ADVANCED ENERGY STORAGE SYSTEM FOR ELECTRIC VEHICLE CHARGING STATIONS FOR RURAL COMMUNITIES IN THE PACIFIC NORTHWEST

FINAL PROJECT REPORT

by

Dr. Herb Hess
University of Idaho

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Pacific Northwest Transportation Consortium (PacTrans)
USDOT University Transportation Center for Federal Region 10
University of Washington
More Hall 112, Box 352700
Seattle, WA 98195-2700

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16. Abstract

A rural electric vehicle charging system is envisioned with an energy source, e.g., solar panels on a car port, energy storage, e.g., a flywheel energy storage system, and an energy sink, e.g., electric vehicle charging. The focus of this project was on the hardware development of the sensors and actuator subsystems of the energy storage system. The energy storage device will be a reluctance machine operated as either a motor or generator, depending on the direction of energy transfer. The rotor of the reluctance machine will function as a flywheel, storing energy in the rotating mass. The position of the rotating mass (rotor) will be critical to the function and performance of the energy storage control system. Commutating electrical currents will be necessary for the energy transfer by the reluctance machine. Three types of sensors and actuators subsystems were used to control the reluctance machine: 1) position or displacement sensors, 2) electrical current sensors, and 3) electrical current actuators. The hardware interface of each sensor and actuator subsystem was developed, including functional testing of the sensors and actuator subsystem hardware with Simulink Real-Time hardware-in-the-loop. These subsystems could be integrated into the flywheel energy storage system.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATIONS

ac:	Alternating current
AMB:	Active magnetic bearing
CS:	Current sensor
dc:	Direct current
DIN:	Deutsche Institut fur Normung (German Institute of Standards)
DIR:	Direction
ESS:	Energy storage system
EV:	Electric vehicle
FESS:	Flywheel energy storage system
FET:	Field-effect transistor
FRRM:	Field regulated reluctance machine
HIL:	Hardware in the loop
IC:	Integrated circuit
IMEAS:	Measured current
LLC:	Inductor-inductor-capacitor
MATLAB:	MATrix LABoratory, a mathematical simulation software by The Mathworks
MOSFET:	Metal oxide semiconductor field effect transistor
PacTrans:	Pacific Northwest Transportation Consortium
PCB:	Printed circuit board
PI:	Proportional-integral
PNW:	Pacific Northwest
PV:	Photovoltaic
PWM:	Pulse width modulation
PWMH:	
PWML:	
RC:	Resister-capacitor
RES:	Renewable energy source
Simulink:	MATLAB-based graphical programming environment
TSSOP:	Thin shrink small outline package
TTL:	Transistor transistor logic

UI:	University of Idaho
Vac:	Volts alternating current
VCC	Common collector voltage, power supply voltage
Vdc:	Volts direct current
VIOUT:	Analog voltage proportional to a measured current
XMEAS:	Measured displacement

EXECUTIVE SUMMARY

This project developed the mathematical models, MATLAB Simulink simulations, and hardware functional testing of the sensor and actuator subsystems for a flywheel energy storage system (FESS). The mathematical models described ideal sensor and actuator behavior. The simulation facilitated critical evaluation of candidate signal processing (e.g., sampling, filtering, response time, etc.) in the context of the energy storage system. The MATLAB Simulink simulation(s) were extended to Simulink Real-Time hardware-in-the-loop testing with physical sensors and actuators, enabling verification of the modeling assumptions and limitations.

The electrical current actuator was mathematically modeled using H-bridge pulse width modulation current control [23]. While the theory has been well established, the limitations and non-idealities of the physical current actuator subsystem needed to be well understood before integration into the FESS.

The electrical current sensor was well defined in the mathematical model and was based on the manufacturers' data for the actual hardware. The current sensors' ratiometric output sensitivity to the current sensors' 5-V supply voltage warranted careful selection of a 5-V power source. This is an example of a small but important hardware implementation detail that was observed only during physical hardware testing.

The position or displacement sensor was also well defined in the mathematical model and was based on the manufacturers' data for the actual hardware. The physical hardware testing was notably consistent with the mathematical model and MATLAB Simulink simulations.

For all three sensors and actuators subsystems, the physical interface is described and documented for integration into the flywheel energy storage system.

CHAPTER 1. INTRODUCTION

1.1. Typical Application Block Diagram / Overview

The University of Idaho (UI) is developing a flywheel energy storage system (FESS) for applications including electric vehicle (EV) charging stations. A solar carport array of photovoltaic modules could convert solar energy into electricity, as shown in Figure 1.1.

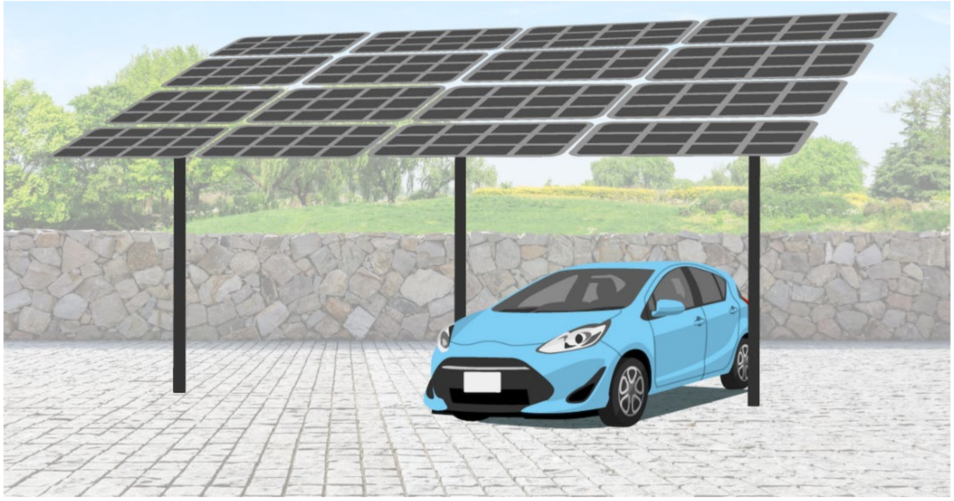


Figure 1.1 Solar Carport

In such a system, all electricity will be consumed as it is generated. If an EV is not present when the sun shines on a solar carport, then energy storage will be needed. The purpose of the UI FESS will be to store energy when the photovoltaic (PV) module array supplies more power than the load consumes, and to supply stored energy when the PV array supplies less power than the load demands. Thus, the UI FESS will be in the business of balancing supply and demand. Ideal UI FESS operation will maintain a constant direct current (dc) bus voltage.

1.2. UI FESS Functional Block Diagram / Overview

The UI FESS is an energy storage flywheel. Energy storage flywheels have very high performance and work on simple principles (see Figure 1.2). To understand their operation, it is best to start with the electric motor-generator. An electric motor-generator is the same machine running in opposite directions. When one puts electrical energy into a motor-generator, it turns into mechanical energy on the spinning rotor; that is a motor. When one puts mechanical energy into the motor-generator by spinning the rotor, electrical energy can be drawn back out; that is a generator. For an energy storage flywheel, the motor-generator is hooked up to a wheel. For the

UI FESS, the rotor is the flywheel. When electrical energy is put into the motor-generator, it accelerates the rotor storing that energy as momentum on the rotor. To retrieve the electrical energy, the momentum of the spinning rotor is allowed to drive the motor-generator, regenerating electricity and slowing the rotor. Because our motor-generator is run in a vacuum and on magnetic bearings, very little energy is lost over time.

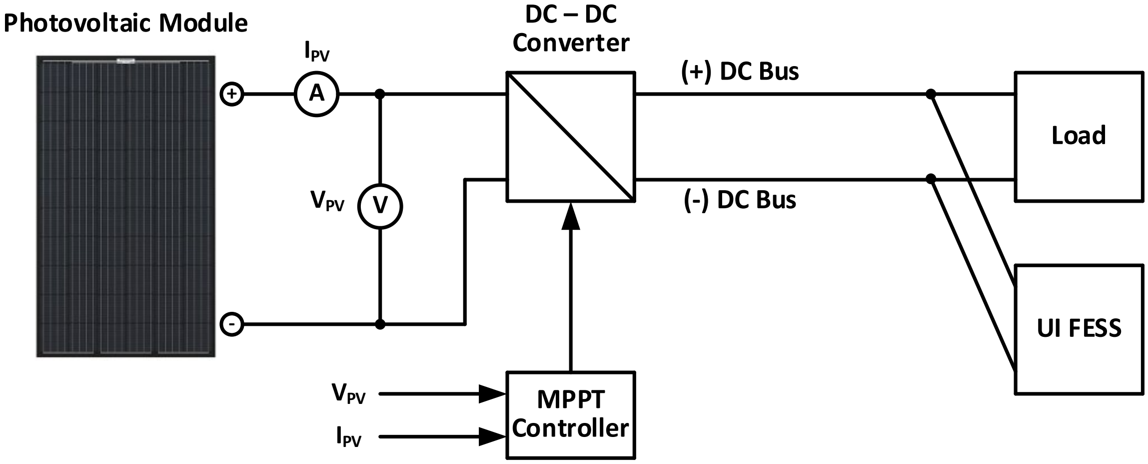


Figure 1.2 Flywheel Energy Storage System Typical Application Block Diagram

Figure 1.3 shows the UI FESS functional block diagram. It shows the measurement, control, and motor-generator energy exchange functions of a six-axis flywheel rotating about a vertical axis. A rotary encoder measures the rotating position of the flywheel’s rotor in its yaw axis. Four displacement sensors measure displacement of the rotor in the two horizontal dimensions. From their measurements, pitch and roll are also calculated. The Halbach Magnet Array provides passive displacement in the vertical axis. These measurements are provided to a real-time digital controller based in a Speedgoat module. The Speedgoat module calculates commands for two sets of Pololu Motor Drivers to stabilize the flywheel in all six dimensions and to regulate the flow of energy by controlling angular velocity and angular position of the flywheel in its yaw axis. Figure 1.3 illustrates these relationships.

