).

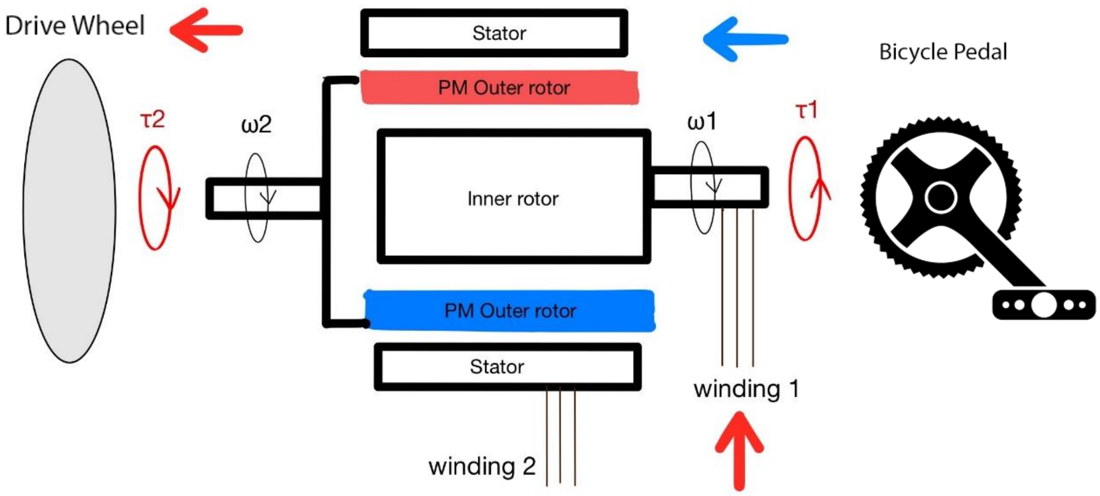

Figure 4.22: Power flow with negative T1 and ω2>ω1

4. If the speed of the drive wheel is lesser than that of the pedal, then the inner rotor is spinning in a positive direction with respect to the outer rotor, with a magnitude equal to the slip between the 2 rotors. Speed and torque are acting in negative directions because a decelerating torque is being applied to the pedal, therefore the machine is acting in generating mode and power is being delivered to the battery (Figure 4.23).

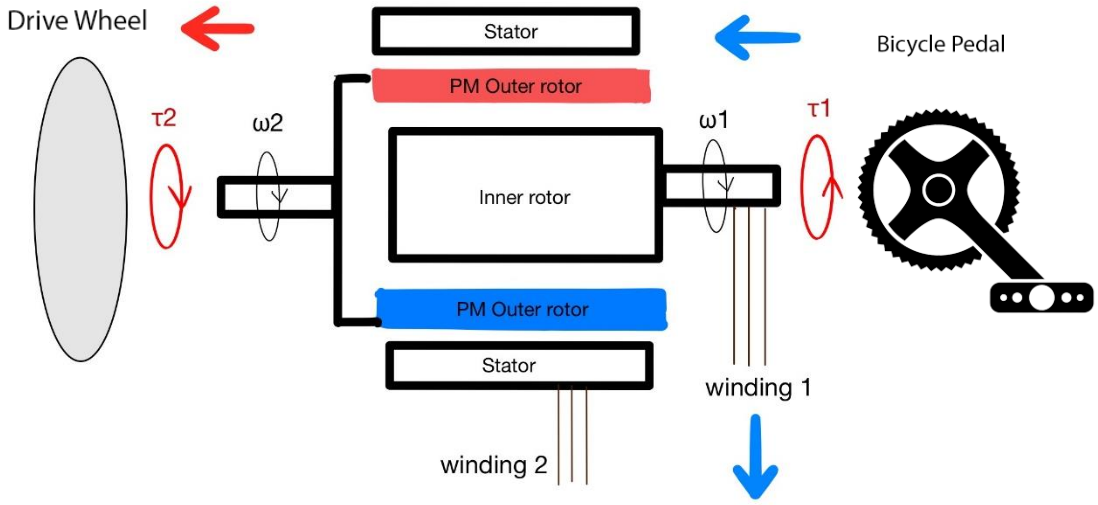

Figure 4.23: Power flow with negative T1 and ω1 > ω2

5. The magnitudes of the power generated or the power drawn will depend on the individual magnitudes of the torque and speeds of the different transmotor parts, as given in the equations stated above.

- When the two flywheels are spinning in opposite directions, the inner rotor has a relative speed (with respect to the outer rotor) with a magnitude equal to the sum of speeds of the inner and outer rotor.
    1. The power flow with respect to the stator remains the same as before and is determined solely by whether the stator is providing a torque in the same direction of rotation of the drive wheel or if it is providing a torque that is in a direction opposite to that of the rotation of the drive wheel.

2. If a positive torque is applied to the pedal, the relative speed of the inner rotor and the torque provided act in the same direction, and therefore power is drawn from the battery. An equal and opposite torque is also provided to the outer rotor.
3. If a negative torque is applied to the pedal, the torque and relative speed are acting in opposite directions, and this net decelerating effect will generate power which is stored in the batteries.

### 4.3.3 Mathematical Model

As with the transmotor, we can develop the mathematical model of a transmotor similar to a permanent magnet machine. There are two electrical ports which can be controlled – the stator and the inner rotor. The reference frame is taken with respect to the outer rotor as it is common to both the ports. For a machine with n pole pairs:

$$\omega_{eir} = n(\omega_{ir} - \omega_{or})$$

$$\omega_{es} = n\omega_{or}$$

Substituting this for the electrical frequency in the general AC machine mathematical model [9], we get:

$$v_{qs} = R_s i_{qs} + \frac{d\psi_{qs}}{dt} + n\omega_{or}\psi_{ds}$$

$$v_{ds} = R_s i_{ds} + \frac{d\psi_{ds}}{dt} - n\omega_{or}\psi_{qs}$$

$$v_{qir} = R_{ir} i_{qir} + \frac{d\psi_{qir}}{dt} + n(\omega_{ir} - \omega_{or})\psi_{dir}$$

$$v_{dir} = R_{ir} i_{dir} + \frac{d\psi_{dir}}{dt} - n(\omega_{ir} - \omega_{or})\psi_{qir}$$

$$\psi_{qs} = L_s i_{qs} + L_m i_{qir}$$

$$\psi_{ds} = \psi_m + L_s i_{ds} + L_m i_{dir}$$

$$\psi_{qir} = L_{ir} i_{qir} + L_m i_{qs}$$

$$\psi_{dir} = \psi_m + L_{ir} i_{dir} + L_m i_{ds}$$

$$T_s = \frac{3}{2} n(\psi_m i_{qs} + \psi_{dir} i_{qs} - \psi_{qir} i_{ds})$$

$$T_{ir} = \frac{3}{2} n(\psi_m i_{qir} + \psi_{ds} i_{qir} - \psi_{qs} i_{dir})$$

$$T_{or} = \frac{3}{2} n\psi_m (i_{qir} + i_s)$$

More details on the mathematical modeling of transmotors can be found in [9], [14] and [15]. Using these equations, we can simulate FOC of a transmotor as shown in the block diagram in Figure 4.24.

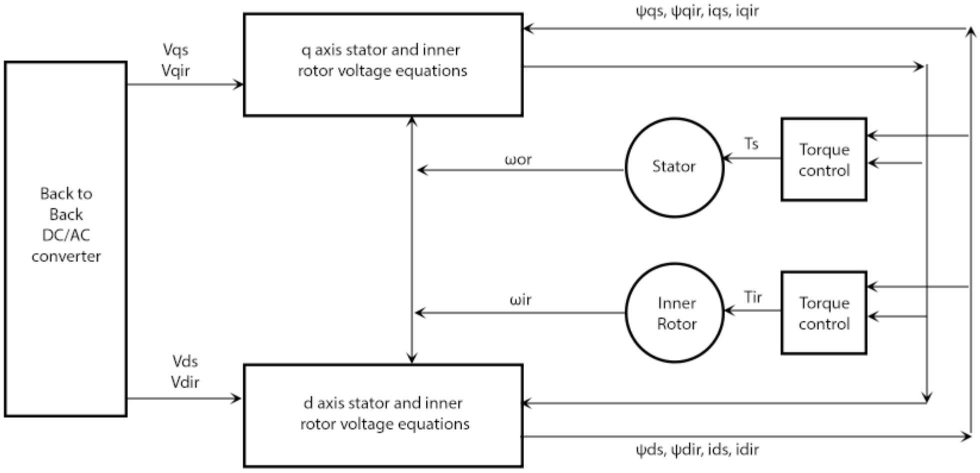

Figure 4.24: FOC block diagram for 3 member transmotor

### 4.3.4 Simulations

As a case study, a transmotor has been simulated on MATLAB to show the phase current control to achieve the speed and torque requirements. The inner and outer rotor speeds for the simulation time is given in Figure 4.25.  Torque requirements from the stator and the rotor is given in Figure 4.26 and Figure 4.27.

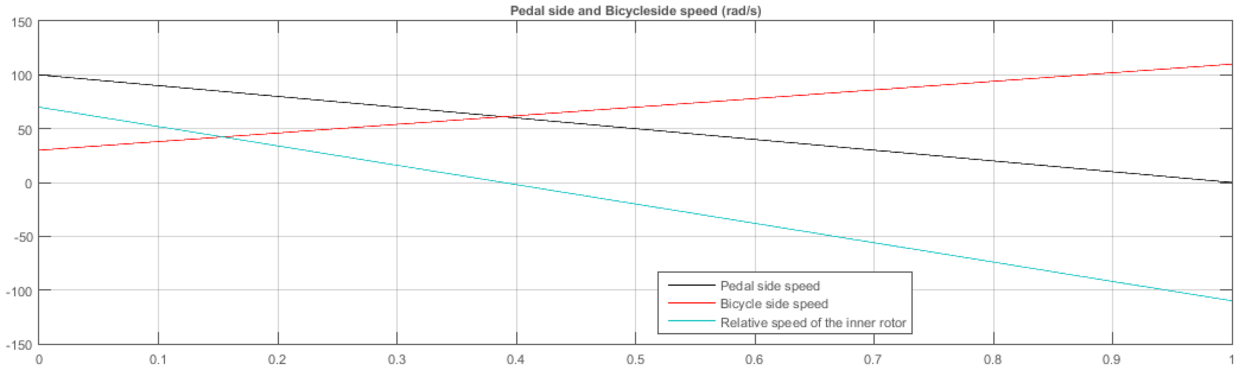

Figure 4.25: Pedal and bicycle speed over time

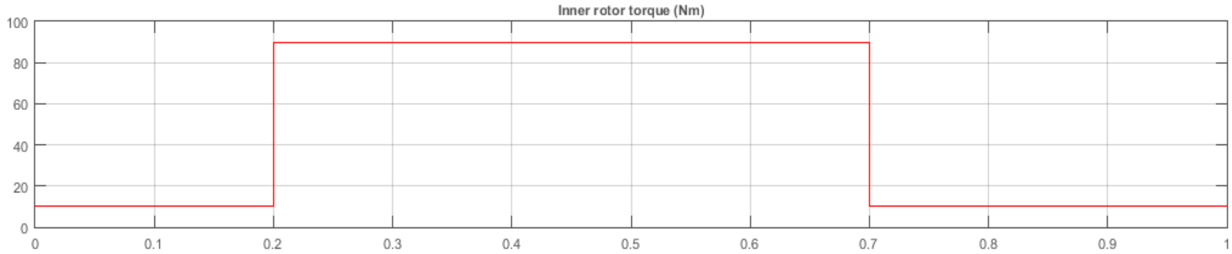

Figure 4.26: The torque requirement from the inner rotor

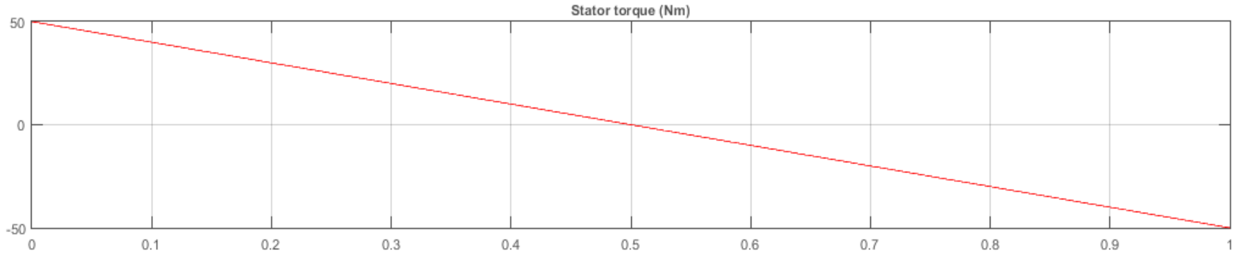

Figure 4.27: Torque requirement from the stator

The dq currents required to generate this torque is given in Figures 4.28-4.29. The quadrature current is directly proportional to the required torque, and the torque constant $K_t$, is assumed to have a value of 2. The $i_d$ reference is set to zero assuming no field weakening and symmetry of flux paths. The phase currents are obtained from the dq currents using inverse Clarke and Park transforms. It is of interest to note the phase currents of the stator and rotor. The stator phase currents look very similar to that of a PM synchronous machine that was given a similar torque and speed demand. The inner rotor phase currents change their phase sequence at somewhere around the middle of the simulation. This is the point at which the slip power becomes zero and energy flow starts to reverse direction as can be seen from Figures 4.30-4.31.

