

Speed and Directional Control of American Flyer Trains

Norbert Doerry

Version 2.1 of December 2013



doerry@aol.com

<http://doerry.org/norbert/train/AFtrain.htm>

Copyright (C) 2012, 2013 Norbert H. Doerry
Permission is granted to copy, distribute and/or modify this document under
the terms of the GNU Free Documentation License, Version 1.3 or any later
version published by the Free Software Foundation; with no Invariant
Sections, no Front-Cover Texts, and no Back-Cover Texts.
A copy of the license is included in the section entitled "GNU Free
Documentation License".

Table of Contents

Table of Contents	iii
Table of Figures	v
Table of Tables	vi
History	vii
1. Introduction.....	1
1.1 Definitions.....	1
1.2 System Description	1
1.2.1 Powering the Track	2
1.2.2 Getting Power from the Track to the Motor.....	5
2. Motors	7
2.1 Universal Series Wound Motors	7
2.2 Open Frame DC Permanent Magnet Motors	9
2.3 DC Can Motors	10
3. Track Power	11
3.1 AC variable voltage	11
3.2 DC variable voltage	12
3.2.1 Full Wave Bridge Rectified AC.....	12
3.2.2 Half Wave Rectified AC	14
3.2.3 Filtered DC.....	15
3.3 Pulse Width Modulation	18
3.4 Fixed Voltage (AC or DC).....	20
4. Communicating Direction.....	21
4.1 Fixed Direction (Forward only)	21
4.2 Manual switch on engine	21
4.3 Time Sequence (American Flyer Remote Control Unit)	21
4.4 DC Polarity	25
4.5 Digital Commands	26
5. Communicating Speed.....	29
5.1 Variable Voltage (AC or DC)	29
5.2 Digital Commands	29
6. Action Car Considerations	31
6.1 AC Track Voltage	32

6.2 DC Track Voltage	32
6.2.1 Separate Transformer	32
6.2.2 Double Pole Single Throw Pushbutton	33
6.2.3 Isolation Relay	33
6.2.4 Half Wave Rectifiers.....	34
7. Sound Activation Considerations.....	37
7.1 Modulated Power	37
7.2 DC Offset ("Railsounds")	38
7.3 Digital Control	40
8. Bibliography	41
Appendix A: unusual technologies	43
A.1 Brushless DC Motors	43
A.2 Filtered Half Wave rectification for DC Directional Control	43
A.3 Power FETs to control DC polarity and motor direction	45
A.4 Control Circuits for Reversing	47
A.5 Relay Based Reversing	49
Appendix B: How a Commutator Works.....	51
B.1 Common Tie-Off	52
B.2 End to End Tie-Off	54
Appendix C: GNU Free Documentation License	57