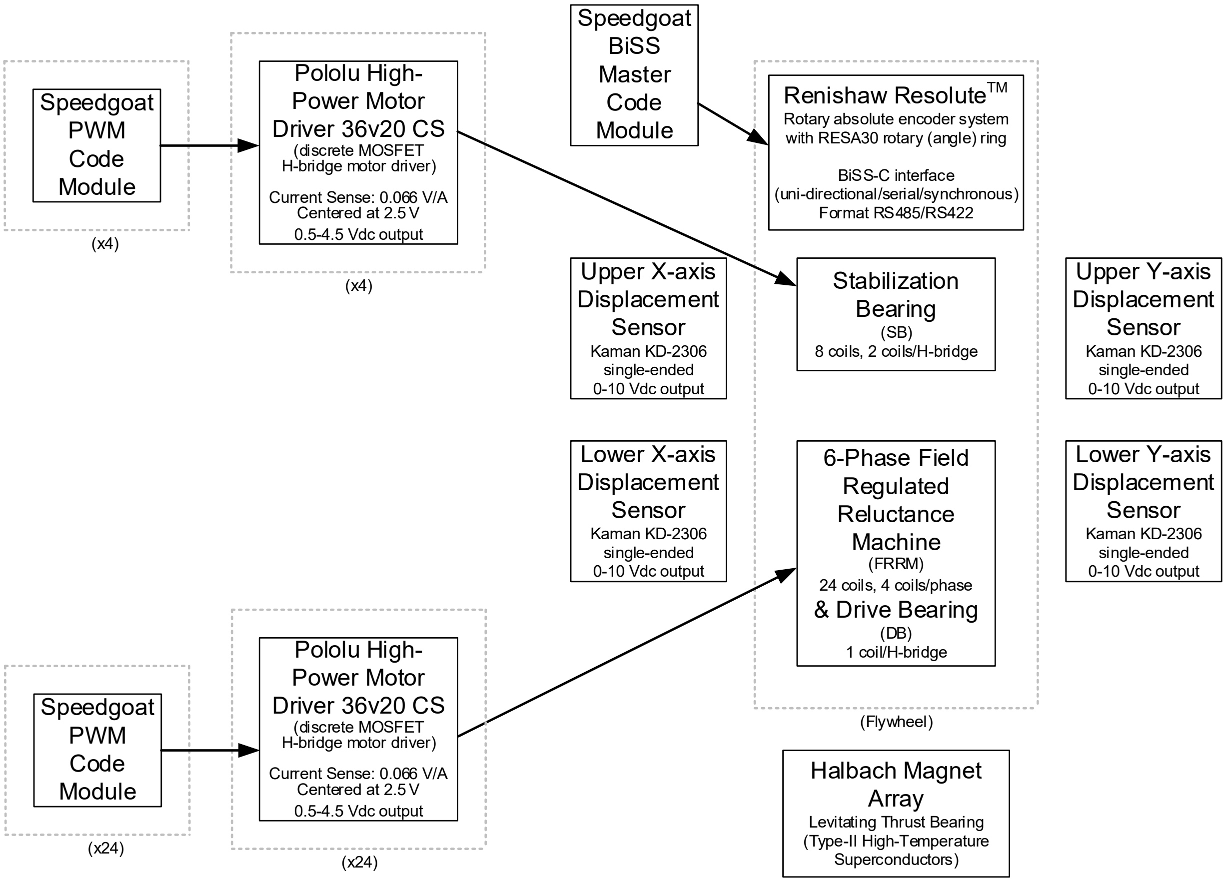


Figure 1.3 UI FESS Functional Block Diagram

1.3. UI FESS Sensors and Actuators Subsystems

1.3.1. *H-Bridge PWM Current Actuators*

The Pololu 36v20 current sensor (CS) discrete metal oxide semiconductor field effect transistor (MOSFET) H-bridge coil driver enables bidirectional control of one high-power coil. The compact 1.8×1.2-inch printed circuit board (PCB) assembly supports 24 volts direct current (Vdc) and is efficient enough to deliver a continuous 20 amperes (A) without a heat sink. The integrated Allegro ACS714 Hall effect-based current sensor outputs an analog voltage proportional to the coil current (VIOUT).

1.3.2. *Hall Effect Current Sensors*

For $I_{COIL} = 0$ A, VIOUT is 2.5 V. The current sensor sensitivity is 66 mV/A. With increasing coil current, I_{COIL}, flowing in the direction from OUTA to OUTB, the VIOUT voltage increases from 2.5 V to 4.5 V. For I_{COIL} = 30 A, VIOUT is 4.5 V. With increasing coil current, I_{COIL}, flowing in the opposite direction, from OUTB to OUTA, the VIOUT voltage decreases from 2.5 V to 0.5 V. For I_{COIL} = -30 A, the VIOUT is 0.5 V.

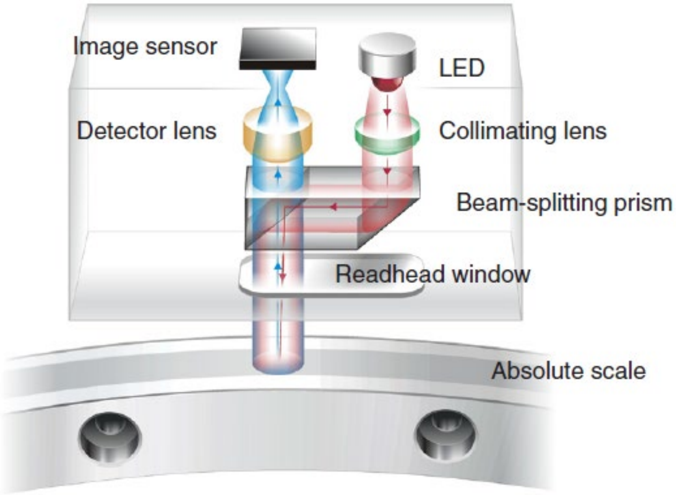
<u>1.3.3.</u> *Non-Contact Eddy Current Displacement Sensors*

The Kaman KD-2306-9U is a non-contact linear displacement measurement system. The KD-2306 sensor signal conditioning electronics module supports the 9U sensor. This 9U sensor makes up one leg of a balanced inductive bridge circuit network. It produces a high-frequency magnetic field by applying a high-frequency (1-MHz) current to the leg of the bridge network inside the sensor head. If there is a conductive target within this magnetic field, then electromagnetic induction causes magnetic flux to pass over the surface of, and eddy currents to flow in, the conductive target. This causes the impedance of the leg of the bridge network to change. As the conductive target gets closer, the magnitude of the eddy current sensor oscillations decreases, and the rectified voltage is smaller. As the conductive target gets farther away, the magnitude of the eddy current sensor oscillations increases, and the rectified voltage is larger. The 0- to 10-V output voltage is linearly proportional to the distance between the face of the 9U sensor and the stainless-steel conductive target. The measured displacement is 0 mm at 0 V and 3 mm at 10 V.

<u>1.3.4.</u> *Rotary Absolute Encoder*

The Renishaw Resolute™ rotary absolute encoder system is a rotational position measurement system consisting of a miniature ultra-high-speed digital camera inside a stationary readhead and a stainless-steel ring with absolute scale code marked directly on the periphery.

The Resolute encoder calculates rotational position on demand. The readhead receives a series of request signals from the host control system (Speedgoat Performance Real-Time Target Machine). Each time it receives a request, the readhead determines rotational position by two independent methods: 1) decoding a single image without any information from previous positions, and 2)



linear extrapolation from the two most recent rotational position readings, assuming constant velocity. Once the two rotational position methods have been calculated, the encoder decides which position to output and whether to set the error flag. If the positions calculated by the two methods agree within ±15 µm (half a scale period) of one another, then the encoder outputs the position from the first method and sets an internal counter to zero.

If the positions disagree, then the encoder outputs the position from the second method and increments the internal counter. If the internal counter ever exceeds four, then the readhead sets the error flag. The readhead makes sure that there is never more than 75 µs between images by capturing extra images between requests if necessary. For a system requesting a position every ≤ 75 µs, the time between outputting the first incorrect position and raising the error flag is five times the request interval. For a slower system requesting a position at 500 µs intervals, this time will be 500 µs, as the readhead will have processed six further images between each pair of requests to make sure that the time between images never exceeds 75 µs. In both cases, the time between outputting an incorrect position and raising the error flag is sufficiently short that appropriate action can be taken in response to the error flag before the incorrect rotational position data can influence the control system.

CHAPTER 2. LITERATURE REVIEW

Electric vehicles (EVs) have the potential to significantly reduce greenhouse gas emissions in the Pacific Northwest (PNW) region of the U.S. and everywhere [1][2]. With the number of EVs on the rise, there is a need for adequate charging infrastructure to serve these vehicles [11]. Rural EV charging stations in the PNW based on abundant renewable energy and flywheel energy storage present both an opportunity and a challenge to significantly reduce greenhouse gas emissions.

EV users need access to charging services within the driving range of their EVs. Hence, there is a need to provide adequate access to charging facilities along different automotive transportation networks. Many of the routes along those transportation networks are isolated from the power grid, and in some cases the expansion of the existing power grid to feed charging stations located along these routes may be impossible, costly, or impractical [3]. For instance, in the PNW many rural communities and national parks are accessible by long, remote highways that are far from any nearby distribution-level power grid.

The planning of grid-tied EV charging stations has been extensively studied in recent literature [3]. In contrast, the planning of stand-alone EV charging stations, i.e., charging stations not connected to the electric grid, have not received as much attention.

A flywheel energy storage system (FESS) as a part of a fully green renewable energy storage system could minimize the operational costs of charging stations and their impacts on the peak demand of the hosting distribution power grid, if connected [7]. A FESS could also be part of a charging station not connected to the electric distribution power grid. For example, EV charging stations might use an energy storage system (ESS), e.g., flywheel ESS, and a renewable energy source (RES), e.g., photovoltaic (PV) modules. ESSs could store the energy generated from intermittent RESs to charge EVs when needed [2]. Combining an ESS and RES in a grid-connected charging station with islanding capability could improve EV charging availability and reliability. Although, PV RESs are inherently intermittent because of diurnal and seasonal cycles and are also affected by cloud cover [10], locations with an adequate PV RES and ESS could operate in an islanded state indefinitely.

An EV charging station may offer multiple charging options, including, from slowest to fastest ac level 1, i.e., 120 Vac charging; ac level 2, i.e., 240 Vac charging; dc fast charging; and battery swapping [4][15]. Level 1 and level 2 ac charging are only available from power grid-connected EV charging stations, unless an inverter is used on the dc bus of an off-grid EV charging station. The trends among the first three options are toward level 2 ac charging at a home or residence and toward dc fast charging at public EV charging stations, with a continual push for faster charging. A full battery swap should take 10 minutes or less in comparison to a plug-in EV charge, which can take 30 minutes to a few hours. The key point is that a rural EV charging system with combined RES and ESS, as envisioned in this study, could offer multiple charging options and hence would not be limited to providing a particular charging option. Such a proposed solution would be flexible and could be optimized toward reducing EV user waiting time.

The lack of public charging infrastructure is a major factor in the slower adoption of EVs in rural areas in the PNW. Dc fast charging increases EV user convenience by reducing charging time. High capital costs and uneven power demand are challenges to deploying EV dc fast charging stations. These issues have been studied in three types of areas—urban, suburban, and rural—within the Columbus, Ohio, USA, region [5]. Ucer et al. [5] decried a 12-minute maximum queuing time for the urban area but were not overly concerned about the 30-minute average queuing duration for the rural area, the 276-minute (over 4 ½ hours) maximum queuing time for the rural area notwithstanding. It is likely that the authors did not live in a rural area. Long queuing durations like these will only further retard the adoption of EVs in rural areas. The suppressed demand due to either long driving distances to get to a charging station or long waiting times (queuing durations) was the focus of consideration by Gan et al. [8]. The authors used both spatial and temporal penalties (costs) to capture the nature of EV users' charging behaviors. The claimed result was a fixed-point equation formulated as a nonlinear integer problem, which determined the optimal locations (i.e., spatial solution) and optimal number of charging ports (i.e., the equivalent to "pumps" at a gas station).

EV user waiting time (queuing duration) modeling leads to the question of optimal capacity sizing for EV charging systems. Ugirumurera and Haas [6] studied the optimal sizing of a complete green charging system that relied entirely on the power generated by RES, specifically by solar panels. Their work can be used to determine the optimal resource size (e.g., the number of solar panels and the energy-storage capacity) that would minimize the charging system's costs while meeting performance metrics. For grid-connected EV charging stations, work by Negarestani et al. [7] can be used to determine the optimal size of the ESS for an EV dc fast charging station to minimize station energy costs and the ESS costs. The approach by Negarestani et al. [7] considered various technical and economic constraints, such as energy loss and the life cycle cost of the ESS.

In economics, competition exists when multiple companies compete for customers. Basic economic theory suggests that when firms must compete for customers, the competition leads to lower prices, higher quality goods and services, greater variety, and more innovation. Duan et al. [9] examined the situation in which multiple fast charging service providers participate in the investment of EV fast charging (dc) stations in competition with one another. They proposed a methodology to optimize EV user queuing time and fast charging station location and number of charging ports. Of interest for this study's work is a charging station-level model to obtain the optimal sizes and operation scheduling of on-site (at a charging station) ESSs. This could be useful in future scaling of our ESS.

