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Design and Analysis of PID Controller for a BLDC Motor in a Battery-Operated Electric Vehicle

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Abstract: We have concluded that the controller utilises cutting-edge technology to regulate power distribution, battery charging, and motor control, thereby enhancing the project's sustainability and performance. The controller provides the vehicle with the necessary information to move and supplies the parts with the required power. We have examined the existing controller in the car and an alternate controller to determine which one would be more effective in enhancing the car's performance. They had several traits that were better than the controller. We compared the two controllers, and the car worked better with the proposed controller. MATLAB simulations have been used to figure out the waveform.

Keywords: Electric Vehicles; Carbon Emissions; Global Warming; Fossil Fuels; Electric Motor; Lead Acid Battery; IC Engine; Electric Trains; Energy Saving; Sensor Measurements.

Introduction

Electric vehicles are becoming increasingly important as they reduce noise and pollution, and they can also be used to reduce the dependence of transport on oil, provided that the power is generated from fuels other than oil [32]. Electric vehicles can also be used to reduce carbon emissions. Production of zero carbon dioxide emissions requires that the energy for electric vehicles is produced from non-fossil-fuel sources, such as nuclear and alternative energy. The worst scenario is that we have only 40 years of oil supply at current usage rates. In practice, increasing scarcity will result in huge price rises, and eventually, oil and other fossil fuels will not be economically viable. Hence, oil will be conserved as usage will decrease [20]. Oil can also be produced from other fossil fuels, such as coal. Traditionally, oil produced in this way was considered around 10% more expensive, but with current oil prices, production from coal is starting to become economic [43].

Electric motors were developed following Michael Faraday’s work in 1821 [39]. British scientist William Sturgeon invented the first commutator-type direct current electric motor capable of turning machinery in 1832 [26]. The first known electric locomotive was built in 1837 by the chemist Robert Davidson and was powered by non-rechargeable batteries. Davidson later built a larger locomotive, which was exhibited at the Royal Scottish Society of Arts Exhibition in 1841. The first use of electrification on a main line was on a 4-mile (6.4km) stretch of the Baltimore Belt Line in the USA in 1895. The trolleybus dates back to 29 April 1882, when Dr Ernst Werner ran his bus in a Berlin suburb. In 1901, the world’s first passenger-carrying trolleybus operated at Bielathal, near Dresden, in Germany. In Britain, trolleybuses were first introduced in

Leeds and Bradford in 1911 [31]. Half a century was to elapse after the first electric vehicles before batteries had developed sufficiently to be used in commercial free-ranging electric vehicles. An early electric vehicle, a Baker Runabout, was made in the USA and imported into Germany by the founder of Varta Batteries. The first car to exceed the ‘mile a minute’ speed (60mph; 97kph) was the electric vehicle known as ‘La Jamais Contente’, which set a new land speed record of 106kph (65.9mph), making this the first car to exceed 100kph.

With the mass production of rechargeable batteries, electric vehicles became rather common by the end of the 1800s. There weren't many private cars, but they were likely to be electric, as were other vehicles like taxis. An electric cab from New York City around 1901, with Lilly Langtree, the actress and Edward VII's mistress, next to it. At the beginning of the 20th century, electric cars must have seemed like a great candidate for the future of road travel. If performance was important, electric cars were better than cars that ran on petrol or steam [33]. The electric car was pretty reliable and began right away, whereas cars with internal combustion engines were, at the time, unreliable, smelled bad, and had to be cranked by hand to start. The steam engine vehicle, the second key competitor, required lights and was inefficient in converting heat into power. By the 1920s, hundreds of thousands of electric vehicles had been made for usage as automobiles, vans, taxis, delivery vehicles, and buses. Although these early electric cars showed promise, the advent of inexpensive oil and the self-starter for the IC engine (developed in 1911) made the IC engine a superior power source for cars [42]. The principal use for rechargeable batteries has ironically been to start IC engines.

When you compare the specific energy of petroleum gasoline to that of batteries, it's easy to see why IC engine vehicles have been more successful so far. The specific energy of fuels for IC engines is about 9000Wh kg-1, while the specific energy of a lead-acid battery is about 30Wh kg-1. When you take into account the IC engine, gearbox, and transmission's (usually about 20%) efficiency, you may get 1800Wh kg-1 of usable energy (at the gearbox shaft) from fuel. A lead-acid battery can only give you 27Wh kg-1 of usable energy (at the motor shaft) because an electric motor is only 90% efficient [25]. To make the issue clearer, a normal car can travel 50 km on 4.5 litres (1 gallon) of petrol, which weighs approximately 4 kg.