Table of Figures

Figure 1: AC Transformer directly powering the track	2
Figure 2: DC Power Source connected directly to the track	3
Figure 3: Hookup instructions for No 14 Electronic Rectifier	3
Figure 4: AC Transformer with Rectifier to provide DC to the track.....	4
Figure 5: Hookup instructions for No 15 Directronic Rectifier	4
Figure 6: Simple Digital Command Control (DCC) system.....	5
Figure 7: Simple Trainmaster Command Control (TMCC) wiring	5
Figure 8: Rectifier and Reverse Switch in a tender.....	6
Figure 9: 4 position and 2 position Electromechanical Remote Control Units.....	6
Figure 10: Electronic E-Unit (Lionel American Flyer 6-48005)	6
Figure 11: Parts of an A.C. Gilbert universal series wound motor for a steam engine.....	8
Figure 12: Open frame motor mounted on train engine chassis	8
Figure 13: Open Frame motor for diesel engine	8
Figure 14: Permanent magnet field for open frame DC motor	9
Figure 15: Cam motor (with flywheel) for Lionel American Flyer Docksider.....	10
Figure 16: Track Voltage Waveform: AC transformer.....	11
Figure 17: Transformer Current Waveform: AC transformer.....	11
Figure 18: Full Wave Bridge Rectifier Schematic	13
Figure 19: Track Voltage Waveform: Full Wave Bridge Rectified.....	13
Figure 20: Circuit Diagram for Full Wave Bridge Rectifier.....	13
Figure 21: Track Current: Full Wave Bridge Rectifier	14
Figure 22: Transformer Current: Full Wave Bridge Rectifier	14
Figure 23: Track Voltage: Half Wave Rectifier.....	15
Figure 24: Circuit Diagram for Half Wave Rectifier.....	15
Figure 25: Track & Transformer Current: Half Wave Rectifier	15
Figure 26: Track Voltage: Filtered DC.....	16
Figure 27: Circuit Diagram for Bridge Rectifier with Filter.....	17
Figure 28: Track Current: Filtered DC Figure 29: Transformer Current: Filtered DC.....	17
Figure 30: PWM Test Circuit	18
Figure 31: PWM waveforms (Top {orange} gate signal; Bottom {blue} motor voltage): (a) slow; (b) medium-slow; (c) medium fast; and (d) fast for unloaded Casey Jones universal motor with a rectified field.....	19
Figure 32: PWM Track Voltage and Track Current for (a) Medium, and (b) Fast speeds	19
Figure 33: PWM Track Voltage and Rectifier Output Current.....	20
Figure 34: Reversing Switch Circuit.....	21
Figure 35: 4 position E-Unit with one set of fingers removed to reveal drum below.....	22
Figure 36: Gilbert American Flyer 4 position Remote Control Unit operation	22
Figure 37: Connecting a Remote Control Unit to a DC motor	23
Figure 38: Gilbert American Flyer 2 position Remote Control Unit Disassembled	23
Figure 39: Gilbert American Flyer 2 position Remote Control Unit operation	24
Figure 40: American Flyer 709 Lockout Eliminator.....	25
Figure 41: DC directional control with a universal motor	26
Figure 42: Voltage waveform for Digital Command Control (DCC).....	27

Figure 43: Special Rail Section.....	31
Figure 44: Action car with power contact shoe	31
Figure 45: Wiring for an Action Car with an AC transformer.....	32
Figure 46: Use of Second Transformer for Action Cars	33
Figure 47: Double Pole Single Throw pushbutton for controlling Action Cars with DC.....	33
Figure 48: Isolation Relay.....	34
Figure 49: Half Wave Rectifier with special rail section	35
Figure 50: American Flyer Air Chime Whistle	37
Figure 51: Engine / Tender Air Chime Whistle circuit.....	38
Figure 52: Transformer Voltage (top) and Track Voltage (bottom) with Air Chime Whistle Generator on.	38
Figure 53: Lionel 6-5906 Sound Activation Button	38
Figure 54: Lionel 6-5906 Sound Activation Button internals.....	39
Figure 55: Schematic of Sound Activation Button	39
Figure 56: Track Voltage when powering an unloaded universal motor and with Sound Activation Button pressed	39
Figure 57: Use of reversing circuit to control both a bell and whistle with same push-button.....	40
Figure 58: Filtered Half Wave Rectifier	43
Figure 59: Track Voltage: Filtered Half Wave Rectification.....	44
Figure 60: Track Current: Filtered Half Wave Rectification	44
Figure 61: Transformer Current: Filtered Half Wave Rectification	44
Figure 62: Power FETs to control DC polarity.....	45
Figure 63: Functional representation of polarity reversing circuit.....	45
Figure 64: Reversing a Universal Motor with power FETs.....	46
Figure 65: Alternate FET circuit for reversing a Universal Motor	46
Figure 66: All N-FET circuit to reverse polarity	47
Figure 67: Functional Representation of N-FET circuit	47
Figure 68: Circuit for reversing a Universal Motor using N-FETs.....	47
Figure 69: AC-DC Reversing Control Circuit	48
Figure 70: AC-DC Reversing Switch Controller.....	48
Figure 71: AC-DC Reversing Control Circuit for use with Railsounds controller.....	48
Figure 72: AC-DC Reversing Control Circuit using a relay.....	49
Figure 73: Example circuits built for an ALCO.....	50
Figure 74: Armature.....	51
Figure 75: Common Tie-Off and End-to-End Tie Off Armatures	52
Figure 76: Common Tie-Off Rotor Forward Direction	53
Figure 77: Common Tie-Off Rotor Reverse Direction.....	54
Figure 78: End-to-end Tie Off Rotor Rotation	55