Focusing on the major challenge to widespread EV adoption, namely a refueling experience similar to that of gasoline vehicles, Tu et al. [11] reviewed emerging extreme fast-charging technologies. Despite significant Li-ion battery technology advancements in the last five years, the energy density of the Li-ion batteries is 40 times lower than the energy density of petroleum. Despite falling costs and major improvements in performance, Li-ion battery degradation at rest and during cycling, charging rate limitations due to the electrochemical processes, and limited energy density (in comparison to petroleum) still pose major challenges to more widespread EV adoption [11]. Beyond Li-ion battery technology limitations, a key remaining challenge for the extensive adoption of EVs is the lack of refueling infrastructure. This is especially true in rural areas such as in the PNW. "Extreme" dc fast-charging refers to the grouping of dc fast charging ports. High power transfer rates are required to speed up EV charging. Designing and building a system that can deliver such high power becomes increasingly challenging and costly. A grid-connected dc fast-charging station may require electrical service upgrades such as a transformer and a feeder, conditioning of the ground surface, conduits from the power source to the service transformer and from the transformer to the fast-charging port, material costs, permits, and administration. The key idea of "extreme" dc fast-charging is for multiple charging ports to share the same costly upstream equipment, thereby spreading the construction overhead over multiple charging ports [11]. While Tu et al. [11] noted that this sharing can reduce the dc fast-charging stations' footprint in densely populated areas, this sharing is more important for cost reduction in rural dc fast-charging station locations, where cost rather than footprint is likely to be the most significant constraint.

At the ESS level, Figure 1.2 shows that the ideal UI FESS operation will maintain a constant dc bus voltage. To use the dc bus voltage to charge an EV will require dc to dc conversion. These converters would interface between the dc bus voltage, which is the output of an ESS, and the EV charging port. Isolated dc-dc converters with galvanic isolation are commonly used in EV battery chargers. He and Khaligh [16] considered a vehicle-to-grid concept in which EVs could be considered as distributed power sources to store and send power back to the grid. This would allow EVs to provide voltage and frequency regulation to the grid, absorb excess electricity, and deliver power to the grid during periods of high demand. The vehicle-to-grid capability would require EVs to have bidirectional charging systems. While vehicle-to-grid capability is not the immediate intent of the UI FESS typical application, unidirectional isolated dc-dc converters would be necessary to interface the RES with the dc bus voltage and the EV charging port with the dc bus voltage. For unidirectional grid-to-vehicle chargers, inductor-inductor-capacitor (LLC) converters are commonly selected as the dc–dc stages [16].

In rural EV charging station applications, ESSs may be required to efficiently store energy for longer periods of time than their urban counterparts. The nature of RESs also means that they need efficient, longer-term ESSs. Pei et al. [17] extolled the benefits of magnetic bearings because they have no friction, are pollution-free, and are maintenance-free. They noted that active magnetic bearing machines, sometimes called bearingless machines, are becoming increasingly attractive in applications such as flywheel ESSs. A 5-degree-of-freedom active magnetic bearing for flywheel ESS was described by Li et al. [18]. Flywheels have great potential for fast charging for EVs. For grid-connected fast-charging stations, using ESSs will reduce the cost of infrastructure upgrades, e.g., transformers and feeders, etc. In comparison with other ESS technologies such as Li-ion batteries, flywheels have longer life cycles and higher power density [18]. Other advantages include operating under low/high temperatures, an accurate state of charge, and recyclability [19].

CHAPTER 3. SINGLE-AXIS ACTIVE-MAGNETIC-BEARING ACADEMIC TEST FIXTURE

A single-axis active-magnetic-bearing (AMB) academic test fixture (Figure 3.1) was created to help develop, test, and improve the AMB control software and hardware used for the University of Idaho (UI) flywheel energy storage system (FESS). The single-axis AMB academic test fixture served as an intermediate step before the design and implementation of the more complex field regulated reluctance machine (FRRM) AMB and stabilization AMB in the UI FESS.

The single-axis AMB academic test fixture had a "U" shaped electromagnet. The coil consisted of 150 turns of 18 American wire gauge (AWG) solid core copper wire coated with a thin layer of enamel insulation. The flotor was free to translate up and down along the vertical axis. The iron core of the electromagnet was M36 electrical steel (µr = 1616).

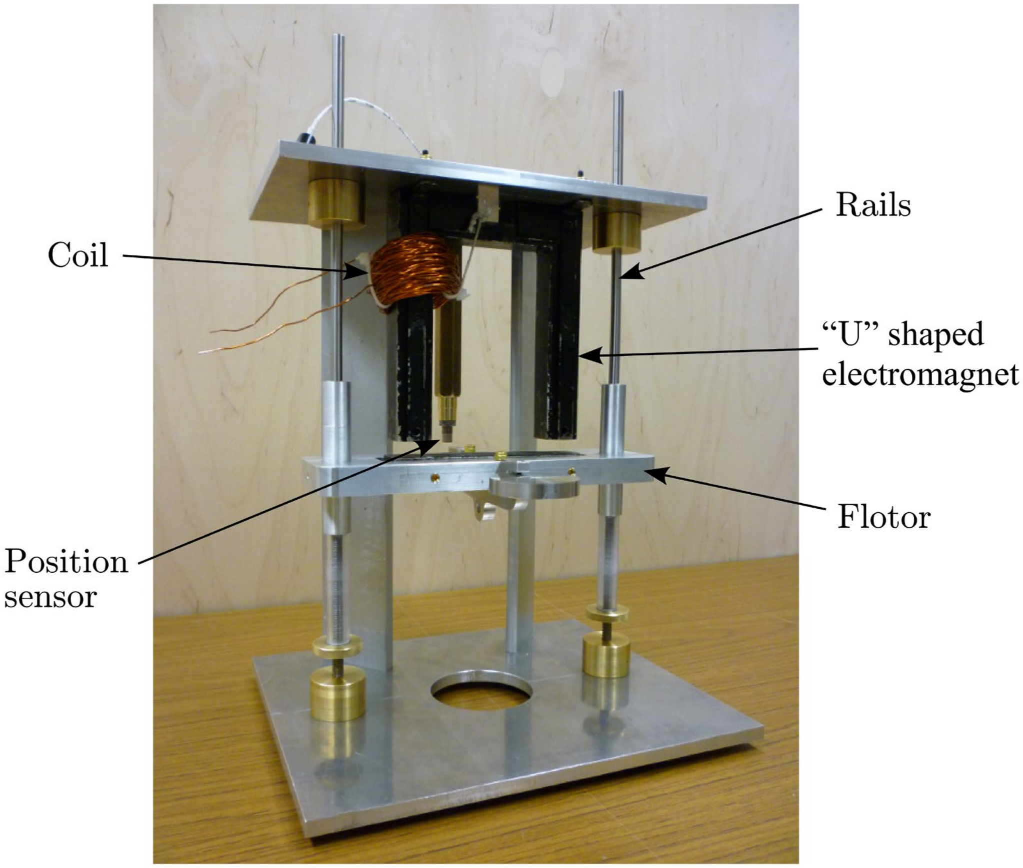


Figure 3.1 Single-Axis Active-Magnetic-Bearing Academic Test Fixture

The “U” electromagnet was oriented to impose an attractive magnetic force on the flotor, against the force of gravity. The flotor was fixed to rails with mechanical bearings.

A discrete MOSFET H-bridge coil driver enabled bidirectional electro-magnet coil current control. A Hall-effect current sensor measured electro-magnet coil current, and a non-contact Eddy current displacement sensor was used to measure the air gap.

Each sensor and actuator interface is described and documented in upcoming chapters for integration into the flywheel energy storage system.

CHAPTER 4. H-BRIDGE PWM CURRENT ACTUATOR

The single-axis active-magnetic-bearing (AMB) academic test fixture electro-magnet coil current was actuated by one Pololu 36v20 CS [20] (Figure 4.1). This discrete MOSFET H-bridge coil driver enables bidirectional current control of one high-power coil, i.e., the electro-magnet coil. The compact 1.8×1.2-inch PCB assembly supports 24 Vdc and is efficient enough to deliver up to a continuous 20 A without a heat sink (at room temperature).

The H-bridge is made up of one N-channel MOSFET [21] per leg, and most of the board's performance is determined by these MOSFETs. The rest of the board contains electrical circuitry to take 5-V transistor transistor logic (TTL) digital inputs, pulse width modulation (PWMH) and direction (DIR), and it controls the MOSFETs.

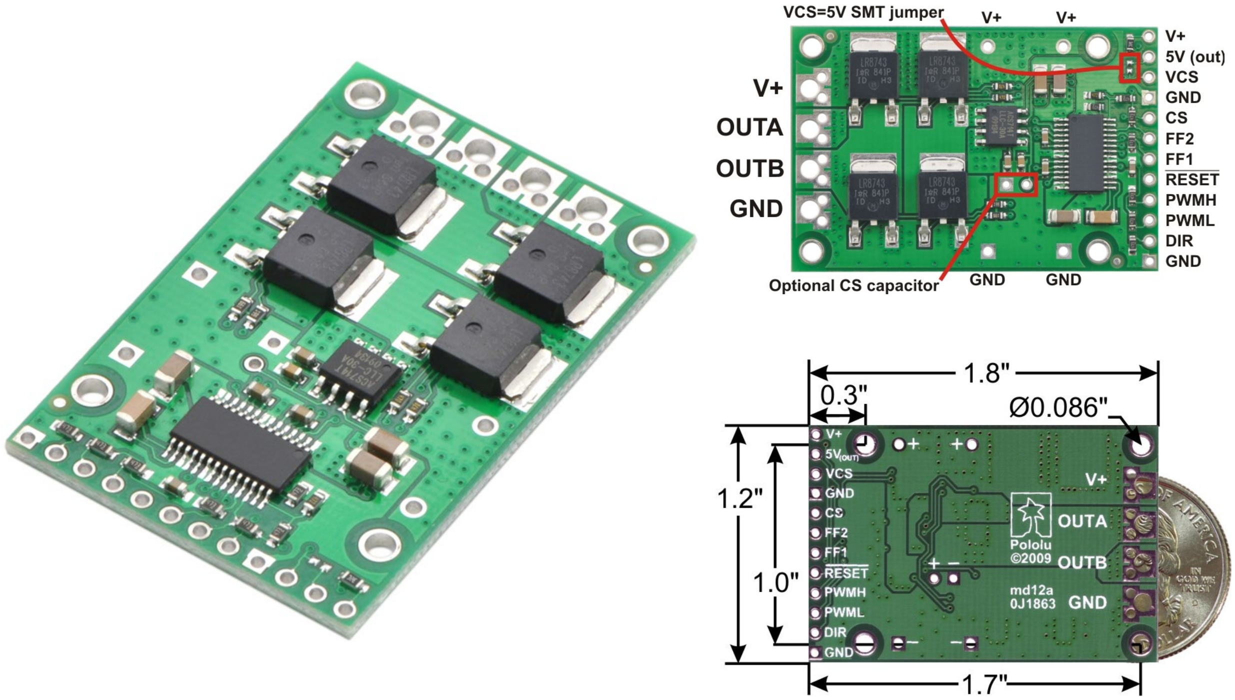


Figure 4.1 Pololu High-Power Motor Driver 36v20 CS [20]

During the active (high) portion of the PWMH 5-V TTL signal, the full dc bus voltage is applied across the machine coil in the polarity or direction determined by the DIR 5-V TTL signal; during the low portion of the PWMH 5-V TTL signal, both sides of the machine coil are connected or shorted to the dc bus negative terminal (Figure 4.2).