In reality, this won't quadruple the range of the electric vehicle because it takes a lot more energy to accelerate and decelerate the 270 kg battery and carry it up hills. Regenerative braking is a method that can help you recover some of this energy. In this system, the engine functions as a generator, slowing down the car and turning its kinetic energy into electrical energy, which is then sent back to the battery storage so it can be utilised again. Taking into account the efficiency of generation, control, battery storage, and sending the electricity back through the motor and controller, it is anticipated that less than a third of the energy will be recovered [40]. Because of this, regenerative braking is often employed as a technique to save energy by stopping large vehicles, which is what electric cars usually are. To get the same amount of energy out of lead acid batteries as 45 litres (10 gallons) of petrol, you would need 2.7 tonnes of batteries. Another significant challenge with batteries is the time it takes to charge them. It takes at least a few hours to charge a lead-acid battery, even when there is enough electricity. In contrast, it just takes about a minute to pump 45 litres of petrol into a car. Some of the new batteries can be recharged in less than an hour, but this is still a lot longer than it takes to fill up a tank with petrol.

In reality, this won't quadruple the range of the electric vehicle because it takes a lot of extra energy to speed up and slow down the 270 kg battery and carry it up hills [37]. Regenerative braking is a method that can help you recover some of this energy. In this system, the engine functions as a generator, slowing down the car and turning its kinetic energy into electrical energy, which is then sent back to the battery storage so it can be utilised again. Taking into account the efficiency of generation, control, battery storage, and sending the electricity back through the motor and controller, it is anticipated that less than a third of the energy will be recovered. Because of this, regenerative braking is often utilised as a means to save energy while stopping big vehicles, which electric cars usually are [27]. It would take a mind-boggling 2.7 tonnes of batteries to get the same amount of energy as 45 litres (10 gallons) of petrol.

Another significant challenge with batteries is the time it takes to charge them [45]. It takes at least a few hours to charge a lead-acid battery, even when there is enough electricity. In contrast, it just takes about a minute to fill a car with 45 litres of petrol. Some of the new batteries can be recharged in less than an hour, but this is still a lot longer than it takes to fill a tank with gas. Another problem with electric cars is that batteries are expensive; thus, any battery-powered car is likely to have a restricted range of energy, 81,000 miles [21]. Why does it cost more than a car with an IC engine that is the same size and quality? For instance, at today's rates, 2.7 tonnes of lead-acid batteries, which can store as much energy as 45 litres (10 gallons) of petrol, would cost about £8000. The batteries have a short life, typically five years, which means you'll need to spend a lot of money every few years to replace them.

When you look at these things, it's easy to see why IC engine vehicles were so popular for most of the twentieth century [36]. The idea of the hybrid vehicle, which uses an IC engine to drive a generator along with one or more electric motors, came about during this time. Ferdinand Porsche made a hybrid car in 1900, which is seen below. In the 20th century, electric trains improved significantly by utilising both DC and AC systems [24]. Railway businesses prefer electric trains because they require less maintenance, both for the locomotive and the track. Due to the abundance of cheap oil and the production of many IC engine vehicles, trams and trolleybuses became less cost-effective and were largely discontinued. Electric road vehicles were never as popular as electric trains, which could get power from supply rails or overhead wires and didn't need batteries. People have been using electric cars since the early 1900s, but they weren't as good as gas-powered cars.

Electric cars have some advantages over cars with internal combustion engines [44]. For example, they don't pollute the air around them and are naturally quiet. Because they don't generate noise or pollute, electric cars are great for places like warehouses, inside buildings, and golf courses. Mobility devices for the elderly and disabled are one prominent use for battery/electric drives. In Europe and the US, this sort of vehicle is one of the most frequent. You can drive it on sidewalks, inside stores, and into many buildings. A range of 4 miles (6.4 km) is usually enough, but larger ranges are feasible [30]. Electric vehicles also stay efficient when you stop and start them, while an internal combustion engine becomes less efficient and more polluting. This made electric cars good for delivery trucks, like the iconic British milk float. In some countries, this has been helped by the fact that people can leave their cars running while they go to the door of a house, for example. Electric trains, which became popular in the middle of the twentieth century, have continued to improve since then. The introduction of the Shinkansen, or bullet train, in Japan marked the first step in making high-speed trains more significant. This picture shows a modern Shinkansen. The Tokaido Shinkansen started running in 1964. It took 4 hours to go from Tokyo to Osaka, a distance of 515.4 kilometres. Japan's modern high-speed trains may go as fast as 300 kilometres per hour. The system runs up to 13 trains per hour, each with 1323 seats, and carries 151 million people every year.

Other countries, including France and China, have successfully deployed high-speed trains. The French have the fastest conventional train right now. A French TGV (Train à Grande Vitesse) went as fast as 574.8 kph. The experimental Japanese JR-Maglev set the world record for a non-conventional crewed train by going 581 kph (361 mph) on a magnetic levitation track [22]. Maglev trains don't have wheels; they run on this specific track. The train is held up by magnets and pushed forward by linear electric motors. Theoretically, the trains can go incredibly fast—for example, a JR-Maglev train on its test track in Yamanashi, Japan [35]. The route regularly slows down trains; thus, it would be best to install a new track with soft curves and no waits at level crossings. High-speed electric trains represent a significant advancement, as they are now achieving speeds that make them competitive with planes for overland travel between cities, particularly on new routes. At first, this was true for shorter routes, but speeds continued to increase. When going from the city centre to the city centre, trains have extra benefits. On the other hand, planes have to land at airports that are often far away from the city centre. Loading and unloading trains is faster than loading and unloading planes. Most crucially, high-speed trains consume a lot less energy than planes [41]. Electric trains don't use fossil fuels and don't release carbon emissions. This is because nuclear power generates most of the electricity in France.