Table of Tables

Table 1: Recommended Minimum Rectifier Current Rating.....	12
--	----

History

Version 1.0: "Speed and Directional Control of American Flyer Trains" June 2012 by Norbert Doerry:
published <http://www.doerry.org>.

Version 2.0 "Speed and Directional Control of American Flyer Trains" September 2012 by Norbert
Doerry: published <http://www.doerry.org>

Version 2.1 "Speed and Directional Control of American Flyer Trains" December 2013 by Norbert
Doerry: published <http://www.doerry.org>



1. Introduction¹

The purpose of this document is to explain how the electrical and electronic components typically encountered with American Flyer trains work and to detail new ways to operate and control American Flyer trains. In particular, this document concentrates on describing how the components work together to implement speed and directional control. The document also discusses how speed and directional control can interact with other components such as sound generators and action cars. Where possible, actual oscilloscope displays have been included to show the voltage and current waveforms under different operating conditions.

Please contact the author if you find any errors. Also, feel free to suggest improvements or additions to this document. Revisions will be produced as needed to correct errors and add more material.

1.1 Definitions

Rotor: the part of a motor that rotates. Also may be called the rotor assembly.

Stator: the part of a motor that is stationary. Also may be called the stator assembly

Field: The part of the motor that establishes a magnetic field. The magnetic field can be created by a permanent magnet, or by a coil of wire. The field usually contains laminated steel to direct the magnetic field to where it will interact with the armature. The field can reside either on the stator or the rotor.

Armature: The part of the motor that carries current through a conductor to interact with the magnetic field created by the field to create a magnetic force. The armature winding usually contains one or more coils of wire around laminated steel. The armature winding can reside either on the stator or the rotor, complimentary to the location of the field. While a field can contain a permanent magnet, an armature will always have a coil.

Commutator: A commutator is a type of switch for controlling the current through the coils of the armature. For most simple motors with the armature on the rotor, the commutator is a rotating mechanical switch that consists of strips of copper connected to the armature windings that slide against carbon brushes. The commutator is designed to electrically connect the proper armature coils to maximize the electromagnetic force that will cause the rotor to rotate in the desired direction.

Remote Control-Unit: A Remote Control Unit (also called an "E"-unit) is a device, either electro-mechanic as with the original American Flyer engines, or completely solid state with modern ones, used to control the direction of the engine. Dalle Electronics, Inc. makes 'Electronic "E" Units' that are often retrofitted into American Flyer engines.

1.2 System Description

With the exception of battery powered trains, the system for powering an electric train motor can be broken into two parts: supplying power to the track, and converting the power picked up from the track (via wheels or pickup "shoes") to the form needed by the motor to achieve the desired direction and speed.

¹ *American Flyer* and *A.C. Gilbert* are trademarks of Lionel Trains, LLP. This document is neither authorized nor approved by Lionel Trains, LLP.

1.2.1 Powering the Track

For most American Flyer trains, power is supplied to the track directly from an AC transformer as shown in Figure 1. The voltage supplied varies from about 7 volts to about 16 volts based on the position of the speed "throttle" knob. The higher the voltage applied, the faster the train operates. Directional control is normally accomplished by briefly interrupting the flow of current by turning the knob to the off position, then reapplying power. Some transformers have a button that will interrupt the power when pressed, thereby eliminating the need to move the knob to off.

A third "post" on the transformer is available to provide a constant voltage between about 15 and 16 Volts as compared to the "base post." This post is used to power accessories, or action cars through a pickup rail.