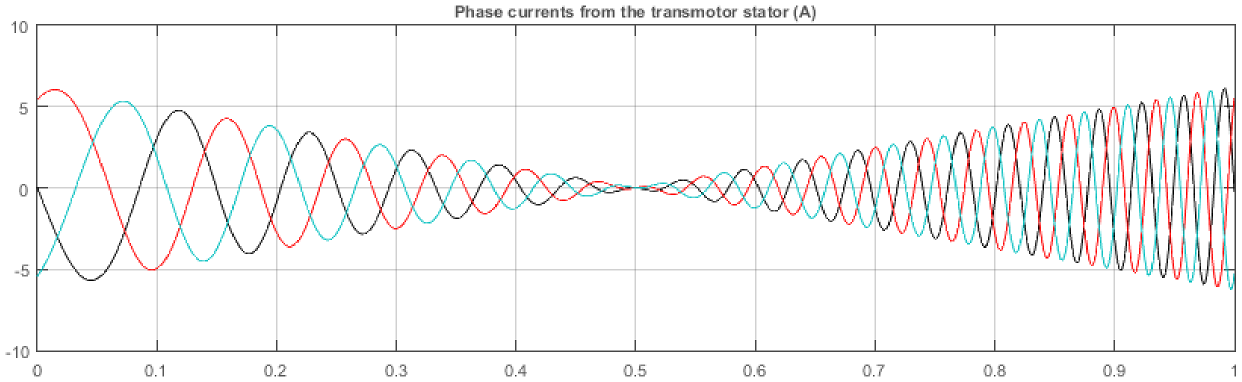

Figure 4.28: Phase currents of the transmotor stator

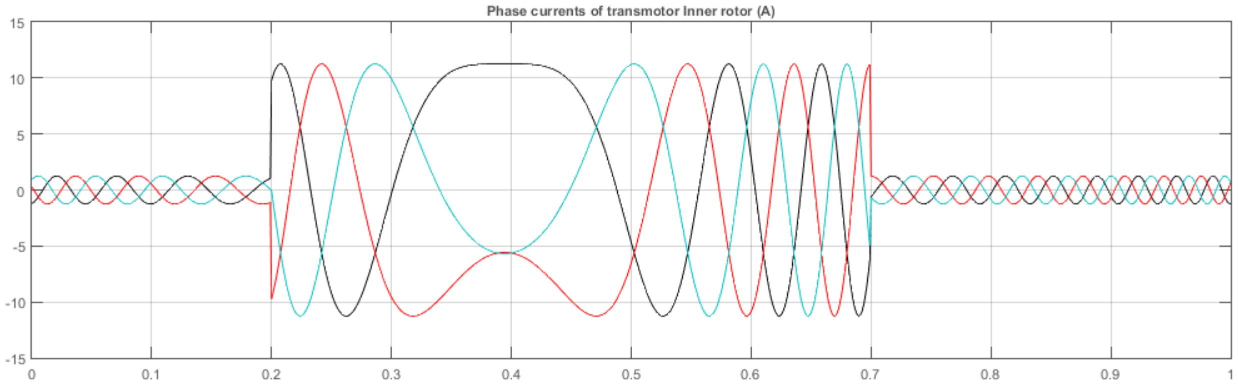

Figure 4.29: Phase currents from the transmotor inner rotor

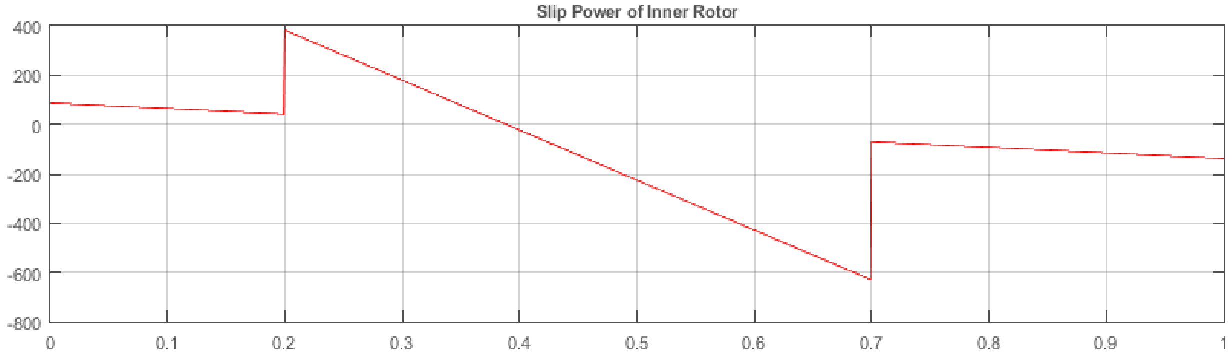

Figure 4.30: Slip power handled by the inner rotor

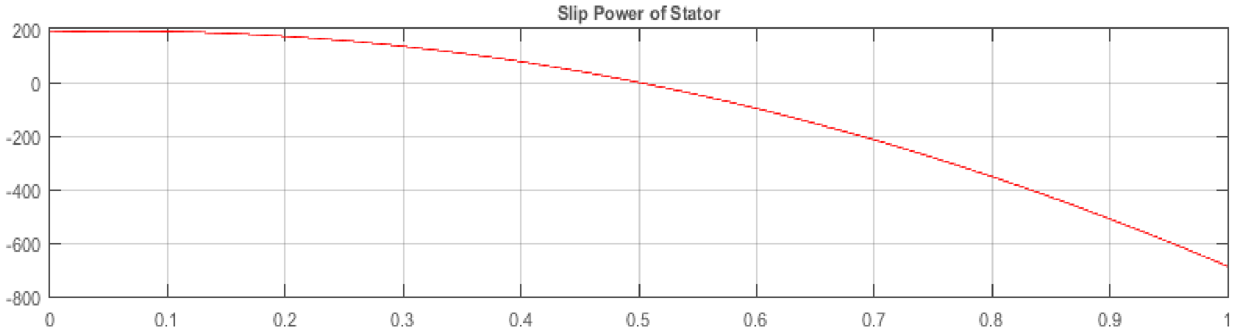

Figure 4.31: Slip power handled by the stator

### 4.3.5 Advantages

The transmotor can have independent speed and torque control at both the mechanical ports of the device. As with the transmotor, it is able to transfer mechanical power that is much greater than its electrically rated value. With independent inputs at both ends, there is a wide variety of power flow combinations which can be taken advantage of in applications pertaining to hybrid electric vehicles. Power flow is bi-directional in that both ends of the transmotor can act as a motor or a generator. Control methods also does not require further complications as the mathematical model for a transmotor is essentially the same as that with PM synchronous machines, but with an added speed element to take in to account the movement of both the outer and inner rotors.

# 5. THE TRANSMOTOR BASED ELECTRIC BICYCLE

## 5.1 Introduction

A 3-member transmotor – the transmotor – provides an integrated solution to the above model. The transmotor, as discussed before, is the combination of a 2-member transmotor and a PMSM. It gives us the configuration required for the model of the previously proposed electric bicycle. The transmotor allows independency of input and output torque and speed. Hence the electric bicycle model, where the user can pedal with whatever torque/speed he or she desires and yet have complete and independent control of output speed and torque for bicycle propulsion, is achievable by using the transmotor as the powertrain as in Figure 5.1.

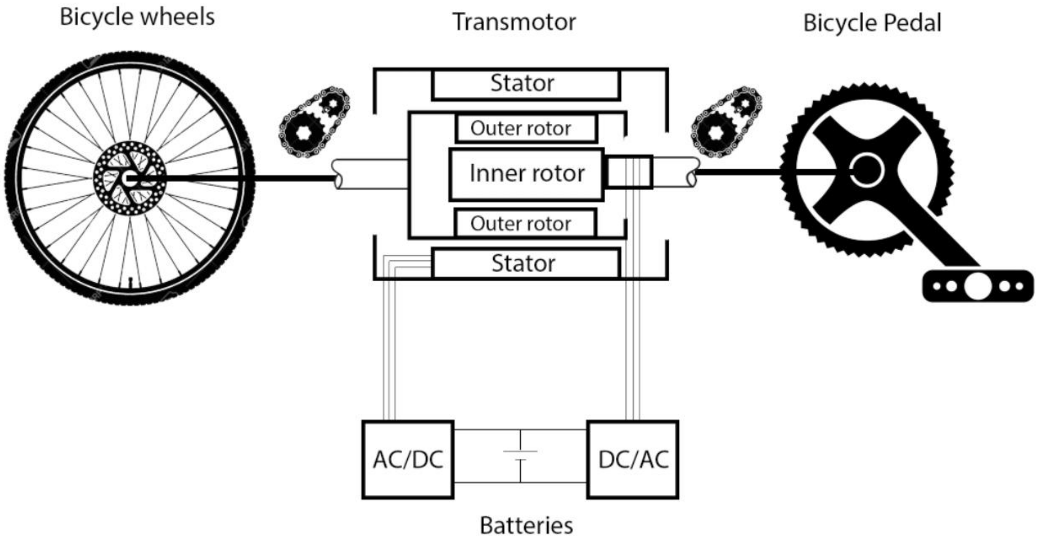

Figure 5.1: A hybrid e-bike based on a transmotor

## 5.2 Realization

The transmotor e-bike can be of mid-hub or rear-hub type as with the e-bikes in the market today. The positioning of the transmotor can be varied to suit the type of application for the e-bike – city driving/mountain biking. With the mid hub configurations (Figures 5.2 -5.3), the transmotor is closer to the pedals, and has the pedals connected to the inner rotor shaft via gearing. The transmotor is connected to the bicycle wheels via a separate gearing.

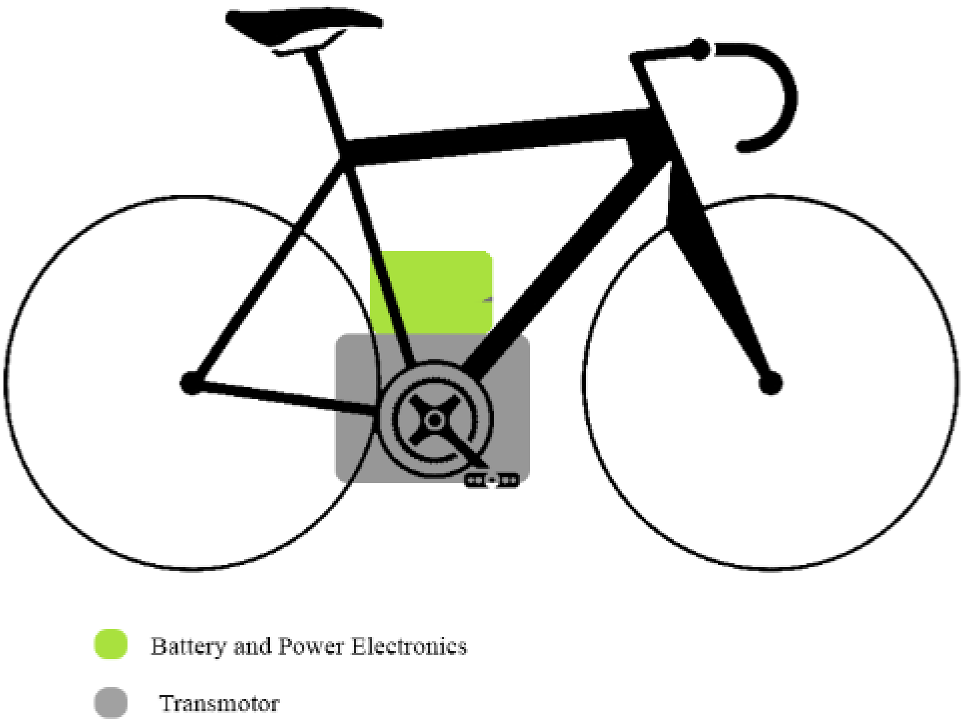

Figure 5.2: Mid-hub realization of the transmotor e-bike

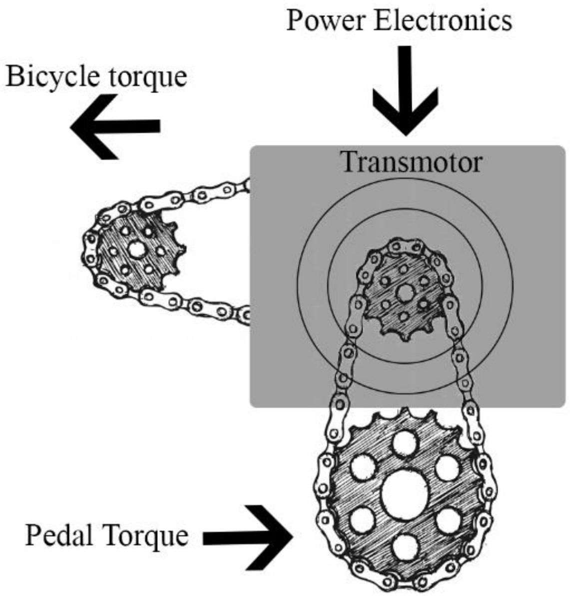

Figure 5.3: Gearing required for the mid-hub transmotor e-bike

With the rear hub configuration, the transmotor is attached to the rear wheels. The wheels are connected through a single-speed gear to the transmotor outer rotor. The inner rotor shaft is connected to the pedals via a separate gear chain (Figures 5.4-5.5).

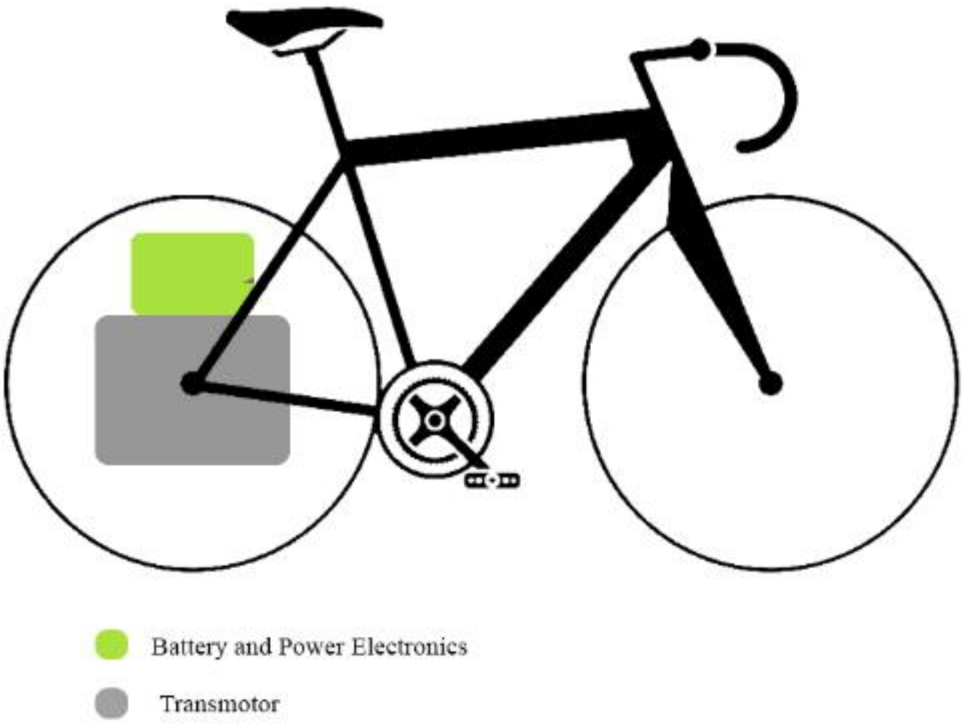

Figure 5.4: Rear hub realization of transmotor e-bike

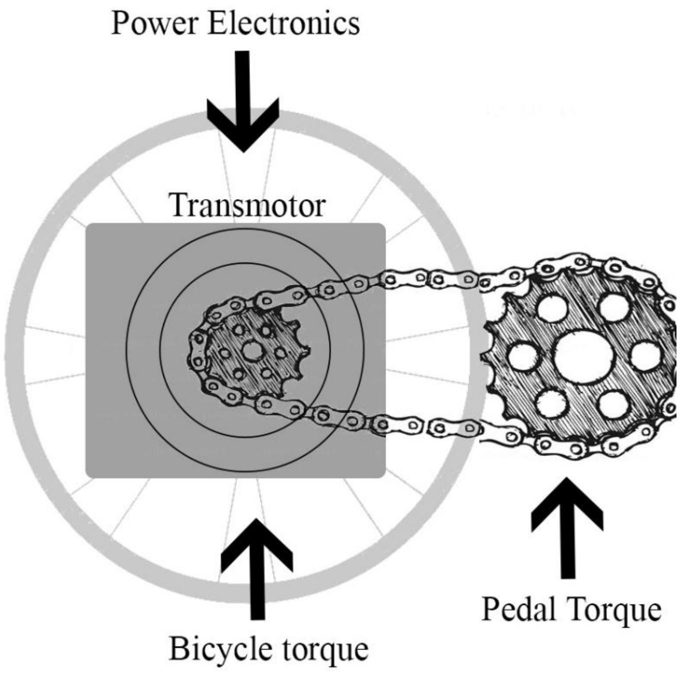

Figure 5.5: Gearing requirements for transmotor e-bike

## 5.3 Power, Speed and Torque Equations

To find the magnitudes of the torque and speed of the different parts of the transmotor bicycle, we apply the mathematical model of the transmotor as follows. The power balance equations for the transmotor were derived as:

$$P_1 = (T_2 - T_1) * \omega_2$$

$$P_2 = T_2 * \omega_2$$

$$P_3 = T_1 * \omega_1$$

$$P_4 = T_1 * (\omega_1 + \omega_2)$$

Assuming we have an ideal lossless machine, these equations can be used to find the magnitudes of the power, torque and speed at the pedal, bicycle wheel and the two batteries. The signs have been changed to assume the normal mode of operation.