In some cities, modern trams are back in style—a tram from the Manchester light rail and tram system. The lithium battery is perhaps the biggest change in electric vehicles in the last several years. It has a respectable specific energy and charge time compared to older batteries. In the end, this has led to some commercial cars, including the Tesla sports car seen recently. Companies like Nissan, Mitsubishi, and Renault have been making a lot of commercial electric vehicles, including the Nissan Leaf and the Mitsubishi MiEV shown below. Hybrids are also making a comeback, starting with those that can't be charged from the mains. The Toyota Prius is an example of a Nonchargeable hybrid that is efficient but still relies totally on oil [28]. Because of this, they can't use mains electricity, which can come from many different places. The Volt, a rechargeable hybrid that is shown in this document, was just produced by General Motors. It can use energy to power many of its trips, and for longer trips, it uses the IC engine as a range extender.

People believed fuel cell vehicles had great potential; consequently, considerable effort was invested in developing prototype fuel cell automobiles. Fuel cells usually run on hydrogen, which the car has to keep on hand. Fuel cell cars can travel farther than battery-powered cars due to their greater range [29]. Honda recently came out with the FCX Clarity, which runs on hydrogen and is shown above. Customers in the US can rent it right now, but it isn't for sale to the public yet. Electric bicycles show a fuel cell bus, which is becoming more and more popular around the world [38]. For instance, in the 1990s, China saw the biggest increase in two-wheeled electric vehicles and bicycle sales in the world. The Citaro fuel-cell-powered bus is one of a fleet that went into service in 2003 (photo used with permission from Ballard Power Systems). In 2008, there were almost 21 million scooters, up from 56,000 in 1998. In 2008, there were only 9.4 million cars.

Saving energy and lowering carbon emissions: Electric vehicles can significantly reduce energy consumption when they replace less efficient modes of transportation [34]. For example, switching from flying to electric trains, which use far less energy per passenger mile, is a smart idea. Another example would be encouraging car drivers to use electric trams instead. If the electricity comes from an efficient grid system with modern power plants, replacing IC automobiles with electric vehicles saves energy [23]. When some of the electricity comes from nuclear or other energy sources that don't produce carbon, it will also reduce carbon emissions further. Nuclear power makes up about 20% of Britain's electricity, and other sources of energy, such as wind and hydro, make up another 10%. France makes 90% of its electricity without releasing carbon.

Literature Review

In 2011, Jong-Hwan Kim and two other people came up with an abstract architecture for an interval type 2 fuzzy logic controller flocking algorithm [19]. This research introduces an innovative interval type-2 fuzzy logic control architecture for a flocking system characterised by noisy sensor measurements [3]. The conventional type-1 fuzzy logic controller (FLC) employing exact type-1 fuzzy sets is incapable of completely modelling and managing the uncertainties inherent in sensor input [14]. Nevertheless, type-2 FLC utilising type-2 fuzzy sets with a footprint of uncertainty (FOU) demonstrates superior performance in noisy situations. In this research, we introduce a reactive control architecture for the flocking algorithm utilising interval type 2 fuzzy logic control (FLC) to facilitate flocking behaviours, including separation, obstacle avoidance, and velocity matching [11]. The type-2-based control system could handle the noise in sensor readings, which led to better performance than the type-1 FLC.

Gunawan Dewantoro wrote about a permanent magnet synchronous motor that uses a fuzzy logic controller in 2011 [6]. The abstract states that the Permanent Magnet (PM) Synchronous Motor is ideal for low-power, high-performance servos due to its controllable nature and superior performance. But the changes in moment inertia, load torque, and motor internal characteristics have made it very hard to manage the speed [13]. This research examines the speed management of a vector-controlled PM synchronous motor drive utilising a fuzzy logic controller. The fuzzy logic is based on the difference in speed and the change in speed between the actual motor and the reference speed [18]. The fuzzy logic controller's strong control performance is tested in different operating settings utilising the specs of a prototype PM synchronous motor and compared to that of a regular PI controller [10]. The design and implementation of the fuzzy logic controller are examined and analysed.