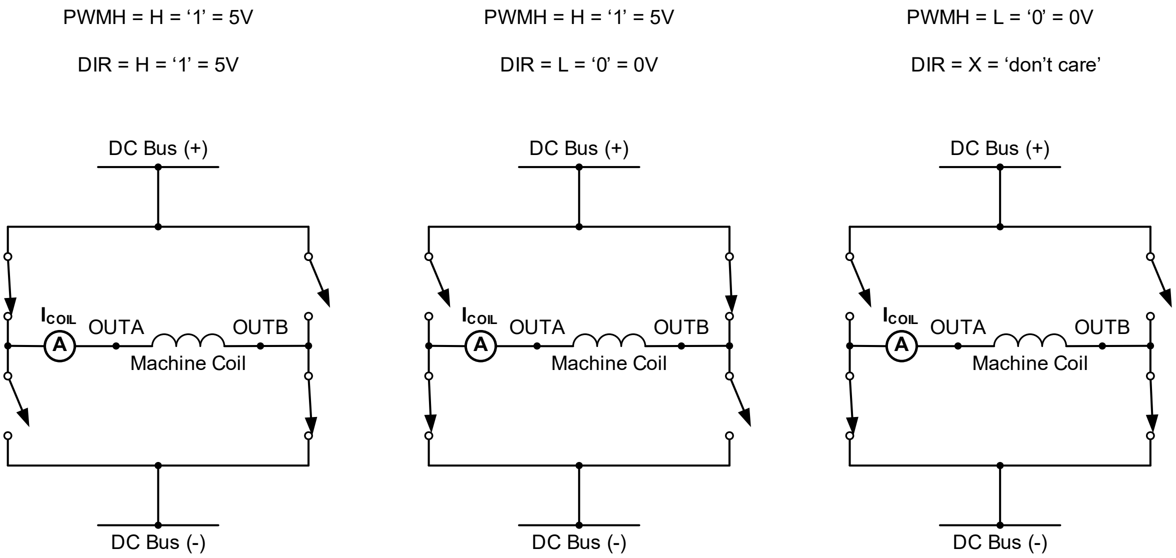


Figure 4.2 Pololu High-Power Motor Driver 36v20 CS [20] Operation Modes

When DIR = '1' the polarity or direction is from OUTA to OUTB. When DIR = '0' the polarity or direction is from OUTB to OUTA (Figure 4.3).

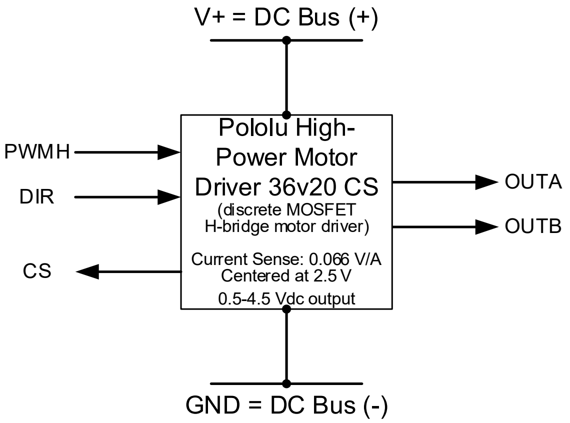


Figure 4.3 Pololu High-Power Motor Driver 36v20 CS [20] Functional Block Diagram

4.1. Pololu 36v20 CS: N-Channel MOSFET

The Pololu 36v20 CS H-bridge is made up of one N-channel MOSFET per leg, and most of the board's performance is determined by these MOSFETs. The MOSFETs are all Infineon IPD048N06L3 G OptiMOS™3 power transistors [21] (Figure 4.4) in a TO-252, also known as a DPAK, package. The key parameters are shown in Table 4.4.

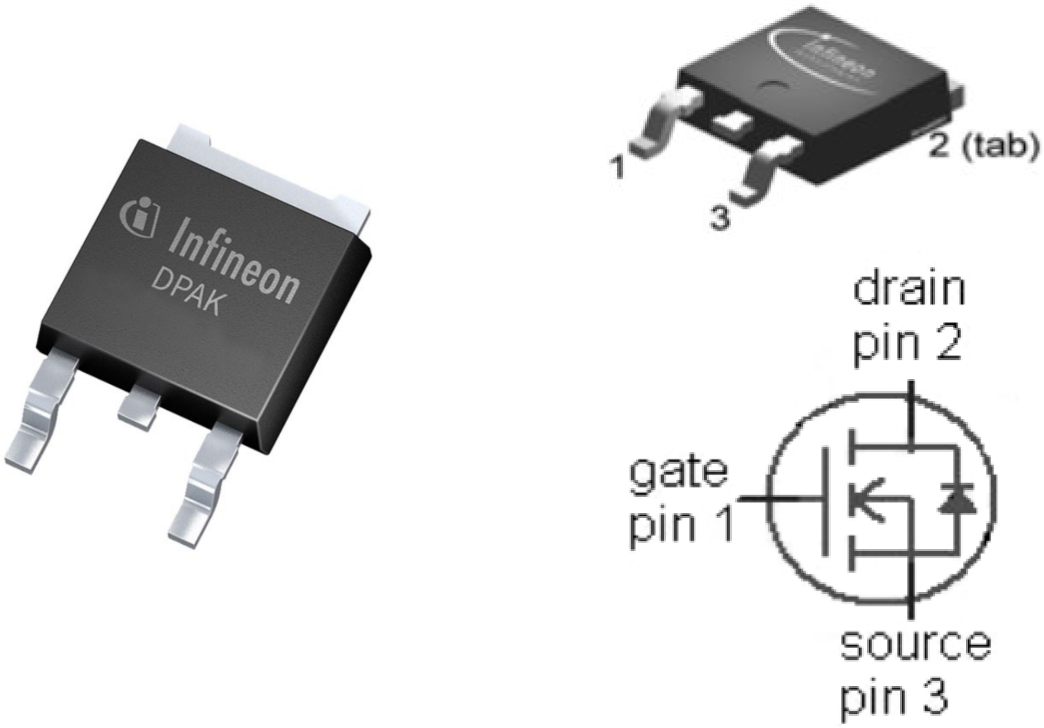


Figure 4.4 Infineon IPD048N06L3 G OptiMOS™3 Power Transistor [21]

Table 4.1 Infineon IPD048N06L3 G Parameters

Parameter	Value	Unit	Notes
$V_{DS,MAX}$	60	V	
$R_{DS(ON),MAX}$	4.8	mΩ	max per H-bridge leg
$I_{D,MAX}$	90	A	at 25°C, infinite heatsink current limited by bond wire
	15	A	at 105°C, no heatsink, minimal footprint
θ_{JA}	62	K/W	minimal footprint
$T_{J,MAX}$	175	°C	operating and storage

Note 1: Infineon IPD048N06L3 G Parameters shown here are from [21].

4.2. Pololu 36v20 CS: Allegro Microsystems A3941 Full Bridge MOSFET Driver

The Allegro MicroSystems, LLC A3941 is a full-bridge controller for use with external N-channel power MOSFETs (Figure 4.5) and is specifically designed for applications with high-power inductive loads, such as motor-generator coils and/or windings.

An integrated switched capacitor charge pump regulator provides full (>10 V) gate drive to external N-channel MOSFETs, even the high-side external N-channel MOSFETs. This internal charge pump allows dc (100 percent duty cycle) operation.

The power MOSFETs are protected from shoot-through current by an external resistor adjustable deadtime. Integrated diagnostics provide indication of undervoltage, overtemperature, and H-bridge faults.

The A3941 integrated circuit is packaged in a 28-pin thin shrink small outline package (TSSOP) with an exposed thermal pad.

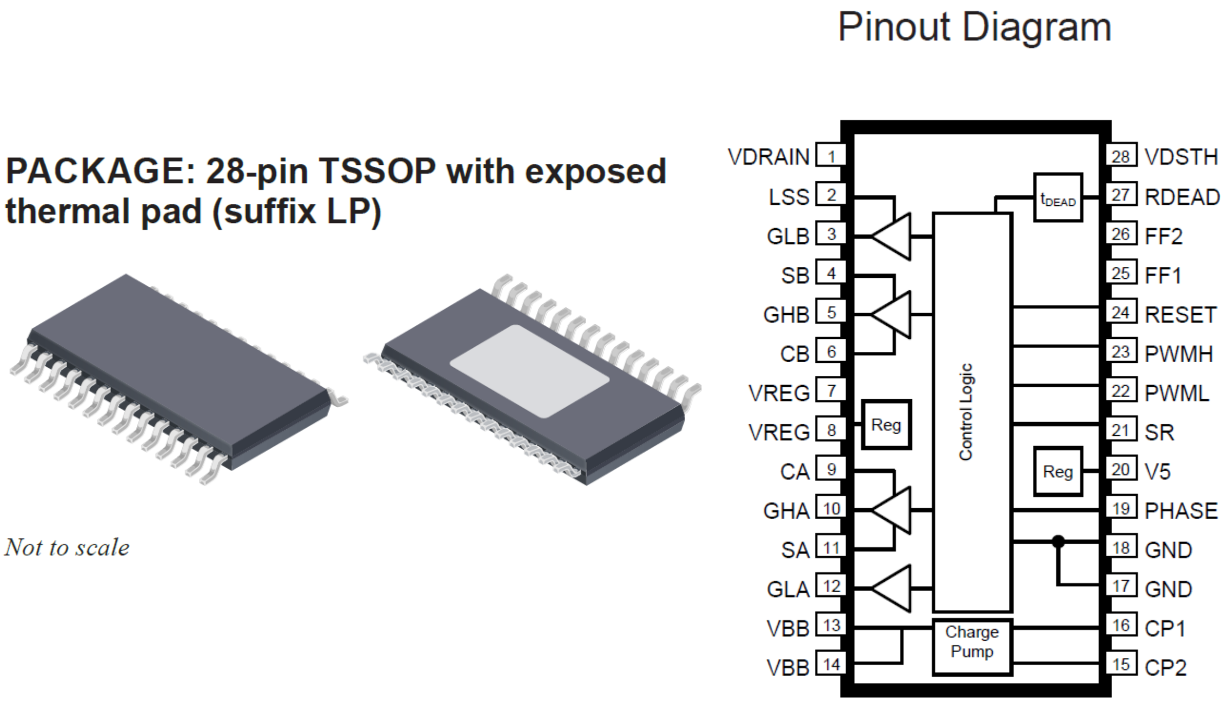


Figure 4.5 Allegro MicroSystems LLC A3941KLPTR-T Full Bridge MOSFET Driver [22]

The A3941 is a full-bridge MOSFET driver requiring a single unregulated supply of 7 to 50 V. It includes an integrated 5-V logic supply regulator. The A3941 includes all the necessary circuits to ensure that the gate-to-source voltages of both high-side and low-side external power MOSFETs are above 10 V, at supply voltages down to 7 V. A single power supply connection is required to the voltage base base (VBB) pin.

The A3941 can be driven with PWM control signals. Cross-conduction (shoot-through current) in the external H-bridge is avoided by a resistor adjustable dead time.

The A3941 includes a number of protective features against undervoltage, overtemperature, and power bridge faults. Fault states enable responses by the device or by the external controller, depending on the fault condition and logic settings. Two fault flag outputs, FF1 and FF2, are provided to signal detected faults to an external controller.

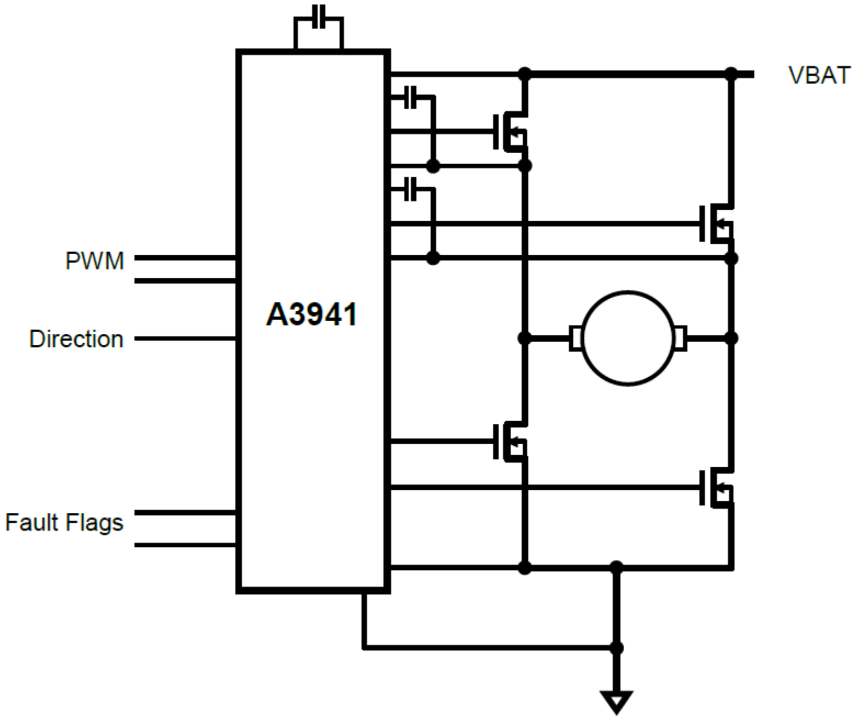


Figure 4.6 Allegro MicroSystems LLC A3941 Full Bridge MOSFET Driver Typical Application

The A3941 is designed to drive external, low on-resistance, power N-channel MOSFETs. It supplies the large transient currents necessary to quickly charge and discharge the external field-effect transistor (FET) gate capacitance to reduce dissipation in the external FET during switching. The charge and discharge rate can be controlled with an external resistor in series with the connection to the gate of the FET.