$$P_{\text{bicycle}} = T_{\text{bicycle}} * \omega_{\text{bicycle}}$$

$$P_{\text{battery2}} = (T_{\text{bicycle}} - T_{\text{pedal}}) * \omega_{\text{bicycle}}$$

$$P_{\text{battery1}} = T_{\text{pedal}} * (\omega_{\text{bicycle}} - \omega_{\text{pedal}})$$

$$P_{\text{pedal}} = T_{\text{pedal}} * \omega_{\text{pedal}}$$

## 5.4 Power Flow on the Transmotor E-bike

For this study, let us consider a model of an e-bike with the pedals connected to the inner rotor and the bicycle wheel connected to the outer rotor of the transmotor. This allows for torque addition at the bicycle end. This provides for the machine being able to provide high torques at low speeds. The total torque acting on the bicycle will be the sum of the torque provided by the user and the torque provided by the stator air gap. For independent control, we would need two throttles/controllers on each handle, with the first throttle controlling the torque the user feels on the pedals and the other controlling the torque propelling the bicycle. The throttle controlling the pedal torque will be referred to as Control 1 and the throttle controlling the bicycle torque will be referred to as Control 2. Let us consider the general use case, where the user is pedaling forward and the bicycle is being propelled in the forward direction.

- The torque the user feels on the pedals is dictated by Control 1. At the default position, the user feels next to no torque at the pedals. Control 1 is used to make a negative torque demand in a direction that is opposite to the direction of pedaling in order for the user to feel a force on the pedals. The user has to provide at least the same amount of torque in order to maintain the speed of the pedals.
    - If the speed at the inner rotor due to pedaling (after being geared up), is greater than that of the outer rotor speed, the machine will act in the generating mode on the inner rotor side. This is because, with respect to the outer rotor, the inner rotor will be spinning in the positive direction. Since negative torque is being provided, the torque and direction of rotation will be in opposite directions, and the machine will be in the generating quadrant of operation. Power will be delivered to the battery.
    - If the speed at the inner rotor due to pedaling (after being geared up), is less than the speed of the outer rotor, then with respect to the outer rotor, the inner rotor is moving in the negative direction. Since torque is also in the negative direction, the machine will act in motoring mode. Power will be drawn from the battery.
- The negative torque provided to the inner rotor in order for the user to feel a torque at the pedals will materialize itself as a reaction torque on the outer rotor which is connected to the

bicycle wheels. With no other control input, this reaction torque provides a positive torque at the bicycle wheels propelling it forward.

- Control 2 is used to control the torque at the bicycle wheels by adding or subtracting to this reaction torque. Power flow to the battery depends only on the direction in which the stator torque is applied.
    - If the user makes a demand to increase the amount of torque on the bicycle wheels using Control 2, a positive torque will be provided by the stator air gap, in the same direction as that of the bicycle wheels and the direction of rotation of the outer rotor. Since they are acting in the same direction, the machine will act in generating mode on the stator side. Power generated will be supplied to the battery.
    - If the user makes a demand to reduce the amount of torque on the bicycle wheels using Control 2, a positive torque is provided by the stator air gap a direction that is opposite to the direction of the bicycle wheels and the outer rotor. Since they are acting in opposite directions, the machine is acting in motoring mode on the stator side. Power is being drawn from the battery.
- Now let us consider the case where the user tries to pedal in a direction opposite to that of the motion of the bicycle. The inner rotor will have a relative speed (w.r.t outer rotor) that a magnitude equal to the sum of the speeds of the inner and outer rotor.
    1. As before, the power flow equations from the stator and the battery is dependent only on whether the stator torque is acting in the same or opposite direction to that of the direction of rotation the bicycle wheels.
    2. If a positive torque demand is made using Control 1, the inner rotor relative speed and the torque provided are acting in the same direction and power is drawn from the

battery. The reaction torque will be acting in the same direction as that of the bicycle wheels and will accelerate it. The user also feels this torque on the pedals acting in the direction of pedaling and hence would find it easier to pedal.

3. If a negative torque demand is made using Control 1, the relative speed of the inner rotor and the torque provided are acting in opposite directions, and power is generated which is delivered to the battery. The reaction torque is opposite to the direction of the bicycle wheels and hence, the bicycle gets decelerated. He will find it more difficult to pedal.

## 5.5 User Experience

Let us try to describe the user experience of using this bicycle. As per the authors envisioning, the bicycle handlebars will have two controls on either handle in order to independently have control over both the pedal and bicycle propulsion (Figure 5.6). Let us assume we have a toggle mechanism that prevents the reaction torque from making the pedals rotate in the opposite direction. The pedals, and by connection, the outer rotor, will spin in a reverse direction if and only if the toggle is activated by the user.

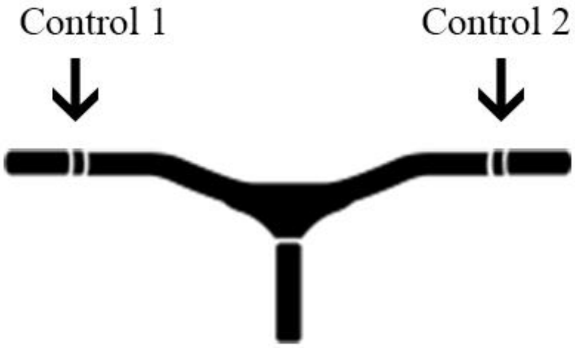

Figure 5.6: Transmotor e-bike throttle control

### 5.5.1 Normal Driving (Pedaling Forward)

Control 1 is used to control the torque felt on the pedals. Control 1 acts by a dial mechanism (Figure 5.7). Each dial position in the downward direction, provides a corresponding degree of torque that is acting in the same direction as that of the rotation of the pedals. The user will hence find it easier to pedal with each dial downward. Similarly, each dial position in the upward direction provides a corresponding degree of torque in a direction opposite to that of the rotation of the pedals. This is done by increasing the loading on the transmotor inner rotor. The user will find it more difficult to pedal in this case, but will generate power, or transfer more power mechanically to the bicycle wheels. In order to maintain the speed at which the user is pedaling he must provide a torque on the pedal that matches this torque. If the user provides a torque that is less than this torque, he will feel the pedals getting decelerated. This can be equated to the deceleration felt in a conventional bicycle when trying to pedal uphill. If the torque that the user provides is more than this torque, the pedals are accelerated and begin to spin faster. For a pedal mechanism with moment of inertia I, spinning at speed ω.

$$\mathrm{I}\frac{\mathrm{d}\omega}{\mathrm{dt}} + \mathrm{T}_{\mathrm{reaction}} + \mathrm{B}\omega = \mathrm{T}_{\mathrm{user}}$$

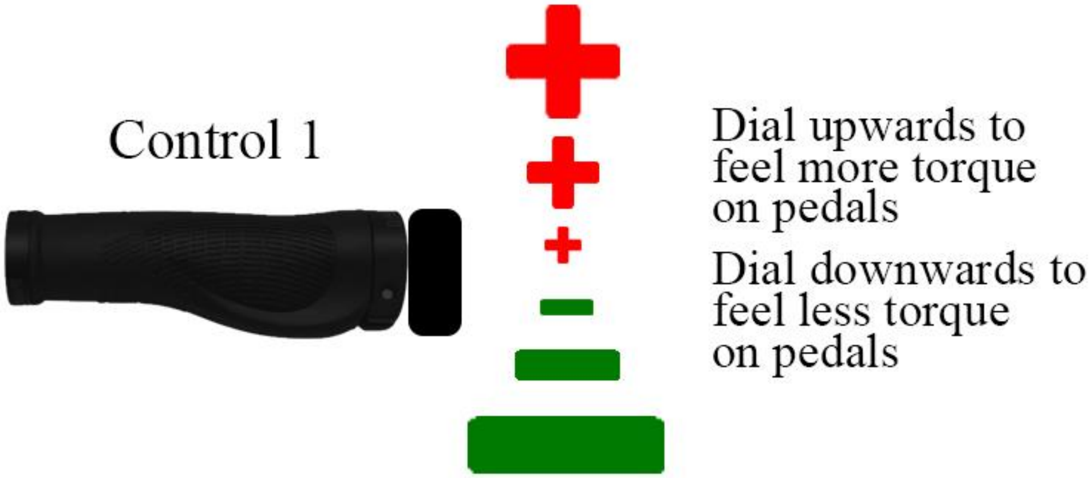

Figure 5.7: Dial to control torque on the pedals

When Control 1 is used to provide a torque at the pedals, the equal and opposite torque acting on the outer rotor is geared up and acts on the bicycle wheels. Control 2 can be used to modify the torque on the bicycle wheels due to the reaction torque. Control 2 activates the stator windings which adds an additional torque to the outer rotor, and by connection, the bicycle wheels. The torque on the wheels is a combination of the stator torque and the reaction torque. Although the reaction torque is determined by torque at the pedal and the terrain, the user can manipulate the stator torque, and in effect, the total torque acting on the wheels such that he has complete control of the magnitude and direction of the torque on the bicycle.

A torque demand is made by twisting the handle as with a conventional motorcycle (Figure 5.8). Twisting it backwards increases the torque on the bicycle wheels and accelerates the e-bike forward, while letting go of the throttle reduces the torque and slows down the e-bike.

The user acts as the speed control and commands an increase in torque when he wants the e-bike to move faster than its current speed.

Figure 5.8: Throttle to control bicycle torquw

### 5.5.2 At Standstill

When the bicycle is at standstill, the outer rotor is locked. The user can still pedal in either direction. The e-bike at this point behaves similar to an exercise bike with the user able to control the torque he feels at the pedals using Control 1. It also provides the added benefit of being able to recharge the batteries by pedal power alone. This is achieved by using Control 1 to produce a torque in a direction opposite to that of the rotation of the pedals.

$$P_{generated} = T_{stator} * \omega_{pedal}$$

### 5.5.3 Pedaling Backward

As we saw from the previous section, pedaling backwards is advisable only when a negative torque demand is made using Control 2. Because the inner and outer rotors are spinning in opposite directions, the relative speed of the inner rotor is the sum of the two speeds, which when multiplied by the negative torque, gives the power generated.

When a positive torque demand is made from the inner rotor, power drawn will be more due to the same reason. However, the power drawn or generated at the battery by the inner rotor is completely independent of this, and depends only on the direction of the stator torque with respect to the direction of pedaling.

Pedaling backwards is in general, a state that needs to be avoided, because the power generated/drawn has the possibility of being much higher than the rated power, because the relative speed is the sum of the inner and outer rotor speeds now. If the sum is too high, the power being handled might be higher than the ratings of the motor and power electronics.

## 5.6 Control Strategy

Describing a control strategy for the operation a 3-member transmotor based bicycle. Algorithm for the control strategy.

- When positive torque demand is made using Control 1.
    - If there is no pedal input from the user
        - Motor alone propelling mode.

$$P_1 = 0$$

$$P_2 = 0$$

$$P_3 = P_4 = T_1 * \omega_1$$

- If user pedal power is sufficient to drive the bicycle at the required speed
  - Pedal alone propelling mode.

$$|P_1| = |P_4|$$

$$|P_2| = |P_3|$$

The power being delivered from generation is used to propel the bicycle.

- If pedal power is more or less than the bicycle power required
  - Hybrid propelling mode

$$P_4 - P_1 = P_3 - P_2$$

Here, we operate with the transmotor equations previously defined. All the torques and speeds are independent of each other,

## 5.7 Power Electronics Needed for Control

Since the windings are on the same machine in the transmotor, in the form of an inner rotor and stator, the same DC bus can be used to control their operation. This can be realized by using power electronics similar to dual converter. The 3 phase inverters connected to either side of the DC bus can be used for power flow in either direction to facilitate motoring as well as well as regeneration. This is shown in Figure 5.9. By varying the PWM for the switches the amount of torque can be adjusted, and this control is achieved through FOC of the transmotor covered in the previous chapter. Mechanism for regenerative braking has been covered in [16], and [17] discusses a method for current sharing between inverters. The design of the inverter components such as the inductor and capacitor has been discussed in [18].

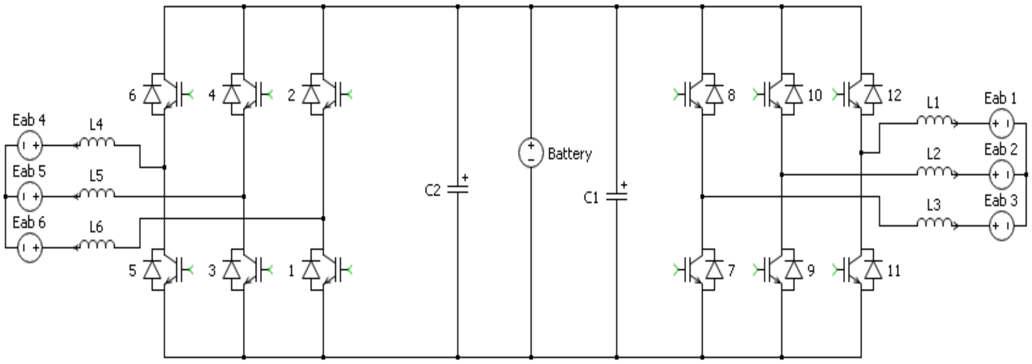

Figure 5.9: Back to back converters for transmotor control

The 3 legs on either side of the inverter depicts the back emf and the winding inductance. Power flow to the battery takes place from both ends and has a magnitude equal to:

$$P_{battery} = P_{electric1} + P_{electric2}$$

If the power flow is negative, battery gets charged, and if it is positive, the battery is discharging in order to maintain motoring. An advantage of this topology is that, whenever the power flow is happening in the same direction (i.e. one side is generating, and other side is motoring), the battery only comes in to picture to support the difference in power flow. The power from generation can directly supply the motoring power.