Mohammed Karimi's 2015 paper on controlling an inverted pendulum online using a type 2 fuzzy logic controller. The study introduces a novel type-2 fuzzy logic controller capable of online control for a nonlinear system, specifically an inverted pendulum [7]. Type-2 fuzzy logic controllers enable us to utilise diverse opinions in developing control systems. This will lessen the impact of uncertainty in fuzzy logic systems that use rules [12]. These controllers are more flexible than typical type-1 fuzzy logic controllers when it comes to using human thought in control system design [1]. However, we have trouble using type-2 fuzzy logic controllers online because they require a lot of calculations. This study proposes a novel type-2 fuzzy controller for online control applications [16].

Roshan Bharti and two others designed an Optimise PID type Fuzzy Logic Controller for Higher Order Systems in 2018 [8]. The abstract of this study proposes a novel structure for a PID-type fuzzy logic controller, whereby a Fuzzy PI controller is integrated in parallel with a traditional PD controller. The Gradient Descent optimisation method is used to figure out the gains of the suggested controller [4]. To test how well the planned structure works, examples are used. The suggested controller outperforms both the regular PID controller and the current fuzzy PID controllers in terms of performance metrics across various plants [17].

Control of a BLDC motor using an adaptive fuzzy logic PID controller Published in 2014 by Hari Krishnan and M Arjun at the International Conference on Green Computing Communication and Electrical Engineering (ICGCCEE), the abstract describes an Adaptive Fuzzy Logic PID Controller for speed control of Brushless Direct Current Motor drives, which are extensively utilised in various industrial systems, including servo motor drives, medical applications, and the automobile and aerospace industries[9]. BLDC motors are electronically commutated motors that offer several advantages over brushed DC motors. These benefits include higher efficiency, longer life, lower volume, and higher torque. This study provides a summary of how well fuzzy PID controllers and adaptive fuzzy PID controllers work using the Simulink model [2]. Tuning parameters and executing calculations with a regular PID controller is challenging, and compared to an adaptive fuzzy PID controller, it yields inferior control characteristics. We can see from the simulation results that the adaptive fuzzy PID controller works better than the fuzzy PID controller [5]. We utilised the software package SIMULINK to control and model the BLDC motor [15].

Methodology

The idea behind battery electric vehicles (EVs) is straightforward [47]. The vehicle has an electric battery to store energy, an electric motor, and a controller. The battery is usually charged from the mains electricity with a socket and a battery charging unit that can be carried on board or installed at the charging site [56]. The controller usually controls the power that goes to the motor, which in turn controls the speed of the vehicle in both forward and reverse. This is usually called a "two-quadrant controller," which means it can move in both forward and reverse directions. Using regenerative braking to get energy back and as a convenient way to brake without friction is usually a good idea. The device also lets you use regenerative braking in both forward and backwards directions [52]. People call it a "four-quadrant controller." 1 There are many different kinds of EVs like this one on the market right now. The simplest types include small electric bikes, trikes, and cars for getting to work. Several companies have made battery-powered electric vehicles for sale. There is additional information about two of these: the Nissan Leaf and the Mitsubishi MiEV—the IC Engine and Electric Hybrid Vehicle [59].

There are many different types of hybrid vehicles because they have two or more power sources. The most common forms of hybrid cars have an internal combustion engine, a battery, an electric motor, and a generator [49]. The parallel hybrid, on the other hand, can be used in a lot of different ways. Electric devices can be smaller and cheaper because they don't have to convert all the energy. You can use a parallel hybrid car in several different ways. It may run on electricity from the batteries, like in a city where exhaust fumes are bad, or it can run only on the IC engine, while you're driving outside the city [54]. A parallel hybrid car, on the other hand, may use both the IC engine and the batteries at the same time, which is more advantageous because it keeps making the IC engine more efficient [60]. It's common to get the fundamental power to run the vehicle from the IC engine, which is usually around 50% of the peak power needs.

The electric motor and battery provide extra power, and when the battery is not needed, the engine generator charges the battery [51]. Modern control methods can be used to change the engine's speed and torque to cut down on exhaust emissions and improve fuel economy. In parallel hybrid systems, it is helpful to define a variable called the "degree of hybridisation" as follows: the more power the electric motor has, the more useful a smaller IC engine is, and the longer it can run at its best efficiency [57]. Hybrid cars cost more than regular cars, but you can save money in several ways. When the motors are arranged in a series, there is no need for a gearbox; the gearbox may be made simpler, and the differential can be removed by putting one motor on each wheel [46]. In series and parallel arrangements, the standard battery starting setup can be done away with.

There are already a lot of hybrid cars on the market, and this type of car is going to grow quickly in the next few years. The Toyota Prius is a hybrid that can't be charged. It has a nickel-metal hydride battery [55]. The electric motor powers the Prius when it starts up or is going slowly, so it doesn't use the IC engine, which is the most polluting and least efficient part of the car [50]. The regenerative braking system in this car helps it get good gas mileage, which is roughly 56.5 miles per gallon (US) or 68 miles per gallon (UK). 2 The Prius can go as fast as 160kph (100mph) and goes from 0 to 100kph (62mph) in 13.4 seconds. The engine is the only thing that charges the Prius battery; it doesn't utilise an external connector. So, it can only be filled up with petrol in the usual way [58]. Also, it comfortably fits four passengers, and the battery, which is a little bigger than average, doesn't take up much space in the trunk [53]. Another great thing about this car is that it has a completely automatic gearbox system. It has made electric cars much more accessible to regular people, which is good because they need to be able to handle a wide range of trips [48].