The A3941 provides two PWM control signals and a phase control for the current direction. A PWM signal is applied to PWMH, and PWML is tied high. The PHASE input is required to reverse the current direction. The PHASE input of A3941 is the DIR input of the Pololu 36v20 CS.

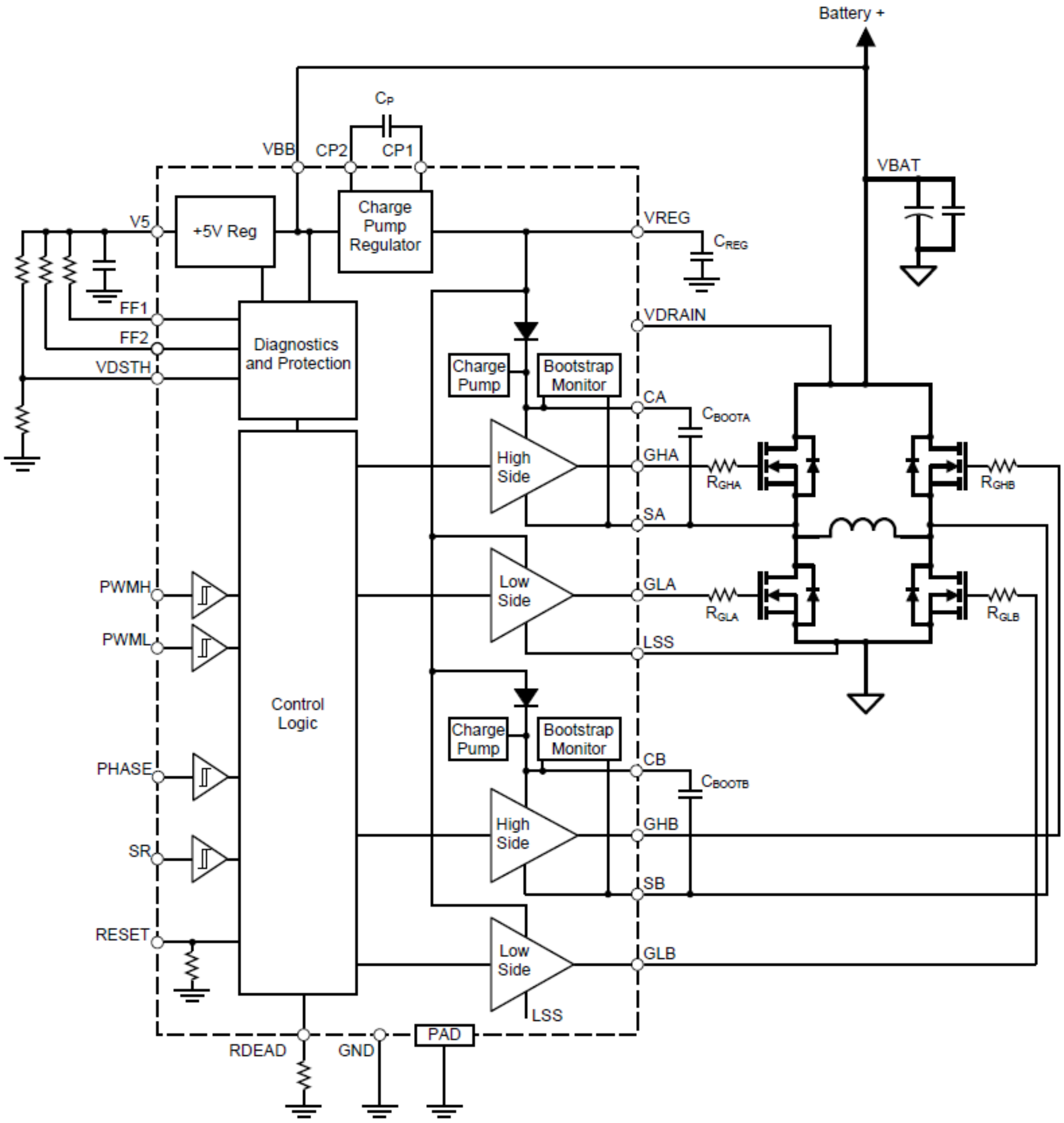


Figure 4.7 Allegro MicroSystems LLC A3941 Full Bridge MOSFET Driver Functional Block Diagram

When PWMH is high and DIR is high, GHA is high and GLB is high, as shown in Figure 4.7 (bridge driven with A high and B low).

When PWMH is high and DIR is low, GHB is high and GLA is high, as shown in Figure 4.7 (bridge driven with B high and A low).

When PWMH is low, DIR is “don’t care,” GLA is high, and GLB is high, as shown in Figure 4.7. In this case the high-side MOSFETs are switched off during the current decay time (PWMH off-time) and the coil current recirculates through the low-side MOSFETs.

This control configuration is commonly referred to as high-side chopping or high-side PWM.

CHAPTER 5. HALL-EFFECT CURRENT SENSOR

The Pololu High-Power Motor Driver 36v20 CS board includes a current sensor IC, the Allegro Microsystems ACS714LLCTR-30A-T (Figure 5.1) [24]. The integrated Allegro ACS714 Hall-effect current sensor IC outputs an analog voltage, VIOUT, proportional to the electro-magnet coil current. This current sensor can measure bi-directional current with a magnitude of up to ±30 A.

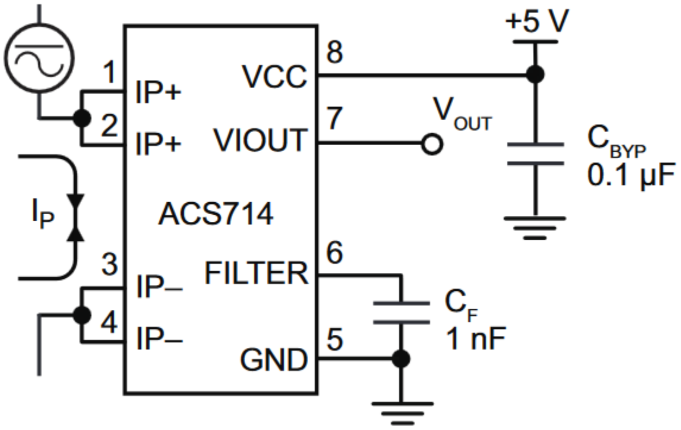


Figure 5.1 ACS714LLCTR-30A-T Typical Application

For I_{COIL} = 0 A, VIOUT is VCC/2 = 2.5 V, where VCC = +5 Vdc (nominal). The current sensor sensitivity is 66 mV/A. With increasing coil current, I_{COIL}, flowing in the direction from OUTA to OUTB, the VIOUT voltage increases from 2.5 V to 4.5 V. For I_{COIL} = 30 A, VIOUT is 4.5 V. With increasing coil current, I_{COIL}, flowing in the opposite direction, from OUTB to OUTA, the VIOUT voltage decreases from 2.5 V to 0.5 V. For I_{COIL} = -30 A, the VIOUT is 0.5 V.

$$\begin{aligned} \text{VIOUT} &= (\text{IP})*(66\text{ mV/A}) + (\text{VCC}/2) \\ &= (\text{IP})/(15\text{ A/V}) + (2.5\text{ V}) \end{aligned}$$

where IP is the current from OUTA to OUTB. The measured current is

$$\begin{aligned} \text{IMEAS} &= (\text{VIOUT} - 2.5\text{ V})/(66\text{ mV/A}) \\ &= (\text{VIOUT} - 2.5\text{ V})*(15\text{ A/V}) \end{aligned}$$

The electrical current sensor's mathematical model is well defined and is based on the manufacturer's data for the actual hardware. The current sensor's ratiometric output sensitivity to the current sensor's 5-V supply voltage (VCC) warrants careful selection of a 5-V power source.

This is an example of a small but important hardware implementation detail that was observed during physical hardware testing.

Table 5.1 Hall-Effect Current Sensor: Allegro ACS714LLCTR-30A-T [24]

Allegro Part Number	VCC (V)	Current Measurement Range (A)	Sensitivity (mV/A)	Operating Temperature Range	Bandwidth (kHz)	Package	Cost ea. (Digi-Key 3k reel)
ACS714LLCTR-30A-T	5	±30	66	-40 to 150°C	80	8-pin SOIC	$2.46

5.1. Pololu 36v20 CS: Allegro Microsystems ACS714 Current Sensor

The Pololu High-Power Motor Driver 36v20 CS [20] board includes a current sensor IC, the Allegro Microsystems ACS714LLCTR-30A-T [24]. The Allegro ACS714 device consists of a linear Hall-effect sensor with a copper conduction path located near the surface of the die. Applied current flowing through this copper conduction path generates a magnetic field that the Hall IC converts into a proportional voltage. The ACS714 outputs an analog signal, V_{IOUT}, that varies linearly with the bi-directional electro-magnet coil current, I_{COIL}. V_{IOUT} is the current sensor (CS) output of the Pololu High-Power Motor Driver 36v20 CS [20] board. For I_{COIL} = 0 A, the CS output is 2.5 V. The ACS714LLCTR-30A-T device sensitivity is 66 mV/A. With increasing coil current, I_{COIL}, flowing in the direction from OUTA to OUTB, the CS output voltage increases from 2.5 V to 4.5 V. For I_{COIL} = 30 A, the CS output is 4.5 V. With increasing coil current, I_{COIL}, flowing in the opposite direction, from OUTB to OUTA, the CS output voltage decreases from 2.5 V to 0.5 V. For I_{COIL} = -30 A, the CS output is 0.5 V. The current sensor measurement error is ±1.5 percent at 25°C and ±5 percent from -40°C to 150°C [24].

The Allegro Microsystems ACS714LLCTR-30A-T [24] senses AC or DC current using a Hall element. Device performance characteristics are specified over the operating temperature range of -40 to 150°C. The Hall current drive, shown in Figure 5.2, forces a known Hall current through the Hall element. The Hall voltage output from the Hall element is proportional to the magnetic field from the primary current flowing through the copper conduction path.