When connecting devices to the same DC bus, there might be problems associated with the generating power being greater than the motoring power resulting in overvoltage. [19] and [20] discusses control strategies to suppress this overvoltage. Sufficient capacitance is also required to ensure that the output does not fluctuate and that ripple is minimized. [21][22].

As mentioned in the previous chapter, FOC offers a simple method to control the transmotor. A block diagram showing the control strategy is given in Figure 5.10 below. Separate loops are used for the inner rotor and the stator to generate their respective PWMs for the switches, which are then fed to the back to back DC/AC converters to control the torque on the transmotor. Torque control is achieved by varying the q axis current as required, whereas field weakening requires varying the d axis currents. A simplified block diagram for field-oriented control in the proposed system, in surface mount permanent magnet device (where torque is generated only by the PM flux linkages) is shown in the figure below. Here, the magnetizing reference Idref will be set to zero and the torque equation is a function of Iq.

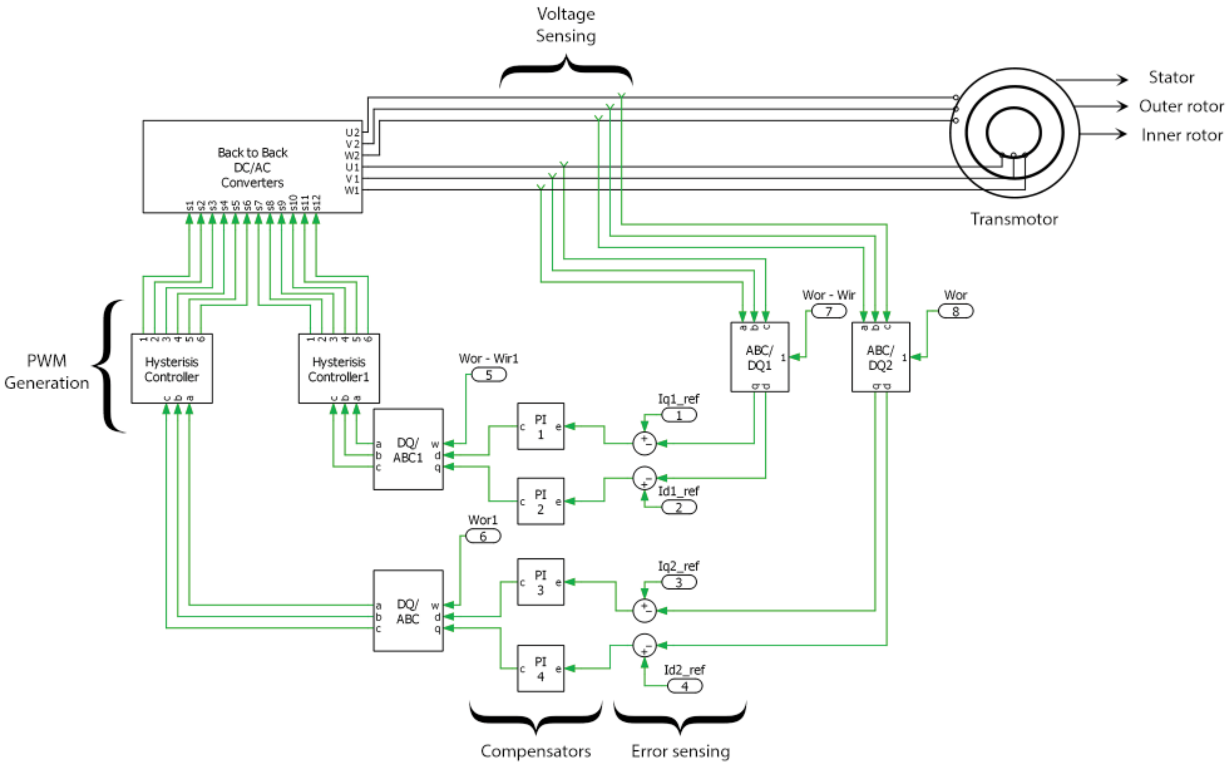

Figure 5.10: FOC of the transmotor using back to back converters

The most common method for current control in electric machines is the Maximum Torque per Ampere (MTPA) control scheme which ensures minimum current is drawn for demanded torque. This reduces copper losses and maximizes efficiency.

## 5.8 Design Flexibilities Offered by the Transmotor Model

As opposed to a traditional e-bike or an e-bike with the motor and generator connected in series, the transmotor based e-bike provides several distinct advantages. First and foremost, the transmotor model is able to provide the independent speed/torque at pedal and bicycle wheel. This gives the user a great amount of flexibility in control. It also lets the user operate at his “sweet spot”, and therefore, the maximum power that the user can give whilst pedaling comfortable can be taken advantage of with this model.

The 3-member transmotor is a combination of a PMSM and a 2-member transmotor. So, the same advantages the transmotor has, over normal electric machines apply here as well. A transmotor is capable of transferring greater mechanical power, than its electrical rating without transforming it [6]. The common mode power in a transmotor is transferred purely mechanically. Only the slip power, i.e. the speed difference between the inner and outer rotor, and the torque difference between the stator and outer rotor, is converted electrically. If the speed difference is zero, then dc current is applied to the three phase windings and there is synchronous coupling between the inner and outer rotors. In this scenario, the transmotor behaves a clutch and can transfer mechanical power at virtually any speed, subjected to the mechanical constraints of the machine.

$$P_{bicycle} = T_{bicycle} * \omega_{bicycle}$$

$$P_{battery2} = \left(T_{bicycle} - T_{pedal}\right) * \omega_{bicycle}$$

$$P_{battery1} = T_{pedal} * \left(\omega_{bicycle} - \omega_{pedal}\right)$$

$$P_{pedal} = T_{pedal} * \omega_{pedal}$$

Let the stator and inner rotor be rated at

$$P_{rated} = T_{rated} * \omega_{rated}$$

Assume pedal torque is $n*T_{rated}$ and the bicycle torque is $(n+1)*T_{rated}$. The outer and inner rotor is spinning with a speed of $\omega_{rated}$. Then,

$$P_{stator} = P_{battery2} = \left((n+1)T_{rated} - nT_{rated}\right) * \omega_{rated}$$

$$P_{stator} = T_{rated} * \omega_{rated}$$

$$\text{Energy transferred mechanically} = n * T_{rated} * \omega_{rated}$$

Next, assume pedal speed is $m*\omega_{rated}$ and the bicycle torque is $(m+1)*\omega_{rated}$. The outer and inner rotor both have a torque of $T_{rated}$ Then,

$$P_{\text{inner rotor}} = P_{\text{battery1}} = \left((m+1)\omega_{\text{rated}} - m\omega_{\text{rated}}\right) * T_{\text{rated}}$$

$$P_{\text{inner rotor}} = T_{\text{rated}} * \omega_{\text{rated}}$$

$$\text{Energy transferred mechanically} = m * T_{\text{rated}} * \omega_{\text{rated}}$$

From this calculation, we can clearly see that a greater amount of mechanical energy is being transferred than the electrical rating of the transmotor.

When operating in pedal-only mode, or motor-only mode, the device performance is similar to that of the SMG model. We would require the same motor/generator ratings and power electronics as before, because there is no counteracting torque or speed which reduces the slip power. However, when operating in hybrid mode – i.e. assuming that the user is pedaling to some extent, the power being handled electrically is reduced. The amount of power handled electrically will depend on how much torque/speed is begin provided by the user. The lesser the difference between the power from the user and the power needed for propulsion, the lesser the power being handled electrically. This is because the inner rotor and stator are dealing only with the slip power associated with the speed difference and torque difference between the ports. This means that the device can be rated at a much lower value than if a motor/generator were used in combination. This translates to being able to use a more compact machine, whilst also reducing the amount of power electronics required in a hybrid mode of operation.

## 5.9 Comparing the Performance of the Transmotor E-bike

As discussed before, the advantages of the transmotor starts to shine through in the hybrid mode of operation. The power flow equations were derived as:

$$\mathrm{P_{bicycle} = T_{bicycle} * \omega_{bicycle}}$$

$$\mathrm{P_{electrical2} = \left(T_{bicycle} - T_{pedal}\right) * \omega_{bicycle}}$$

$$\mathrm{P_{electrical1} = T_{pedal} * \left(\omega_{bicycle} - \omega_{pedal}\right)}$$

$$\mathrm{P_{pedal} = T_{pedal} * \omega_{pedal}}$$

We can see from these equations that while in an SMG model, the total power handled electrically is:

$$\mathrm{P_{motor} + P_{generator} = P_{pedal} + P_{bicycle}}$$

However, in a transmotor bicycle the total power handled electrically is:

$$\mathrm{P_{electrical1} + P_{electrical2} = P_{bicycle} - P_{pedal}}$$

The total power handled by the transmotor electrically is always going to be less than in an SMG model in a hybrid mode of operation. What is interesting is how this electrical power is being handled by the two electrical components (i.e the motor/generator or the inner rotor/stator windings). The various possible conditions of operation have been discussed below to understand this further.

### 5.9.1 When Operating in Pedal Only Mode

The power from pedaling is equal to the power handled by the inner rotor windings. The transmotor will be handling the same amount of power as with the generator in the SMG model.

### 5.9.2 When Operating in Motor Only Mode

The power for bicycle propulsion is entirely provided by the stator windings. The transmotor will be handling the same amount of power as with the motor in the SMG model, or a motor in a standard electric bicycle.

### 5.9.3 When $T_{bicycle} >> T_{pedal}$

When the torque from the bicycle is much greater than the torque provided by the pedals, the power handled electrically is almost the same as the total power required for bicycle propulsion. The transmotor stator will be handling almost as much power as the motor in the SMG model.

$$\begin{aligned} \mathrm{P_{electrical2}} &= \left(\mathrm{T_{bicycle}} - \mathrm{T_{pedal}}\right) * \omega_{\mathrm{bicycle}} \\ &\simeq \mathrm{T_{bicycle}} * \omega_{\mathrm{bicycle}} \\ &= \mathrm{P_{bicycle}} \end{aligned}$$

### 5.9.4 When $T_{pedal} >> T_{bicycle}$

When the torque from pedaling is much greater than the torque on the bicycle wheels, the transmotor stator will be handling a power equal to the product of the pedal torque and bicycle speed.

$$\begin{aligned} \mathrm{P_{electrical2}} &= \left(\mathrm{T_{bicycle}} - \mathrm{T_{pedal}}\right) * \omega_{\mathrm{bicycle}} \\ &\simeq -\mathrm{T_{pedal}} * \omega_{\mathrm{bicycle}} \end{aligned}$$

To ensure that this value remains below the rated electrical value of the inner rotor, we need to ensure that the gear ratios are appropriate.

$$\omega_{\text{bicyclemax}} * \frac{\text{gr}_{\text{bicycle}}}{\text{gr}_{\text{pedal}}} \leq \omega_{\text{pedalmax}}$$

### 5.9.5 When $\omega_{\text{pedal}} >> \omega_{\text{bicycle}}$

When the speed of pedaling is much greater than the speed on the bicycle wheels, the power handled electrically is almost the same as the total power recovered from pedaling. The transmotor inner rotor will be handling a power similar to that of the power being handled by the generator in the SMG model.

$$\begin{aligned} \text{P}_{\text{electrical1}} &= \text{T}_{\text{pedal}} * (\omega_{\text{bicycle}} - \omega_{\text{pedal}}) \\ &\simeq -\text{T}_{\text{pedal}} * \omega_{\text{pedal}} \\ &= \text{P}_{\text{pedal}} \end{aligned}$$

### 5.9.6 When $\omega_{\text{bicycle}} >> \omega_{\text{pedal}}$

When the speed of the bicycle is much greater than the speed of pedaling, the transmotor inner rotor will be handling a power equal to the product of the pedal torque and bicycle speed.

$$\begin{aligned} \text{P}_{\text{electrical1}} &= \text{T}_{\text{pedal}} * (\omega_{\text{bicycle}} - \omega_{\text{pedal}}) \\ &\simeq \text{T}_{\text{pedal}} * \omega_{\text{bicycle}} \end{aligned}$$

Again, to ensure that this value stays within the rated electrical value of the stator, we have a further constraint on the gear ratios:

$$\text{T}_{\text{pedalmax}} * \frac{\text{gr}_{\text{bicycle}}}{\text{gr}_{\text{pedal}}} \leq \text{T}_{\text{bicyclemax}}$$

In these corner cases, the transmotor will be handling electrically, a power very similar to that handled by the motor/generator in the SMG model. However, in the general scenario of the transmotor e-bike acting in hybrid mode, the power handled electrically will be less than in the SMG model because of the counteracting torque and speed. In the following simulations and comparisons, this general case is assumed in order to highlight the area where the transmotor e-bike gives a superior performance.

