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Investigation of DC Motors for Electric and Hybrid Electric Motor Vehicle Applications Using an Infinitely Variable Transmission

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Investigation of DC Motors for Electric and Hybrid Electric Motor Vehicle Applications Using an Infinitely Variable Transmission

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A thesis submitted to the faculty of
Brigham Young University
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Master of Science

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ABSTRACT

Investigation of DC Motors for Electric and Hybrid Electric Motor Vehicle Applications Using an Infinitely Variable Transmission

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Since the early 1900's demand for fuel efficient vehicles has motivated the development of electric and hybrid electric vehicles. Unfortunately, some components used in these vehicles are expensive and complex. AC motors, complex electronic controllers and complex battery management systems are currently used in electric (EV) and hybrid vehicles.

This research examines various motors and speed control methods in an attempt to help designers identify which motors would be best suited for an EV powertrain application. The feasibility of using DC motors coupled with an Infinitely Variable Transmission (IVT), to obtain an innovative new electric or hybrid electric powertrain is also presented.

The results of this research include an extensive review of the many motor types including a comparison chart and motor hierarchy. An experiment was designed and built to test motor speed control methods. Testing with two DC separately-excited motors and a differential as an IVT was also conducted. These tests revealed that field weakening appears to be a viable low-cost speed-control method. Testing of these motors, coupled with an IVT revealed that the output of a differential or planetary gear set can be controlled by varying the speed of the inputs. Combining this information in a product development mentality led to the concept of using one DC motor as a power or traction motor while another motor acts as a speed controller, with the method of speed control on the speed control motor being field weakening. This concept allows most of the power to be delivered at an efficient rate with a simple form of speed control. This concept may also eliminate the need for expensive, complex electronic motor controllers. This approach could be used to improve the safety and reduce battery management requirements by lowering the operating voltage of the entire system.

Keywords: Benjamin Groen, electric vehicle, motor selection, motor testing, CVT, IVT, low cost, DC, AC, LabView, shunt wound, DC motor, hybrid

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NOMENCLATURE

Variables

E	Voltage/EMF
I	Current
R	Resistance
P_M	Mechanical power as measured using instrumentation
P_E	Electrical power measured by multiplying voltage and current
Φ	Magnetic Flux
T	Number of Turns
N	Torque
p	Permeability
B	Magnetic Field
ρ	Resistivity
F_B	Magnetic Force
L	Length
π	3.14

Units

V	Volts
MHz	MegaHertz
kHz	KiloHertz
ppr	Pulses Per Revolution
Nm	Newton Meters
mA	MilliAmps
kg	Kilogram
$in \cdot lb$	Inch Pounds
RPM	Revolutions Per Minute
RPS	Revolutions Per Second

Glossary of Frequently Used Terms and Acronyms

Armature/Rotor	Rotating component conducting majority of current
Back EMF	Opposing electromotive force induced in a motor (sometimes called counter EMF)
Commutator	Method of conducting current to a rotating armature typically via brushes
EMF	Electromotive Force
Field/Stator	Stationary component providing magnetic field
Series Motor	A DC motor with a wound field connected in series with the armature
Separately Excited	A DC motor with a separate power supply for the field
Shunt Motor	A DC motor with a wound field connected in parallel with the armature

AC	Alternating Current
CAFE	Corporate Average Fuel Economy
CARB	California Air Resources Board
CVT	Continuously Variable Transmission

DC	Direct Current
EREV	Extended Range Electric Vehicle
EV	Electric Vehicle
EV1	Electric Vehicle produced by General Motors
FPGA	Field Programmable Gate Array
IGBT	Insulated-Gate Bipolar Transistor
IC Engine	Internal Combustion Engine
IVT	Infinitely Variable Transmission
POT	Potentiometer or Variable Resistor
PGS	Planetary Gear Set
VFD	Variable Frequency Drive
ZEV	Zero Emissions Vehicle

CHAPTER 1. PROBLEM STATEMENT

1.1 Problem Statement

The first electric car was first introduced as early as 1910 [15], however most automobiles today use a petroleum based fuel. In the past several years the increase in demand for fuel efficient and less polluting vehicles has motivated the redevelopment of electric (and hybrid electric vehicles (EVs) [16]. Great progress has been made, and the viability of mass producing an electric vehicle is shifting to reality. However, this development has come at a great sacrifice. The current electric vehicles intended for production by automotive manufacturers use expensive components, such as complex electronic controllers, AC motors and many cells in a battery pack. This dramatically raises the complexity and cost of the vehicle [17]. One possible method of reducing the complexity and potentially reducing the cost of an EV is through the implementation of DC motors and an Infinitely Variable Transmission (IVT). Selecting the correct motor can be a difficult task and the feasibility of using these components in an EV powertrain has not been well explored in the literature.

The proposed research will examine various DC motors and speed control methods in an attempt to help designers identify which motors would be best suited for an EV powertrain application. Additionally, this research will investigate how an IVT could be implemented in an EV powertrain to benefit the entire system.

1.2 Research Objectives

Expected results from this research would include:

1. A document explaining factors affecting motor performance of different types of electric motors.
2. Testing of armature voltage variation and field weakening speed control methods.

3. Construction and testing of hypothesized equations that relate multiple inputs to a single output on a continuously or infinitely variable transmission.
4. Plausible recommendations based on testing and literature review for implementing DC commutated motors and IVTs in an electric vehicle powertrain. These recommendations will be described as cause and effect relationships that would potentially provide performance or efficiency improvements.

1.3 Research Benefits

Vehicles with an electric powertrain can reduce and even eliminate consumer dependency on gasoline. This leads to cleaner vehicle emissions, energy independence and reduced fuel costs [18]. The goal of this research is to provide information to automotive engineers to aid them in selecting which DC motors to use in an electric powertrain. Specifically, the research will guide readers in motor selection by identifying cause and effect relationships to some key equations governing motor performance. This research will also help to define two less commonly used motor speed control methods. The reader of this research will also gain insight into how an IVT works and the equations governing the inputs and outputs. The impact of this research could affect several components of the electric powertrain system including: cost, reliability, safety, efficiency, weight, size, maintenance, and operating life. This information should enable auto manufacturers to make performance and cost improvement in electric vehicles. Potentially this information could aid manufacturers in finally being able to produce an electric vehicle that is both affordable and profitable in comparison with current gasoline or diesel powered vehicles.

1.4 Motive

The rising cost of fuel and energy dependence concerns have sparked interest in vehicles with alternative energy sources. The use of electrical powertrains is believed to be one potential solution to this problem. Electric vehicles are not the only application for electric vehicle powertrains. Other types of vehicles that use electrical propulsion systems include: traditional hybrids like the Toyota Prius, 2 mode hybrids like the Chevy Tahoe Hybrid, Fuel Cell vehicles like the Chevy Equinox and Honda FCX, and Extended Range Electric Vehicles (EREV) like the Chevy Volt. The use of electrical components in hybrid vehicles has already demonstrated an increase in fuel economy, but has come with an increased cost. Fully electric vehicles and fuel cell vehicles are currently being designed, but they have an even higher cost, and so the question remains whether or not this technology will be a success in the market.

This puts the auto industry in a very precarious situation. Auto producers must evaluate and decide which technology to implement in their vehicles. Now is the time when automotive companies have a chance to demonstrate which technologies will work and which will fail. The last time this happened was in the late 1990s with the brief period of the EV1 and Toyota Rav4-EV where a select few early adopters embraced EV technology, but programs ended abruptly and left disdainful impressions in some of the eyes of the public. The rest of the population has yet to cast their vote.

Investing in an alternative propulsion system requires huge capital and resources. Some companies such as General Motors and Nissan have decided to pursue fully electric vehicles anticipating that the technology will be a success; others like Toyota and Honda have focused on hybrid technology. Now that several companies have invested in these new technologies, they must prove that their technology will work and be economical for consumers. In order to win the vote of the public and gain market share, these companies are designing the very best cars and using the very best components possible (which also are generally the most expensive components). Automotive companies are willing to lose money on their first vehicles just so they can earn the respect and support of their customers. Once the vote has been won and the 'green' label attached to the company, then cost reduction measures will be identified and pursued.

To win the vote of the public, car companies must produce a vehicle that performs as well or better than one with an internal combustion engine. This means that it must be powerful, have a long range and be approximately the same price as an IC engine vehicle. To accomplish this, auto companies are using powerful batteries, a very efficient motor, reducing the weight of the car, and absorbing additional cost themselves.

Typically AC induction, switched reluctance, and synchronous motors have been used in electric vehicles [16, 17]. DC motors have been labeled in much of the literature as heavy, less efficient, requiring more maintenance and generally inferior to AC motors. Auto companies have avoided the use of DC motors because they must first prove to the public that EVs are fully competitive with IC engine vehicles. However, recent developments such as the use of permanent magnets, have greatly reduced the weight of the DC motor, in addition improved life of the brushes and increased efficiency has been realized by DC motors. Additionally, shunt or separately excited DC motors can be controlled relatively inexpensively. Using DC motors in EV propulsion systems therefore has potential in making EVs a viable solution as an alternative propulsion system for vehicles.

1.5 Electric Powertrain Construction

Hybrids, fuel cells and electric vehicles all use electric power differently, but the basic components that are used are similar. Each of these vehicles require an electric power source, an electric motor and a controller.

1.5.1 Controller

The controller in an EV is typically used for speed control of the motors. Speed control of the motor can be accomplished in several ways. Non-brushed motors typically use a form of electronic commutation with sophisticated electronics that send very accurate AC signals to the motor. This often requires an inverter and variable frequency drive (VFD). Brushed motor speed control can be accomplished through pulse width modulation (PWM), armature voltage variation or field weakening, all of which are explained in more detail in Chapter 2.

VFD and PWM methods of speed control in motors have been complex and also expensive. The complexity and costs arise from the need to switch current flow on and off in a controlled manner. Because a large amount of power is needed to propel a vehicle, large amounts of current have to be supplied to the motor. This also forces the need for the controllers to be able to handle large currents. Since power is the product of voltage times current, in controller design, many systems use an increased operating voltage as an attempt to maintain electrical power, while reducing the current, and thereby reduce the price of an otherwise even more expensive controller. However, this high voltage has safety implications. Above 60V the vehicle can be potentially dangerous to operators and technicians who interact with the vehicle.

Using DC motors and field weakening for speed control, it may be possible to eliminate the need for an expensive controller, and at the same time, reduce the operating voltage of the system.

The lower operating voltage used in this approach may thereby reduce the potential safety hazard of high voltage for consumers and technicians.

1.5.2 Power Source

The most common form of power in an EV powertrain is a battery. Although many types of batteries are being explored, all of these batteries produce direct current (DC) power. Sometimes power is generated on the vehicle by an IC engine/generator or a fuel cell but ultimately when power is delivered to or from the batteries it must be in the form of DC.

The complexity of the battery system is largely dependent on the system operating voltage. The output voltage of each cell is dependent not on the size of the cell, but rather the chemistry of the cell. To achieve the desired vehicle operating voltage for today's controllers, cells in a battery must be connected in series. Because battery chemistry determines battery cell voltage, Table 1.1 illustrates that the higher the operating voltage, the higher the number of cells required in the battery pack. Because each cell must be carefully monitored for voltage and temperature, the number of cells contributes to the complexity and cost of the battery pack.

Table 1.1: Number of Cells in a Battery Based on Operating Voltage

Operating Voltage	375V	60V	48V
Typical Cell Voltage	3.75	3.75	3.75
Min. Req Cells	100	16	12.8

1.5.3 Motors

Because batteries provide a DC electrical source, it is logical that the use of DC motors be explored for use in an electric vehicle. The use of DC motors eliminates the need to transform the power source to an AC sine wave and thus eliminates losses incurred in any inverter or conversion device, as well as reduces cost. The use of DC motors also allows for a simpler motor speed control system. Instead of having to supply a precise AC frequency to the stator, DC motors use a non-oscillating supply voltage and commutator to accomplish rotation [12, 19].

A preliminary investigation of the literature about DC motors reveals several types of DC motors. These are generally broken up into two groups: self-excited DC motors and separately-excited DC motors [20]. Of the self-excited motors, there are Shunt, Series and Compound configurations which are variants in how the field and armature are connected. Of the separately-excited DC motors, there are Wound and Permanent Magnet varieties. Each of these motors has inherently different characteristics because of the difference in motor construction. These characteristics are of great importance to EV engineers and should be explored further.

1.6 Using an Infinitely Variable Transmission

Another consideration, would be the use of an infinitely variable transmission. Research has already shown that IVT powertrains can be more efficient than conventional transmissions [21]. The IVT would allow the motor to run at its most efficient RPM for longer periods. One form of an IVT is a planetary gear set. Constructing the IVT with a planetary or differential gear set may allow the torque and RPM of the output of the system to be controlled by varying inputs. This presents a new and innovative method of control of an electric vehicle powertrain. Theoretically it should be possible to control the output of the differential by simply varying the speed of the inputs. Using this design, it may be possible to have one motor act as a speed controlling motor for the vehicle, while the other motor provides most of the traction to propel the vehicle. This is illustrated in Figure 1.1. Based on a literature search we believe this approach has not previously been utilized [7]. Additionally the IVT could allow inputs from other sources such as an internal combustion engine or another electric motor for hybrid architecture.

1.7 Current Status

Figure 1.2 shows that the demand for motor vehicles in the U.S. continues to increase, with an especially notable increase in demand for higher fuel consuming trucks [2]. As nations like India and China continue to develop, along with strong growth in South America, the demand for vehicles will continue to rise along with the demand for gasoline. The diminishing supply of gasoline and major sources of oil located in foreign countries, lead to energy dependence concerns for this country and concern of rising fuel costs throughout the world. Figure 1.3 shows that the

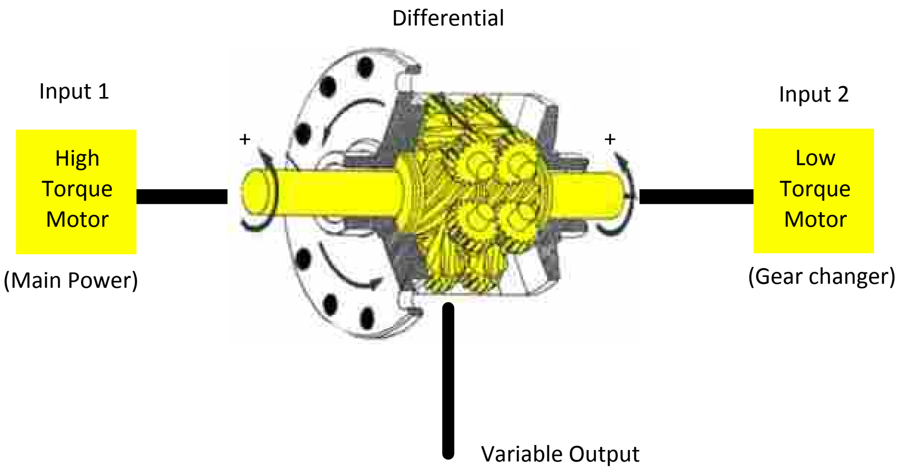


Figure 1.1: Speed Control Using an IVT [1]

price of gasoline in the United States is still on the rise, with the price having already peaked at over four dollars per gallon [3].

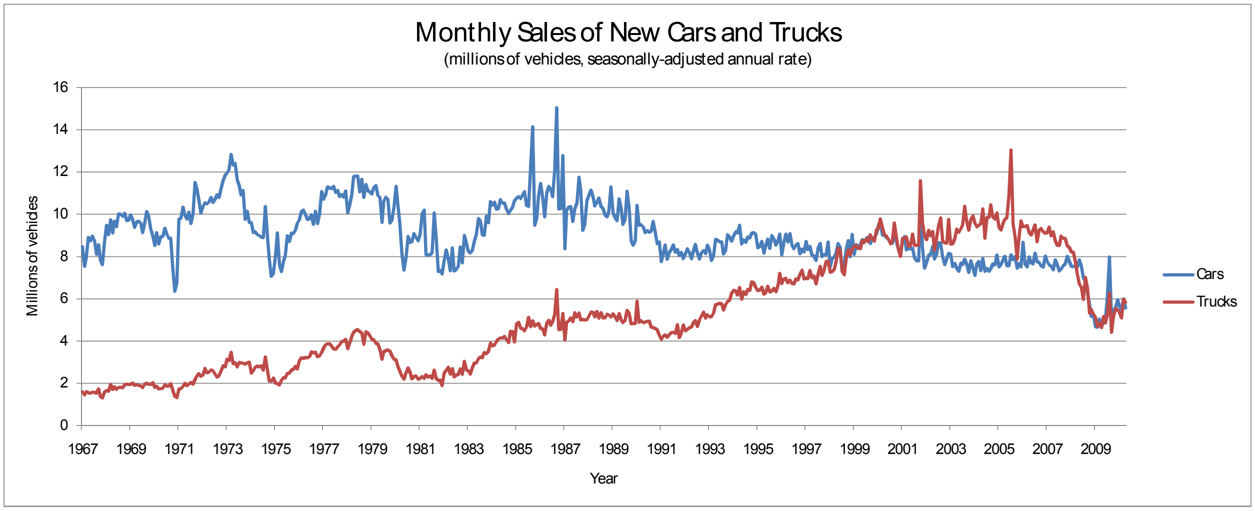


Figure 1.2: Motor Vehicle Demand [2]

Environmental impacts from increased motor vehicle activity in urban areas has caused government entities to regulate emissions from vehicles. Legislation is currently being worked on to increase the Corporate Average Fuel Economy (CAFE) standards by 25% by the year 2017 [22]. Agencies like the California Air Resources Board have instituted a Zero Emissions Vehicle (ZEV)

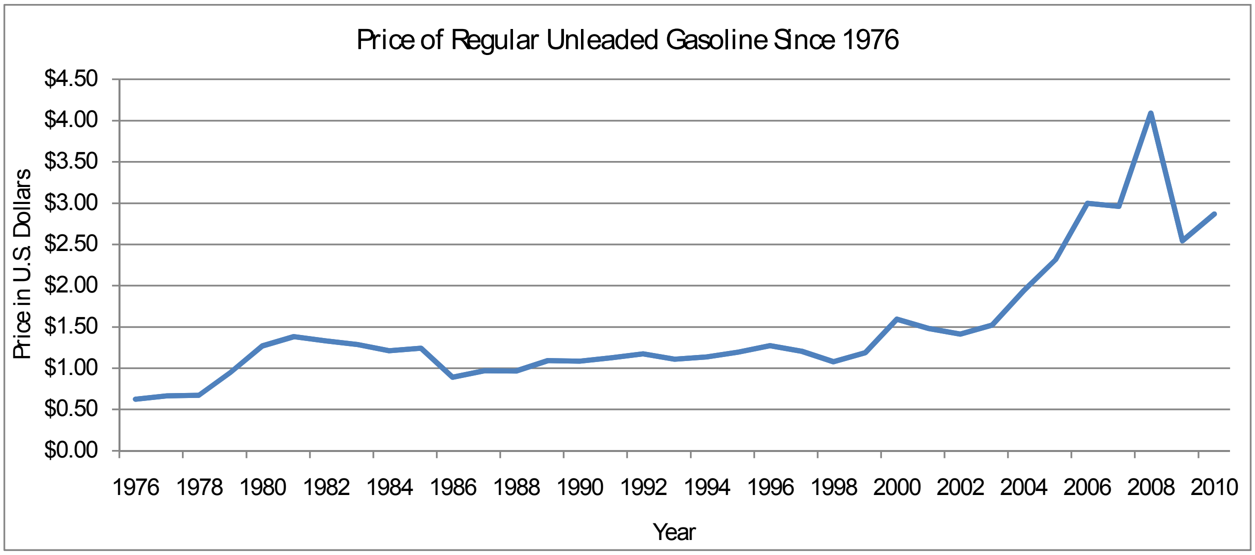


Figure 1.3: Gas Price History [3]

mandate which requires auto makers in California to sell a certain percentage of their vehicles with no harmful emissions [23, 24].