Result and Discussion

The Prius is mostly a parallel hybrid because the IC engine can directly power the car [76]. However, it features a separate motor and generator, allowing it to work in series mode, and is not a "pure" parallel hybrid. It has a somewhat complicated "power splitter" gearbox that uses epicyclic gears. This allows power from the electric motor and the IC engine to be directed to the wheels or gearbox in nearly any amount (Figure 1). You can also send power from the wheels to the generator to use regenerative braking [87].

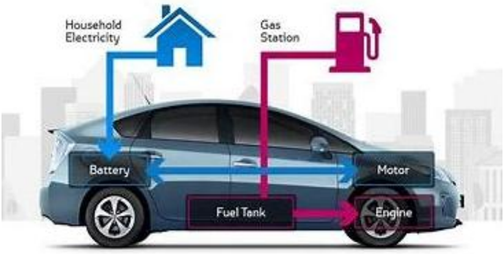

Figure 1: Hybrid Electric Vehicle

Solar-powered cars, such as the Honda Dream, which won the World Solar Challenge in 1996, are expensive and only perform well in areas with abundant sunlight. The Honda Dream Solar car went an average of 85 kilometres per hour (50 miles per hour) across Australia, from Darwin to Adelaide [67]. This kind of car may not be ideal for everyday use, but the efficiency of solar photovoltaic cells is continually improving, and their cost is decreasing [90]. It's a great idea to use solar cells that can be wrapped around the outside of a car to keep the batteries of a commuter vehicle charged. This could work as the price goes down and the efficiency goes up.

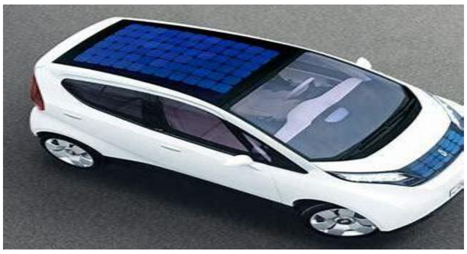

Figure 2: Solar-Powered Vehicle

Of course, the future of electric vehicles is still up in the air. But we urgently need cars that do less harm to the environment [85]. Much of the technology required for these cars is already available, and the current high price will decrease as demand increases, making it feasible to produce a large number of them. This has already been shown to be true in the case of the lithium-ion battery (Figure 2). The next chapters discuss the key technologies that comprise EVs today and in the future. These are batteries and other energy storage devices, a hydrogen supply, and electric motors. After grasping the fundamental concepts, the integration into automobiles can be tackled. Vehicle performance modelling is a very significant part of this, and it is what this book is about [75]. The next chapters discuss the key themes of making safe and stable cars, as well as the "comfort facilities" necessary in a modern car. Lastly, we need to be honest about how EVs affect the environment. How much do they help reduce the damage we cause to the ecosystem by allowing us to move around? Cities and municipalities could greatly benefit from zero-emission automobiles, and vehicles that utilise electrical technology to reduce fuel consumption are also possible [96]. Engineers, scientists, and designers are the ones who need to make this happen.

Electric vehicles (EVs) frequently get a lot of attention for their sleek appearance and eco-friendly features, but the controllers that are buried under the hood are what push them into the future. Controllers are the computer brains behind every acceleration, turn, and regenerative stop. They are particularly important for the performance and efficiency of electric vehicles [77]. These advanced electronic gadgets control a symphony of electrical currents to make driving smooth and exciting. They do everything from controlling power distribution to optimising energy use. Let's take a closer look at how controllers have played a key role in the development of electric mobility, from their humble beginnings to their cutting-edge innovations. We'll also talk about how these quiet protectors are guiding us towards a cleaner, smarter, and more electrifying future on the road. The motor controller, which is sometimes called an inverter or motor drive, controls the flow of power to the motor to manage its speed and torque [66]. It changes the battery pack's direct current (DC) into alternating current (AC), which the electric motor may use. Motor controllers are necessary for controlling the EV's propulsion system, which makes sure that acceleration, deceleration, and energy use are all smooth and efficient.

The motor controller, which is sometimes called an inverter or motor drive, is an important part of electric vehicles (EVs) since it controls the speed, torque, and direction of the electric motor [95]. It converts the battery pack's direct current (DC) into three-phase alternating current (AC), which the electric motor can utilise. The motor controller takes care of this conversion and controls the frequency, voltage, and phase angle of the AC output to make sure the motor works exactly as it should. The motor controller adjusts these settings to ensure the electric car accelerates smoothly, uses energy efficiently, and responds quickly to changes in speed. This all helps the vehicle's performance and driving experience [84]. The motor controller is crucial for electric cars as it performs several vital functions. These are some of them. Motor controllers change the frequency and voltage of the electricity that powers the electric motor to control its speed. This ensures the car can speed up and slow down smoothly. Motor controllers change the amount of current that goes to the motor windings to change the electric motor's torque output. This gives the driver exact control over how much power the vehicle gets.