## 5.10 Simulations

### 5.10.1 Comparison with respect to Motor/Generator Sizing

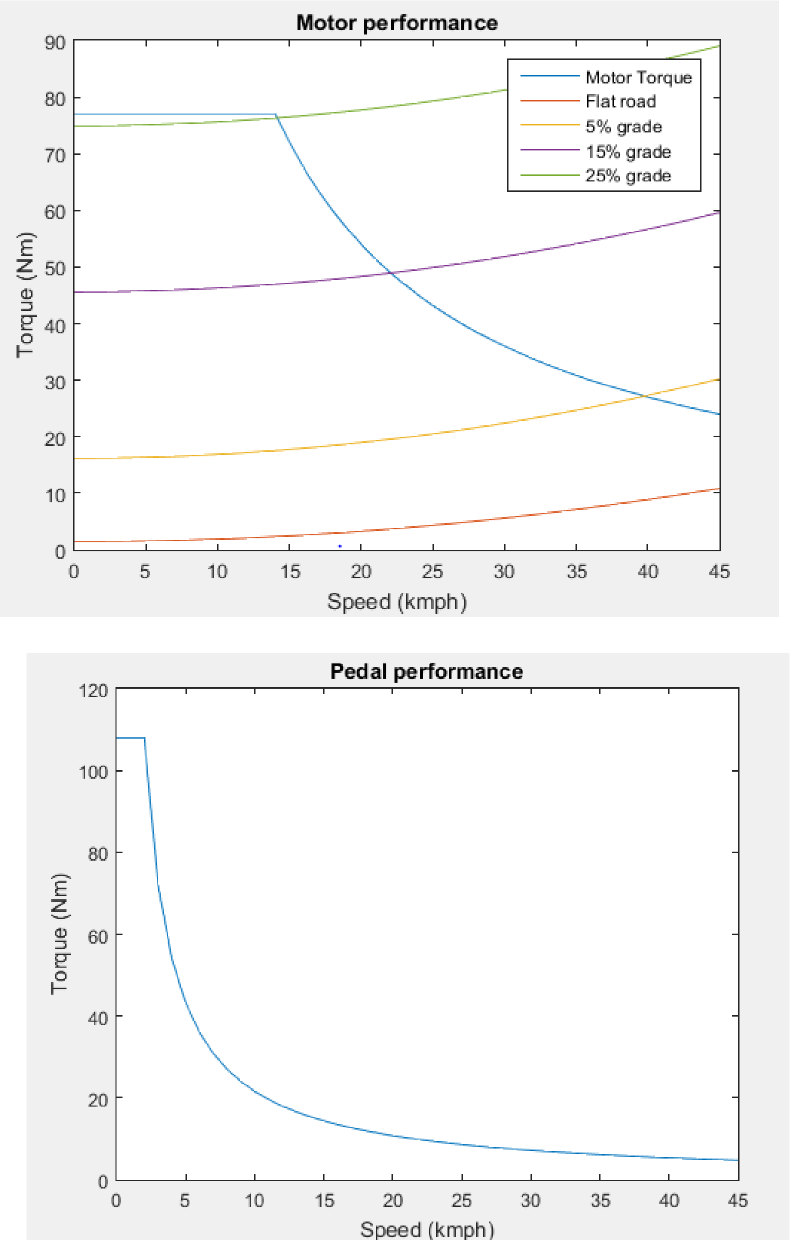

Figure 5.11: Torque speed curves of the 1kW motor and the user’s pedaling

As an example, from the previous design of an electric bicycle with the requirements stated in Table 3.2, we found that a 1kW motor was required. The performance characteristics are shown in Figure 5.11. For the generator connected in series we would need an additional machine that is capable of handling the power generated from pedaling. This second machine would have to be rated for another (300-400) W. The additional machine would also require additional permanent magnet parts, whereas the transmotor which is a combination of these two devices requires permanent magnets only in the outer rotor.

However, in the case of the 3-member transmotor bicycle, the torque acting on the bicycle is a combination of the reaction torque used to oppose pedaling and the torque provided by the stator. If we assume that a human capable of providing 200W is pedaling, we get a torque speed curve for the pedaling as in Figure 5.12:

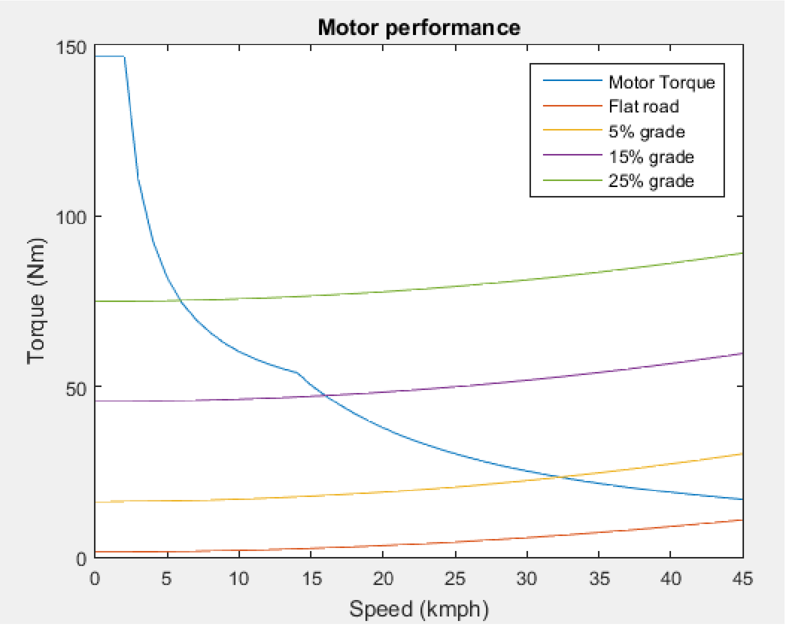

Figure 5.12: Performance charachterstics of the transmotor e-bike

The opposing torque for the pedals will be provided by the inner rotor windings and the reaction torque from this act on the outer rotor which has torque added on to it from the stator. With this added torque, an electric machine rated for 500W (half the previous) is able to meet the same performance requirements as before. This is summarized in the graph below.

The acceleration performance is also shown in Figure 5.13. We notice that the time taken to accelerate to 20kmph is more or less the same as before, however, this machine takes a longer time to accelerate to its maximum speed. This is expected because at higher speeds, the human is no longer able to provide a significant torque that can be added to the bicycle torque. The propulsion is largely taken care of by the electric machine which is not rated as high as before. However, the ability to use a machine that is rated at half the previous value to achieve a similar level of performance more than makes up for this shortcoming.

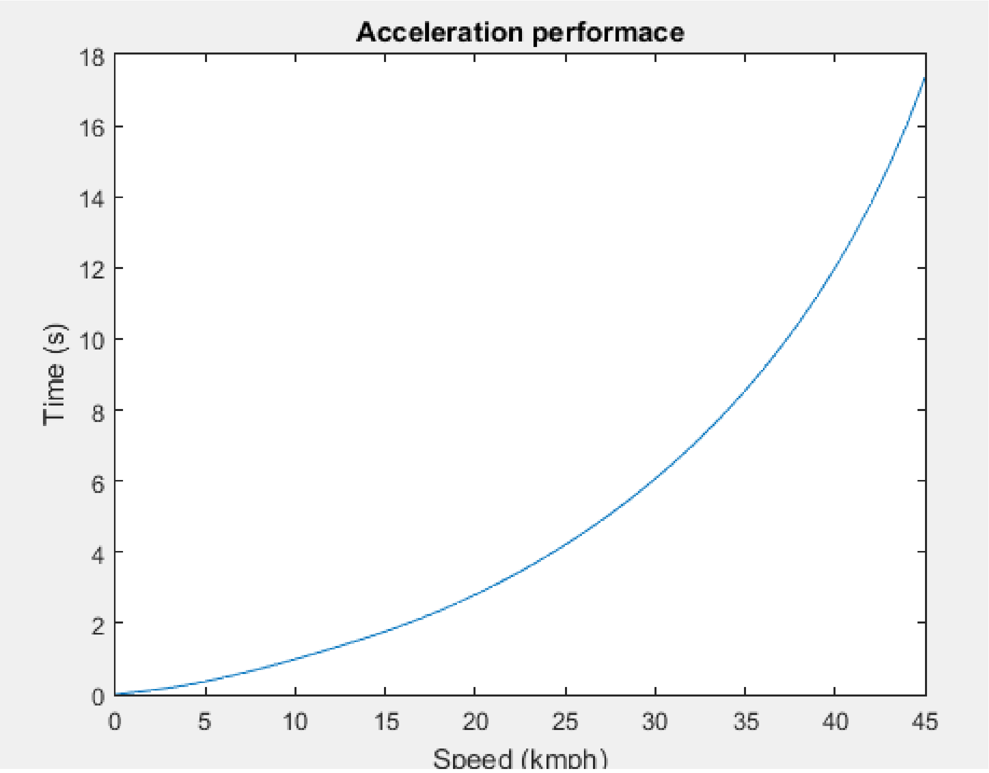

Figure 5.13: Acceleration performance of the transmotor e-bike

### 5.10.2 Comparison with respect to Power Electronics Required

To further understand the advantages of the 3-member transmotor model, a simulation has been set up to compare the output phase currents for a particular torque and speed demand (Figure 5.14) for the SMG model and the 3-member transmotor model.

The case considered is described as follows. The speed of the inner rotor from pedaling decreases from 100rad/s to 0 rad/s. The speed of the outer rotor connected to the bicycle side increases from 40rad/s to 60rad/s. The torque at the outer rotor for bicycle propulsion is increased from 80Nm to 180Nm, and the torque demand on the inner rotor for pedaling is 80Nm.

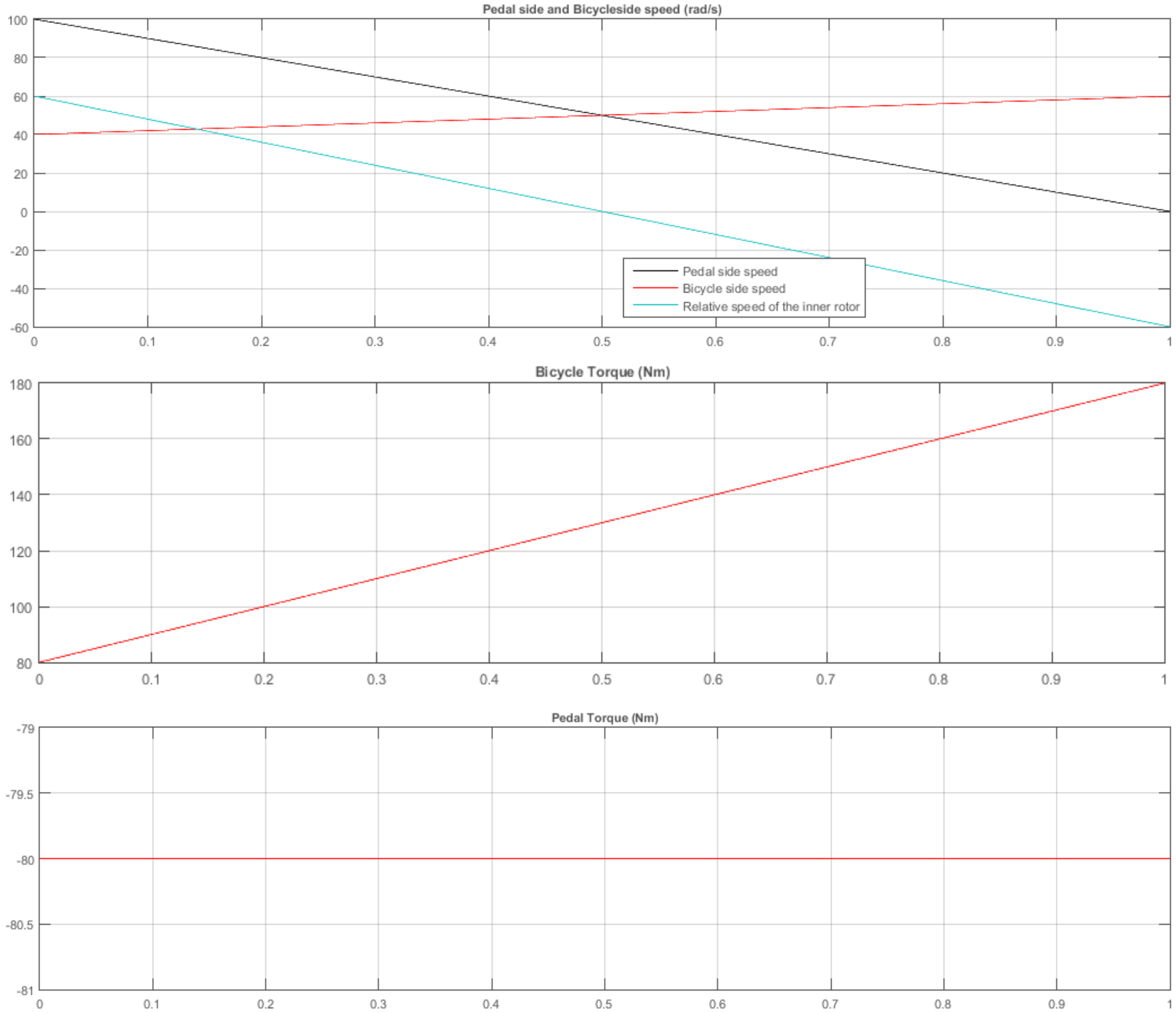

Figure 5.14: Torque and speed demands for the drive cycle

The torque demanded from the stator will be the difference between the inner and outer rotor torques (Figure 5.15), and the electrical frequency of the inner rotor will be the slip between the inner and outer rotor speeds.

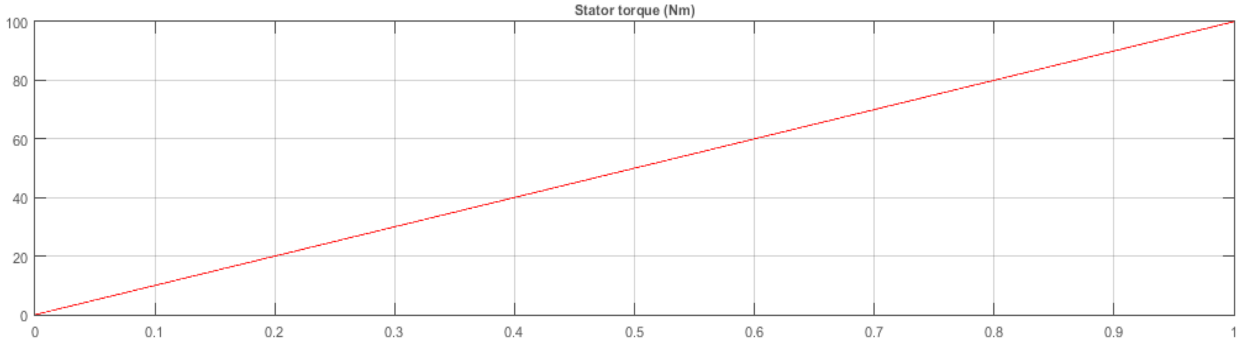

Figure 5.15: Torque demand from the transmotor stator

On simulating these demands for both, the transmotor model and the SMG model, the following results are obtained for phase currents on the pedal side and bicycle wheel side (Figures 5.15-5.17). Since the torque demand is the same on the pedal side for both the inner rotor on the transmotor model and the generator on the SMG machine, the amplitude of the phase currents is the same for both the models. However, we can see that the frequency of the currents is much higher in the SMG machine. This is because the transmotor is only handling the slip speed and has an electrical frequency that is equal the speed of the inner rotor relative to the outer rotor. The power handled by both the e-bikes are given in Figures 5.18-5.19. As expected, the slip power that is being handled by the inner rotor is much less than the power being handled by the generator in the SMG model, in this example by a factor of more than 40%.