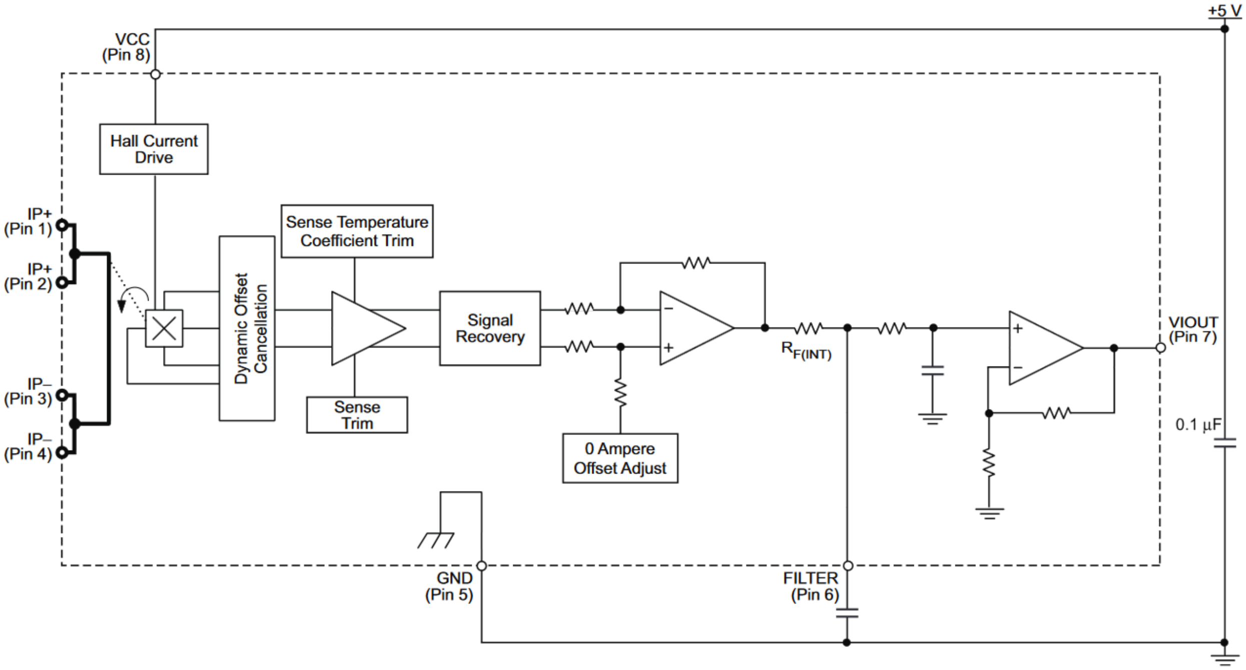


Figure 5.2 ACS724KMATR-20AB-T Functional Block Diagram

The Hall voltage is amplified by a temperature compensated gain (sensitivity). An integrated filter resistance, $R_{F(int)}$, can be combined with an external capacitor to RC low-pass filter the amplifier output before the non-inverting output buffer. The device V_{CC} = +5 V, and the analog output voltage is nominally $V_{CC}/2$ = 2.5 V with I_P = 0A. With a ±30 A I_P measurement range, the sensitivity is 66 mV/A and the analog output voltage range is 0.5 to 4.5 V.

CHAPTER 6. NON-CONTACT EDDY CURRENT DISPLACEMENT SENSOR

A single Kaman KD-2306-9U non-contact Eddy current displacement sensor (Figure 6.1) was used to measure the air gap. The output of the KD-2306-9U is an analog voltage, VOUT.

$$V_{OUT} = \left(\frac{1\,V}{0.3\,mm}\right) \times (displacement[mm])$$

The Kaman KD-2306 is a non-contact, linear, analog displacement measuring system. The system operates on a traditional inductive bridge circuit. This system can be utilized for precision static and dynamic measurements of conductive targets.

The 0 to 10 V analog output voltage, VOUT, was linearly proportional to the distance between the face of the displacement sensor and the 303 stainless-steel conductive target on the flotor assembly. VOUT = 8.333 V for a displacement of 2.5 mm, VOUT = 5 V for a displacement of 1.5 mm, and VOUT = 1.667 V for a displacement of 0.5 mm.

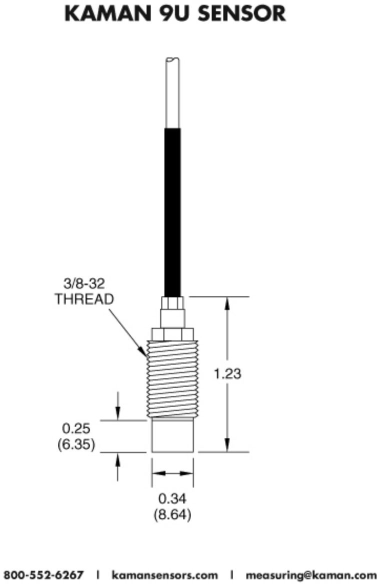


Figure 6.1 Kaman 9U Sensor [27]

6.1. Kaman KD-2306-9U

The Kaman KD-2306-9U is a non-contact linear displacement measurement system. The KD-2306 sensor signal conditioning electronics module supports the 9U sensor. This 9U sensor makes up one leg of a balanced inductive bridge circuit network. It produces a high-frequency magnetic field by applying a high-frequency (1 MHz) current to the leg of the bridge network inside the sensor head. If there is a conductive target within this magnetic field, then electromagnetic induction causes magnetic flux to pass over the surface of, and eddy currents to flow in, the conductive target. This causes the impedance of the leg of the bridge network to change.

As the conductive target gets closer, the magnitude of the eddy current sensor oscillations decreases and the rectified voltage is smaller. As the conductive target gets farther away, the magnitude of the eddy current sensor oscillations increases and the rectified voltage is larger. The 0 to 10 V output voltage was linearly proportional to the distance between the face of the 9U sensor and the 303 stainless-steel conductive target on the flotor assembly. The measured displacement was 0 mm at 0 V and 3 mm at 10 V.

Table 6.1 Kaman KD-2306-9U Displacement vs Output Voltage

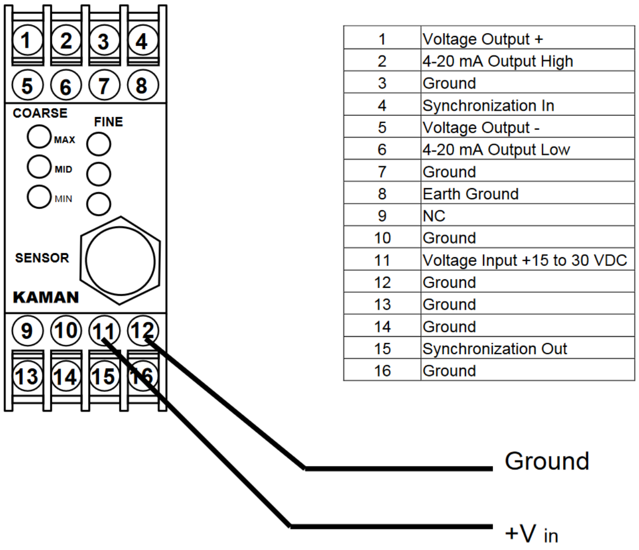
Displacement	Output Voltage
0.0 mm	0.000 Vdc
0.5 mm	1.667 Vdc
1.5 mm	5.000 Vdc
2.5 mm	8.333 Vdc
3.0 mm	10.000 Vdc

Table 6.2 Kaman KD-2306-9U Parameters

Parameter	Value	Unit	Notes
Output	0 – 10	Vdc	
Resolution	0.01	%FS	Full Scale (FS) is 4 mm 0.01% of 4 mm is 0.4 µm
Static Resolution	0.4	µm	
Measuring Range	0 – 4 0 – 3	mm mm	Uncalibrated Calibrated
Offset	1	mm	Calibrated offset
Integral Cable Length	6 ½	ft	6.5 ft = 2 m
Operating Temperature Range (Electronics)	0 to 55	°C	
Operating Temperature Range (9U sensor)	cryogenic to 200	°C	
Frequency Response	50	kHz	-3dB point
Power Supply Requirements Voltage Voltage Regulation Current	 +15 to +30 ±0.5 150	 Vdc Vdc mAdc	 Maximum
Terminal Screw Torque	7	lb-in	Maximum 7 lb-in = 0.8 N-m

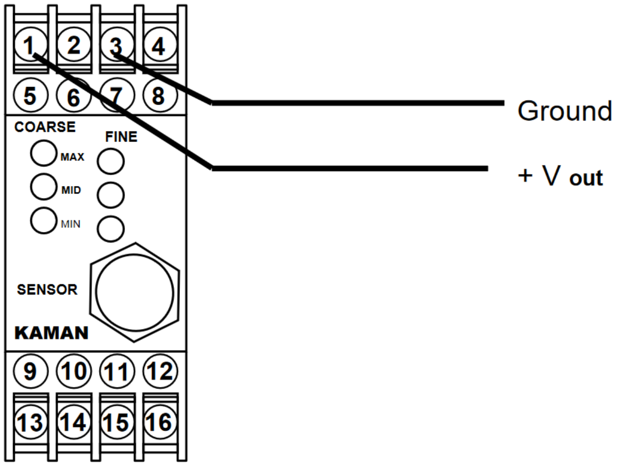
Note 1: Kaman KD-2306-9U Parameters shown here are from [25][26].

The KD-2306-9U consists of two subassemblies: a 9U sensor with an integral cable and the KD-2306 signal conditioning electronics module in a DIN mounting enclosure (Figure 6.2). The system is preconfigured at the factory for a particular sensor (9U), cable length (6 ½ feet), target material (303 stainless steel), and calibrated measuring range (0 to 3 mm, 1 mm offset).



1	Voltage Output +
2	4-20 mA Output High
3	Ground
4	Synchronization In
5	Voltage Output -
6	4-20 mA Output Low
7	Ground
8	Earth Ground
9	NC
10	Ground
11	Voltage Input +15 to 30 VDC
12	Ground
13	Ground
14	Ground
15	Synchronization Out
16	Ground

Input Power Supply Connections



Single Ended Voltage Output

Figure 6.2 Kaman KD-2306 [25][26]

Input power was connected to terminals 11 and 12, as shown. A 15- to 30-Vdc ±0.5 Vdc and 150 mA capable supply was required. The single-ended voltage output was from terminal 1 to terminal 3, as shown.

CHAPTER 7. SINGLE-AXIS ACTIVE-MAGNETIC-BEARING DYNAMIC PLANT MODEL

This chapter describes the development of a dynamic plant model for the single-axis active-magnetic-bearing (AMB) academic test fixture. A plant model may be created by directly specifying a model or with system identification techniques using measured data. The single-axis AMB plant model was directly specified. While initial plant model parameter values may be calculated, refining some of these parameter values on the basis of the measured data may improve overall performance.

7.1. Equations of Motion

The H-bridge PWM current actuator applied a voltage across the electro-magnet coil. The equilibrium equation for the voltage across the electro-magnet coil was

$$e = L\frac{di}{dt} + k_b v + iR$$

where L is the electro-magnet coil inductance, k_b is a counter-electromotive force constant, v is the velocity of the flotor, i is the electro-magnet coil current, and R is the electro-magnet coil resistance. Expanding each term with a constant and a change, delta, resulted in

$$e + \Delta e = (L + \Delta L)\left(\frac{di}{dt} + \Delta\frac{di}{dt}\right) + (k_b + \Delta k_b)(v + \Delta v) + (i + \Delta i)(R + \Delta R)$$

Assuming L, k_b, and R were constants, and subtracting out the equilibrium equation, resulted in

$$\Delta e = L\Delta\frac{di}{dt} + k_b\Delta v + \Delta i R$$

which gives the voltage change or delta as a function of constants L, k_b, and R, and dynamic variables $\Delta\frac{di}{dt}$, Δv, and Δi.

The force of the electromagnet was proportional to the square of the electro-magnet coil current over the square of the gap or distance between the stationary “U” shaped electro-magnet and the flotor.

$$F = k_f\frac{i^2}{g^2}$$

Applying the same approach to this equilibrium equation resulted in

$$\Delta F = \frac{k_f 2i}{g^2}\Delta i - \frac{k_f 2i^2}{g^3}\Delta g$$

which gives the force change or delta as a function of constants k_f, i, and g, and dynamic variables Δi and Δg. Note that a parameter x may have a constant portion x and a dynamic portion Δx.

At equilibrium, the force of gravity on the flotor was equal to the applied force of the electro-magnet.

$$F_{applied} - F_{gravity} = m\alpha$$

Applying the same approach to this equilibrium equation resulted in

$$\Delta F = (1 + \mu)m\Delta\alpha$$

which gives the change or delta in the flotor acceleration due to the change or delta in applied force. The flotor mass and coefficient of friction were assumed constant, and the dynamic variable was Δα.