Regenerative Braking: Motor controllers make regenerative braking possible. This is when the electric motor works as a generator, turning kinetic energy into electrical energy and putting it back into the battery pack. This makes the car go farther and use less energy (Figure 3).

Direction Control: Motor controllers tell the electric motor which way to turn, which lets the vehicle go forward or backwards as needed.

Safety Features: Motor controllers may have safety features like overcurrent protection, overvoltage protection, and temperature monitoring to keep the motor from becoming damaged and make sure the vehicle runs safely.

Some motor controllers offer diagnostic and monitoring features that allow you to see how well the motor is working in real time, helping you identify any problems or flaws [68]. Motor controllers are crucial components of electric cars, as they regulate the electric motor's operation to ensure optimal performance, safety, and efficiency [78].

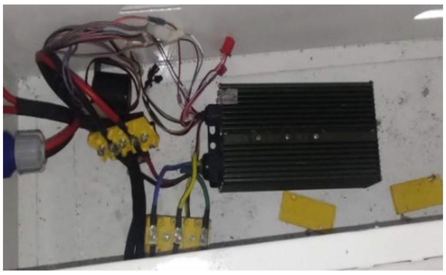

Figure 3: Motor Controller

Also, the torque ratio that the motor gets is higher, which makes it beneficial in situations where weight and space are important. This application note will talk about BLDC motors in depth, including how they are built, how they work, their features, and the kinds of things they are usually used for [74]. For a list of common words that describe BLDC motors, see Appendix B: "Glossary." How It Was Made and How It Works: A type of synchronous motor is a BLDC motor [86]. This means that the magnetic fields made by the stator and the rotor spin at the same rate. Induction motors often "slip," whereas BLDC motors don't. There are single-phase, two-phase, and three-phase versions of BLDC motors. The stator has the same number of windings as its kind. Of them, 3-phase motors are the most common and commonly utilised [61]. This application note is all about 3-phase motors.

The stator of a BLDC motor is made up of stacked steel laminations with windings in the slots that are cut along the inner edge. The stator looks like an induction motor, but the windings are arranged differently. Three stator windings are usually connected in a star pattern in most BLDC motors. Many coils are coupled to each other in each winding. A winding is made by putting one or more coils in the slots and connecting them. To make an even number of poles, each winding is spread out over the outside of the stator. There are two kinds of stator winding variants: trapezoidal and sinusoidal [91]. This distinction is based on how the coils in the stator windings are connected to create the different forms of back electromagnetic force (EMF). For further details, see the section under "What is Back EMF?"

The trapezoidal motor's back EMF is trapezoidal, and the sinusoidal motor's back EMF is in a sinusoidal shape. The phase current likewise contains trapezoidal and sinusoidal changes, just like the back EMF. This makes the torque output of a sinusoidal motor smoother than that of a trapezoidal motor. However, this costs more because sinusoidal motors require more winding interconnections due to the arrangement of coils around the stator's edge [69]. This makes the stator windings take in more copper. You can choose the motor with the right voltage rating for the stator based on how much power the control power supply can handle. Automobiles, robots, minor arm movements, and other things employ motors that are rated for 48 volts or less [97]. Figure 4 shows that motors with ratings of 100 volts or above are used in appliances, automation, and industrial settings.

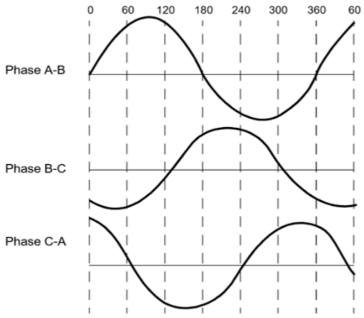

Figure 4: Waveform of Back Emf

Sensors in Hall. The stationary section of the motor has Hall sensors built into it. It is challenging to install Hall sensors within the stator because misalignment with the rotor magnets makes it difficult to determine the rotor's position [79]. Some motors may have Hall sensor magnets on the rotor in addition to the main rotor magnets. This makes it easier to attach the Hall sensors to the stator. These are a smaller version of the rotor [100]. So, when the rotor turns, the Hall sensor magnets work just like the main magnets. The Hall sensors are usually put on a PC board and attached to the enclosure cap at the end that doesn't drive. This lets users move the whole assembly of Hall sensors around so that it lines up with the rotor magnets for the greatest performance (Figure 5). The shaft's driving end is the rotor magnet S. How It Works During each commutation sequence, one of the windings is powered by positive power (current flows into the winding), the second winding is powered by negative power (current flows out of the winding), and the third winding is not powered at all [62].