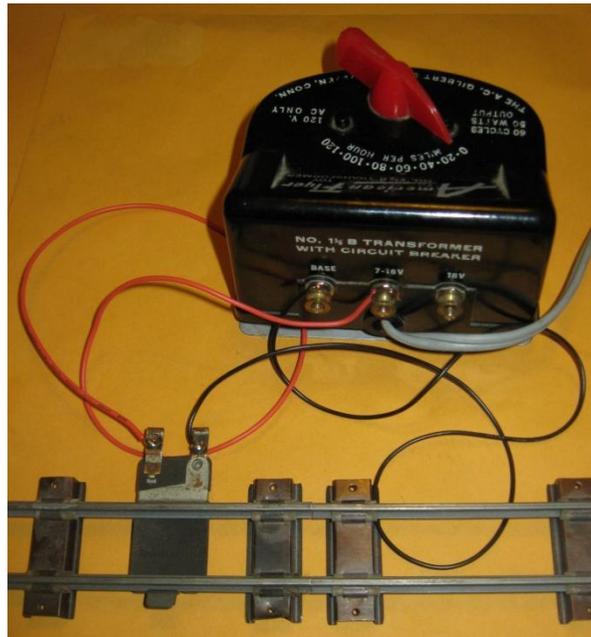


Figure 1: AC Transformer directly powering the track

For trains that are designed for DC operation, a DC power source can be connected as shown in Figure 2. As with the AC transformers, the knob controls the voltage and the higher the voltage, the faster the train travels. For DC operation though, the maximum voltage is generally higher, up to 21 volts (Note that some DC engines are designed for lower voltage - ensure the DC power source is compatible with the DC engine). For trains that are designed for DC operation, a reverse switch on the DC power source will reverse the polarity of the power applied to the tracks (which rail is + and which rail is -). For these DC engines, the polarity signals which direction the engine should move. Convention is that when the right hand rail (when looking forward) has a positive voltage with respect to the left hand rail, the locomotive should move forward. Additionally, as shown in Figure 3, these DC power sources typically provide two posts for supplying a constant AC voltage to accessories.



Figure 2: DC Power Source connected directly to the track

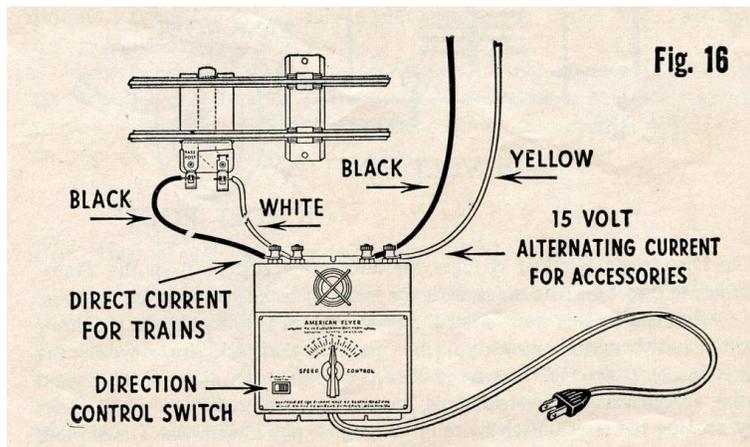


Figure 3: Hookup instructions for No 14 Electronic Rectifier²

Engines designed for DC operation can be powered from an AC transformer if a rectifier is inserted between the transformer and the track as shown in Figure 4 and Figure 5. These rectifiers convert the AC into DC and then incorporate a reverse switch to enable the operator to reverse the polarity of the DC power applied to the track.

² *Instructions for Assembling and Operating American Flyer 3/16" Scale Trains and Equipment*, Developed at the Gilbert Hall of Science, 1949.