These recent developments in political, consumer and environmental arenas have sparked interest in vehicles with some form of electric powertrain. This has forced auto makers into a revolution with a very narrow window for profit and a very volatile market. It has been more than a decade since the EV1 and other major electric vehicles have been seen on public roads. Recently Tesla has released its electric roadster with a price tag of over $100,000. This price is of course too high for the general public. This year, two plug-in electric vehicles are scheduled for launch, the Chevy Volt and Nissan Leaf priced at approximately $41,000 and $33,500 respectively [9]. Even though this price will be partially offset by a government tax credit, it is still predicted to be too high for the average consumer. Every other major automotive manufacturer also has plans to release a vehicle with an electric powertrain in the near future. If the electric vehicle is to be a success, the cost of the vehicle must be reduced so that it can be affordable to most people and still be profitable for manufacturers.

1.8 Approach

Part of this research will require a thorough investigation into how DC machines operate and the theory behind how these motors work. This will be accomplished with a literature review of DC commutated motors, specifically shunt-wound DC motors. It is expected that this review will focus on understanding how parameters in the motor can be varied to optimize performance or efficiency. A comparison will then be made to distinguish which applications are best suited for each motor, and how that applies to an electric or hybrid drivetrain.

A table-top test experiment will be developed to gain a better understanding of DC commutated motors. This will involve measuring the voltage and current in the field and in the armature of a DC shunt motor while under various loading conditions. After this is complete, the setup will be modified to help verify hypothesized equations that relate multiple input torques and RPMs to a single output torque and RPM. Two shunt motors will drive two of the inputs/outputs of a differential and an array of sensors and a data acquisition system will allow the RPM, current, voltage and torque to be measured at various locations. This test will help in determining the feasibility of implementing this drivetrain architecture into a working prototype vehicle.

If this testing is successful, the next and final phase of this research will be to develop plausible recommendations on how to implement this technology into a working prototype. The intent of these plans is to provide considerations for alternative drive train architectures that may be less costly.

1.9 Scope

As described in the research objective, the proposed research will identify the potential for using DC commutated motors in an EV powertrain, including advantages and disadvantages. Because it is not possible to evaluate in this research all types of DC motors, the research will focus on field weakening in DC Shunt motors and implementation of this type of DC motor with an IVT. Also, only a few of the many parameters that affect motor efficiency and performance will be evaluated. Conclusions and results will only be obtained from the IVTs used in the experiments.

CHAPTER 2. LITERATURE REVIEW

A literature review was conducted to better understand the principles and applications of this research. Below are the findings of this review.

2.1 Magnetism

2.1.1 Electromagnetism

In order to investigate the effects of using different types of electrical motors it is necessary to understand the basic operating principles of a motor. To begin with, current carrying conductors emit a magnetic field according to Equation 2.1 [13, 25].

$$\vec{F_B} = \vec{L}I \times \vec{B} \tag{2.1}$$

Where L is a vector pointing in the direction of current flow with a magnitude equal to the length of the conductor, I is the current, B is a vector in the direction of the magnetic field and F_B is the resultant force vector of the interaction. Thus increasing the strength of the magnetic field by increasing the current in a wire will increase the force exerted on the wire.

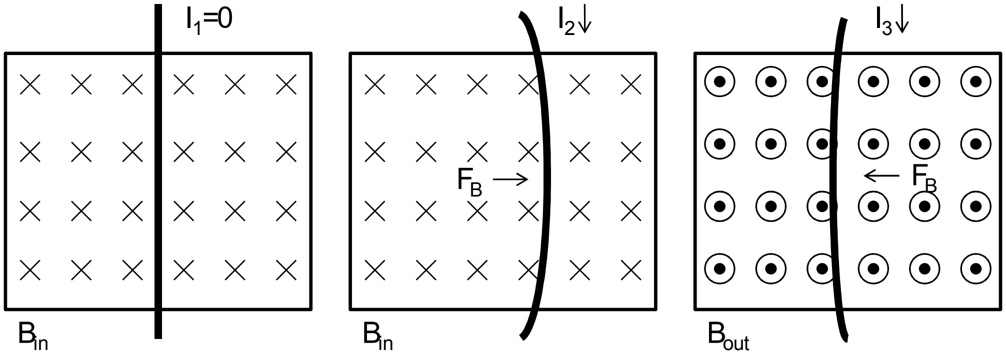


Figure 2.1: Current Carrying Wire Moves in the Presence of a Magnetic Field

As shown in Figure 2.1, when wire with a current passing through it is placed in the presence of another magnetic field, this causes the wire to move [25]. Because of Equation 2.1, the direction of movement can be predicted using the right hand rule, where the thumb is the direction of the current (I), the index finger is the direction of the magnetic field (B), and the middle finger is the resultant force vector (F_B) [25].

In motors, the magnetic field is provided by permanent magnets or by multiple turns of a wire with a current flowing through it, surrounding an iron core. In the latter, the magnetic field strength is calculated using Equation 2.2,

$$\Phi = NI \tag{2.2}$$

Where Φ is the magnetic field flux, N is the number of turns of a wire and I is the current passing through the wire. It can be inferred from this equation that the magnetic moment produced in a motor can be increased by increasing the number of turns or increasing the current in the wire. Typically it is more desirable to increase the number of turns as opposed to increasing the current in the wire. This is because of the Power Loss Equation 2.3, which represents the amount of power lost typically to heat generation.

$$P_{loss} = I^2 R \tag{2.3}$$

In this equation I is the current in the wire and R is the resistance of the wire as calculated by Equation 2.4. As can be seen in this equation, the power lost to heat is a square of the current! So, increasing the number of turns in a motor (as opposed to increasing current flow) is normally done to increase magnetic strength and hence torque. However this must be done in moderation. Equation 2.4 shows that the resistance of a wire depends on the length and diameter of the wire.

$$R = \rho \frac{l}{\pi \frac{d^2}{4}} \tag{2.4}$$

Where l is the length of the wire, d is the diameter of the wire and ρ is the resistivity per unit length of the wire, measured in ohms. As conductor diameter decreases, the resistance increases, again contributing to power lost through heat dissipation. On the other hand if the conductor diameter is too large it becomes difficult to bend and manipulate, thereby preventing multiple turns of the wire in the motor. Additionally, and more notable, is the fact that an increase in wire diameter also directly increases the weight and cost of the motor. Some common conductors with their resistivities and cost per kilogram are listed in Table A.1 in Appendix A. In practice, copper is by far the most common conductor material used in motors, with aluminum being a very distant 2nd place.

In summary there are several fundamental parameters in these equations that should be carefully considered when designing and selecting a motor. For example, the resistance, length and gauge of the wire that is used, is very important in determining magnetic flux, motor capabilities, cost and weight. In general, electromagnets can be much more powerful than permanent magnets because they are only restricted by the amount of current and the number of turns [4, 25].

2.1.2 Back EMF

According to Faraday's law of induction, shown in Equation 2.5, the Electro Motive Force (EMF) induced in a circuit is directly proportional to the time rate of change of the magnetic flux through the circuit.

$$E = -\frac{d\Phi_B}{dt} \tag{2.5}$$

The rotation of the armature in the magnetic field causes the change in magnetic flux mentioned above. Therefore, all motors generate a back EMF. Additionally, Lenz's Law states that the induced current in a loop is always in the direction that creates a magnetic field that opposes the change in magnetic flux through the area enclosed by the loop. Therefore, the back EMF is always in opposition to the flow of current in the armature [25]. It is also interesting to note that the change in magnetic flux can be accomplished by varying the voltage and current in the windings of the field, and not just the position of the coil in the field. This is of particular interest in electric motors as a means of varying the speed of the motor.

2.1.3 Eddy Currents

Faraday's and Lenz's law also explain the formation of eddy currents. Similar to those in fluid dynamics, eddy currents are circular currents that produce losses. In a motor, these eddy currents form within the motor armature. The eddy currents produce heat loss in the armature and thus have a negative impact on the efficiency of the motor. To attempt to reduce the prevalence of eddy currents, motor armatures are built with laminations. These layers of metal reduce the formation of Eddy Currents, while still allowing the armature to perform its function [13].

2.1.4 Permanent Magnets and Electromagnets

Some crystalline materials exhibit a strong magnetic effect called ferromagnatism. As the name suggests, iron is one of these materials. Substances like iron contain regions called domains that have net magnetic moments. When these types of materials are subjected to an external magnetic field, the random magnetic moments in the material begin to become aligned, eventually to the point where all the moments in that material are aligned. This point is called saturation [4].

As the magnetic field is released from these materials, some of the magnetic moments return to randomness, but some stay aligned. This retention in magnetism is called hysteresis and is illustrated in Figure 2.2.

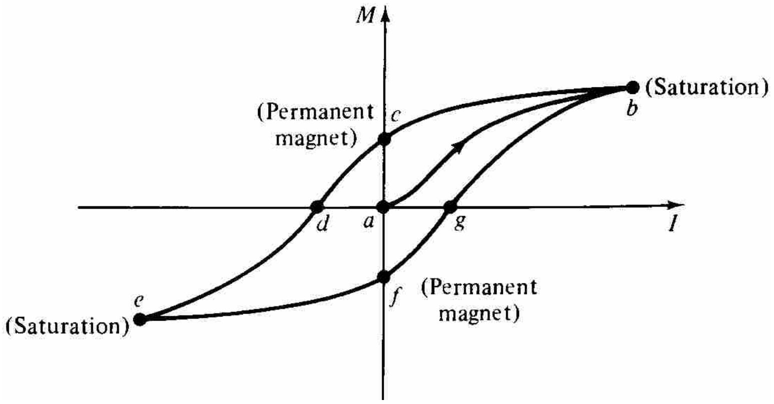


Figure 2.2: Magnetic Hysteresis Loop [4]

Figure 2.2 represents what happens when an object, with notable permeability, is wrapped with multiple turns of wire and then a current is sent through the wire. As the current increases in the wire, the magnetic field increases until saturation is reached at point b. At this point, any additional increase in current will have no effect on the magnetic field that is produced by the object. When the current is decreased the graph approaches point c where there is now zero current in the wire but a magnetic field remains. In this case a permanent magnet has been created. If current is now sent through the wire in the opposite direction, the magnetic field decreases to point d when the magnetic field strength is null. If the current continues to increase, point e is obtained where the object is again in saturation, but with the opposite pole.

In motors this has a special application during installation. For most motors to start rotating there must be a net magnetic moment in the field for the armature to react with. If a field is wired backwards during installation, current will flow in the wrong direction, thereby reducing the magnetic moment in the field and causing the motor to have problems starting.

Each material has a different hysteresis curve. Some materials like iron alloyed with neodymium and boron retain their magnetic moments very well. Other material like metglass have very low magnetic hysteresis. Materials that retain a magnetic moment or have a very wide hysteresis graph are often referred to as hard magnetic materials. Substances which have a narrow hysteresis curve and do not retain a magnetic moment are referred to as soft magnetic materials. An inference gained from this information is that materials with wide hysteresis graphs would probably be more suited to applications like the field of a DC motor, where high magnetic moment is desired. Soft magnetic materials would be better suited in applications where the magnetic field is changing often, like the armature of a DC motor for example.

Random thermal motions do compete during the aligning process, but at lower temperatures this competition is limited. However, above certain temperatures, the material properties change and it is possible for the domains to realign and remove any net magnetic moments. In such a case, the material can lose its ferromagnetic properties. This point was discovered by Pierre Curie (1859-1906) and is referred to as the Curie temperature. The Curie temperature is the point where materials change from being ferromagnetic to paramagnetic. This change is not gradual, but rather like a freezing or melting point of a metal [4]. Motors that carry large amounts of current are most susceptible to heating and therefore are also susceptible to approaching Curie temperatures.

When this is the case, motors must incorporate some sort of cooling as protection. Most motors use air cooling, but some use liquid coolant flowing through the stator to avoid approaching Curie temperatures. Curie also discovered that the magnetic field in paramagnetic substances is proportional to the applied magnetic field and inversely proportional to the absolute temperature [25]. This is important especially in Homopolar motors which are discussed in Section 2.7.

Magnetic geometry is also important in motor construction. Often permanent magnets are shaped in arcuate segments, which create points at the ends of the magnet which direct flux into the armature. This happens because the ability to conduct magnetic flux lines is different for different materials. For example, magnetic flux lines would much rather flow through iron than through air. This is because iron has a higher permeability than air. So, by carefully constructing a motor it is possible to concentrate flux lines and maximize the magnetic moment that is produced. A great example of this is the Lynch permanent magnet motor as shown in Figure 2.3.

Figure 2.3: The Lynch Motor [5]

Magnetic moments can often be rearranged through impact. This can be both a positive and negative effect depending on the desired application. For permanent magnet motors used in vehicle applications, this is noteworthy. Designers must be careful that the vibrations and impacts from the vehicle use do not interfere with motor performance. This vibration can be overcome through the use of compliant mounting.

Permanent magnet strength is limited to the magnetic moment that can be created in the material. However, some of the permanent magnets that exist today are capable of pushing materials like iron into regions well above saturation. As these permanent magnets are being produced they are becoming cheaper and a more viable solution for use in motors. A very powerful magnet can often replace many turns of expensive copper wire, reduce the mass of the motor and also improve the efficiency of the motor.

2.2 Motors

2.2.1 Motor Construction

In order to understand the parameters affecting a motor, it is necessary to understand the basic construction and function of its components. Figure 2.4 shows some of these components.

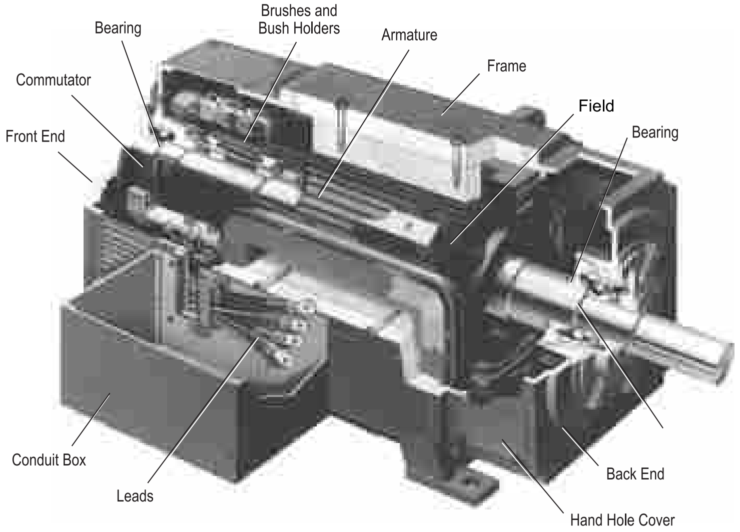


Figure 2.4: Components of a DC Motor [6]

2.2.2 Field

The field or stator is typically the stationary part of the motor that provides a magnetic field for the armature to rotate in. It is located in the frame of the motor. The magnetic field can be powered by an electromagnet or permanent magnets. Typically wound fields consist of many turns of fine wire as opposed to few turns of large wire. As mentioned previously, this has reference to Equation 2.2 and Equation 2.3, since the power lost to heat generation is the square of the current, it is more economical to increase the number of turns of the wire as opposed to increasing the current. The fine wire is often easier to turn than larger diameter wire.

2.2.3 Armature and Commutator

The armature is a conductor that provides current flow for the load portion of the motor [13]. In DC motors the commutator is attached to the armature and transmits current via brushes to the armature. The commutator is the part of the motor that converts the DC input to an alternating current in the armature. In alternating, the armature is able to accomplish complete rotation. The commutator typically consists of wedge shaped segments of hard drawn copper that are fastened using v rings or clamping flanges. The segments of the commutator are insulated from each other by thin strips of mica [19].

2.2.4 Poles

The poles of the motor are the number of magnetic north and south poles that the motor uses to provide a magnetic moment. These poles can be provided by permanent magnets, or electromagnets. Because the elusive magnetic mono pole is not yet practically implementable, poles in a motor will always come in pairs, and the number of poles in a motor will always be a multiple of two [26].

2.3 Motor Configurations

The construction of the motor can be accomplished in several main configurations. These variations arise because of the variety of power that can be supplied to the armature or field. The three main configurations are: direct current motors, permanent magnet motors, synchronous motors and induction motors. The configurations for these motors are shown in Table 2.1 [13].

2.4 Common Non-Brushed Motors

These motors are not the main focus of the research at hand, but it is relevant to discuss the basic operation of these motors for comparison. For this discussion the stator refers to the station-

Table 2.1: Configurations of the Four Types of Electric Motors

Motor Type	Winding	Winding Type	Location	Current
DC Wound	Input and Output Magnetizing	Armature Field	Rotor Stator	AC @ wind. DC @ brush DC
DC Permanent Magnet	Input and Output Magnetizing	Armature Field	Rotor Stator	AC @ wind. DC @ brush No Current
Synchronous	Input and Output Magnetizing	Armature Field	Stator Rotor	AC DC
Induction	Input Output	Primary Secondary	Stator Rotor	AC AC

ary component of the motor, and the rotor refers to the rotating portion of the motor. As described below, a magnetic field can be created in both components. The non brushed motors use a form of electronic commutation to accomplish rotation. Typically sophisticated and expensive electronics switch the DC current from the power source to an AC sine wave which changes the polarity of the magnetic field during rotation. As with DC, these electronic components in the controller must be capable of handling large amounts of current. This drives the cost of the controller up.

Thus far, major automotive manufacturers have focused their work and development on AC motors that have high efficiencies. As a result of this research, there have been significant advances to AC motor performance and motor control. Ehsani, Gao and Miller have explained the developments that have been made to induction motor and switch reluctance motor design, but these improvements have not significantly reduced the cost of using AC motors in an electric powertrain [27]. One of the major cost challenges of using AC motors is that an inverter is required to change the DC current to AC current. Additionally, Xue, Cheng and Cheung have illustrated that expensive sophisticated control systems are required to provide the correct AC frequency to the stator for motor operation. Despite these complexities, researchers have continued to investigate and focus development on AC motors. Particularly, a lot of time and resources have been devoted to comparing synchronous (also known as permanent magnet brushless motors), induction and switch reluctance motors [17,27,28].

2.4.1 AC Induction (Asynchronous) Motor

AC Induction motors operate with an AC current being provided to the stator, and the current in the rotor is formed via induction. This is very similar to how a transformer works, and so induction motors are often closely compared with transformers. In fact, the rotor and stator are often referred to as primary or secondary coils. The induction motor typically uses three phase power with the coils being offset by 120 degrees or a third of a rotation [13].

Because the current in the rotor is induced, there is no need for brushes or slip rings in an induction motor. The absence of brushes permits the motor to have very high speed capabilities, and life capabilities well beyond brushed motors [28]. Additionally the lack of brushes allows the motor to operate in hazardous environments because there is no spark produced by the arcing of the brushes between commutator gaps [29].

In order for the induction to work properly, the speed of the rotor must be slightly slower than the speed of the rotating magnetic field in the stator. Because of this offset in speed, the motor is often referred to as Asynchronous. The difference in speed of the rotor and the rotating magnetic field in the stator is referred to as slip [13]. The more load that is applied, the more slip is generated, which causes the rotor to pull more current. The larger current will produce more torque, which will bring the rotor back up to speed.

In some cases applying too much of a load will cause the motor to approach the break down torque. This is the point where the torque of the motor begins to break down. At this point providing more current to the motor will not help, and the motor will stall [28]. This occurs because the motor slip becomes so great that the rotor begins to be attracted to its following magnetic field. Generally, for most induction motors the critical torque is two times the rated torque of the motor [12]. The breakdown torque is of special concern in vehicle applications because of the high starting torque needed to propel the vehicle. This has led to the development of the variable frequency drive (VFD). By starting the motor with a low frequency the breakdown torque can be avoided, and the frequency can be incrementally increased to achieve higher speeds.

To create a VFD or even the rotating magnetic field in the stator, a sophisticated and often expensive controller is needed. As mentioned previously, this drives up the cost of the system. Additionally the characteristics of the motor cause it to have a critical torque which is referred to as breakdown torque, A development known as Field Orientation Control (FOC) allows the induction motor to behave in the same manner as a separately excited DC Motor. This allows the motor to employ field weakening as a means of control and push the limits of constant power, but again, the breakdown torque will be an important factor [27, 28, 30].There are two main types of induction motors; the squirrel cage and wound rotor. The difference between these two is that the squirrel cage motor uses short bus bars in the rotor, where the wound rotor uses many turns of wire [13, 26].