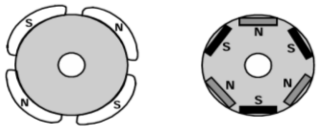

Figure 5: Stator Diagram

The interaction between the magnetic field created by the stator coils and the permanent magnets causes torque. The best time for maximal torque to happen is when these two fields are 90° apart and get weaker as they get closer together. The magnetic field created by the windings should move as the rotor travels to catch up with the stator field for the motor to remain running [83]. The order in which the windings are energised is called "Six-Step Commutation." For more details and an example of a six-step commutation, see the "Commutation Sequence" section. There are two types of output, depending on where the Hall sensors are located. The Hall sensors could be out of phase with each other by 60° or 120°. The motor manufacturer then sets the commutation sequence that should be used to control the motor.

So far, we have only witnessed commutation based on the Hall sensor's position of the rotor [72]. Instead of using Hall sensors, you can commutate BLDC motors by watching the back EMF signals. Figure 7 shows how the Hall sensors and back EMF are related to the phase voltage. As we learnt in earlier parts, each commutation sequence contains one positive winding, one that is negative, and one that is open. When the voltage polarity of the back EMF changes from positive to negative or from negative to positive, the Hall sensor signal changes state [89]. In a perfect world, this would happen when the back EMF crosses zero, but in real life, there will be a delay because of the winding characteristics. The microcontroller needs to make up for this delay.

Very low speeds are another thing to think about. The back EMF is related to the speed of rotation; therefore, at a very low speed, it would have a very low amplitude, making it hard to detect zero-crossing. The motor must be started in an open loop from a stop. When enough back EMF has built up to find the zero-cross point, the control should switch to sensing the back EMF. The back EMF constant of the motor is used to determine the lowest speed at which back EMF can be detected [65]. This method of calculation enables the elimination of Hall sensors, and in some motors, it also eliminates the need for magnets used in Hall sensors. This makes building motors easier and cheaper. This is helpful if the motor works in dusty or oily places, where the Hall sensors need to be cleaned from time to time to work properly [80]. If the motor is located in a more difficult-to-reach area, the same applies (Figure 6).

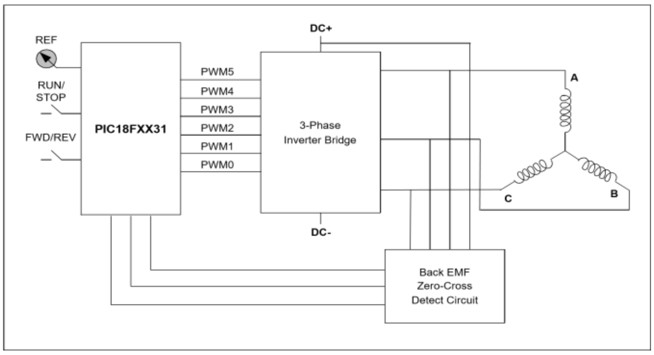

Figure 6: Block Diagram of Sensor less Control

These are the kinds of applications where the load on the motor changes with speed [92]. These applications might need precise control at high speeds and quick responses to changes. Examples of this are home appliances, washers, dryers, and compressors. In the car business, good examples are electronic steering control, fuel pump control, engine control, and electric vehicle control. In aerospace, there are several uses for these, such as for pumps, robotic arm controls, gyroscope controls, and centrifuges [63]. These programs may use speed feedback devices and work in a loop that is only partially open or completely closed. These applications require more complicated control algorithms, which makes the controller more difficult to use. This also makes the whole system more expensive.

This includes most industrial and automation uses. In this group of applications, there is some form of power transfer, like a simple belt-driven system or mechanical gear timer belts. In these situations, the speed and torque response to changes is quite critical. These applications may also need to change the direction of rotation often. Figure 11 shows that a normal cycle includes three parts: an accelerating phase, a constant speed phase, and a deceleration and positioning phase [73]. The load on the motor might change at any time during these phases, which makes the controller complicated. Most of the time, these systems work in a closed loop. The Torque Control Loop, Speed Control Loop, and Position Control Loop could all work at the same time. To find out how fast the motor is going, you can use optical encoders or synchronous resolvers.

In other cases, the same sensors are employed to collect information on relative position. If not, you can utilise independent position sensors to determine absolute positions. A good example of this is a computer numerical controlled (CNC) machine. There are numerous applications for process controls, machinery controls, and conveyor controls within this group. The rates of acceleration and deceleration don't change over time. In these cases, the load is directly connected to the motor shaft. For instance, these uses include fans, pumps, and blowers. These applications require inexpensive controllers that largely work in open-loop mode [81]. This is where most industrial and automation uses fit in. In this group of applications, there is some form of power transfer, like a simple belt-driven system or mechanical gear timer belts. In these situations, the speed and torque response to changes is quite critical. Also, these apps can often switch the direction of rotation [93]. There are three parts to a normal cycle: an accelerating phase, a constant speed phase, and a deceleration and positioning phase. During all of these phases, the load on the motor may change, which makes the controller complicated.