7.2. Dynamic Plant Model Block Diagram

Using the equations of motion described in section 7.1, a block diagram of the single-axis AMB dynamic plant model was developed, as shown in Figure 7.1.

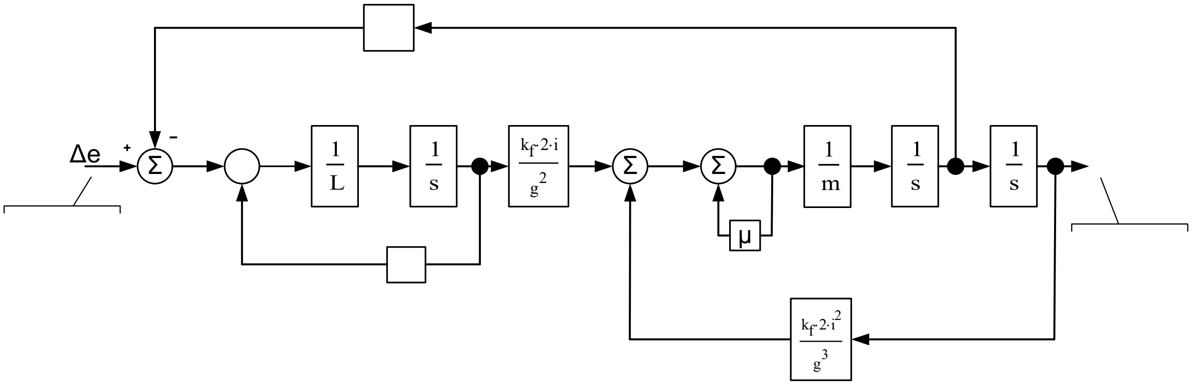


Figure 7.1 Single-Axis Active-Magnetic-Bearing Dynamic Plant Model Block Diagram

The input to the plant was a change in voltage, Δe, applied to the electro-magnet coil by the discrete MOSFET H-bridge. The output of the plant was the change in gap, Δg, between the face of the non-contact Eddy current displacement sensor and the 303 stainless-steel conductive target on the flotor assembly.

CHAPTER 8. SINGLE-AXIS ACTIVE-MAGNETIC-BEARING CONTROL SYSTEM DEVELOPMENT

This chapter describes a single-axis active-magnetic-bearing control system that was designed, built, and tested (Figure 8.1). The system model forms the basis for control system design. This model provides a basis from which to calculate appropriate commands and then enables understanding of the subsystems shown in previous chapters of this report to achieve appropriate signals and energy inputs for powering and controlling the single axis magnetic bearing plant.

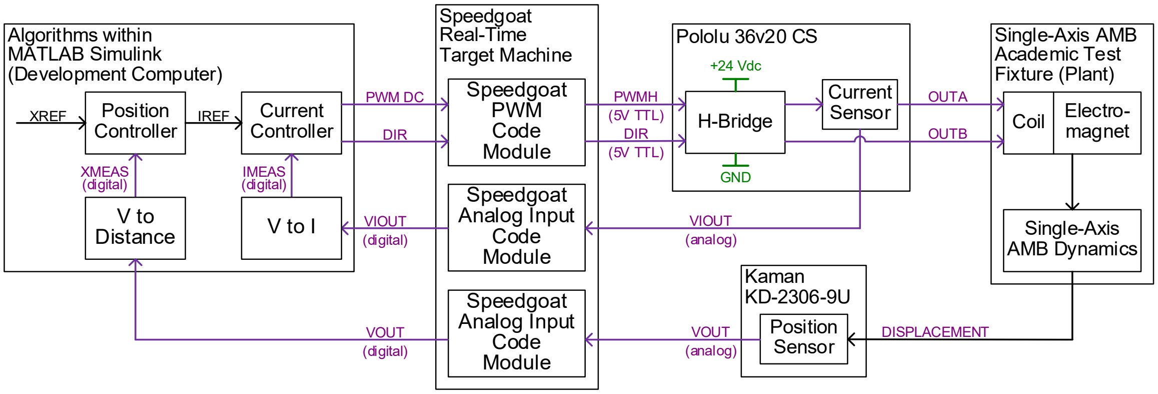


Figure 8.1 Single-Axis Active-Magnetic-Bearing Academic Test Fixture Block Diagram

This single-axis active-magnetic-bearing (AMB) test fixture implements a hardware-in-the-loop (HIL) with MATLAB Simulink Real-Time models. A Speedgoat performance real-time target machine connects a development computer running MATLAB Simulink with hardware consisting of one actuator and two sensors. It allows the coil current to be actuated by an H-bridge and measured by a current sensor. The displacement of the single-axis AMB is measured by a displacement sensor.

This single-axis AMB test fixture allows for prototyping current and position controllers in MATLAB Simulink.

8.1. Design

A proportional-integral (PI) controller for the single-axis AMB academic test fixture was designed and simulated in MATLAB Simulink with HIL. Tables 8.1 through 8.9 describe features of the system.

Table 8.1 Current Controller Signals

Name	Direction	Data Type	Description
IREF	In	Double	Reference current
IMEAS	In	Double	Measured current
PWM DC	Out	Double	Commanded PWM duty cycle between 0 (0% duty cycle) and 1 (100% duty cycle).
DIR	Out	Boolean	Commanded direction of current flow. DIR = ‘1’ means current flows from OUTA to OUTB. DIR = ‘0’ means current flows from OUT B to OUT A. Using a Boolean data type reduces memory requirements.

Table 8.2 Position Controller Signals

Name	Direction	Data Type	Description
XREF	In	Double	Reference displacement
XMEAS	In	Double	Measured displacement
IREF	Out	Double	Commanded coil current

Table 8.3 Voltage to Current, V to I, Signals

Name	Direction	Data Type	Description
VIOUT	In	Double	The Pololu High-Power Motor Driver 36v20 CS board includes a current sensor IC, the Allegro Microsystems ACS714LLCTR-30A-T. VIOUT (digital) is the ADC digital output of the current sensor analog output voltage, VIOUT.
XMEAS	Out	Double	IMEAS = (VIOUT – 2.5 V)/(66 mV/A) = (VIOUT – 2.5 V)*(15 A/V)

Table 8.4 Voltage to Distance, VOUT to XMEAS, Signals

Name	Direction	Data Type	Description
VOUT	In	Double	VOUT (digital) is the ADC digital output of the Kaman KD-2306-9U non-contact Eddy current displacement sensor output voltage.
XMEAS	Out	Double	XMEAS = (VOUT)*(0.3 mm / 1 V)

Table 8.5 Speedgoat PWM Code Module Signals

Name	Direction	Data Type	Description
PWM A DC	In	Double	Reference PWM duty cycle between 0 (0% duty cycle) and 1 (100% duty cycle).
PWM B DC	In	Double	Reference current polarity or direction (DIR). PWM B DC = ‘1’ means reference current polarity or direction is from OUTA to OUTB. DIR = ‘0’ means reference current polarity or direction is from OUT B to OUT A.
Period	In	Double	The PWM period value in seconds. This port is only active when **Show Period Input Port** is checked.
Halt PWM	In	Double	PWM generation is halted at the next model step after this port is set to 1. This port is only active when **Show PWM Generation Halt Input Port** is checked.
PWMH	Out	5-V TTL	Pulse width modulation output; intended for the Pololu 36v20 CS PWMH input. During the active (high) portion of PWMH, the Pololu 36v20 CS outputs put the full V+ voltage across the coil in the direction determined by DIR; during the low portion of PWMH, the Pololu 36v20 CS shorts both coil terminals to ground.
DIR	Out	5-V TTL	Direction output; intended for the Pololu 36v20 CS DIR input. When DIR = ‘1’ the polarity or direction is from OUTA to OUTB. When DIR = ‘0’ the polarity or direction is from OUT B to OUT A.

Table 8.6 Pololu High-Power Motor Driver 36v20 CS Signals

Name	Direction	Data Type	Description
PWMH	In	5-V TTL	Pulse width modulation input. During the active (high) portion of PWMH, the Pololu 36v20 CS outputs put the full V+ voltage across OUTA and OUTB in the polarity determined by DIR; during the low portion of PWMH, the Pololu 36v20 CS shorts both OUTA and OUTB to ground.
DIR	In	5-V TTL	Direction input. When DIR = ‘1’ the current polarity or direction is from OUTA to OUTB. When DIR = ‘0’ the current polarity or direction is from OUTB to OUTA.
OUTA	Out	High Power	High-power output pin; OUTA and OUTB are intended to be connected across a coil.
OUTB	Out	High Power	High-power output pin; OUTA and OUTB are intended to be connected across a coil.
VIOUT	Out	Analog	Current sensor analog output voltage signal. 66 mV/A output sensitivity. At zero current, VIOUT = VCC/2 where VCC = +5 Vdc (nominal). VIOUT = (IP)*(66 mV/A) + (VCC/2) = (IP)/(15 A/V) + (2.5 V) where IP is the current from OUTA to OUTB
V+	Supply	High Power	DC bus positive terminal.
GND	Supply	High Power	DC bus negative terminal; also signal ground.

Table 8.7 Kaman KD-2306-9U Non-Contact Eddy Current Displacement Sensor Signals

Name	Direction	Data Type	Description
+Vin	In	Power	Input power supply voltage, +15 Vdc.
Ground	In	Power	Input power supply ground.
VOUT	Out	Analog	Displacement sensor analog output voltage signal. The 0 to 10 V output voltage is linearly proportional to the distance between the face of the displacement sensor and the stainless-steel conductive target on the flotor assembly. VOUT = (displacement [mm])*(3.33 V/mm) = (displacement [mm])/(0.3 mm/V)
Ground	Out	Analog	Displacement sensor analog output voltage signal ground.

Table 8.8 Speedgoat Analog Input Code Module Signals (1 of 2)

Name	Direction	Data Type	Description
VIOUT	In	Analog	The Pololu High-Power Motor Driver 36v20 CS includes a current sensor IC, the Allegro Microsystems ACS714LLCTR-30A-T. VIOUT is the current sensor analog output voltage signal. VIOUT has 66 mV/A output sensitivity. At zero current, VIOUT = VCC/2 where VCC = +5 Vdc (nominal). VIOUT = (IP)*(66 mV/A) + (VCC/2) = (IP)/(15 A/V) + (2.5 V) where IP is the current from OUTA to OUTB
VIOUT	Out	Double	The ADC digital output of the current sensor analog output voltage signal, VIOUT.

Table 8.9 Speedgoat Analog Input Code Module Signals (2 of 2)

Name	Direction	Data Type	Description
VOUT	In	Analog	Displacement sensor analog output voltage signal. The 0 to 10 V output voltage is linearly proportional to the distance between the face of the displacement sensor and the stainless-steel conductive target on the flotor assembly. VOUT = (displacement [mm])*(3.33 V/mm) = (displacement [mm])/(0.3 mm/V)
VOUT	Out	Double	The ADC digital output of the displacement sensor analog output voltage signal, VOUT.

8.2. Implementation

The Simulink real-time hardware-in-the-loop testing with physical sensors and actuators, enabling verification of modeling assumptions and limitations, was implemented.

The position and current controllers consisted of a proportional-integral (PI) feedback control loop. The Discrete PID Controller Simulink block was used to implement discrete-time PI control. The Discrete PID Controller Simulink block included features such as anti-windup, external reset, and output saturation. The PI gains could be automatically tuned by using the 'Tune…' button (required a Simulink Control Design license).

8.3. Test Results and Observations

The measured current (IMEAS) (digital) signal shown in Figure 8.2 was observed to be noisy.