When an induction motor starts ’direct on line’, a very high current is drawn by the stator, on the order of 5 to 9 times the full load current. This high current can, in some motors, damage the windings. In addition to this, because it causes heavy line voltage drop, other appliances connected to the same line may be affected by the voltage fluctuation. To avoid such effects, several other strategies are employed for starting motors [13]. These strategies and other modifications are incorporated into other AC induction motors including: The split phase induction motor, the capacitor start motor, the permanent capacitor motor, the shaded pole motor, the repulsion induction motor, the repulsion start induction motor and the single phase induction motor [26].

In summary, modifications made to induction motors make them customizable to many applications. Its rugged construction, lack of brushes and high efficiency make it a practical solution for many applications including vehicles [16]. It is no surprise that the induction motor is by far the most widely used motor in industry [13,31]. However the cost of the motor system is inevitably high when powered by a DC source, due to the need of a sophisticated controller and inverter.

2.4.2 AC Synchronous

Wound

In the synchronous wound motor, an AC current is delivered to the stator and a DC current is supplied to the rotor. The DC current in the rotor creates a magnetic field that remains constant. The AC current in the stator creates a rotating magnetic field that is always aligned with the rotor. This is why the motor is called synchronous. Synchronous motors are not very commonly used in industry, mostly because they are not self starting and require an AC and DC power supply. The most common use for wound synchronous machines is in power generation. When used for power generation the synchronous motor is known as an alternator.

The permanent magnet synchronous motor uses permanent magnets in the rotor instead of a DC current to provide the field in the motor. In addition, complex electronics built into the motor provide the AC signal needed in the stator. Such a configuration is often referred to as the DC brushless motor [13].

Some synchronous motors have been known to incorporate additional elements to allow the motor to self start. This includes an additional winding, a separate motor called a pony motor, or a variable frequency drive. Once the motor is in operation, the speed of the motor is dependent only on the supply frequency. When the motor load is increased beyond its capability, the motor falls out of synchronization and stalls [20].

Synchronous motors are not self-starting motors. This property is due to the inertia of the rotor. When the power supply is switched on, the armature winding and field windings are excited. Instantaneously, the armature winding creates a rotating magnetic field, which revolves at the designated motor speed. The rotor, due to inertia, will not follow the revolving magnetic field. In practice, the rotor must be rotated by some other means near to the motor's synchronous speed to overcome the rotor's inertia. Once the rotor nears the synchronous speed, the field winding is excited, and the motor pulls into synchronization.

DC Brushless

As mentioned above, this motor is not really a DC motor, but rather a permanent magnet synchronous machine. Brushless DC motors have special electronic controllers that allow the motor to have a DC input which is then switched to AC and supplied to the stator. The construction of the DC brushless motor gives it several advantages. First of all it has a longer life than a DC brushed motor, because of the lack of brushes. Second, the lack of brushes allows the motor to achieve very high RPMs. Third, the permanent magnets in the rotor can be made to push iron into the saturation regions which give the motor tremendous starting torque. Fourth, the power delivered to the motor can be extremely high. In fact, the only concern with delivering power is heat generation. If the conductors generate too much heat from the current, it can drive the permanent magnets beyond their Curie temperatures and impact the magnetic properties of the material.

The downside of this motor is that the high tech electronics drive the cost of the motor up. Additionally, the motor requires an encoder to know the exact position of the rotor, so that the stator can provide the right magnetic pole at the right time to cause rotation [32].

2.5 DC Wound Motors

These motors use mechanical means of commutation. Gaps in the commutator provide an opportunity for the direction of the current to switch as the armature rotates. Control of the speed of this motor can be accomplished in four ways. These four methods involve modifying the voltage in the field or the armature.

The first method is to change the voltage of the armature using a resistor. This is a very inexpensive way to control the speed of a motor, but it is also inefficient. The power that would have been consumed by the motor is instead dissipated in heating the resistor.

The second method of motor speed control is through control of the input voltage provided to the motor (Armature Voltage Variation). For example, a desktop AC power supply can rectify AC supply voltage and filter it to produce a variable DC voltage. Varying this voltage will change the speed of a motor. This can also be applied to a vehicle. If a battery has multiple cells, switches or relays can allow the cells to be connected in series to increase the operating voltage. If the motor needs to run faster, more switches can be turned on. This method of control is more expensive than the first method mentioned above, but is still very inexpensive and very reliable. There are some drawbacks to this particular form of control especially in vehicle applications. For example, this type of speed control would not use battery cells evenly, and so charging would be a more complicated process, and battery system efficiency would also be affected. These effects could be overcome with a smart charging system and a good battery management system, but further research would be needed to make a good judgment.

Another method of armature variation is referred to as Pulse Width Modulation (PWM) [18,33]. This is where a controller consisting of IGBTs pulse the power to the armature to vary the output. These controllers are more expensive than just using a resistor, but they are still cheaper than most AC controllers. PWM is a very efficient way of controlling DC motors.

The fourth method of speed control is referred to as field weakening. In this type of speed control, the strength of the magnetic field is weakened by adding a resistor in series with the windings of the field. The weakening of the field causes a decrease in Back EMF that is generated and so the motor speeds up. Typically field weakening is used to speed up the motor permanently. The use of field weakening as a variable speed control is yet to be investigated, and is one of the objectives of this research. If field weakening is a viable control method, then applying it to EVs would dramatically reduce the cost of the vehicle.

Although the control methods for DC motors are the same regardless of construction, the performance characteristics of wound DC motors depends very much on their construction. The field/armature arrangements can exist in four varieties as noted below. These varieties have similar cost and weight characteristics because they only are different in the wiring of their terminals.

2.5.1 Separately Excited

In separately excited motors the field and armature are connected to separate power supplies as shown in Figure 2.5 [12,20]. Unless otherwise specified, whenever the behavior of a shunt motor is described, the separately excited motor is included too [12].

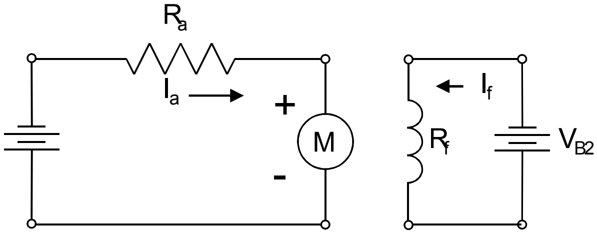


Figure 2.5: Schematic of a Separately Excited DC Machine

2.5.2 Shunt

Shunt-wound DC motors have the field connected in parallel with the armature as shown in Figure 2.6 [12,20]. This motor has natural speed governing characteristics. The speed of the motor is essentially controlled by the production of back EMF. When a load is applied to the motor, the motor begins to slow down; as this happens less back EMF is generated according to Equation (2.5). With less back EMF being generated, this allows the motor to pull more current to the armature which produces more torque, which again speeds up the motor to its original speed. In summary the DC shunt motor's characteristics make it a constant speed motor, even under no load. The field in a shunt motor is typically many turns of fine wire because the current flowing in the field is much smaller than that in the armature.

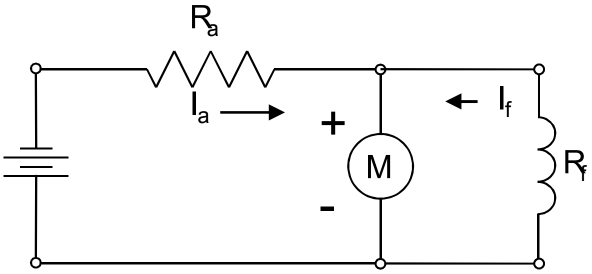


Figure 2.6: Schematic of a Shunt-Wound DC Machine

2.5.3 Series

Series-wound DC motors have the field connected in series with the armature as shown in Figure 2.7 [12, 20].

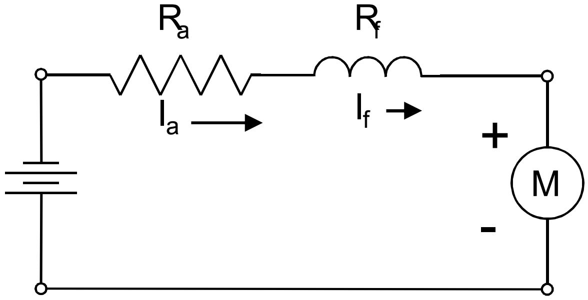


Figure 2.7: Schematic of a Series-Wound DC Machine

The series motor has a higher starting torque than the shunt motor. This is because during startup, the current flowing to the armature also flows through the field. As current flows through the field it increases the magnetic flux thereby giving the motor more starting torque. The disadvantage to this is that the field windings must be capable of handling the same current as the armature. This makes construction awkward because the wire has to be a larger diameter to handle the current without a lot of heat loss (see Equation (2.3)). Additionally the larger wire can be heavier and less malleable, which makes it difficult to bend into loops or turns. This means that the field winding in a series motor will be few turns of large wire as opposed to the shunt machine which is many turns of fine wire.

2.5.4 Compound

Compound-wound DC motors have two sets of field windings, one set is connected in series and the other set is connected in parallel with the armature as shown in Figure 2.7 [12,20].

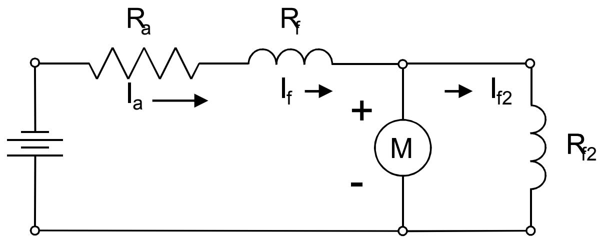


Figure 2.8: Schematic of a Compound-Wound DC Machine

Compound motors can be wired in a cumulative or differential manner. In a cumulative setup, current flows into the shunt and series windings to produce a greater positive magnomotive force. In a differential setup the shunt and series magnomotive forces subtract from each other. The cumulative compound motor's design allows it to have a hybrid effect of the series and shunt wound motors. It has better starting torque than the shunt motor, but less starting torque than a series motor. Additionally because of the shunt characteristics, this motor will not over speed while running with no load [12]. The differential compound motor is theoretically possible but is practically un-useful. The circuit setup makes it almost impossible to start such a motor. Additionally it draws more current in the armature while under load and the flux in the motor also decreases under load. This causes the motor to be very unstable and not suited for any application. A differential motor is never intentionally used, but a compound motor may turn differential if conditions allow it to happen. This implies that for vehicle applications, if a compound motor is used, precautions should be taken to ensure that compound motor will not turn differential. This precaution could be in the form of a reverse-power trip circuit that would kill power to the motor if flow in the field reverses [12].

2.6 DC Permanent Magnet Motors

Permanent magnet DC motors have permanent magnets that supply the field as shown in Figure 2.9 [12,20].

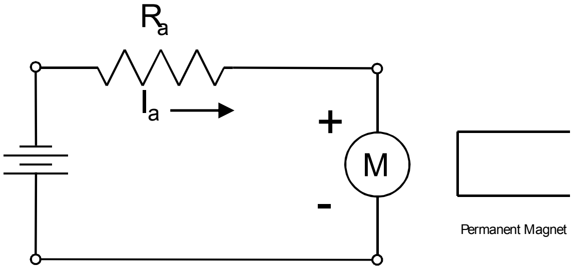


Figure 2.9: Schematic of a Permanent Magnet DC Machine

Because they use a permanent magnet field, these motors cannot be controlled using field weakening. Typical speed control is accomplished through pulse width modulation. Putting a resistor in series with the armature is also possible, but is very inefficient and normally not used. The advantage of the PM motor is that power from the batteries is no longer needed to power the field. This results in much better efficiency; typically PM motors will be in the 85-95% efficiency range.

The magnets used in PM motors are very capable of pushing iron into regions above saturation. Therefore a tremendous amount of starting torque is capable from these electric motors. This can be up to 300% of the rated torque of the motor for short periods. However, because of the use of permanent magnets, these motors are more susceptible to Curie temperature problems. Additionally, there is concern with PM motors that random vibrations and unintentional impact may cause magnetic moments in the material to become misaligned and therefore weaken the field strength over time.

2.7 Homopolar Motor

Of particular interest to this research group is the homopolar motor. Originating from Faraday's disk, the homopolar motor operates under the right hand rule principle, which states, as noted previously, that force is always orthogonal to the current flow and the magnetic field [34,35]. In this manner, this motor is unique in that it does not require any sort of commutation during operation. A simple DC current is enough to create the necessary environment for the motor to turn. This current is provided through brushes or slip rings [36].

The advantage of a homopolar motor is that it can be built to handle tremendous amounts of current. Subscale homopolar motors for naval ship applications have been tested to handle in excess of $30kA$, with the potential for even larger currents [36, 37]. This is of particular interest to the automotive industry because a low voltage system would require a motor that was capable of handling large amounts of current. Additionally, the lack of commutation means that there will be less arcing, and therefore a longer life on the brushes and contact ring, as well as overall life improvement for the motor.

Because of the strong correlation to magnetism, one area of development in homopolar motors is super conductivity. Cooling the motor, or parts of the motor, to cryogenic temperatures has desirable magnetic and electrical properties [38]. Methods are being developed to allow this technology to be applied to smaller applications and possibly even vehicle applications. Another development area of homopolar motors is the use of magnetically levitated bearings [39].

2.8 Wanlass Motor

Another area of interest to this research group is the Wanlass motor. This is also commonly known as an induction motor with run capacitors. The Wanlass motor was conceptualized by C.L. Wanlass during the late 1970's energy crisis. This concept offered theoretical energy savings in single phase induction motors by implementing a capacitor in series with the windings of the motor [40–42].

Testing performed by Rockfield and Mauldin, the DOE and Ensign and Marchbank concluded that the Wanlass motor did have efficiency improvements, but that it was highly dependent on correct capacitor choice. Their recommendations were that the capacitor be chosen on a case by case study. Huang, Fuchs and White developed a more analytical explanation as to why the motor performs better with the run capacitor [43].

According to them, the capacitor enables the current to change in magnitude and phase shift. This ultimately has the effect of improving the current densities in the windings of the motor. With more uniform current densities there are fewer copper losses which cause the overall efficiency of the motor to increase. This capacitor can be placed in the main or auxiliary windings, but each option has advantages and disadvantages which should be taken into consideration when designing a Wanlass motor. With a correctly sized capacitor, Huang et al. were able to improve motor efficiency of a single phase induction motor by 11% for a total motor efficiency of 88.2% [43].

Over time the concept of the capacitor run motor has also evolved to include a capacitor start motor, as well as implementation to three phase induction motors [44]. Some critics who were skeptical of the improvements that the Wanlass motor claims, modified the design further to include other variations [45]. In particular the Unity Plus Method of winding was also introduced as a substitute for the Wanlass method [46].

Because Wanlass motors use extra capacitors, they do have more initial cost associated with them. However, the pay back period of a Wanlass motor is typically within a few years of operation [43]. For automotive applications the Wanlass addition could be beneficial in increasing the performance of induction motors that are already being used in production vehicles.

2.9 Safety

Because the proposed research intends to increase the safety of electric vehicle powertrain in general, it is appropriate to discuss the factors affecting safety in an electric vehicle powertrain.

2.9.1 Direct Dangers

One of the direct dangers of electric vehicles is the risk of electrical shock. The danger in electrical shock is the current that passes through the body. Current can cause pain, injury and even death depending on the amount and the path of the current through the body. Table 2.2 shows the physical sensation associated with various amounts of current [47].

Table 2.2: The Physical Effects of Electric Currents

Current (mA)	Physical Sensation
<3	Not Sensed
3-10	Mild Sensation
10-20	Painful
20-30	Cannot let go
30-40	Muscular paralysis
40-100	Severe shock, can be fatal
100-200	Usually fatal
200-1000	Severe burns, breathing stops, often fatal
>1000	Dismemberment

The amount of current that actually flows through the body is dependent on the applied voltage and the resistance to current flow of the body. This is often referred to as Ohm's Law of Safety and is represented in Equation (2.6).

$$I = E/R \tag{2.6}$$

This equation demonstrates why signs often read 'Danger High Voltage'. The higher the operating voltage the greater the potential for higher current flow through the body [47]. When dealing with high voltages, precautions are often taken to increase the resistance of the body. This includes things like wearing high resistance gloves, sealed shoes and making sure the workers' hands are dry [48, 49]. Safety standards also recommend using only one hand while working on the vehicle, but this can be cumbersome for the technician. Because the average resistance of a human body including skin ranges from 1000Ω to 10000Ω, less than 60V is considered a safer point of operation.

2.9.2 Indirect Dangers

Indirect dangers of working on electric vehicles are falls, fires, explosions and malfunctions [47]. Particularly in an automotive environment, fires and explosions can happen in short circuits when components fail or cables touch. In this event, excessive current heats up the surroundings, igniting flammable materials. With brushed motors, arcing occurs between commutator segments, especially at high speeds. This can be another source for igniting combustible materials. Motors under operation tend to get hot and this too can be a cause for injury. The inference of this is that motors should be located away from combustible materials and insulated with non flammable materials. If motors will become hot from operation, they should be located so that they cannot be touched by an unknowing consumer, or at least insulated so that burns are not as likely.

When working with wound motors there exists a special danger in the instance of loss of field. If for some reason the field is lost then the amount of back EMF that is generated goes to zero. This causes a tremendous amount of current to flow into the armature which increases the motor speed rapidly. Chapman provides an example of this from his own life in his Electric Machinery Fundamentals text:

> The result of an open field circuit can be quite spectacular. When the author was an undergraduate, his laboratory group once made a mistake of this sort. The group was working with a small motor-generator set being driven by a 3-hp shunt DC motor. The motor was connected and ready to go, but there was just *one* little mistake - when the field circuit was connected, it was fused with a .3-A fuse instead of the 3-A fuse that was supposed to be used.
>
> When the motor was started, it ran normally for about 3s, and then suddenly there was a flash from the fuse. Immediately the motor's speed skyrocketed. Someone turned the main circuit breaker off within a few seconds, but by that time the tachometer attached to the motor had pegged at $4000 RPM$. The motor itself was only rated for 800 RPM. Needless to say, that experience scared everyone present very badly and taught them to be *most* careful about field circuit protection [12].

For vehicle applications this situation could be devastating; therefore, if a wound DC motor is used in a vehicle, it should also incorporate a precaution like a field loss relay that kills power to the motor in the case that the field ever loses power.

CHAPTER 3. METHOD

This chapter will describe the objectives and methodology used to test and investigate various motor and CVT/IVT characteristics. Much of the time spent during this research was in developing a testing procedure, writing code and acquiring the testing equipment. Because the method of testing used in this research is applicable to many types of motors and CVT/IVT testing, it is the hope of the author that by outlining this experiment in detail, future testing may be accomplished more quickly. The objective of this chapter is to provide sufficient detail that will allow any researcher the ability to recreate the testing setup, with minimal investment in code development and hardware compatibility analysis.

3.1 Objectives

The objectives of the experiment were to:

1. Develop a motor testing setup and identify instrumentation that could be used to measure motor performance.
2. Test motor controlling methods such as armature voltage variation and field voltage weakening to see how they could be applied to EVs and hybrid vehicles.
3. Verify analytical models for predicting performance of a continuously or infinitely variable transmission.

3.2 Experiment Overview

Two sets of experiments were performed. The first set of experiments involved understanding motor characteristics. These experiments were used to verify information obtained in the literature review, as well as gain a deeper understanding of motors with wound fields. By constructing this table top experiment it was possible to gain insight into the performance of a separately excited shunt wound DC motor. In this experiment two identical motors were set up as shown in Figure 3.1 and were tested by varying the voltage in the armature and the field, both while under load and with no load. Data on the voltage, current, RPM and torque were measured and then analyzed.