On the bicycle side, the torque demand from the transmotor stator, is much less than the motor in the SMG model as the transmotor stator only needs to provide the difference in torque to the outer rotor. The phase currents on the SMG model motor have an amplitude almost double that of the transmotor stator. The slip power handled by the transmotor is almost 60% less than that of the SMG model.

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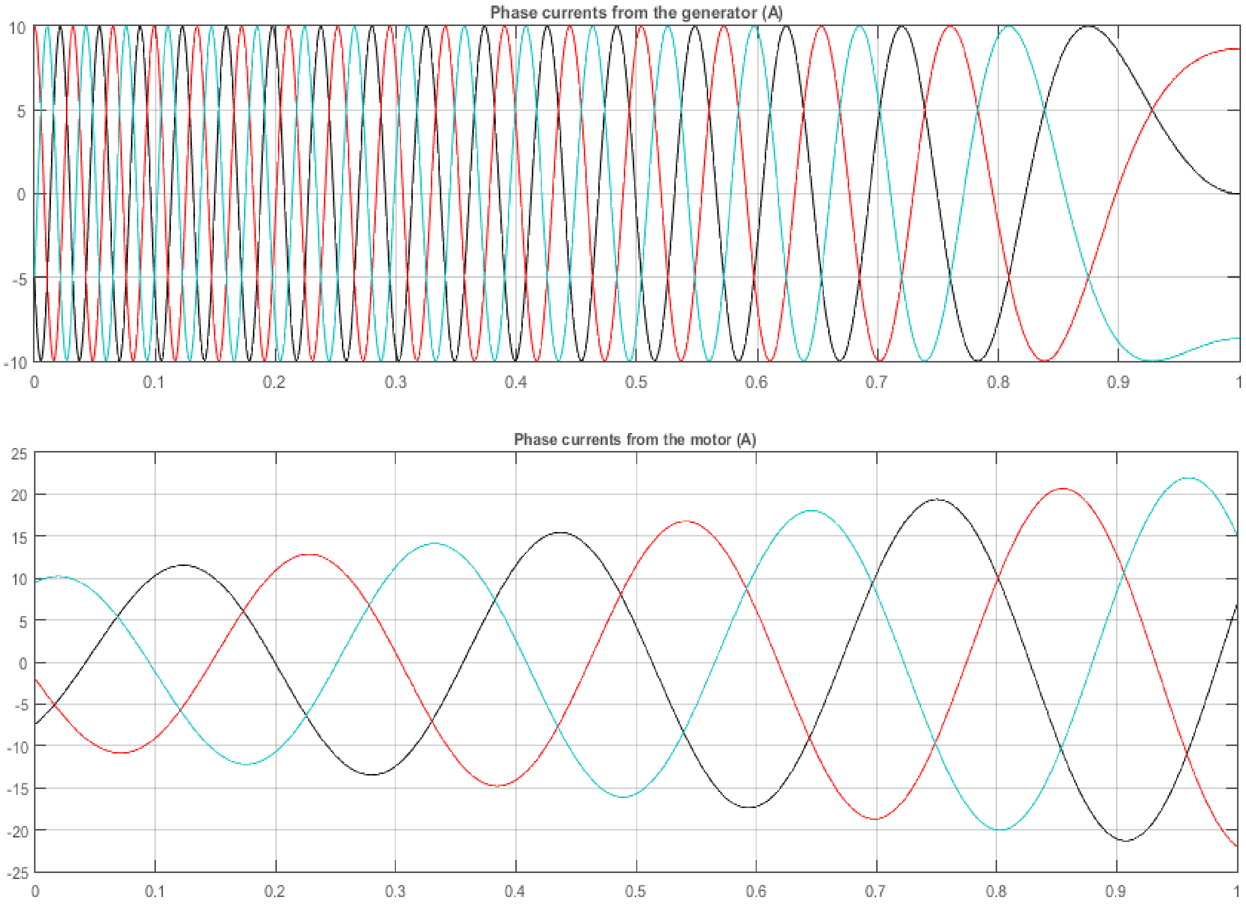

Figure 5.16: Phase currents of the SMG E-bike

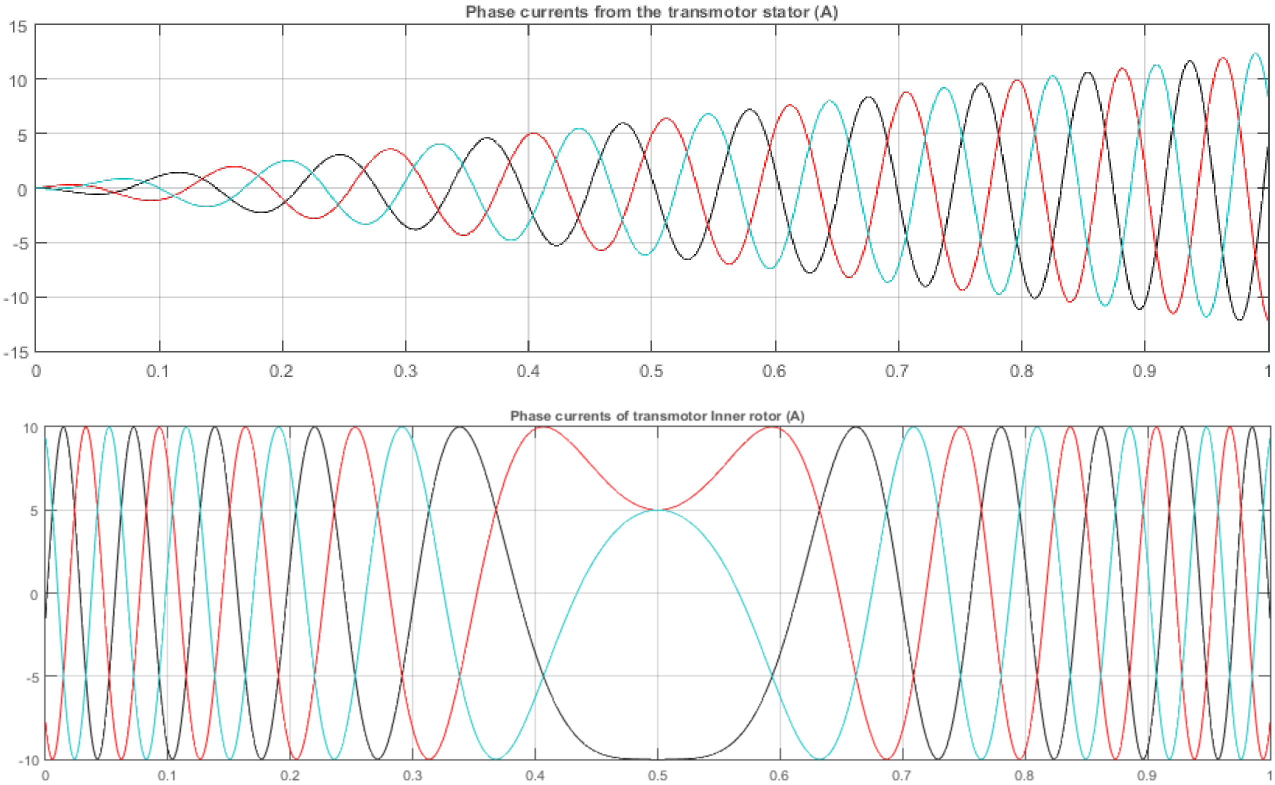

Figure 5.18: Phase currents of the Transmotor E-bike

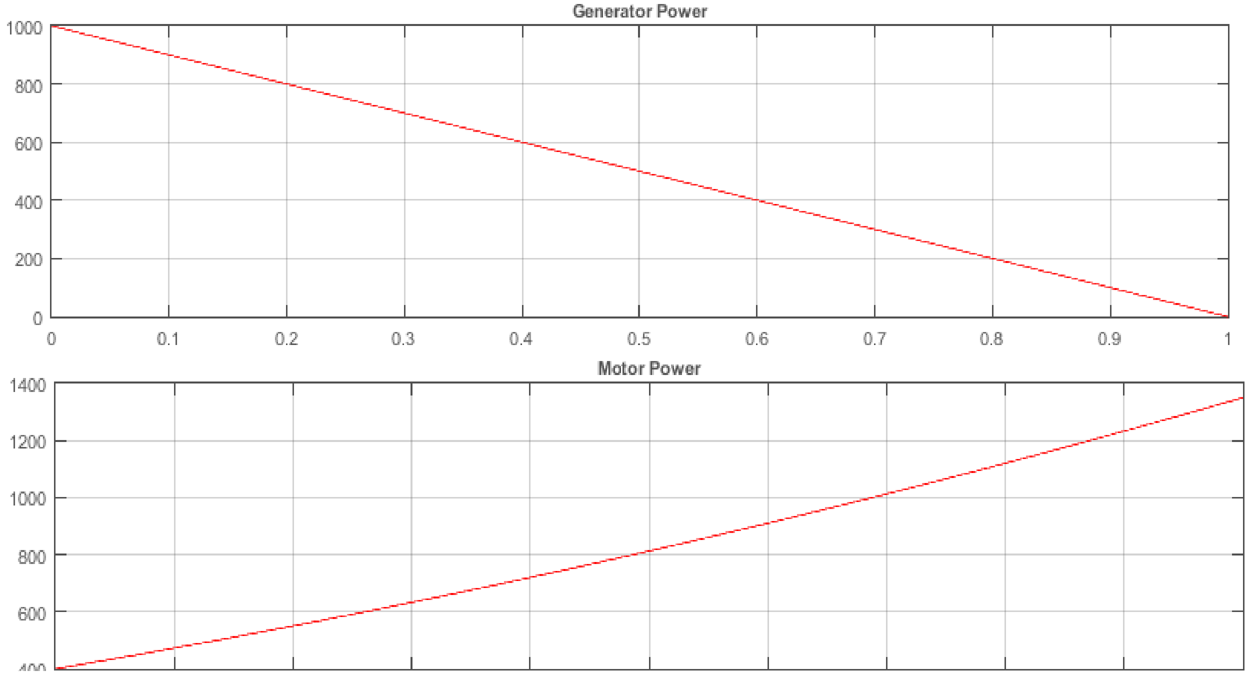

Figure 5.17: Slip power of the SMG E-bike

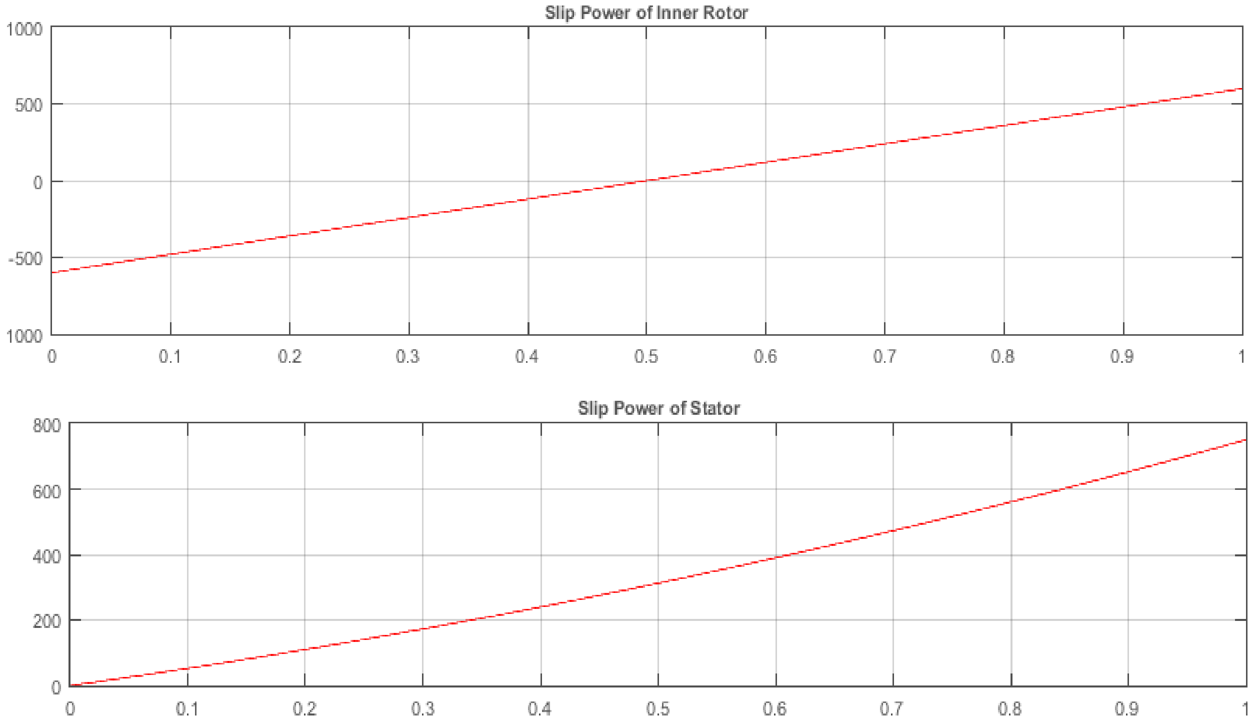

Figure 5.19: Slip Power of the Transmotor E-bike

The higher power and current values of the SMG model will have a detrimental effect on the power electronics in place. Even with similarly rated parts, the transmotor model will be able to achieve a much better lifetime of the power electronics because of the reduced power and stress being handled. The currents will rarely be at rated values that would stress the components, as opposed to the motor in the SMG model, where the components will be stressed each time a high torque demand is made on the bicycle wheels. With careful design, taking in to account a hybrid mode of operation, we can even have the power electronics rated for much lesser values. This might affect performance with the pedal only, and motor only modes. But in the general case where the user is pedaling along with the bicycle motion, the same performance of the SMG model, or even the motor in standard Pedelec models, can be achieved using power electronics and electric machines with lower ratings than their counterparts.

### 5.10.3 Advantages of having Independent Control of Pedal Torque/Speed

The transmotor e-bike realizes the proposed e-bike model where the user is able to pedal at the speed and torque of his choice, whilst having complete control of bicycle propulsion. In addition to an almost unlimited range of driving options, it also lets the user pedal at his/her own sweet spot, allowing the maximum possible power that can be generated whilst pedaling comfortably. To highlight this case, a simulation has been set up through a custom drive cycle. The following assumptions are made for this simulation.

- The user does not exert himself any more in the traditional e-bike, than in the transmotor e-bike.
- The torque provided by the user across the drive cycle is the same in case of both the e-bikes.
- The speed at which the user can drive the most comfortably is at 60rpm. He does not wish to pedal at a rate higher than that.

The parameters for the drive cycle have been summarized in the graphs (Figures 5.20-5.22) below in terms of the speed, torque and power requirements.