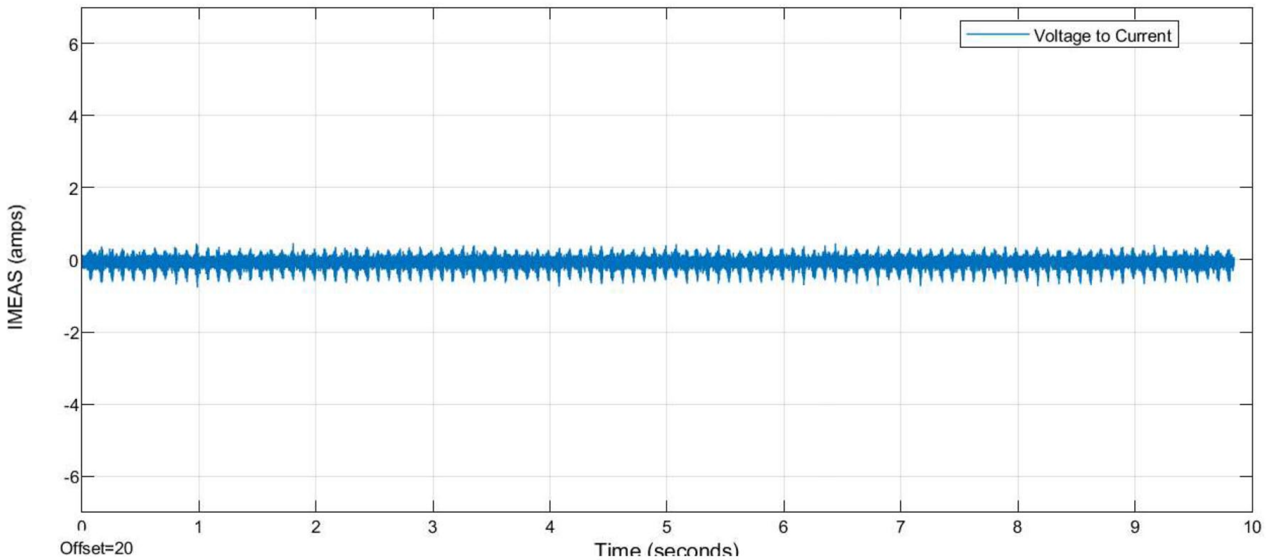


Figure 8.2 IMEAS (Digital) Signal *Before* Reducing the Cut-Off Frequency of the Analog Low-Pass-Filter

Three actions were taken to mitigate the observed sensor noise:

1) the current sensor integrated circuit's (IC) supply voltage implementation was changed from a +5-Vdc wall-wart to a +5-Vdc linear voltage regulator,
2) the dc bus voltage was filtered, and
3) the analog bandwidth of the current sensor was reduced, i.e., the cut-off frequency of the analog low-pass-filter was reduced.

The first two actions had no appreciable effect on the current sensor noise. The third action reduced the observed measurement noise, at the expense of the current sensor's step response (Figure 8.3). This reduction in step response caused by low-pass filtering the analog signal was less than the reduction in step response caused by low-pass filtering the digital signal (i.e., after the Speedgoat Analog Input Code Module).

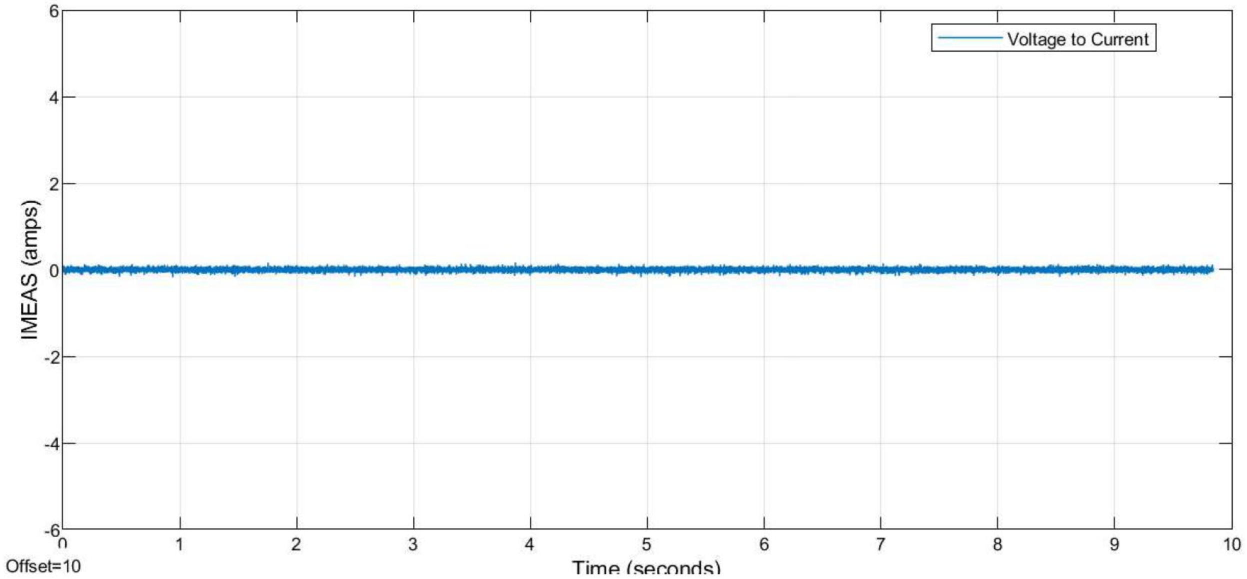


Figure 8.3 IMEAS (Digital) Signal *After* Reducing the Cut-Off Frequency of the Analog Low-Pass-Filter

The measured displacement (XMEAS) (digital) signal, i.e., the position sensor signal, was not noisy. A PI controller was implemented but not tuned for the current controller. Current control was achieved. The ability to “snap” the flotor to the zero gap position was demonstrated. The ability to accurately maintain a non-zero gap was not achieved. Controller development is ongoing.

CHAPTER 9. CONCLUSIONS

The research presented herein established the feasibility of using AMB control software and hardware for the University of Idaho's flywheel energy storage system (FESS). A single-axis AMB academic test fixture was used to test the sensor and actuator subsystems.

The H-bridge pulse width modulation (PWM) current actuator operation was developed, as described in chapter 4.

The Hall-effect current sensor mathematical model was defined, as described in chapter 5, from the manufacturer's data for the actual hardware. The sensor-measured output voltage data were obtained and observed to be noisy. Increasing the current sensor's filter capacitor, and thereby reducing the current sensor's bandwidth, significantly reduced the observed noise of the signal representing the sensed current.

The non-contact Eddy current displacement sensor mathematical model was defined from the manufacturer's specification and sensor calibration data, as described in chapter 6. The physical hardware testing was notably consistent with the mathematical model, and no significant sensor signal noise was observed.

For all three sensors and actuator subsystems, the physical interface is documented for integration into the flywheel energy storage system.

The equations of motion and a dynamic plant model of the single-axis AMB academic test fixture were developed, as described in chapter 7. The plant model developed was the foundation for control system development. Simulink Real-Time hardware-in-the-loop testing with the physical sensors and actuators was implemented, as described in chapter 8.

The current sensors' ratiometric output sensitivity to the current sensors' 5-V supply voltage warrants careful selection of a 5-V power source. This is an example of a small but important hardware implementation detail that is observed only during physical hardware testing.

The current sensors' digital signal was observed to be noisy, as shown in Figure 8.2. Reducing the analog bandwidth of the current sensor, i.e., reducing the cut-off frequency of the analog low-pass-filter of the current sensor analog output signal, reduced the observed measurement noise, as shown in Figure 8.3.

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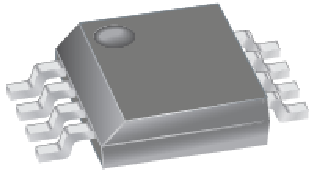
APPENDIX A: ALLEGRO ACS714 CURRENT SENSOR THEORY OF OPERATION

Sensing machine coil current is required for motor-generator control. This appendix discusses the Allegro ACS714 device, which provides an economical and precise way of sensing ac and dc currents based on the Hall-effect. This discussion provides an overview of the ACS714 sensor and its characteristics.

ACS714 Evaluation Board



Package: 8-pin SOIC (suffix LC)

Not to scale

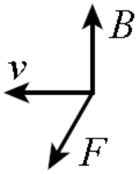
A.1. Hall-Effect

The Allegro ACS714 current sensor is based on the principle of the Hall-effect, which was discovered by Dr. Edwin Hall in 1879. According to this principle, when a current carrying conductor is placed into a magnetic field, a voltage is generated across its edges perpendicular to the directions of both the current and the magnetic field.

The fundamental physical principle behind the Hall-effect is the Lorentz force. When an electron moves along a direction, v, perpendicular to the appliced magnetic field, B, it experiences a force, F, the Lorentz force, which is normal to both the applied magnetic field and the electrical current flow.

Lorentz Force

$$\vec{F} = q\,\vec{v} \times \vec{B}$$



In response to the Lorentz force, F, the electroncs move in a curved path along the conductor, and a net charge, and therefore a voltage, develop across the plate (orthogonal to the direction of current flow). This Hall voltage, V_H, obeys the formula below, which shows that V_H is proportional to the applied field strength and that the polarity of V_H is determined by the direction, either north or south, of the applied magnetic field. **By this property, the Hall-effect is employed as a magnetic field sensor.**

$$V_H = \frac{I B_\perp}{\rho_n q t}$$

where:

V_H is the Hall voltage across the Hall element

I_H is the current passing through the Hall element

q is the magnitude of the charge of the charge carriers ($q = 1.602 \times 10^{-19}$ coulombs)

ρ_n is the charge carrier density (n signifies that the charge carriers are electrons)

t is the thickness of the Hall element plate.

A thin plate of semiconductor material (called a Hall element) carries the current (I_H) and is placed into the magnetic field ($B_\perp$), which is perpendicular to the direction of current flow. Because of the presence of the Lorentz force, the distribution of current (I_H) is no longer uniform across the Hall element, and therefore a potential difference is created across its edges perpendicular to the directions of both the current (I_H) and the magnetic field ($B_\perp$). This voltage, V_H, is known as the Hall voltage, and its typical value is in the order of few microvolts. The Hall voltage is directly proportional to the magnitudes of I_H and $B_\perp$. So if one of them (I_H) is known, then the observed Hall voltage can be used to estimate the other ($B_\perp$).

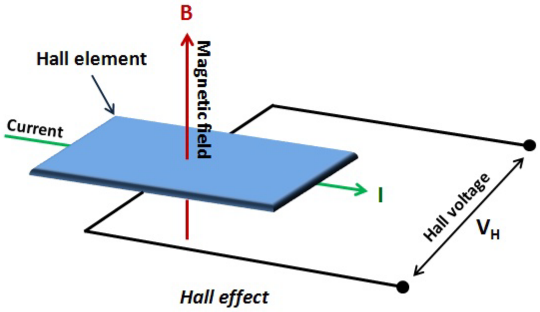


Figure A.1 Principle of the Hall-effect

The Allegro Microsystems ACS714LLCTR-30A-T [24] device is packaged in an 8-pin surface mount small outline integrated circuit (SOIC). Note that the primary current, I_P, flows through the primary copper conduction path (from pins 1 and 2, to pins 3 and 4) and does not flow through the Hall element. The primary current, I_P, induces a magnetic field, $B_\perp$, which is sensed by the Hall element. The Hall element is employed as a magnetic field sensor. The magnitude of the magnetic field, $B_\perp$, is linearly proportional to the magnitude of the primary current, I_P, providing a linear relationship between the output Hall voltage, V_H, and the input primary current, I_P.

A.2. Hall Element Structure

Allegro Hall-effect-based current sensor ICs are manufactured on silicon wafers. The Hall elements are part of the monolithic integrated circuits. Each Hall element is an area of doped silicon that creates an n-type plate that will conduct current, I_H. When a current, I_H, is forced from one corner of the plate to the opposite corner, a Hall voltage, V_H, develops across the other two corners of the plate when in the presence of a perpendicular magnetic field, $B_\perp$. The Hall voltage is zero when no magnetic field is applied.