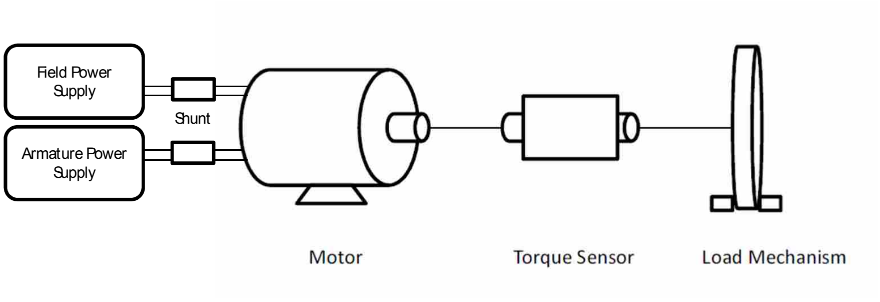


Figure 3.1: Motor Testing Setup

The second set of experiments involved testing with a differential to simulate a continuously variable transmission. These experiments were designed to help understand how a DC shunt motor may be best suited for application with a continuously variable transmission. A secondary objective of this experiment was to verify equations derived by Wells which were intended to predict output torque and RPM based on various inputs. To accomplish this, two motors were hooked to a differential as shown in Figure 3.2, and the voltages in the field and armature were varied. The output torque and RPM of this system were measured and the performance of the system was observed.

The differential testing setup was more complex, and therefore it will be described in more detail below. The differential setup included all of the hardware and software that was used in the motor testing experiments.

3.3 Hardware

In order to gain the desired insight from the experiment, voltage and current needed to be measured in each motor, in both the field and the armature. The RPM of each motor also needed to be determined in addition to the torque of the output shaft of the differential. In total this required that 4 Voltages, 4 Currents, 3 RPMs and 1 Torque be measured in the system. To make this possible, the following hardware was needed for the experiment:

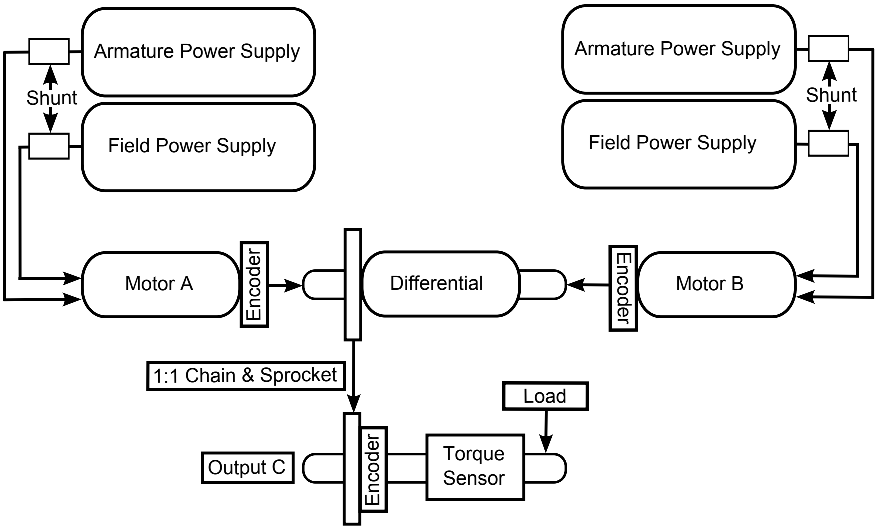


Figure 3.2: Differential Testing Setup [7]

- National Instruments cRIO (1)
- National Instruments Modules (4)
- DC Shunt Wound Motors (2)
- Differential (1)
- Power Supplies (4)
- Braking Mechanism (1)
- DC Shunt (4)
- Encoders (3)
- Independent Power Supplies (4)
- Torque Sensor (1)

The hardware was setup as shown in Figure 3.3. Components were used from the Mechanical Engineering, Physics and Electrical Engineering Departments at Brigham Young University. The location of testing was in a space acquired in the northwest corner of building B-38 on the university campus.

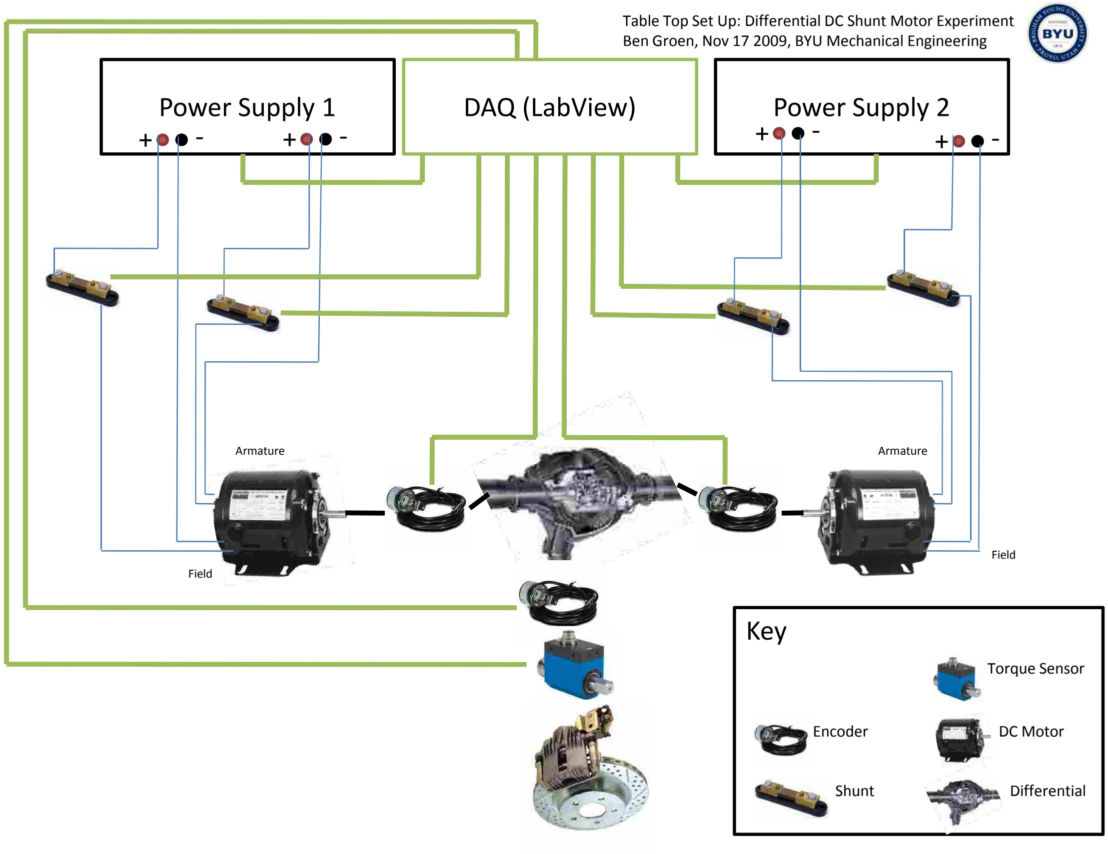


Figure 3.3: Experiment Layout

3.3.1 National Instruments cRIO

The National Instruments' cRIO was selected because of its versatility and availability. This device works as an interface with the LabView program and is a data collection point for all of the instrumentation. This device, with the aid of the software, takes the raw voltages from the sensors and power supplies and converts this to useful information. The cRIO is also the physical location where data are stored during testing. The on-board clock of the Field Programmable Gate Array (FPGA) was capable of measuring responses up to $40MHz$. This resolution was especially necessary due to the high frequency of pulses delivered by the encoders at high RPMs. Additionally the re-programmable features of the FPGA allowed for easier modification of the code. The cRIO also used plug-in modules that could interface with hardware for data acquisition.

3.3.2 Modules

As depicted in Table 3.1, four modules were used in the experiment with the following specifications:

Table 3.1: National Instruments cRIO Modules Used in Experiment

Module	**Quantity**	**Av. Channels**	**Measurement**	**Connection**	**Voltage**
9219	1	4	Voltages	Wire	$+/-60V$
9219	1	4	Currents	Wire	$+/-60V$
9401	1	8	RPM	D Pin	$+5V$
9237	1	4	Torque	Ethernet	Var. Excit.

3.3.3 Motors

Two identical DC Shunt-wound motors, shown in Figure 3.4, were used for this experiment. The motors were first independently tested to ensure that they had the same performance characteristics. The motors also had high and low voltage settings, which were both tested. For most of the testing the motors were configured to accommodate the lower voltage setting which worked better for the power supplies that were used. Table 3.2 gives the specifications of the motors that were used.

Table 3.2: Specifications of Motor Used
in Table Top Experiment

Parameter	Specification
Manufacturer	Century Electric
Arm Voltage	$90V$
Arm Current	$2.69A$
Field Voltage	100/50
Field Current	$.32/.64A$
Power	1/4 HP
Max RPM	1750
Part	6-217375-01
Frame	B56C

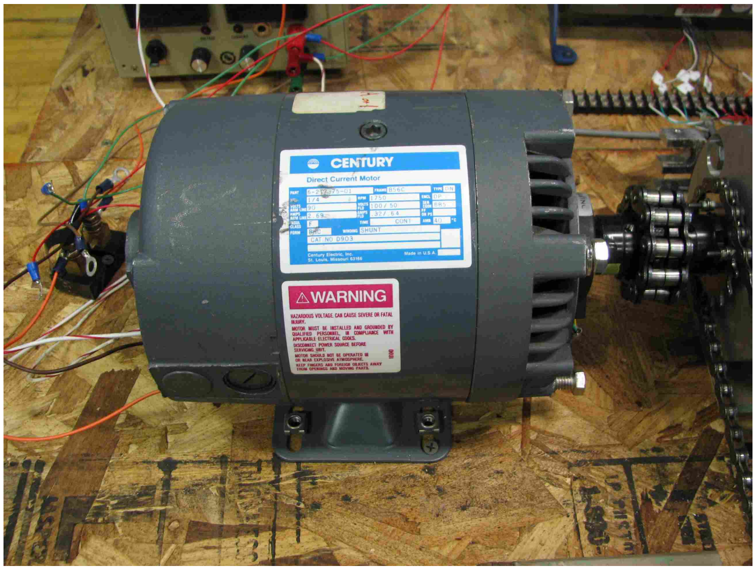


Figure 3.4: DC Shunt Wound 1/4 HP Motor Used in Testing

3.3.4 Differential

A differential from an SAE Formula Vehicle was used. The manufacturer was JTEKT Torsen North America INC model: 012000 or M021-DHU. This differential had a gear ratio of 1:1 and was collinear in its configuration. The differential that was used was a Gleason-Torsen differential, which used a helical gear set as pictured in Figure 3.5.

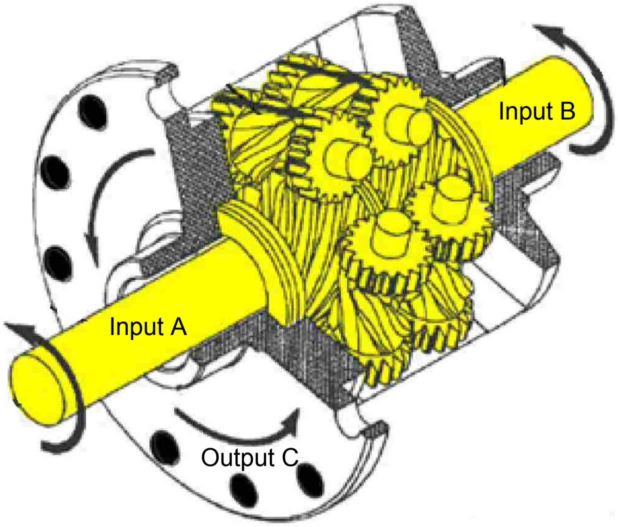


Figure 3.5: Gleason-Torsen Differential [1]

3.3.5 Power Supplies

Two types of power supplies were used. The first type of power supply was a Mastech two channel $30V-3A$ power supply model No:TE HY3003F3, which was used to power the field of each motor. Because this type of power supply could only put out a maximum of $30V$ and $3A$ per channel, the two channels were hooked up in series to add the voltages, thereby allowing the power supply to produce a total of $60V$ at $3A$. Voltage was regulated manually by means of the controls on the power supply. The second type of power supply was a single channel Electronics Manufacturing Inc. HCR150-2-110. This power supply produced up to $150V$ at $3A$ and was used to power the armature of each motor. Voltage was regulated manually by means controls on the power supply. Power for the sensors came through a dedicated fixed $+5V$ channel on the power supplies.

Both power supplies had current limiting features. This current limit was utilized during the experiment to protect the equipment and the motors from receiving too much current. The armature current limit was set at approximately 2.7 Amps and the field current limit was set at .69 Amps.

3.3.6 Braking Mechanism

To load the motor, a braking mechanism was used. This mechanism consisted of brake pads that were applied to a rubber rotor. These brake pads were applied by hand while the operator monitored the applied load via the LabView program. To avoid problems with chatter, the tests were performed at lower speeds that would minimize chatter. The brake pads were also carved to match the contour of the rotor. Additionally the operator stabilized the brake pads by resting them on block near the rotor surface.

3.3.7 Sensors

Encoders

Three identical encoders were used to measure the RPM of each motor. Their specifications are listed in Table 3.3. These encoders had two optical channels that measured counts. This was necessary for the quadrature encoding described in section 3.4.1. An index channel was also available on the encoders, but was not used because position of the encoder shaft was not needed for any analysis.

Table 3.3: Specifications of Encoders Used in Experiment

Parameter	Specification
Pulses Per Revolution	1000
Type	Optical Quadrature
Supply Voltage	$+5V$
Frequency Response	$100KHz$
Output Type	Voltage
Quantity	3

Torque

The torque sensor that was used had specifications as shown in Table 3.4.

Table 3.4: Specifications of Torque Sensor Used in Experiment

Parameter	Specification
Type	Slip Ring
Measurement Method	Angular Deflection
Excitation Voltage	$+5V$
Calibration	$2mV/V_{exc}$
Max torque	$20\ NM$

Current

To measure the current, four DC shunts were used. These operate under the principle that by measuring the voltage drop across a known resistance, the current in the circuit can be calculated. This relationship is also linear and can therefore be interpolated using scaling factors to find the measured current. In this experiment, shunts rated at $10A = 50mV$ were used. Shunts were all connected on the positive side of the motor for consistency. Two leads from each terminal measured the voltage drop across the shunt, which was scaled by LabView to convert the output voltage to a current.

Voltage

The 9219 module was capable of handling voltages accurately up to $+/-60V$. This module is also designed with redundant systems that protect the components should it be exposed to $> 60V$. Because of this, leads from the terminals of the power supplies were connected directly to the inputs on the module to measure voltage. During testing, care was taken to ensure that the voltage during testing was less than $60V$. By keeping the motor supply voltage below $60V$ it was then possible to read the voltage directly into LabView without the need for a voltage divider.

3.3.8 Completed Assembly

Once all of the hardware was collected it was assembled as shown in Figure 3.6. This setup allowed the operators access to control and monitor the various components during testing.

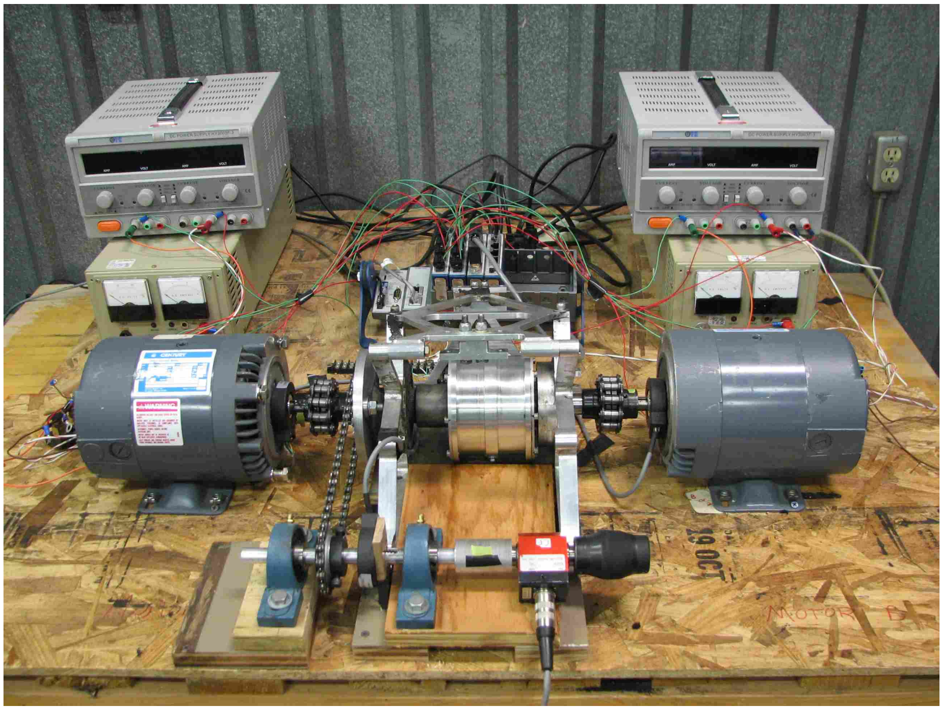


Figure 3.6: Picture of Experimental Setup Including all Components

3.4 LabView Code

3.4.1 FPGA

With the motor capable of running at 1750 RPM, and the encoder having 1000 pulses per revolution (PPR), it was necessary to utilize the $40MHz$ clock of the FPGA in order to determine actual RPM. The FPGA program first used boolean logic to determine when the encoder had a count. A count is the rising or falling edge of the encoder signal. Because the encoder can measure the rising and falling edges of the signal, it allows the encoder to have twice the resolution per channel. When two channels are separated by an offset, it was possible to utilize quadrature encoding. In essence, when the channels are offset as shown in Figure 3.7, the overall resolution of the encoder can be increased to four times the listed resolution. Quadrature encoding also allows the direction of rotation to be calculated, based on which signal rises or falls first [50].

Using the on-board clock of the FPGA it was possible to determine the duration between counts. As illustrated in Figure 3.8, a time stamp was made at each count and the time per count was calculated by subtracting the current time from the time of the previous count. This value was measured in ticks of the on board clock, which was eventually converted to seconds. The final value output to the display was in revolutions per second. This code was duplicated two times so that a total number of three loops were executed simultaneously, one for each encoder.

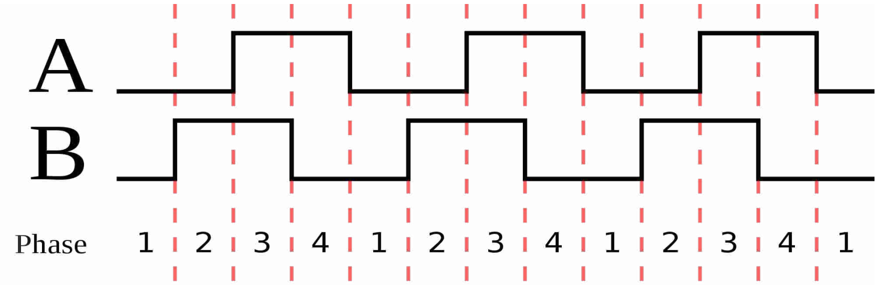


Figure 3.7: Quadrature Encoding [8]

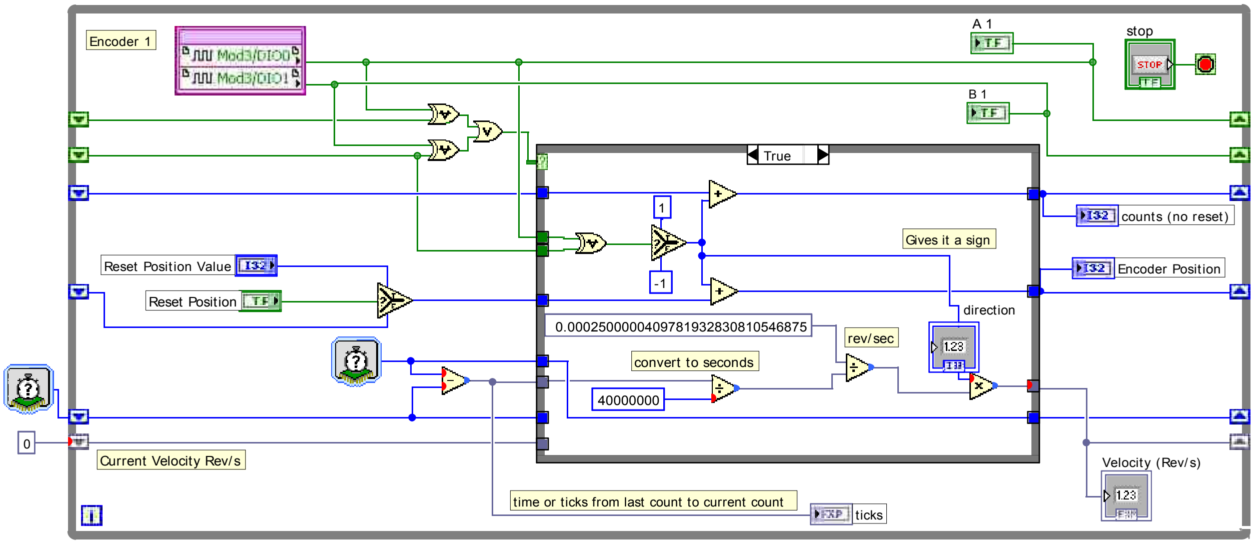


Figure 3.8: FPGA Block Diagram

3.4.2 Block Diagram (Real Time)

The real time component of the LabView program was designed to make testing, data acquisition and data interpretation easy. As shown in Figure 3.9, upon initial execution, the program displayed each variable on the front panel. Once the operator verified all sensors were operational, data acquisition could begin. Data acquisition was accomplished through the use of one data acquisition button located on the front panel. During data acquisition the program was designed to grab the value of each variable, once per loop, and store that value into an array. The operator specified the number of data points via a dialog box on the program display. Once the desired number of data points were gathered, the loop could be terminated, which would cause the program to move to the next sequence of the program.