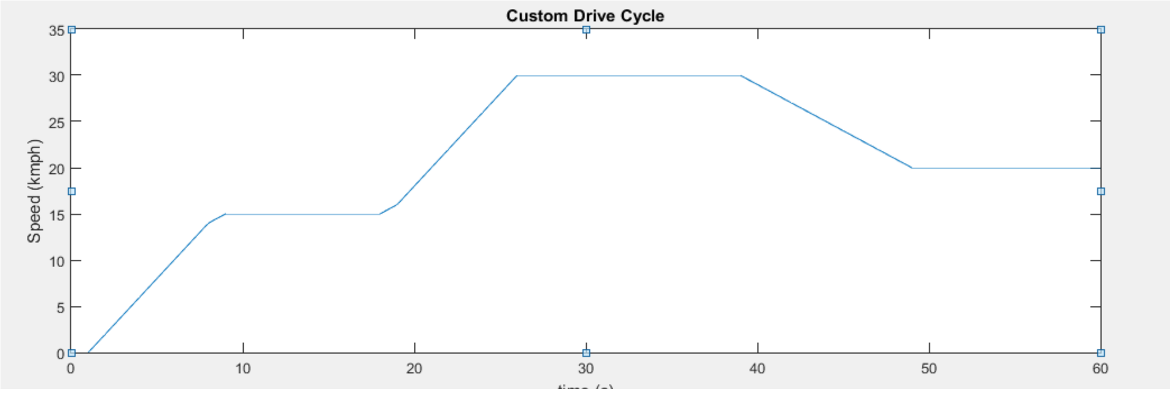

Figure 5.20: Custom drive cycle for the e-bike

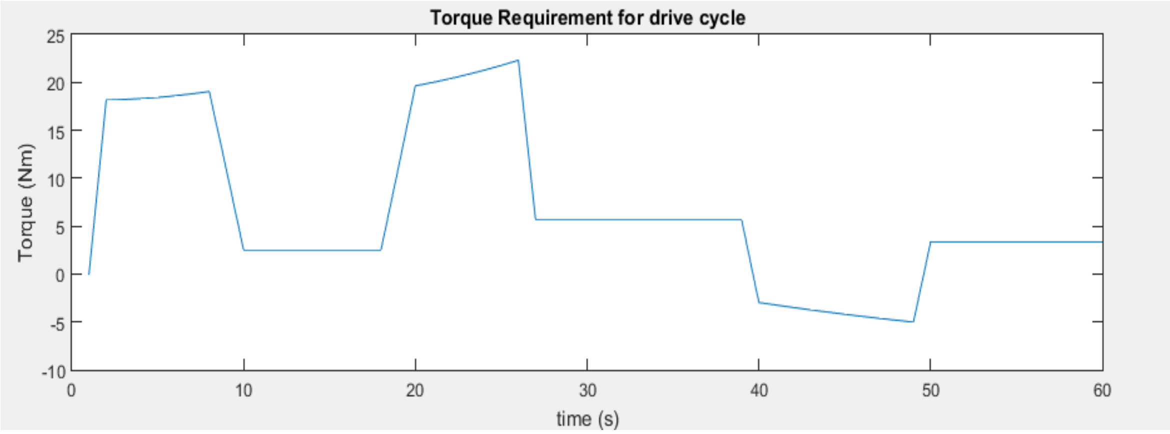

Figure 5.21: Torque required for the custom drive cycle

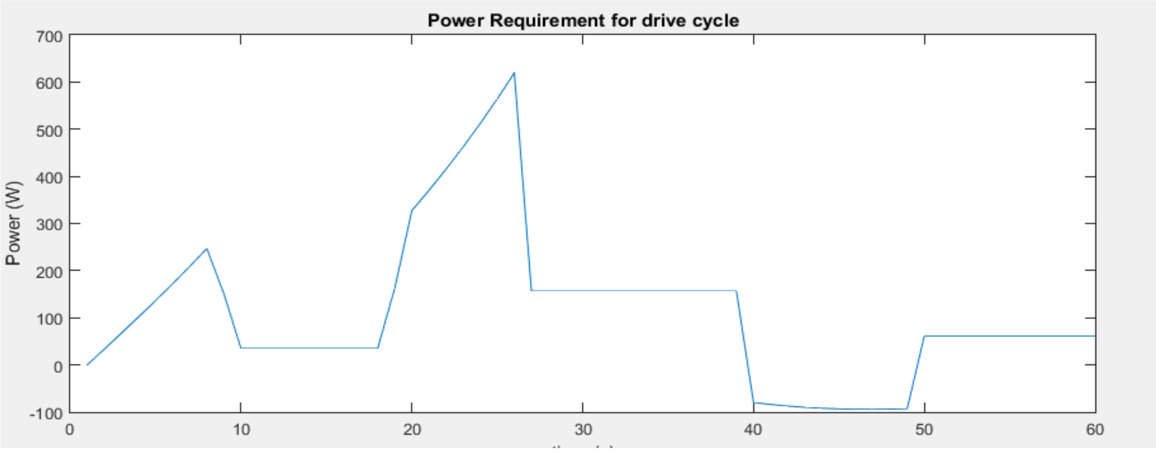

Figure 5.22: Total power required for the custom drive cycle

The torque provided by the user on the pedals and the speed with which he/she is pedaling at the most comfortable rate are shown in the following graphs (Figures 5.23-5.25). The power delivered has also been negative. Power is negative, because the user is delivering power to the pedals.

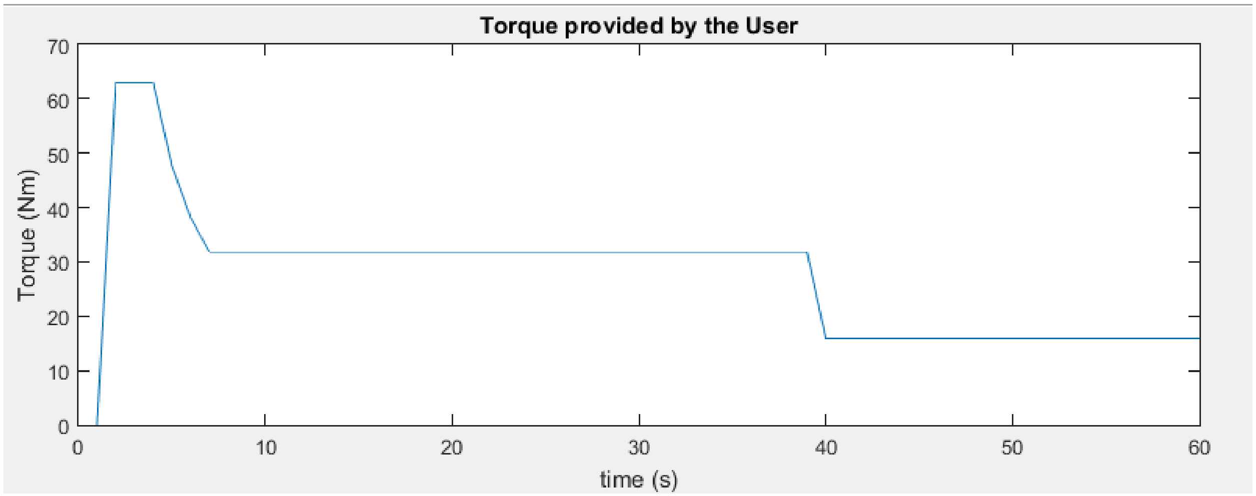

Figure 5.23: Torque provided on the pedals by the user

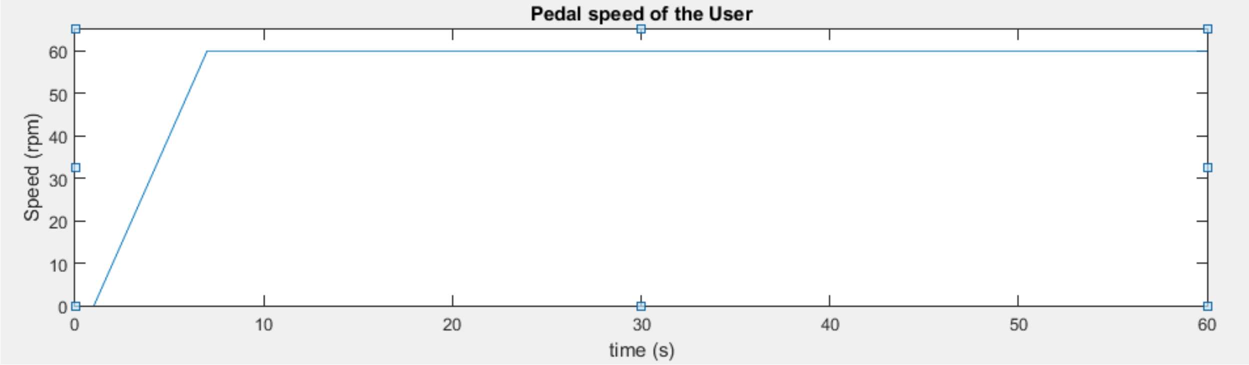

Figure 5.24: Speed of the users pedaling

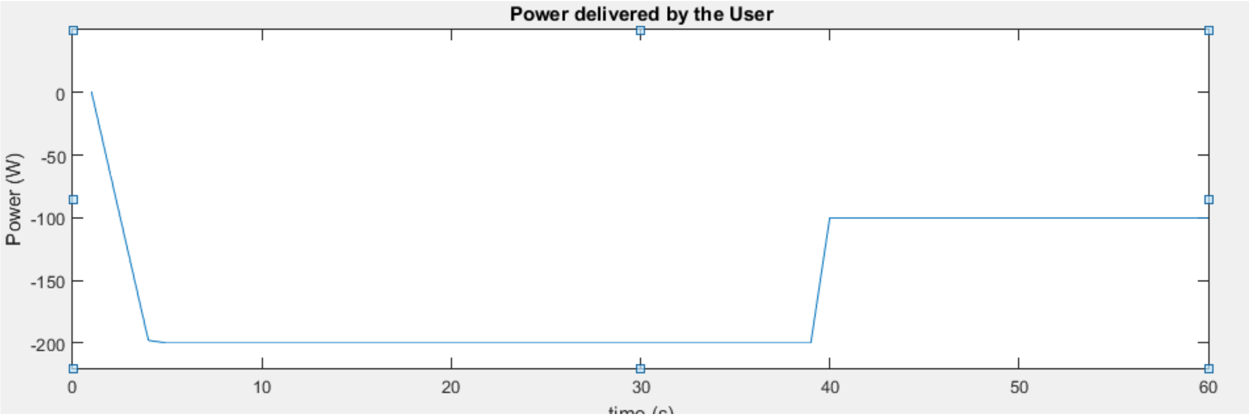

Figure 5.25: Total power delivered by the user over the drive cycle

Table 5.1 shows the design choices made for simulation:

Table 5.1: Design choices for simulation

| | |
|---|---|
| Gear ratio | 3 |
| Bicycle wheel radius | 0.3 m |
| Total mass of rider + bike | 100 kg |
| SOC of battery | 100 Wh |
| Max pedal speed of user | 60 rpm |
| | |

On simulating through the drive cycle, the following graph in Figure 5.26 was obtained for the power being handled by the inner rotor and the stator. We can see that the power being handled is individually less than the power requirement at the bicycle wheel end and pedal end for the stator and inner rotor respectively. Because of being able to handle all the power being generated by the user and with help from regenerative braking, we can see that the Battery SOC has an upward trend, and gets charged as seen in Figure 5.27.

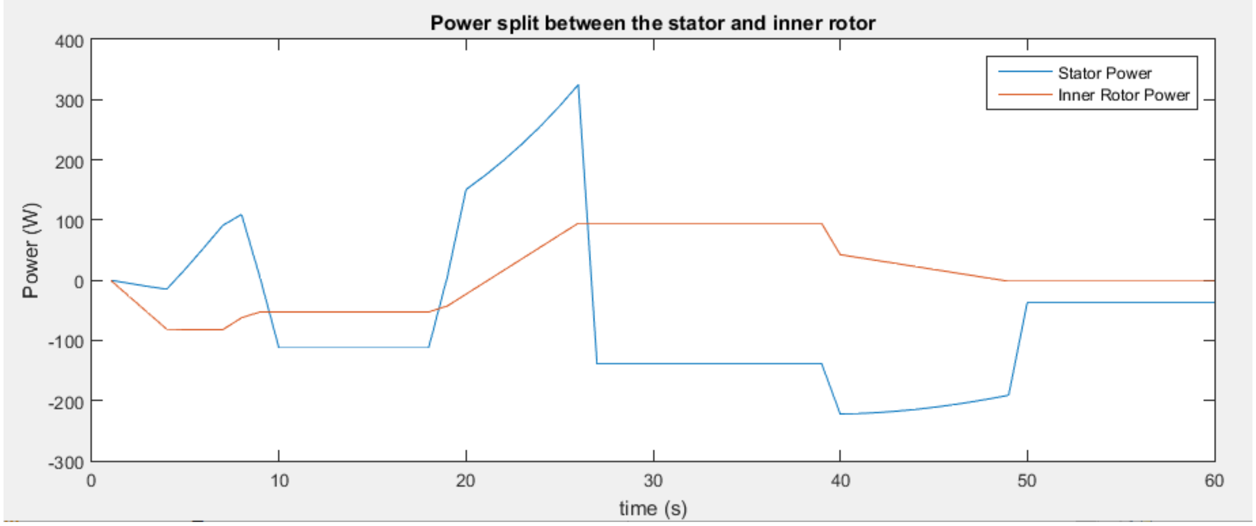

Figure 5.26: Power delivered by the Transmotor over the drive cycle

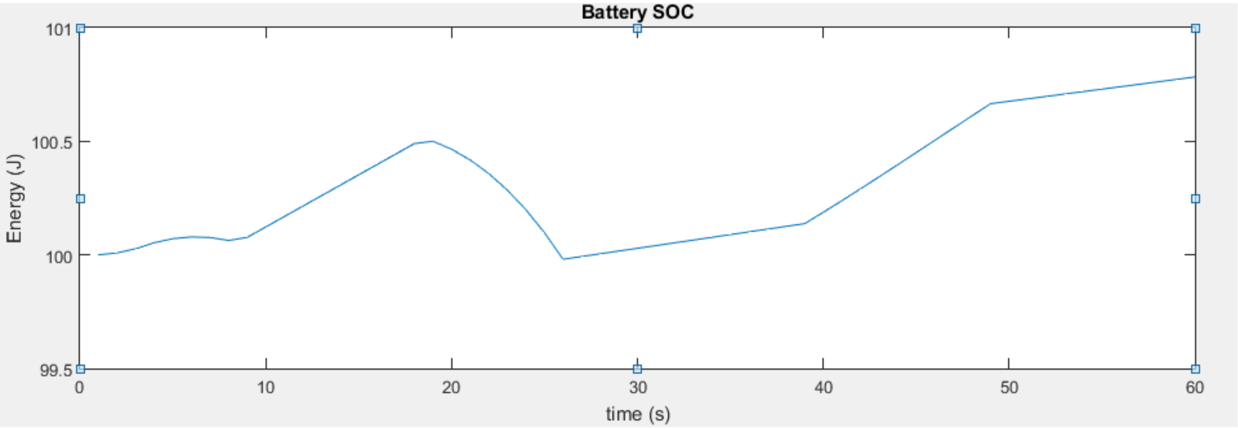

Figure 5.27: State of Charge of Battery over the drive cycle

Without independent torque/speed control of the pedals, in a parallel configuration, the speed of pedaling is greatly restricted by the drive cycle. Here, the speed of pedaling has to be scaled down to match the drive cycle rate (after gearing), with the maximum speed of the drive cycle corresponding to the maximum pedal speed at which he can pedal comfortable (60 rpm in this study), shown in Figure 5.28. Because of this, power delivered by the user is much less than in the transmotor model (Figure 5.29). The user is unable to stay in his “sweet spot” of operation throughout, and so the power delivered by him is not maximized.