Most of the time, these systems work in a closed loop. There could be three control loops working at the same time: the Torque Control Loop, the Speed Control Loop, and the Position Control Loop. To find out how fast the motor is going, you can use optical encoders or synchronous resolvers. In other cases, the same sensors are employed to collect information on relative position [71]. If not, you can utilise independent position sensors to determine absolute positions. A good example of this is a computer numerical controlled (CNC) machine. There are several uses for process controls, machinery controls, and conveyor controls in this group. The controller for electric vehicles plays a significant role in how electricity is shared. Some electric cars may use a fuzzy logic controller as part of the system that controls the motor [101]. Fuzzy logic control is a way to create a control system that uses linguistic variables instead of exact numbers to make choices.

For electric vehicles (EVs), a fuzzy logic controller can be used to improve various aspects of motor performance, such as controlling torque, regenerative braking, and traction control. The fuzzy logic controller can make nuanced decisions about how to change the motor's operation in real time by taking into account some input variables (like vehicle speed, battery state of charge, road conditions, etc.) and their linguistic descriptions (like "low," "medium," or "high"). This improves efficiency, stability, and overall performance (Figure 7). Fuzzy Logic Controls are particularly useful when creating exact mathematical models is challenging or when the system is uncertain or subject to change [94]. They excel at controlling complex, nonlinear systems, such as electric cars, where traditional methods may be less effective. The motor controller is the fitted controller for the car, and it has been installed for the reasons listed above.

Figure 7: PID Controller

Fuzzy logic controllers (FLCs) are often employed in electric cars (EVs) for several reasons, which is why they have been recommended. There are a lot of different things that affect how an electric vehicle works, like the level of charge of the battery, the temperature of the motor, the road conditions, and the driver's behaviour. FLCs are particularly effective for controlling complex, nonlinear systems where it can be challenging to develop precise mathematical models [64]. The environment in which EVs work is always changing and unclear. FLCs may deal with uncertainty and changes by making decisions based on language descriptions instead of exact numbers. FLCs are well-suited for contexts that change quickly, as they can learn and adapt from experience [98].

Because they may change, FLCs can change the control strategy in real time based on information from sensors and other sources. FLCs are designed to function similarly to how people make decisions, making them easy to comprehend and use [88]. This makes them especially appealing for uses where easy-to-use control systems are needed (Figure 8). FLCs are strong against noise and other disturbances, making them suitable for use in electric vehicles (EVs) where factors like bad weather and road conditions might impair performance. Fuzzy logic controllers are well-suited for managing the complex and dynamic nature of electric car systems due to their flexibility, adaptability, and robustness.

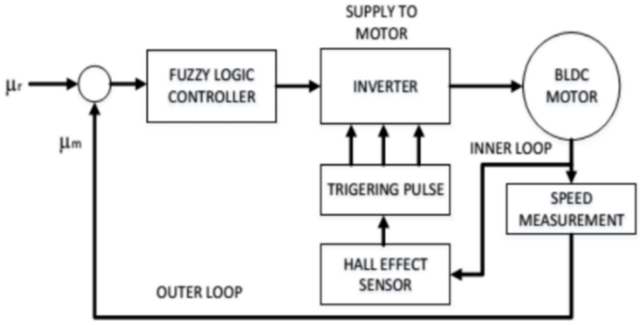

Figure 8: Block Diagram

People have used the motor controller for electric cars in their homes. A motor controller, on the other hand, is a device or group of devices that controls how an electric motor works [82]. It controls the motor's speed, torque, and direction based on the input it receives [99]. Motor controllers can range from simple on/off switches to more complex systems that utilise feedback control methods, such as PID controllers, for precise motor control. A PID controller, which stands for Proportional-Integral-Derivative controller, is a common way to provide feedback in control loops for systems that need very precise process control. It finds the error value by taking the difference between the measured process variable and the desired setpoint [70]. To reduce the error over time, the control inputs are changed based on this error.

Conclusion

On the other hand, a motor controller is a device or group of devices that controls how an electric motor works. It controls the motor's speed, torque, and direction based on the input it receives. Motor controllers can be as simple as switches that turn the motor on and off, or as complicated as systems that use feedback control methods like PID controllers to get very accurate control over the motor. By combining these two, the PID controller can govern how the motor controller works, making sure that the motor runs at the right speed, position, or torque.

The PID controller keeps the control signals sent to the motor controller in sync with the difference between the desired and actual motor performance. This helps keep things stable, accurate, and responsive in a wide range of fields, including robotics, automation, and industrial control systems. The MATLAB Simulink indicates that the motor controller is less effective than the PID controller, primarily due to the PID controller's greater efficiency. We can also say that the PID controller is better than the motor controller and can be used in the future.

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