The next sequence took the array, inverted it, and added column headings. It then took the array and output to a file on the cRIO server, which could then be imported into Excel for interpretation. The data acquisition button was designed so that it could only be clicked once until all of the desired data acquisition had been completed. Shift registers were employed to store data between loop executions. Other tools like the verification array, filename output and case structures for the graphs were for convenience for the operator.

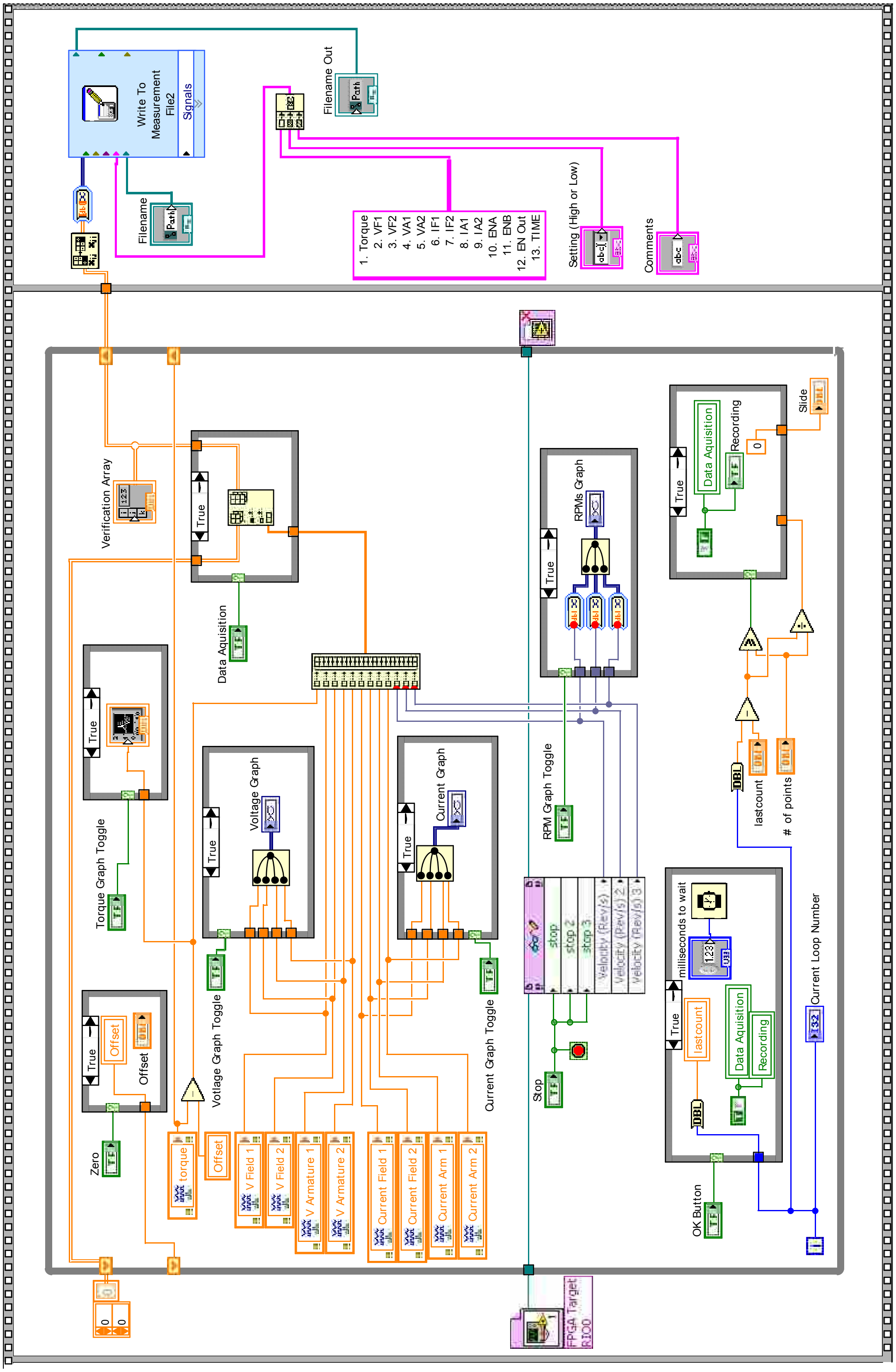
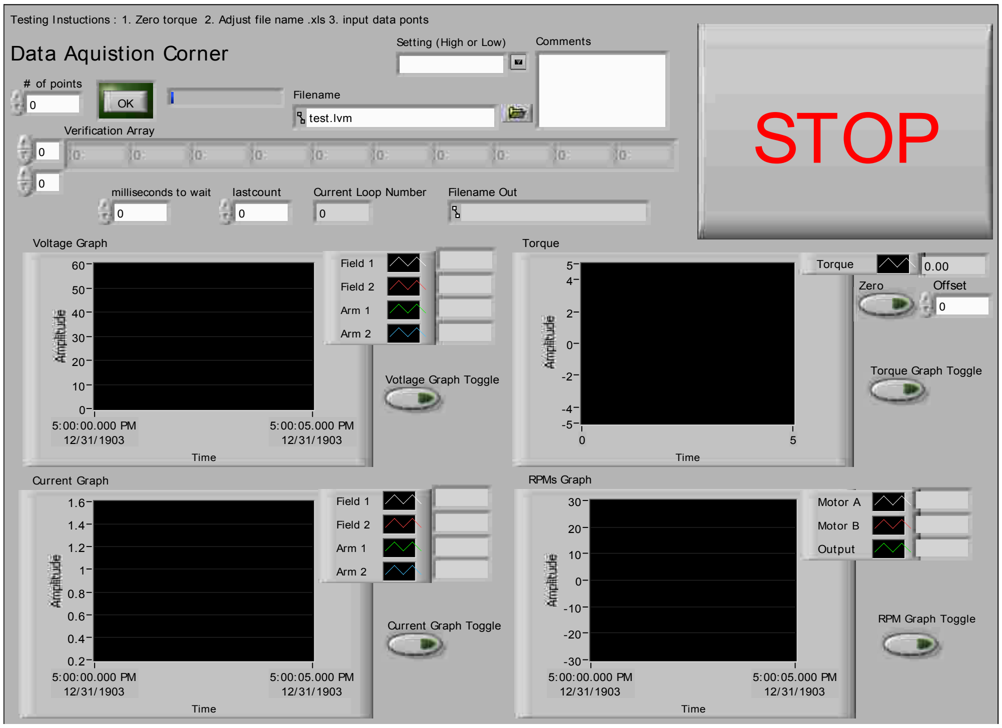


Figure 3.9: Real Time Block Diagram

3.4.3 Front Panel (Real Time)

The front panel of the LabView program was also designed to make testing intuitive and easy to operate. The upper portion of the front panel allowed the tester to input important parameters such as, which motor was being tested and what configuration it was in. There was also an area for extra comments if the user needed to put any relevant information or observations. After input, this information was appended to the actual data file that was created, so that each test could be easily identified. Each variable was displayed on a graph that could be turned on and off. In total there were four graphs representing the four areas of data acquisition: Voltage, Current, Torque and RPM. Certain other features were included such as: a progress bar for use during data acquisition, a large emergency stop button and a verification array. As pictured in Figure 3.10, the layout of the front panel was designed such that the user would never have to scroll to operate the program.



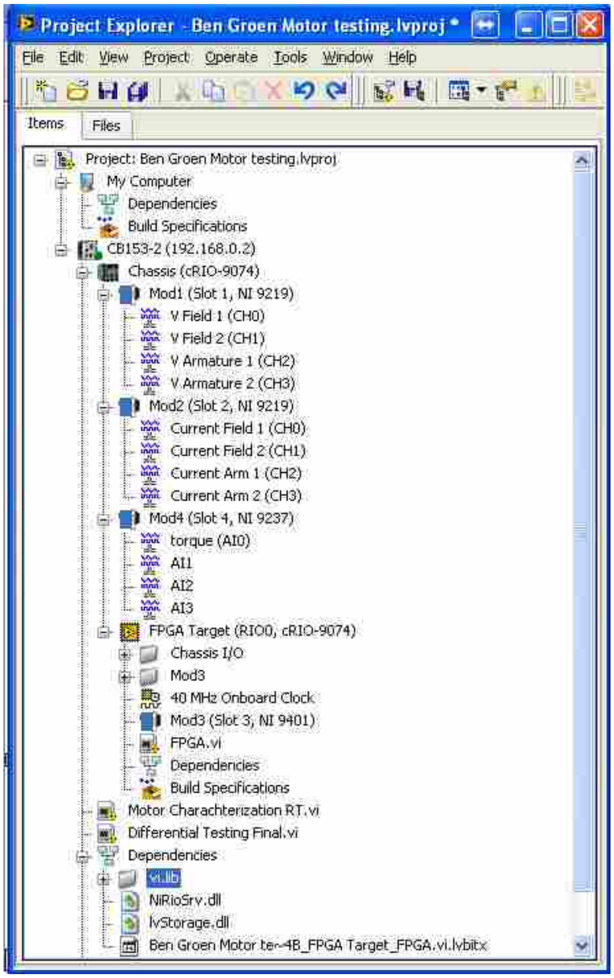
Testing Instuctions : 1. Zero torque 2. Adjust file name .xls 3. input data ponts

Filename: test.lvm

Figure 3.10: Real Time Front Panel

3.4.4 Project Settings

Scaling factors and excitation voltages had to be set in the project window. Additionally, all channels on the modules were labeled in the project window during wiring and to reduce confusion. Figure 3.11 shows the respective variable assignments for each channel. In this project window the excitation voltage for the torque sensor was also set. Originally $10V$ was assigned to this sensor, but upon measurement it was observed that $10V$ was not actually being delivered to the sensor, and the excitation voltage was changed to $5V$ which performed much better. The scaling factors for the torque sensor and DC shunts were also input for their respective module properties. The voltages could be read directly without scaling factors, but the properties of the module had to be set to allow voltages of up to $+/-60V$.



- Project: Ben Groen Motor testing.lvproj
  - My Computer
    - Dependencies
    - Build Specifications
  - CB153-2 (192.168.0.2)
    - Chassis (cRIO-9074)
      - Mod1 (Slot 1, NI 9219)
        - V Field 1 (CH0)
        - V Field 2 (CH1)
        - V Armature 1 (CH2)
        - V Armature 2 (CH3)
      - Mod2 (Slot 2, NI 9219)
        - Current Field 1 (CH0)
        - Current Field 2 (CH1)
        - Current Arm 1 (CH2)
        - Current Arm 2 (CH3)
      - Mod4 (Slot 4, NI 9237)
        - torque (AI0)
        - AI1
        - AI2
        - AI3
      - FPGA Target (RIO0, cRIO-9074)
        - Chassis I/O
        - Mod3
        - 40 MHz Onboard Clock
        - Mod3 (Slot 3, NI 9401)
        - FPGA.vi
        - Dependencies
        - Build Specifications
    - Motor Charachterization RT.vi
    - Differential Testing Final.vi
    - Dependencies
      - vi.lib
      - NiRioSrv.dll
      - lvStorage.dll
      - Ben Groen Motor te~4B_FPGA Target_FPGA.vi.lvbitx

Figure 3.11: Project Window

3.5 Wiring

To reduce possible confusion, color coordinating was used during wiring, and components were connected using a terminal block. For consistency, shunts were always connected on the negative side of the motor. Figure 3.12 shows the complete setup with wiring.

3.6 Calibration and Troubleshooting

Upon completion of programming and compiling, the entire system was checked and verified to make sure that sensors were reading accurately and functioning properly. Torque sensors were compared and verified using a calibrated torque wrench, and RPMs were verified with a strobe meter. Voltages and currents were verified with a digital multi-meter.

During troubleshooting errors were corrected, and measures were taken to improve program performance. For example, during one of the first executions it was observed that the loop time on the program was extremely slow when all of the graphs were turned on. This was a problem because it took more than a minute to gather 100 data points. This introduced extra variation especially because it was difficult for the operator to apply the load consistently over such a long period of time. At this point the graph toggles were added to the program so that the graphs could be turned off for more speedy data acquisition.

3.7 Testing Procedures

The motor characterization tests were performed first and then the setup was modified to accommodate motor testing with the differential. Tests were designed to stay within safe operation limits and within bounds that the equipment could measure. The experiments were performed with the motor loaded, not loaded, and at a variety of operating voltages. A complete list of the tests performed is included in Table 4.1.

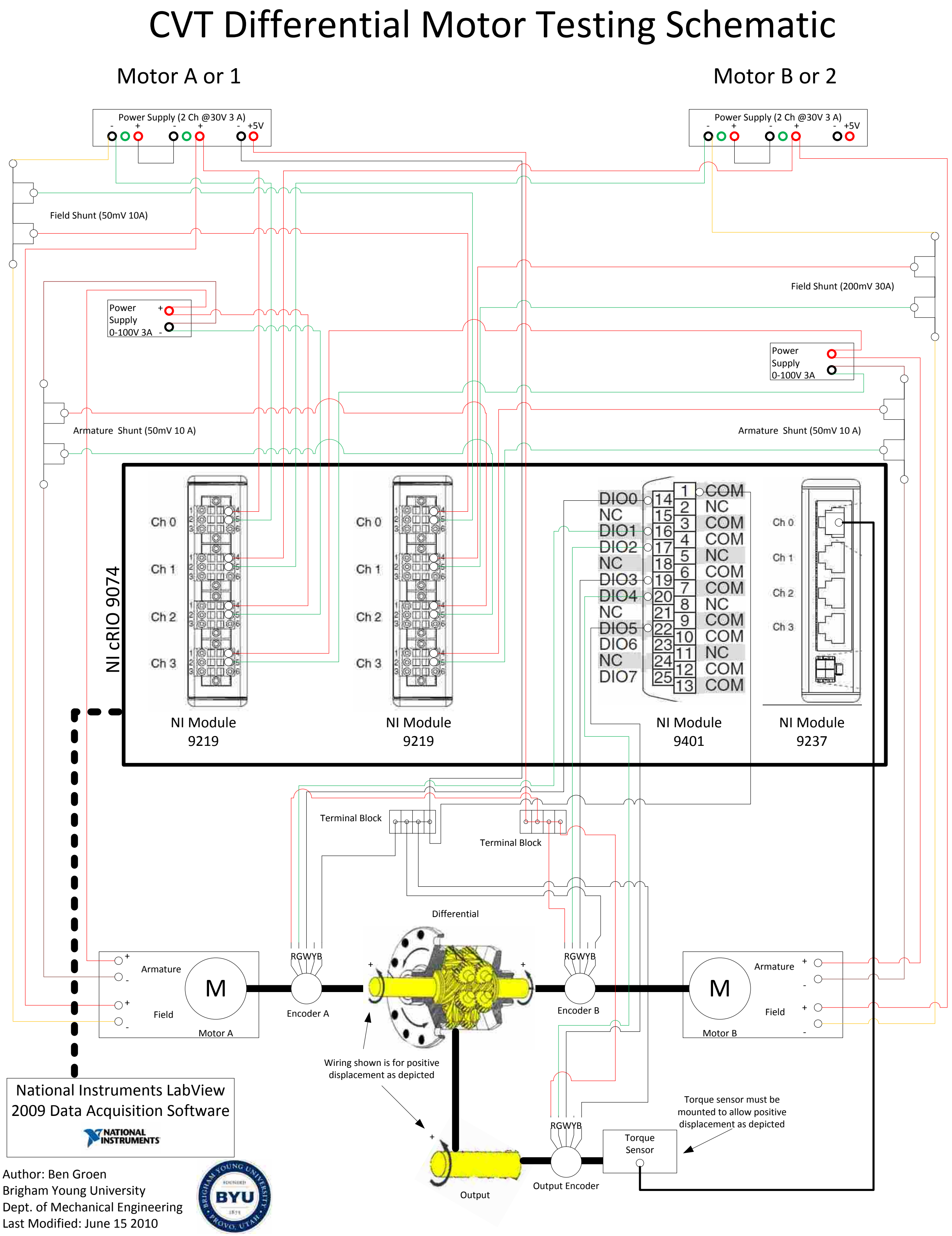


Figure 3.12: Final Experiment Wiring

CHAPTER 4. RESULTS

4.1 Literature Review Results

Since the objective of the literature review was to gain a better understanding of types of electric motors and their performance, a document summarizing the performance and construction characteristics of several motors was constructed. This was accomplished in the form of a comparison chart which can be found in Appendix A Figures A.1, A.2 and A.3. This chart compares key characteristics that are relevant specifically to electric vehicle design [10–13].

A motor hierarchy chart, shown in Figure 4.1, was also created to help summarize motor families and construction. This chart will enable users to understand the variety of motors that exist. Additionally, because motor performance is largely based on construction, this chart will allow users to more easily identify alternate options for various applications [13, 14, 51].

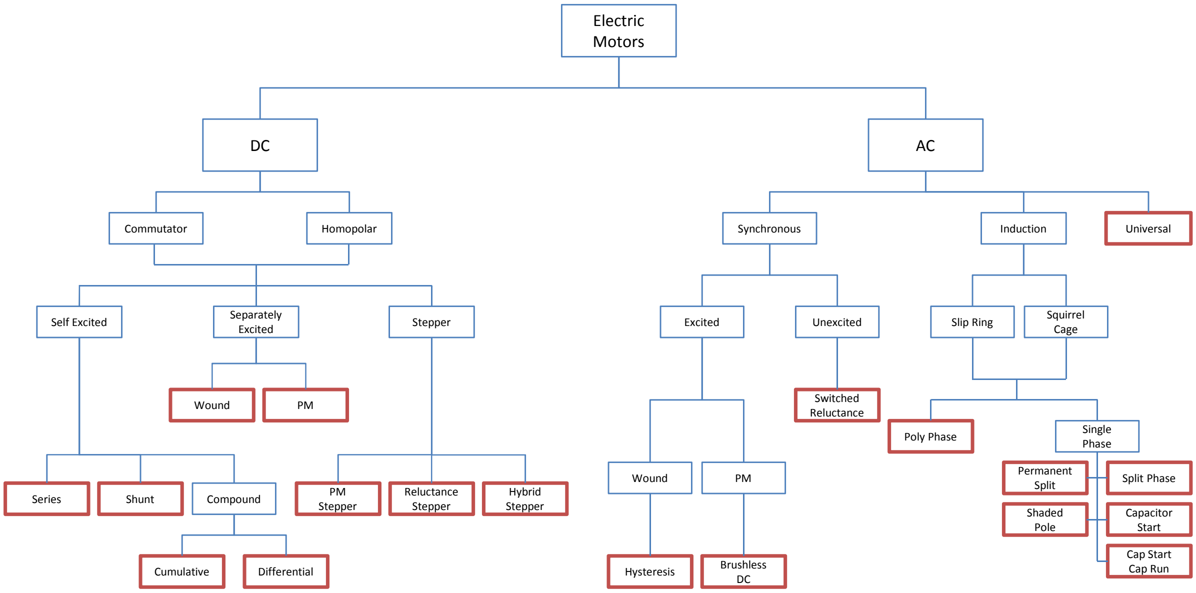


Figure 4.1: Motor Hierarchy

4.2 Testing

Motor testing with the separately excited motors was performed first. This was done to characterize the motors, and determine if the motors performed equally. This testing involved varying the field and armature voltage of the motors while measuring the speed and current draw of the motors. Upon completion of the motor characterization tests, the setup was modified to perform the differential testing. During differential testing the armature and field voltages were varied while under several different loads, with the motors spinning in opposite directions and then in the same direction. Table 4.1 identifies each of the tests that were performed, and the conditions for that test.