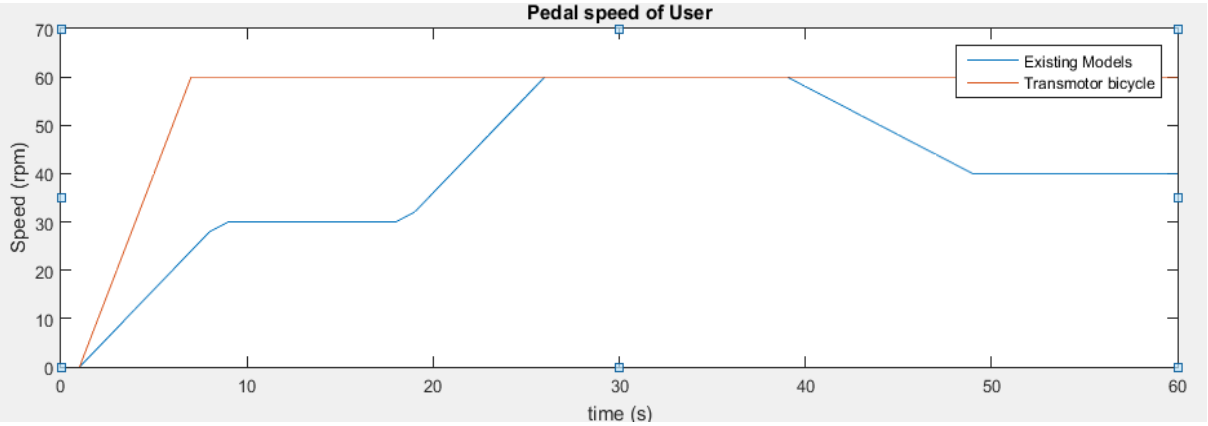

Figure 5.28: Pedal speed of the user in a pedelec e-bike

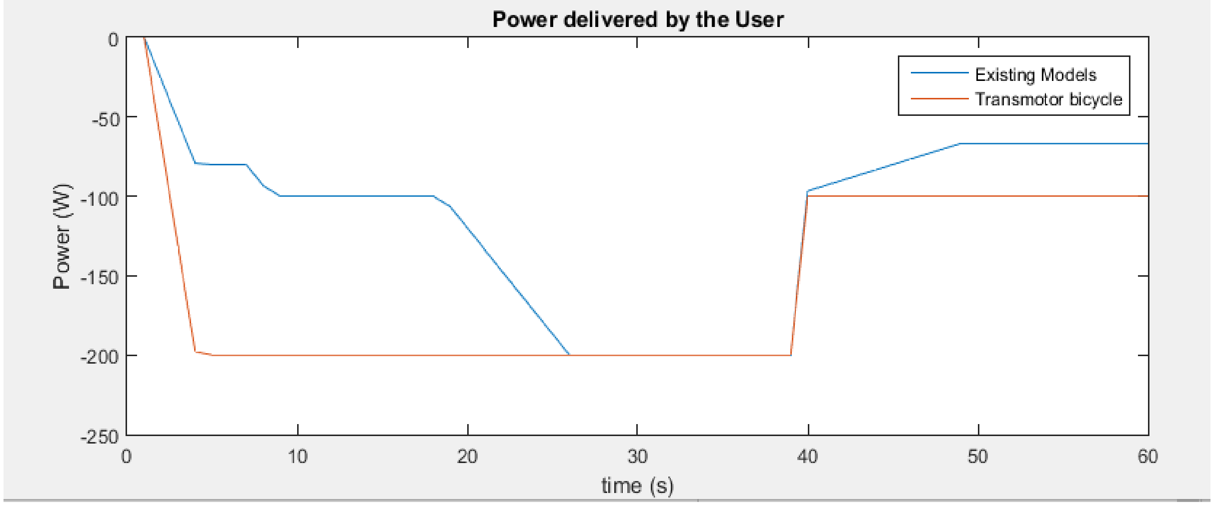

Figure 5.29: Power delivered by the user in a Pedelec e-bike

Because the user is not able to provide his maximum power at comfortable levels at all times, the motor has to supply more power to be added to the pedal power in order to meet the custom drive cycle requirements, as shown in Figure 5.30. The battery SOC, shown in Figure 5.31, is less than in the transmotor model mainly because, in the case of the transmotor bike, the entire power from pedaling is taken advantage of, either directly for bicycle propulsion, or stored in the battery. In the standard e-bikes, there is no concept of the user being able to provide excess power, and as such, the only charging action that takes place is due to regenerative action.

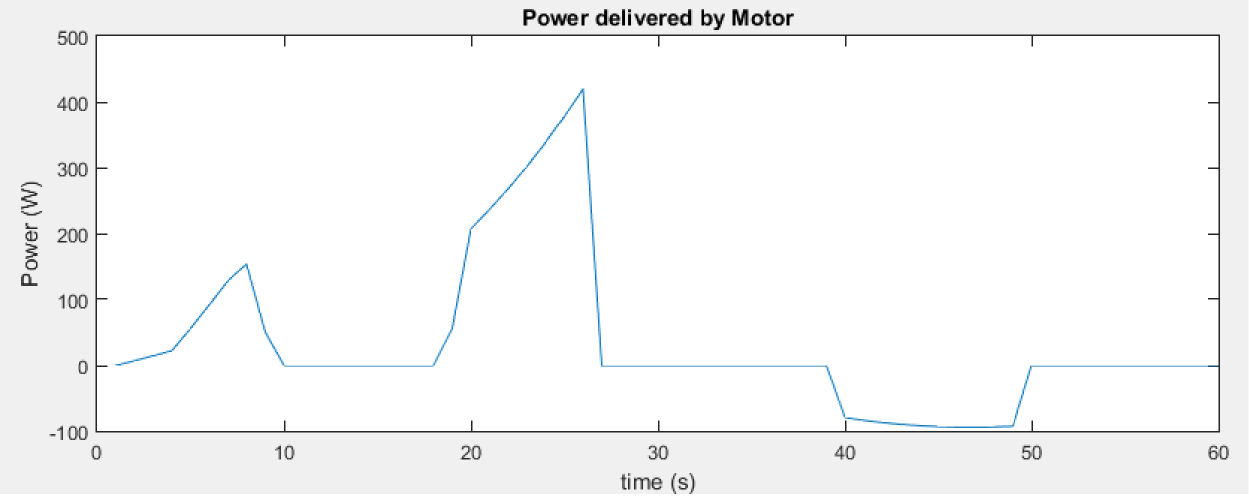

Figure 5.30: Power delivered by the motor in a pedelec e-bike

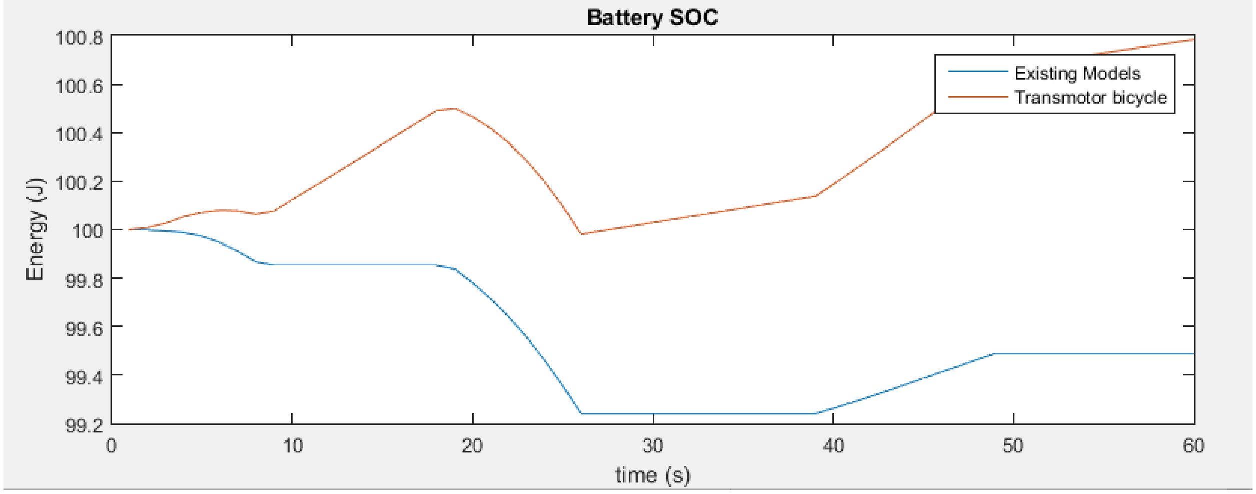

Figure 5.31: State of charge of the battery over the drive cycle for Pedelec e-bikes

# 6. CONCLUSIONS

## 6.1 Drawbacks of the Transmotor E-bike

The 3-member transmotor is a relatively complex machine that has two moving parts and multiple magnetic interactions to account for. This can make design a tedious process with multiple factors playing a role in any given operation. Because the transmotor, as discussed in this thesis, is an electric machine with a permanent magnet and two electrical windings, we have to deal with mutual inductances between all these different components. Particularly, the added element of mutual inductance between the inner rotor and the stator, gives an added level of complication. Although, by itself, it is a smaller and more compact option to the model consisting of a motor and a generator, the design process to incorporate the control and manage operations such as field weakening becomes a much more complicated task.

It was also found that for maximum efficiency, the inner and outer rotor speed and torque need to be as close to each other as possible. In this case, the slip power is minimized, and the power handled electrically becomes a very small value. However, with the speed and torque at either ends operating in opposite ends of the spectrum, the slip power being handled becomes a value close to that of normal independent machines, albeit, slightly smaller. Nevertheless, in these conditions of wide disparity, the advantage the transmotor offers of handling less power electrically becomes negligible. It is also interesting to note that there are actually some cases where the transmotor inner rotor needs to handle more power than the generator in the SMG model. This is particularly apparent in the case where the speed of the bicycle is much much higher than the speed with the user is pedaling. These situations need to be avoided while choosing the gear ratios.

It was also shown that pedaling backwards, was an altogether undesired state because the power being generated/drawn would be greater than the rated values if the speed/torque differences were high enough. Either the power electronics have to make provisions for these conditions, so as to prevent damages to the elements and restrict the power flow, or the clutch and lock mechanisms should prevent backwards pedaling altogether. In the SMG model, there was no restriction on pedaling backwards or forwards, and it had no effect on the user driving whatsoever. Pedaling backwards in the transmotor bicycle while braking, does offer some advantages such as adding an additional decelerating force in addition to the mechanical brakes. However, pedaling backwards while accelerating provides no advantage whatsoever and in fact, drains the battery faster. This is one condition that is best left out of the e-bike operating modes.

## 6.2 Conclusions

This study focused on developing a better model of the electric bicycle that would give the user a great deal of flexibility in control. Existing electric bicycle topologies were studied and their advantages were discussed. A better alternative to existing models was proposed in the form a bicycle where the user is able to pedal at the speed and torque of his choice whilst maintaining complete and independent control of the bicycle propulsion. A possible architecture for this model was looked at where a motor and generator were connected in series. An alternative and more integrated solution to this model was discussed in the form of the 3-member transmotor.

The transmotor was studied in detail and its various operating modes were analyzed to give a clear picture of how it would operate in tandem with a bicycle. In this process, the equations that described the power balance for the 3-member transmotor was derived in the form of 4 simple speed-torque equations. This was then applied to electric bicycle to achieve a model where the user is able to pedal at the speed and torque of his choice whilst having complete control of bicycle propulsion. It was also shown that the transmotor could transfer virtually any amount of mechanical power, as long as the slip power being handled was within electrical ratings. This opened up a variety of design flexibilities, particularly in the hybrid mode of operation. It also gives the opportunity to reduce the ratings of the power electronics, or to extend their lifetimes, because the power and currents being handled are much less than their counterparts. The e-bike was conceptualized and the user experience was described during different operating modes. The power electronics required was also discussed, where a back to back DC/AC converter that shared the same DC link could be used to control the stator and inner rotor of the transmotor. This also showed the current sharing advantages that was possible, because the power being generated could directly supply the power needed for propulsion without first having to be converted to battery energy.

Simulations were set up to determine the difference in power ratings possible with the transmotor acting as a mechanical coupling device. It was found that for hybrid operation, the transmotor could be rated for up to 50% less than an equivalent traction motor. The phase currents required to control the transmotor at a custom torque and speed demand was also looked and found to be less than that of the equivalent motor generator combo in hybrid operation. This was expected, as the transmotor would only be handling the difference in speeds or the difference in torques between the inner and outer rotors. As a consequence, the power being handled would also be a much lesser value. For the set of torque speed values that was set up, in order to show a typical hybrid operation, it was found that the power being handled was around 40-60% less than their equivalent counterparts. The advantages of having independent control of speed and torque at the pedals was also studied, and it was found that letting the user operate at his “sweet spot" of operation let him generate more power than he would have been able to, had he been constrained by the drive cycle. As a result, the simulations showed a better battery SOC at the end of the drive cycle with the transmotor model as compared to the existing models.

The transmotor bicycle, is in no way, the perfect bicycle. Several of its drawback were discussed, particularly the complications in design with having two moving parts and three interacting inductances. The advantages that it offers in hybrid mode is not replicated when operating with wide disparities in torque/speed at either end.

Nevertheless, it is a promising step forward in terms of bringing a better and more efficient model of electric vehicles to the market, and one where the user has a great deal more of control flexibility than he does with existing models today. And when operating in hybrid mode, i.e., the user pedals along with the bicycle operation, the transmotor bicycle proves to be an efficient solution as it minimizes the power being handled electrically.

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