4.3 Separately Excited Motor Testing Results

4.3.1 No Load Testing

Armature Voltage Variation

This included tests M1 and M2 which were designed to understand how varying the armature voltage affected motor speed. During this test, the motor was not loaded, and the field voltage was fixed at 60V. Figure 4.2 shows that varying the armature voltage has a direct linear relationship with the speed of the motor. When comparing motor A to motor B it can be observed that both motors had the same trend.

Field Voltage Variation (Field Weakening)

This included tests M3 and M4 which were designed to understand how field weakening affects motor speed. Since actually changing the resistance of the field would have required modification to the motor, the voltage provided to the field was varied instead using the power supply. This method has the same result as field weakening based on Ohm's Law in Equation (2.6). During this test, the motor was not loaded, and the armature voltage was fixed at $60V$. Figure 4.3 shows that varying the field has a nonlinear relationship with the speed of the motor. As the field is weakened, there is an increasing change in motor speed. When comparing motor A to motor B it can be observed that both motors had the same trend.

Table 4.1: Summary of Tests Performed

Test No.	Description	Motor A Rotation	Motor B Rotation	Load Location	Motor A Field V.	Motor A Arm Voltage	Motor B Field V.	Motor B Arm Voltage
Motor Testing No Load								
M1	Motor A Arm Var.	+	N/A	None	$50V$	$0V - 50V$		
M2	Motor B Arm Var	N/A	+	None			$50V$	$0V - 50V$
M3	Motor A Field Weakening	+	N/A	None	$0V - 50V$	$50V$		
M4	Motor B Field Weakening	N/A	+	None			$0V - 50V$	$50V$
Motor Testing Loaded								
M5	Motor A Arm Var.	+	N/A	MotorA	$50V$	$10V - 50V$		
M6	Motor A Field Weakening	+	N/A	MotorA	$20V - 40V$	$50V$		
Differential Testing								
D1S	CVT Same Dir.	+	+	Output	$50V$	$30V$	$50V$	$0V - 50V$
D1O	IVT Opposite Dir	+	-	Output	$50V$	$30V$	$50V$	$0V - 50V$
D2S	CVT Same Dir	+	+	Output	$50V$	$50V$	$50V$	$0V - 50V$
D2O	IVT Opposite Dir	+	-	Output	$50V$	$50V$	$50V$	$0V - 50V$
D3S	Constant Ratio Same Dir.	+	+	Output	$50V$	$0V - 50V$	$50V$	$0V - 25V$
D3O	Constant Ratio Opposite Dir.	+	-	Output	$50V$	$0V - 50V$	$50V$	$0V - 25V$
D4	Load Test Crossover	+	+/-	Output	$50V$	$30V - 50V$	$50V$	$^{-}60V - 50V$
D5	Speed Testing Armature Var.	+	-	None	$50V$	$30V$	$50V$	$0V - 60V$
D6	Speed Testing Field Weakening	+	-	None	$50V$	$50V$	$0V - 50V$	$15V$

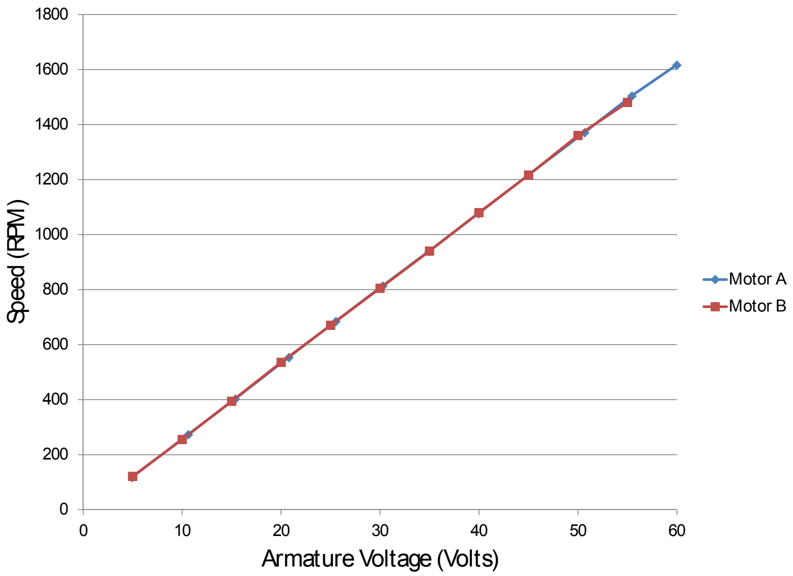


Figure 4.2: Motor Speed Control Using Armature Variation (Tests M1 and M2)

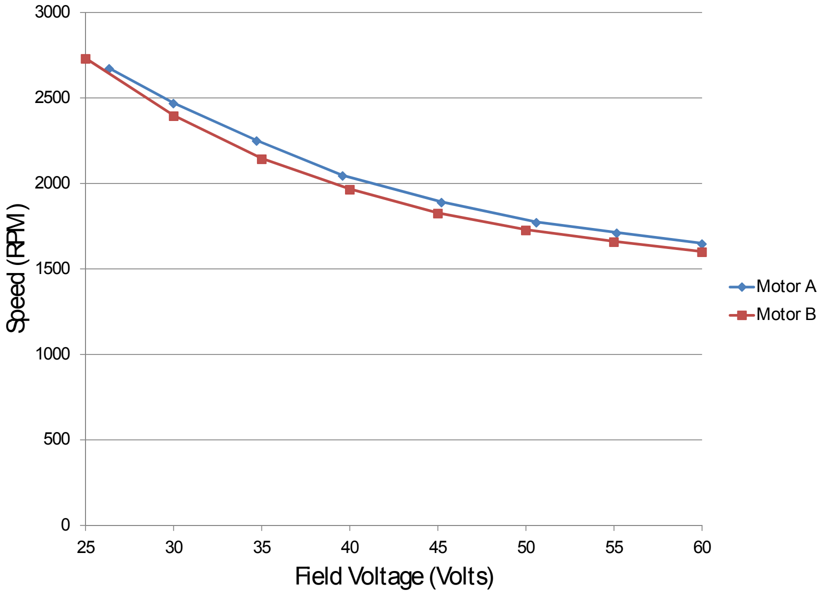


Figure 4.3: Motor Speed Control Using Field Variation (Tests M3 and M4)

As can be seen in the figures referenced above, the motors performed with approximately the same characteristics. Motor testing beyond this test was then only performed on one motor to save time and resources.

4.3.2 Loaded Testing

By loading the armature with a certain resistive torque, it was possible to see how much current the motor pulled in the field and the armature. This test was performed both while the armature voltage was varied and while the field voltage was varied.

Armature Voltage Variation

This test corresponds to test M5. During each run of this test the motor was loaded at approximately 1 $in \cdot lb$, 3 $in \cdot lb$ and 5 $in \cdot lb$. Three runs were made, the first run with the armature at $50V$, Run 2 was at $30V$ and Run 3 was at $10V$. The results of loading the motor while varying the armature voltage are shown in Figure 4.4. This figure shows that the current increased in the armature proportionally with the load, but the current in the field remained constant.

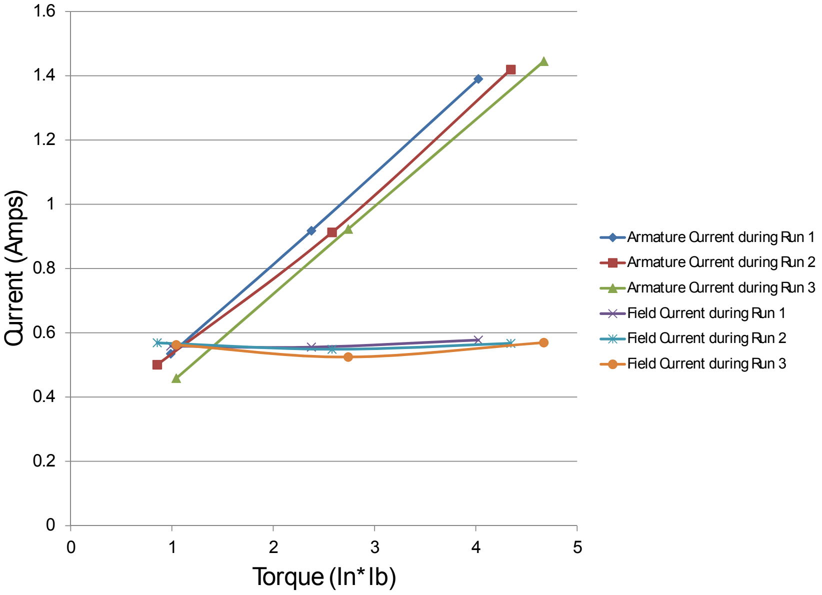


Figure 4.4: Loading with Armature Variation (Test M5)

Field Voltage Variation (Field Weakening)

This test corresponds to test M6. This test was performed in the same manner as the test described in 4.3.2, only the voltage in the field was changed for each run. Run 1 had a field voltage of $40V$, Run 2 was at $30V$ and Run 1 was at $20V$. Again the current increased in the armature proportionally with the load, but the current in the field remained constant.

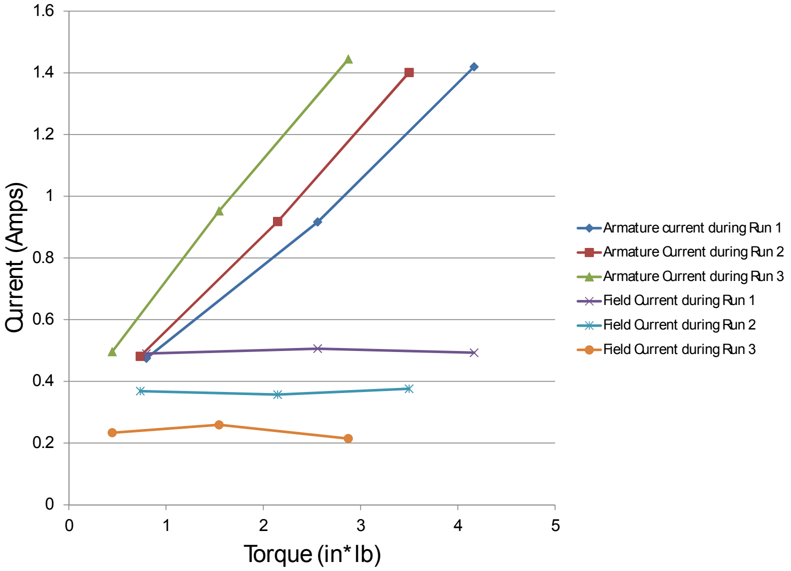


Figure 4.5: Loading with Field Variation (Test M6)

4.4 Differential Model Results

Research in conjunction with Dax Wells yielded two important equations predicting CVT/IVT performance. The first equation that came as a result of Wells's research, predicted that the output RPM of a CVT in the form of a differential, is simply an average of the inputs. This is shown in Equation(4.1).

$$RPM_{out} = \frac{RPM_A + RPM_B}{2} \tag{4.1}$$

The second equation discovered by Wells explains the power relationships between the three I/O's of the differential gear set, and is shown in Equation (4.2).

$$T_A * RPM_A + T_B * RPM_B + T_{out} * RPM_{out} = 0 \tag{4.2}$$

This equation can be rearranged to solve for the output torque as shown in Equation (4.3).

$$T_{out} = \frac{-T_A * RPM_A + T_B * RPM_B}{RPM_{out}} \tag{4.3}$$

Substituting the RPM_{out} found in Equation (4.1) into Equation (4.3) the output torque can be solved for, as shown in Equation (4.4).

$$T_{out} = \frac{-T_A * RPM_A + T_B * RPM_B}{\frac{RPM_A + RPM_B}{2}} \tag{4.4}$$

4.5 Differential Speed Testing Results (No Load)

The setup was completed as described in Chapter Three. Once the setup was calibrated and confirmed to be reading accurate results, the testing commenced and the following results were obtained.

4.5.1 Armature Voltage Variation

The results of test D5, shown in Figure 4.6, revealed that the armature voltage variation method performed exactly as predicated by the theoretical model. The output speed of rotation is simply calculated by an average of the two inputs. Because armature variation was used, the speed change is linear just like in motor testing.

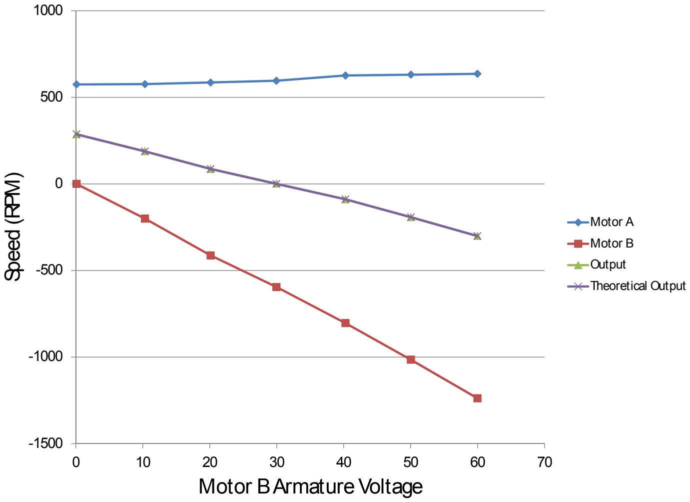


Figure 4.6: Differential Speed Control Using Armature Variation (Test D5)

Furthermore, if the polarity of the motor is switched as in Test D4, it is possible to get a wider range of speed control, allowing the differential to perform very much like an IVT. The results from this test are shown in Figure 4.7.

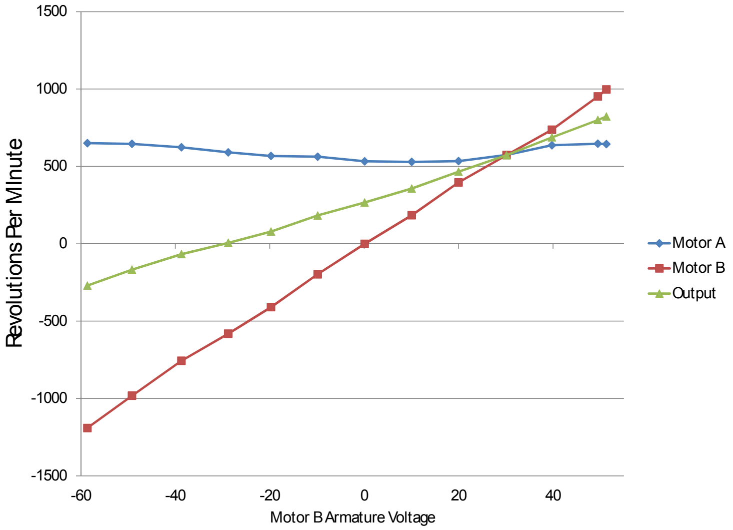


Figure 4.7: IVT Speed Control of a Differential (Test D4)

4.5.2 Field Weakening

The results of test D6, shown in Figure 4.8, revealed that the field weakening method of speed control also performed exactly as predicted by the theoretical model. The output speed of rotation is still calculated by an average of the two inputs. However, because field weakening was used, the speed change is nonlinear. The rate of change is increased at the extremities.

4.6 Differential Torque Testing Results (Loaded)

As part of this research, tests D1S, D1O, D2S, D2O, D3S and D3O were performed cooperatively with Dax Wells. These test results are examined in his thesis, but the conclusions are relevant to this thesis also. The objective of these tests were to see if a differential could still function as a CVT and an IVT while under load.

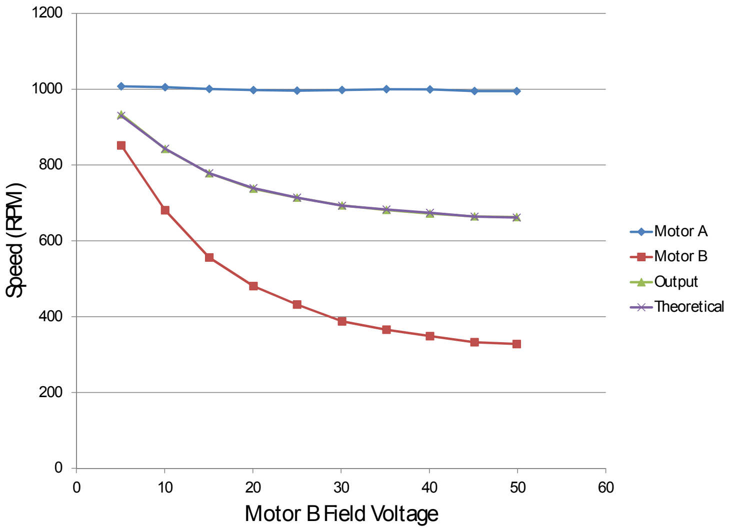


Figure 4.8: Differential Speed Control Using Field Weakening (Test D6)

While testing the differential with the motors spinning in opposite directions, an interesting observation was made. As the load was applied to the output, one motor would draw more current, while the other motor would draw less current. This occurred at all load levels. At the extreme, when the output was loaded so that it would stall (0 RPM), then one motor would pull maximum current, while the other motor generated current. This meant that whenever a load was applied to the output the motors would drive each other instead of the output. This is particularly undesirable for a vehicle application. It is preferred that the motors always drive the output and not each other.

A deeper investigation showed that during the test when the motors were both turning in the same direction, the motor which was spinning faster, always took more of the load, or in other words, it pulled more current. This was most evident in the crossover test as shown in Figure 4.9.

During this test the output was loaded at $1.5in \cdot lb$ and the speed of Motor A was not changed. Motor B was varied from $-60V$ to $+50V$. At first with Motor B spinning in the opposite direction as Motor A, it was Motor B that absorbed most of the load. However as Motor B approached the speed of Motor A (-30V mark) the load shifted and was absorbed by Motor A. This trend continued until Motor A and Motor B were spinning at the same RPM (+30V mark). From this point on Motor B resumed absorbing most of the load. From this experiment it was evident that in all cases, the motor which was spinning faster was the motor which absorbed the majority of the load.

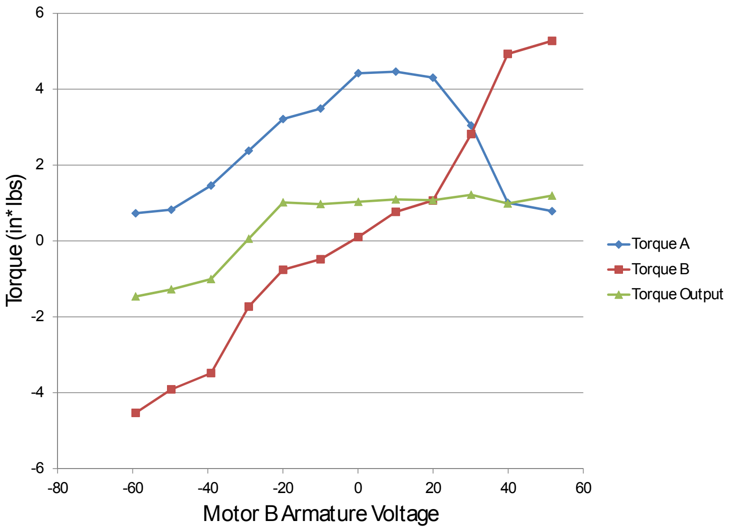


Figure 4.9: Torque Output During Crossover Test (Test D4)

Ultimately what was learned from this test is that the differential needed to be modified in some way so that it could be used in a vehicle application. Somehow the arrangement would have to be modified so that the power motor would always be the motor to absorb the load, regardless of the other motor's speed. The inferences of this interesting observation, as well as other observations are described in Chapter 5.

CHAPTER 5. DISCUSSION OF RESULTS AND POTENTIAL APPLICATIONS

5.1 Motor Selection for an Electric Powertrain

Based on the literature review and research performed, it can be concluded that there are many types of motors and continual improvements are being made to these motor types. As such, it is difficult to choose one specific motor for an EV powertrain. This of course depends on the system itself. AC motors, are very efficient and have great performance characteristics for an electric powertrain. This is further supported by the fact that AC motors are being used on current electric vehicles such as the Chevy Volt, Toyota Prius, Nissan Leaf and Tesla roadster. DC motors do not require an inverter but in the past have required a form of pulse width modulation (PWM) controller. The maintenance issues with the brushes and commutator as well as speed limitations due to arcing have greatly reduced the use of DC motors for full size electric vehicles. However, the research that has been conducted suggests that there may still be some advantages in using DC motors in electric powertrains.

5.2 Motor Speed Control

5.2.1 Armature Voltage Variation

The motor testing results showed that armature voltage variation was a practical means of motor speed control. The speed related linearly to the armature voltage which is very convenient for an electric vehicle powertrain application. However, in a real world application, unless PWM were used, armature voltage variation would require multiple switches in the battery pack to connect cells and raise or lower the system voltage accordingly. These switches would be an additional cost to the system and would require a complex controller to switch them on and off. This method of speed control could also cause uneven battery usage. For example at high speeds all of the switches would be turned on to produce maximum pack voltage and all of the cells would be used.

At lower speeds some of the cells would be disconnected causing them to remain more charged than the other cells. Unbalanced cells can create a multitude of problems especially when charging. A complex scheme could be utilized that would switch on only the highest cells, but this would add to the complexity of the vehicle and so this method of speed control would be challenging.

5.2.2 Field Weakening

The testing results also showed that field weakening is a viable means for controlling the motor speed of a DC wound motor. The relationship is nonlinear, but manageable nonetheless. The weakening of the field could be accomplished in a few ways. A PWM type of control could be used to weaken the field, which may be very effective. Since the current in the field would be relatively low, the cost for this controller could be substantially less than typical PWM controllers. Varying the voltage supplied to the field is also another alternative method of field weakening, however as mentioned above, this would require multiple switches and could be very complex.

The last form of field variation would be to use a resistor or potentiometer in series with the field windings. Although this method of field weakening does dissipate some electrical energy as heat through the resistor, this can be limited. Only a small percentage of the motor's power is used to power the field. Testing also concluded that the size of the torque load on the motor does not affect the amount of current the field draws to produce the electromagnet. In contrast, if the resistor were placed in series with the armature, this would be a considerable amount of energy that would have to be dissipated as heat and this amount would increase with motor load.

Several inferences to the application of the field weakening technique can be gained from this research. First, a motor selected for field weakening should be a wound motor. Second, the construction of the motor should be such that the current delivered to the field is minimized. This is because the losses due to heat are a function of the current squared. Since the current and number of turns of the wire are what contribute to the strength of the magnetic field, it is best to limit the current and increase the number of turns. Increasing the number of turns has some side effects. To have many turns, the wire must be of long length and small diameter to allow for manufacturing. The resistance of the wire is strongly tied to its diameter and length. Additionally many turns of wire could weigh more than few turns of large diameter wire with high current. In summary designers should look carefully at the actual design of the motor before implementing it into a field weakening application. When designing the motor, it is recommended that an optimization be performed in considering current, length and wire diameter for field weakening applications.

Another inference gleaned from this research shows that field weakening cannot reduce motor speed beyond a certain point. In other words when the magnetic field is at its strongest the motor will be generating the most back EMF, and will have the slowest speed. Field weakening does not allow the motor to be slowed down any further. This is cause for concern that the motor can never reach zero RPM unless all power to the motor is switched off.

Field weakening is a less expensive form of speed control because it does not require any type of controller other than a variable resistor. of a size appropriate for a vehicle can cost between $600 and $2,000. The variable resistor or potentiometer needed for field weakening would only have to handle small currents and would be less than $20 [52]. Traditional PWM controllers for DC traction motors sized to propel a small EV, cost between $600 and $2,000. AC controller and inverters would cost between $4,000 to $7,000 [52]. Even though the method of control is inexpensive, its effect on efficiency is still unclear. There is also questions as to what can be done to allow a motor with field weakening to be controlled to zero RPM. The next step in this research is to see if the inefficiencies that result from field weakening overwhelm its cost benefits, and develop a method for controlling the speed through all speed ranges including zero RPM.

One possible method that should be researched is the combination of several speed control techniques. For example, it is possible to use a combination of permanent magnets and wound electromagnets in the field of a motor. In essence this would work as a permanent magnet motor, but can have a torque boost when the windings in the field are energized. It is unknown however, how the permanent magnets would interact with the wound fields when energized. Similarly it could be possible to have a motor where there are multiple windings of the field, and these windings could be switched on an off based on the desired output. Not having all of the windings energized at the same time has efficiency advantages.

Another idea to work around the zero RPM problem of field weakening is the use of armature voltage variation, and field weakening. PWM could be used on the armature to allow control of the motor up to the field weakening range, and after that, field weakening could take over control of the motor. These ideas have not yet been tested, but are very encouraging and have the potential to solve several problems and improve motor performance, efficiency and reduce controller cost.

5.3 Differential Application

The testing results shown earlier imply that field weakening and armature variation accomplish not only speed control of an individual motor, but can also be used to effectively control the output of a differential. This can also be applied to other CVT and IVT powertrains, like a planetary gear set for example.

Many arrangements can result from this discovery. One such arrangement of interest to vehicle applications, is where one motor serves as a power motor, while the other serves as a speed changing motor, as proposed in Figure 1.1. In this setup, the high powered motor would be switched only on or off, and the low power motor would be varied using field weakening, to change the output or speed ratio. In this arrangement the large motor would be able to run at its most efficient RPM over longer periods of time. This is a method of speed control that has not yet been considered for vehicle applications.

As discovered during testing, one important design consideration with this setup is the ratio of the differential. As each motor provides torque, the torque has an option of which output to go to as illustrated in Figure 5.1. The choice of the torque will always be the path of least resistance. In the 1:1 differential setup, because of the common ratio between the two inputs, that path of power was not always to the output. Sometimes, one motor would drive the other motor as a generator.

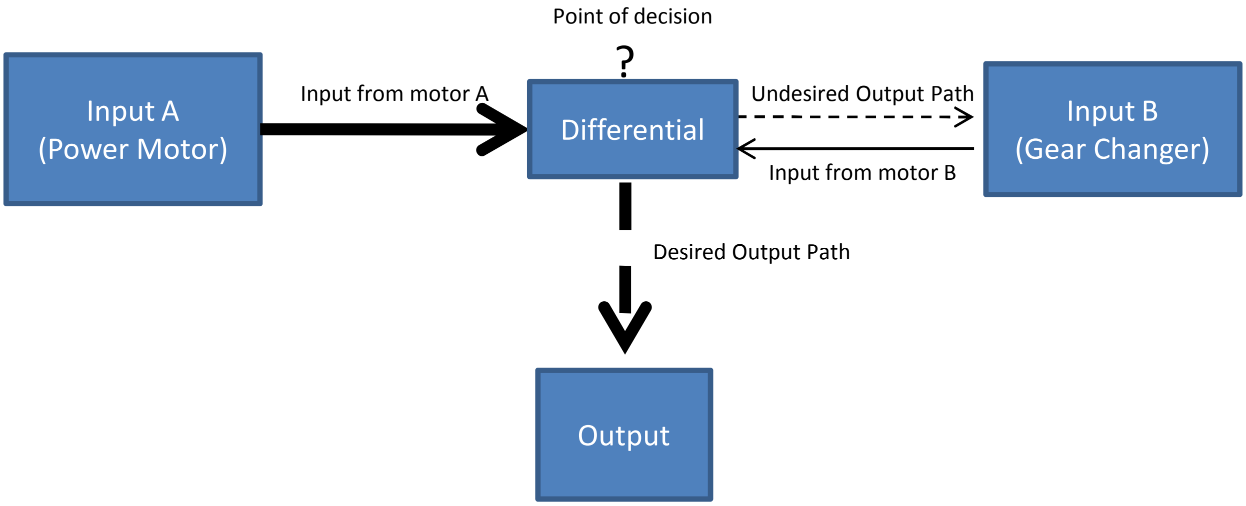


Figure 5.1: Torque Paths in a Common Ratio Differential

In a vehicle application it is preferred that the motors drive the output and not each other. In this application of a differential it would be preferred that one motor remains the power motor while the other motor remains the speed control motor. If the flow of energy is mostly between the power motor and the output, then power will be delivered at a more efficient level. Power flow from the power motor to the output would be traction, while power flow from the output to the motor would be regenerative braking. A modification to the differential would enable this to be accomplished. The path of least resistance can always be between the power motor and the output if an appropriate gear ratio is chosen for the speed control motor. The type of gear set is also an important consideration. For example, worm gears are not backdrivable and can have a very high reduction ratio. Implementing a gear set like this on the speed control motor input would cause the output to always be the path of least resistance. However, different gear types have different friction characteristics and ultimately affect the efficiency of the overall system.

Worm gears are generally inefficient at low speeds, so an alternative option should be pursued. The idea of gearing the speed control motor is still a feasible concept, but should be done efficiently. The use of a different type of gear may be an acceptable substitute. Spur gears are known for having the best efficiency and could be implemented as shown in Figure 5.2. This and several other options have been investigated by Wells in his thesis [7].

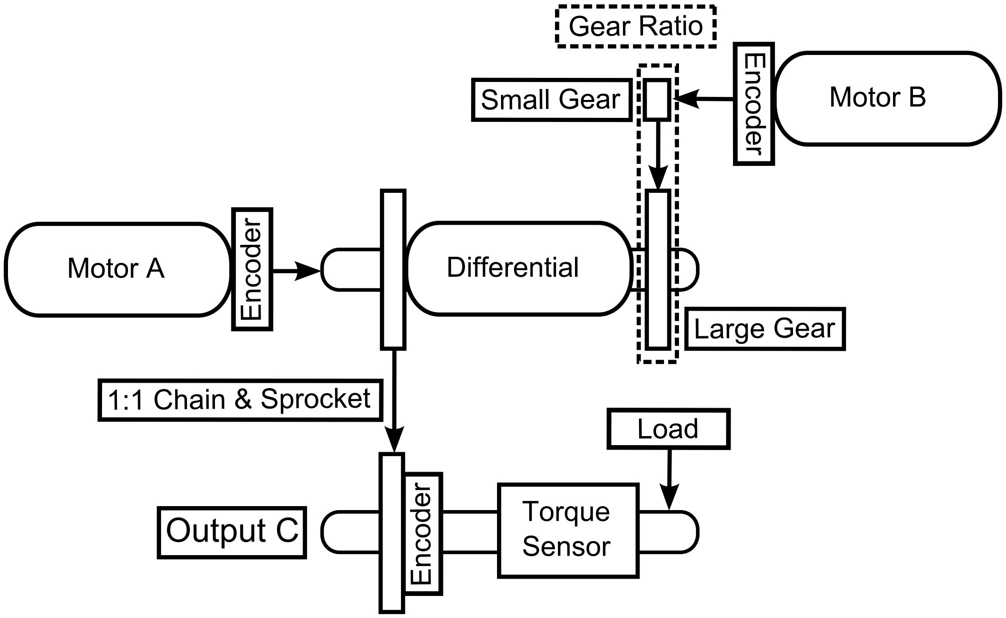


Figure 5.2: Nonbackdrivable Differential Setup with a Spur Gear Set [7]

5.3.1 Lever Analogy

Using the equations formed in Chapter 4 it is possible to predict the output RPM and Torque for a differential. The testing revealed that the theorized equations are valid. Similar equations can be derived for a planetary gear set. However, determining the correct gear ratio and most appropriate gear type that would prevent backdrivability is something that requires future work.

One tool that can be used to help calculate this ratio is the lever analogy. This method converts motion in a rotary domain to a linear domain and makes the problem easier to understand [53]. Thus the differential or any other gear set can be represented pictorially. To accomplish this gears are represented as nodes on a free body diagram, gear ratios or gear diameters are represented as distances between those nodes, and velocities are represented as forces as shown in Figure 5.3.

Once represented pictorially, parameters can be manipulated to yield various results. For example increasing the distance between two nodes by a multiple of two also increases the gear ratio by a factor of two. The arrangement shown in Figure 5.4 is a result of manipulating the gear ratios and yields interesting observations, especially for a vehicle application.

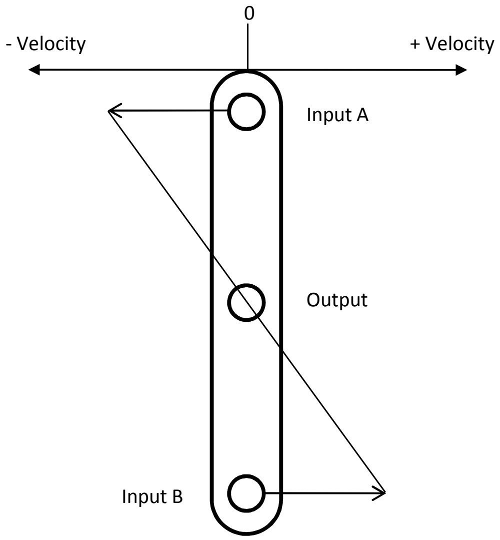


Figure 5.3: 1:1 Ratio Setup (Opposite Directions) Using Lever Analogy

By changing velocities and distances between gear nodes, it is possible to experiment with different gear ratios. From the results of these experiments it can be observed that using a gear ratio on the speed changing motor does not come without side effects. The proposed gearing shown in

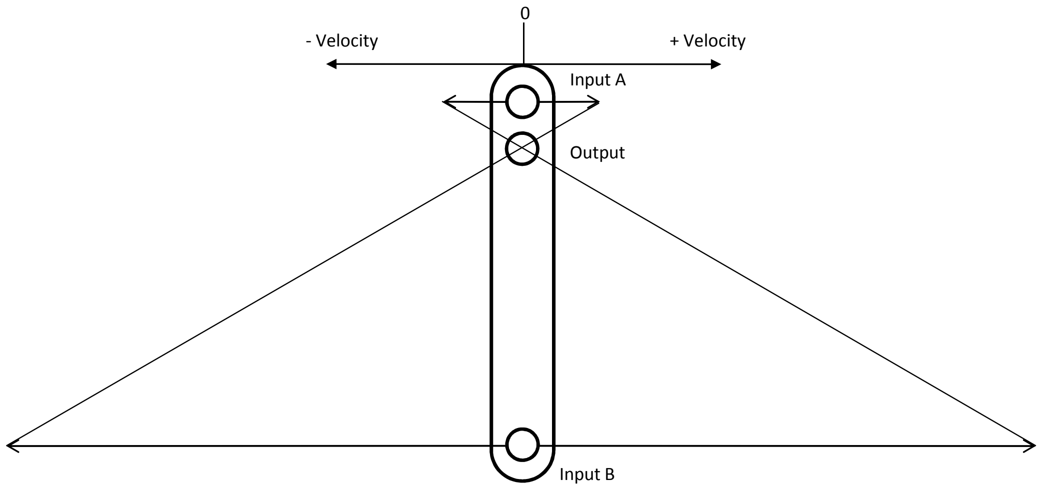


Figure 5.4: Lever Diagram for a Non Equally Geared Differential Setup

Figure 5.4 makes it so that this motor has to spin faster than in a 1:1 ratio setup. Looking at this practically, a trade off is observed: In reducing the torque requirement of the gear changer, the speed requirement of the gear changer increases.

The proposed system shown in Figure 5.4 would be more practical for a vehicle application than that shown in 5.3. This system should still allow for the use of regenerative braking. Because the path of least resistance is between the power motor and the output, it can be assumed that when the output is being driven during stopping, the power motor will be the one that acts as a generator, and not the gear changing motor. In fact, regenerative braking may work better because the speed changing motor, set at an appropriate speed, could cause the traction motor to spin at a high enough RPM to drive voltage into the batteries.

5.4 Motor Selection for a IVT

5.4.1 Power Motor

In the proposed IVT setup, the power motor does not need a controller, but rather just a set of contactors to switch it on and off. The contactors would have to be able to handle large amounts of current, especially because of the lower operating voltage. For example, a 90kW motor run at 60V would pull about 1500A at max capacity. A set of contactors capable of handling this amount of current can range in price from $400 to $800 if purchased individually (cost at mass production should decrease significantly) [52].

A potential candidate for the traction motor would be the permanent magnet DC motor. This motor is light weight for its power output capabilities. The permanent magnets remove the need to power an electro magnetic field, and make the motor more efficient. This is especially true when compared to DC wound motors. As mentioned previously some PM DC motors have reached efficiencies in the 80-95% range. Wound DC motors must provide their own field and have lower efficiency range as a result, typically they would be in the 40-70% range. The pancake style PM motors also have great torque producing capabilities. This is because the pancake configuration naturally has more of a lever arm exerted on the armature. Using a DC motor eliminates the need for any inverter and works well with regenerative systems. Using the PM DC motor with the IVT also removes the need for a DC motor controller. Because this motor uses brushes, there will need to be periodic maintenance on the vehicle, but this would be substantially less frequent than an oil change on a conventional IC engine vehicle and also not costly.

5.4.2 Speed Controlling Motor

The speed controlling motor will need to be able to vary through a large range of motor speeds, especially if a gear ratio is used as described in Section 5.3. Additionally, this motor will be most cost effective if field weakening is used as the control method. The shunt DC motor is therefore a good candidate for this speed controlling motor. In the shunt motor there can exist two different currents one for the armature and one for the field. If the principles described in section 5.2 are utilized this would result in the field current being minimized with minimal effects to the armature current. The series motor requires the same current in both the armature and the field, which would result in greater losses if field weakening were used. The compound-wound motor would have a similar disadvantage.

Because the speed control motor requires a wide range of speed capability, it is recommended that PWM be used to supplement field weakening in speeds where the field cannot be weakened any further. PWM for this application should not be as costly because there is much less power delivered to the speed control motor, and therefore much less current flows through the armature of this motor. As mentioned previously the cost of PWM is typically due to the need for

IGBTs and other components to be able to handle high currents. If the motor uses relatively low power, and does not use high currents, the components for PWM control would be much less expensive. PWM is also recommended because it is the most efficient speed control method known for DC motors.

5.5 Effects on Vehicle Safety

Sophisticated electronics like IGBTs are the main reason designers use high voltage. The higher voltage reduces the amount of current that these components must handle. The use of the IVT and field weakening on a shunt-wound DC motor would eliminate the need for these transistors and IGBTs to switch the current on and off. This means that the operating voltage can be lowered to a safer level. This would reduce the hazard to technicians and customers who will be in contact with the vehicle.

If the operating voltage is lowered to below 60 Volts and the resistance of the average human body is between 1500Ω to 10000Ω, then this would equate to approximately 40-60mA current flow in the case of accidental contact. According to Section 2.9, this would cause a substantial shock, but would be much less dangerous than the voltage used in current hybrid and electric vehicles, and would probably not be fatal. Ideally it would be best to lower the voltage to less than 24V, but this will require a power or traction motor that would need to handle substantially higher current flows. Theoretically, the homopolar motor would be the best candidate for this vehicle architecture, because of its low internal resistance. Unfortunately the homopolar motor is still under development and as of right now is not a practical solution. This idea should be pursued later when technology for homopolar motors has matured.

5.6 Effects on Battery Management

With the operating voltage lower, it is possible to reduce the complexity of the battery system. Instead of using many cells in series, there can be fewer yet larger cells in parallel. This reduces the cost by not having to purchase as many cells, and also reduces the equipment needed to manage these cells. For example, in battery packs that use active heating and cooling, there would be fewer plumbing connections and cooling fins needed because of the reduction in cell count. The reduction in cell count would also increase reliability simply because there are fewer electronic connections to make. In the past battery performance has been greatly limited by the quality and contact of battery terminals or tabs.

5.7 Effects on Efficiency

By using a permanent magnet DC motor as the power motor, most of the power to propel the vehicle will be delivered at a high efficiency (typically in the 80-95% range). Most of this efficiency gain is achieved in the PM motor because no power is used to create the magnetic field. The permanent magnets are capable of driving materials like iron into regions near saturation, thereby providing the same torque that would be capable of any wound motor.

For the speed control motor, the DC shunt-wound motor is less efficient, but significantly smaller than the DC PM traction motor. In addition, the control method of field weakening make desirable for this application. The energy losses can be minimized if the current in the field is optimized. The use of PWM control to supplement field weakening is very efficient. In general, the amount of power delivered through the speed control motor would be small, and the actual amount of power dissipated as heat through the resistor or other voltage control device would be yet a smaller percentage of this amount.

The elimination of several components on the proposed concept may also reduce the weight of the vehicle, which would improve efficiency of the system. Some components that are eliminated include, inverters, extra windings in the motors, AC controllers and part of the battery conditioning system. It is unknown exactly if and or how much weight this would save in the vehicel and this is something that needs to be researched further.

5.8 Effects on Cost

Using the approach described in Section 5.3 would not require a PWM controller or an AC/DC inverter for the traction motor. Instead the traction motor would require a set of heavy duty contactors, and the speed changing motor would require a variable resistor or potentiometer. The potentiometer could be purchased relatively inexpensively but the contactors could be more expensive. If PWM were used on the speed control motor, this would be an additional cost, but would likely not be as costly as a full blown traction motor controller. As stated previously the speed control motor would require much less power and could be made with less expensive components. There are potentially other speed control methods, or combinations of methods that could reduce the cost further.

This approach, as previously discussed requires two motors to operate the vehicle instead of just one. Some electric vehicles like the Nissan Leaf have been able to manage a powertrain with only one motor. Other examples like the Chevy Volt and Toyota Prius use two motors. The cost savings therefore depends on which system it is being compared to.

This design architecture would require a complex IVT powertrain. This powertrain could come in the form of a planetary gear set or a differential. Although the transmission is complex, it should not be as complex as transmissions used in current electric vehicles, or automatic transmissions used in internal combustion powered vehicles. The Chevy Volt and Toyota Prius both use IVT transmissions like the one shown in Figure 5.5. It is anticipated that the transmission cost for the proposed system would be about the same as current EVs

Figure 5.5: Chevrolet Volt Transmission [9]

The battery management system costs would be reduced in this system. This is because fewer cells would be needed, which means that there would be less hardware and fewer sensors for thermal and electrical management. Fewer cells also correlates to higher reliability because there are fewer connections that can fail. Ultimately this could lead to a reduction in warranty costs.

It is estimated that the maintenance costs for the proposed system would be more than current EVs, but still not substantial. This comes from the need to maintain the brushes and commutator on the DC motors. Brushes for the motors are inexpensive, typically less than $50 [52], so the cost increase would be minor and the cost would reside with the consumer and not the manufacturer.

From a safety standpoint, the lower operating voltage would also reduce the amount of required electrical insulation on the wiring, and reduce the amount of placards and badging. As mentioned above, the shunt-wound DC motor should be equipped with a field loss relay to prevent over current in the case of a total field loss. Taking into account these items, there would most likely be some reduction in safety related costs. This information is summarized in Table 5.1 below, with the cost estimations in Table 5.2.

Table 5.1: Comparison of Components for EV, Hybrid and IVT Concept Vehicles

	Toyota Prius Hybrid Vehicle	**Nissan Leaf Fully Electric Vehicle**	**Proposed IVT Electric Concept**
Motor	(2) AC Ind. Motors	(1) AC Synch. Motors	(1) DC PM + (1) DC Shunt-Wound
Inverter	AC/DC	AC/DC	None required
Controller	VFD Electronic	VFD Electronic	Contactors and POT
Battery	HV Multi Cell	HV Multi Cell	LV Few Cells
Transmission	Planetary	Gear Reduction	Non-Backdrivable Diff.or PGS
Maint. Costs	None	None	Brush/Commutator Replacement
Safety Costs	Insulate HV/Placards	Insulate HV / Placards	Field Loss Relay

Because there are so many factors affecting cost, and many of the values are not yet known, it cannot be concluded from this research what the cost savings would be for this system. It is the opinion of this research group that there would be enough savings to substantiate implementation for mass production, but this is speculation and should be evaluated in future research.

Table 5.2: Hypothesized Cost Implications of IVT Concept Vehicle Based on Table 5.1

	Proposed IVT Electric Concept
Motor	No Change
Inverter	Decrease ($4000)
Controller	Slight Decrease
Battery	Decrease
Transmission	No Change
Maint. Costs	Slight Increase
Safety Costs	Slight Decrease

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

6.1 Restatement of Objectives

The objectives for this research described in Chapter 1 were as follows:

1. Develop a document explaining factors affecting motor performance and summarizing different types of electric motors.
2. Test armature voltage variation and field weakening speed control methods for DC motors.
3. Construct and test hypothesized equations that relate multiple inputs to a single output on a continuously or infinitely variable transmission.
4. Provide plausible recommendations based on testing and literature review for implementing DC commutated motors and IVTs in an electric vehicle powertrain. These recommendations will be described as cause and effect relationships that would potentially provide performance or efficiency improvements.

Objective 1 was accomplished in the literature review results contained in Chapter 2. Results from the literature review showed that the motor is made up of several fundamental components including a controller, stator, rotor, commutator and brushes. The production of eddy currents and back EMF are also principles on which motor performance is dependent. One of the key factors that was found to affect motor performance was the strength and type of magnetism used in a motor. Electromagnets are created by running current through a wire, where the dimensions of length, turns and wire diameter are all interrelated. The use of permanent magnets can eliminate the need for a wound field, and these permanent magnets are created using the hysteresis effect. Also learned in this literature review was that DC wound machines can exist in several varieties including shunt, series, compound and differential configurations. In the literature review motors were compared in Figures A.1, A.2 and A.3 and a motor hierarchy was also created in Figure 4.1.

Objective 2 was accomplished through the testing explained in Chapter 3. As part of this testing a motor testing procedure and LabView program were developed. This program and setup were carefully designed to ensure that future users and researches could perform similar tests. This testing involved measuring current and voltage, in the field and the armature while simultaneously measuring the RPM and torque output of the motors. The results of the motor speed control tests were graphed in Figures 4.2 and 4.3. The results of these graphs showed that the armature voltage variation relates linearly to motor speed, while field weakening methods of speed variation have a nonlinear relationship that is exaggerated at the extremities.

Objective 3 was accomplished by constructing the RPM relationship shown in Equation 4.1 which is also shown in Equation 6.1 below. This equation shows that the output speed of a 1:1 differential is simply an average of the inputs. Verification of this equation was performed during testing and was found to be valid. In addition to the speed equation a torque equation was also derived as shown in Equation 4.4 and Equation 6.2 below.

$$RPM_{out} = \frac{RPM_A + RPM_B}{2} \tag{6.1}$$

$$T_{out} = \frac{-T_A * RPM_A + T_B * RPM_B}{\frac{RPM_A + RPM_B}{2}} \tag{6.2}$$

The recommendations referenced in objective 4 are explained in Chapter 5 of this thesis. In this chapter a concept electric powertrain is explored. This concept utilizes an IVT in the form of a differential to control output speed. In this concept, two motors are connected to a differential, where one motor acts as a power or traction motor, and the other motor acts as a speed changing motor. In this manner speed control is accomplished without an expensive motor controller. For the IVT concept that is proposed, it was recommended that the PM DC motor be used as the traction motor, and a shunt wound DC motor be used as the speed changing motor with the method of control being field weakening supplemented by PWM.

6.2 Conclusions

There are several benefits and conclusions that can be drawn from this research. To begin with, the literature review provides good background material for persons interested in learning about motor construction and the different types of motors that exist. The material covers basic and some advanced principles of motor operation. The literature review presents information that has been collected from many sources into one helpful overview. By having this information altogether, it becomes easier for engineers and designers to understand how motor principles are interrelated and helps them decide which motors to choose for an electric vehicle powertrain.

The inferences from the tests performed have shown that DC motors can be controlled effectively without PWM on the armature, and less expensively with field weakening and that this can be applied to an IVT powertrain. Furthermore it was demonstrated that this testing procedure was successful in measuring interactions with an IVT in the form of a differential. The presented testing setup and LabView program will also allow other researchers to repeat the experiment and test other motor parameters as desired.

As a result of this research a new and innovative concept for electric vehicles was developed. This concept applied a method of motor and vehicle speed control that has previously not been applied to electric or hybrid electric vehicles. This concept has the potential to improve the safety of the vehicle by lowering the operating voltage of the system. Lowering the operating voltage also reduces the complexity of the battery system. There is potential to reduce the cost of several components of the EV powertrain, however, it is unclear exactly what the savings would be without building a prototype vehicle and further research.

6.3 Recommendations for Future Work

In addition to meeting the objectives of this research, a list of recommendations for future work have been identified.

1.) One of the first steps of future work would be to design a conceptual gear train and calculate the gear ratio needed for the differential to be non-backdrivable over the speed changing range of the control motor. This involves choosing an appropriate gear style (bevel, spur, helical, worm, etc.), and determining a ratio using the lever analogy presented in this research. There are also a number of other potential gear train solutions as noted by Wells, like the planetary gear set differential, which also require future work [7].

2.) It is recommended that a working prototype be constructed with motors better sized for vehicle applications, as opposed to the ones used in the preliminary research described in this thesis. The cost of the proposed EV powertrain concept should also be priced, and the cost compared and contrasted with current powertrains to see if this could be applied to a production vehicle.

3.) The shunt-wound motor should also be researched further, specifically an attempt should be made to optimize wire diameter, the number of turns, magnetic flux and field current. These parameters are all interrelated and will affect performance and efficiency. Research should be done to see if there is a way to minimize the amount of losses due to heat, especially when using field weakening.

4.) The application of the homopolar motor is also something that requires future work. These motors have been successfully constructed for large scale applications, using superconductors that are cooled with liquid helium. The large currents in homopolar motors necessitate these type of materials so that large current amounts can be handled. In order for this to be applied to a vehicle, the scale and size of these motors must be reduced. Specifically, Cho has recommended that the superconducting coil be researched further [38]. Brushes for the homopolar motor are also an area that must be researched since they will need to handle high current loads [36]. As discoveries and technology emerge to reduce the size, and improve the practicality of this type of motor it may also be beneficial to investigate or perform testing of homopolar motors for vehicle applications.

5.) Using fewer but larger battery cells is also recommended for future research. The thermal characteristics and charging/discharging characteristics of these large cells is not well known. Some vehicles do use large format pouch cells in their battery packs, but the proposed battery would need to discharge more current than the existing models. An investigation into how current would flow in such a battery and how this would affect system performance is needed.

6.) The method of field weakening is also yet to be determined. As mentioned previously, there are three known methods to accomplish field weakening. These are: voltage variation, pulse width modulation or connecting a resistor or potentiometer in series with the field windings. Other methods of field weakening may also exist, or the use of soft magnetic materials like metglass may be beneficial. Further investigation in these areas is needed.

7.) Combining several speed control methods shows some promise and may have positive effects to the cost and efficiency of the proposed concept. It is recommended that this topic be included in future research. Particularly it is recommended that the following areas be looked into:

- Using multiple field windings that can be switched on and off
- Using permanent magnets and a wound field together
- Supplementing PWM with field weakening to allow a full range of speed control (including zero RPM)
- Using PWM as a form of field weakening instead of a potentiometer

8.) One final area of future work could be in the area of contactors. For the proposed concept architecture, contactors would need to be able to handle large amounts of direct current for the traction motor, and be able to switch on an off more frequently than a typical electric powertrain. Contactors using existing technology at these higher current levels would drive up the cost of the system. If the price of these contactors could be reduced, this would have a positive and perhaps significant effect.

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APPENDIX A. SUPPLEMENTAL MATERIALS

A.1 Material Properties

Table A.1: Resistivities and Cost per Pound of some Common Conductors

Material	Resistivity(Ωm)	Cost($/kg)	Density(g/cm^3)
Silver	1.59×10^{-8}	624	10.49
Copper	1.7×10^{-8}	6.53	8.96
Gold	2.44×10^{-8}	41728	19.32
Aluminum	2.82×10^{-8}	2.52	2.7
Tungsten	5.6×10^{-8}	7.39	19.25
Platinum	11×10^{-8}	56568	21.45
Lead	22×10^{-8}	1.721	11.36

Sources: [25], [54] as of 20 May 2010,

Table A.2: Relative Permeability of some Common Materials

Material	Relative Permeability(μ/μ_0)
Electrical Steel	4000
Steel	100
Nickle	100-600
Aluminum	1.000022
Vacuum	1
Mumetal	50000
Ferrite	640
Metglas	80000

Sources: [25]

A.2 Motor Comparison Charts

Motor Comparison

Motor Name	Series	Shunt	Cumulative Compound	Differential Compound	Separately Excited	PM Stepper
Construction						
Type	DC	DC	DC	DC	DC	DC
Family	Commutator, Self Excited	Commutator, Self Excited	Commutator, Self Excited	Commutator, Self Excited	Separately Excited Wound	Stepper
Power to Rotor	DC	DC	DC	DC	DC	PM
Power to Stator	DC	DC	DC	DC	DC	Pulsed DC
Overall Cost	Low	Low		N/A		
Weight	heavier due to windings	heavier due to windings	heavier due to windings	heavier due to windings	heavier due to windings	Low
Commutation method	Mechanical commutation	Mechanical commutation	Mechanical commutation	Mechanical commutation	Mechanical commutation	External Electronic
Controller Cost	Low	Low	Low	Low	Low	High
Pros	Inexpensive, can use field weakening, maintains constant speed, higher starting torque	Inexpensive, can use field weakening, maintains constant speed	Combines pros of Series and Shunt	None	Inexpensive, can use field weakening, maintains constant speed	Highly reliable, long life low noise, nonzero holding torque even when motor is switched off
Cons	Require Maintenance, Bulky, Limited Rotation Speed, Requires large windings in field	Require Maintenance, Bulky, Limited Rotation Speed	Require Maintenance, Bulky, Limited Rotation Speed	Not practical, only occurs as a phenomenon	Require Maintenance, Bulky, Limited Rotation Speed	Cogging at most speeds, fixed increments
Maintenance Requirements	Brushes wear	Brushes wear	Brushes wear	Brushes wear	Brushes wear	Low
Speed Control Method	PWM or Field Weakening	PWM or Field Weakening	PWM or Field Weakening	PWM or Field Weakening	PWM or Field Weakening	Frequency Dependent
Performance						
Starting Torque	>175% of rated torque	125-200% of rated load	>175% of rated torque	N/A	125-200% of rated torque	Medium, equal to holding torque
Speed Range	Limited by brushes, Easy Control	Limited by brushes, Easy Control	Limited by brushes, Easy Control	N/A	Limited by brushes, Easy Control	Low 0-1000 rpm
Power to Weight Ratio						
Efficiency	Low	Low	Low	Low	Low	Low
Applications	Industrial Applications	Industrial Applications	Industrial Applications	Industrial Applications	Industrial Applications	Robotics

Figure A.1: Motor Comparison Chart Page 1 [10–14]

Motor Name	Reluctance Stepper	Hybrid Stepper	PM	Hysteresis Synchronous	Brushless DC	Switched Reluctance
Construction						
Type	DC	DC	DC	AC	AC	AC
Family	Stepper	Stepper	Separately Excited	Synchronous -Excited-wound	Synchronous Excited PM	Synchronous Unexcited
Power to Rotor	DC	DC/PM	DC	DC	PM	Induced
Power to Stator	Pulsed DC	Pulsed DC	PM	AC	Pulsed DC	Pulsed DC
Overall Cost				High	High	Medium
Weight	Low	Low	Medium	High	Low	Medium
Commutation method	External Electronic	External Electronic	Mechanical commutation	External Electronic	Internal Electronic	External Electronic
Controller Cost	High	High	Medium	High	Very High	High
Pros	Highly reliable, long life low noise, Quick response	Highly reliable, long life low noise, Quick response	High starting torque	Reliable, quiet and smooth, constant speed	Outstanding torque and speed, Fast responses, tremendous power, long life	Low inertia, Can be tailored for specific applications, runs cool
Cons	requires motor to be energized to maintain holding torque	low inertial load ability	Susceptible to damage if dropped, Requires Maintenance, Bulky, Limited Rotation Speed	Voltage variations reduce efficiency, low supply voltage= reduced torque output	Very Expensive, limited economically to small size motors	Not very powerful, large ripple in torque, requires position sensing
Maintenance Requirements	Low	Brushes wear	Brushes wear	Low	Low	Low
Speed Control Method	Frequency Dependent	Frequency Dependent	PWM	Frequency Dependent	Frequency Dependent	Frequency Dependent
Performance						
Starting Torque	Low	Medium	>200% of rated torque	100% of rated torque	>175% of rated torque	up to 200% of rated torque
Speed Range	Low 0-1000 rpm	Low 0-1000 rpm	Limited by brushes, Easy Control	Constant speed (can be high speed)	Excellent	Controllable
Power to Weight Ratio				High	High	
Efficiency	Low	Low	High	High	High	Less than PMDC
Applications	Robotics	Robotics	Vehicle	Disk drives, clocks	RC vehicles, robotics	Vehicles, industrial drives

Figure A.2: Motor Comparison Chart Page 2 [10–14]

Motor Name	Poly Phase Induction	Permanent Split	Shaded Pole	Split Phase	Capacitor Start	Capacitor Start / Capacitor Run	Universal
Construction							
Type	AC	AC	AC	AC	AC	AC	AC
Family	Induction, Slip ring or Squirrel Cage	Induction, Slip ring or Squirrel Cage	Induction, Slip ring or Squirrel Cage	Induction, Slip ring or Squirrel Cage	Induction, Slip ring or Squirrel Cage	Induction, Slip ring or Squirrel Cage	Universal
Power to Rotor	Induced	Induced	Induced	Induced	Induced	Induced	AC/DC
Power to Stator	AC	AC	AC	AC	AC	AC	AC/DC
Overall Cost	Medium	High	Medium	Medium	High	High	
Weight	Medium	High	High	High	High	High	Medium
Commutation method	External Electronic	External Electronic or Field Weakening	External Electronic or Field Weakening	External Electronic	External Electronic	External Electronic	Mechanical Commutation
Controller Cost	High	High	Medium	Medium	High	High	High
Pros	High efficiency	Quiet, High efficiency	Simple Low cost, reliable, quiet, can use field weakening	Low cost general purpose motor	Good with high inertial loads, improved	Quiet, High starting torque better efficiency than conventional induction	Best power to weight ratio of any single phase ac motor
Cons	Expensive controller	Most expensive of capacitor motors, performance very dependent on correct capacitor size	Low Efficiency runs warm, low power and low starting torque	Not suited for frequent starts and stops, starting current high	Performance very dependent on correct capacitor size	Performance very dependent on correct capacitor size	Poor speed control, cannot be reversed, noisy
Maintenance Requireme	Low	Low	Low	Low	Low	Low	Low
Speed Control Method	Frequency Dependent	Frequency Dependent	Frequency Dependent	Frequency Dependent	Frequency Dependent	Frequency Dependent	Frequency Dependent
Performance							
Starting Torque	High	50-100% of full load	50-100% of full load	130-200% of rated torque	up to 300% of rated torque	>200% of rated torque	>175% of rated torque
Speed Range	Controllable	Controllable	Constant Speed	Constant	Controllable	Controllable	Varies with load
Power to Weight Ratio							Excellent
Efficiency	High	High	Low	Low	Medium	Medium	Low-Medium
Applications	Electric vehicles, industrial applications	Fans and blowers	consumer electronics	fractional hp applications	High inertial loads	High Torque	Constant Speed applications

Figure A.3: Motor Comparison Chart Page 3 [10–14]