Figure 4: AC Transformer with Rectifier to provide DC to the track

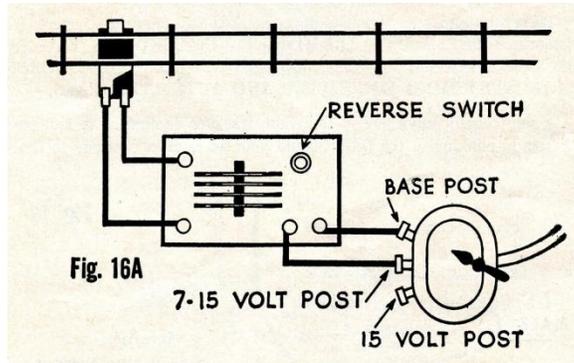


Figure 5: Hookup instructions for No 15 Directronic Rectifier³

Digital Command Control (DCC) is another method for powering the track and signaling to the engine the intended speed and direction. With DCC, the light weight hand throttle can be moved around the layout and still control a number of engines and other devices. Some hand throttles are wireless and hence do not need to be directly connected to the Command Station. The Command Station / Booster encodes digital commands in the track power that are used by a decoder on the engine to determine the engine direction and speed. See Figure 6.

³ *Instructions for Assembling and Operating American Flyer 3/16" Scale Trains and Equipment*, Developed at the Gilbert Hall of Science, 1949.

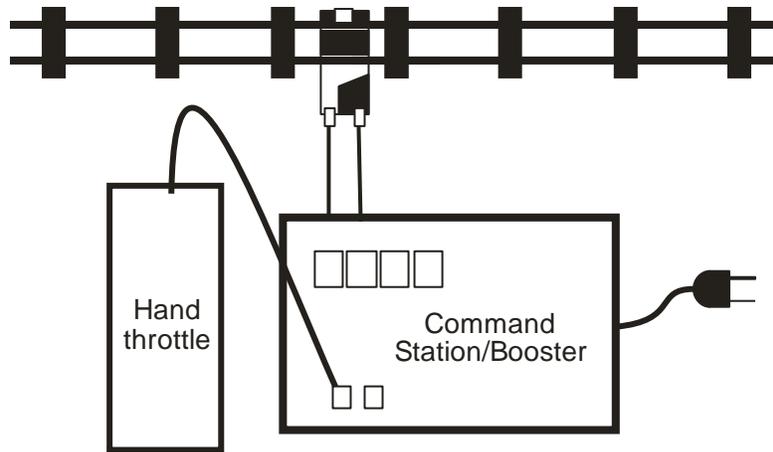


Figure 6: Simple Digital Command Control (DCC) system

Trainmaster Command Control (TMCC) is a proprietary train control system produced by Lionel and incorporated in some recent American Flyer engines. As shown in Figure 7, a constant voltage (typically AC) is provided to the track. The Command Base couples a signal onto one of the track rails which is picked up by the engine. A TMCC decoder on the engine receives and executes the commanded speed and direction.

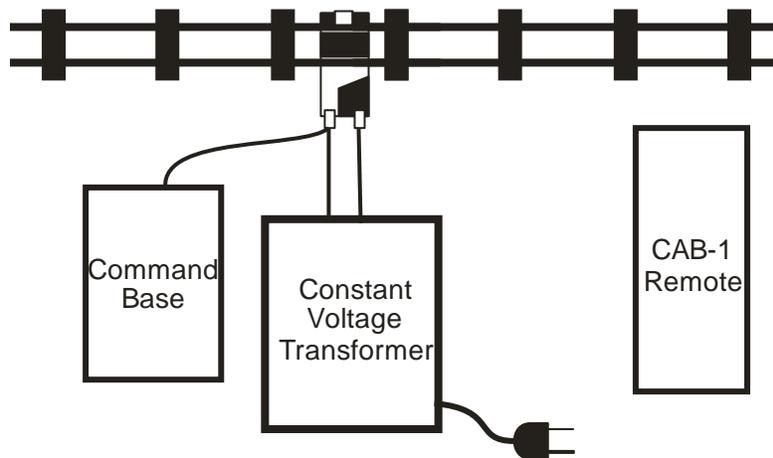


Figure 7: Simple Trainmaster Command Control (TMCC) wiring

1.2.2 Getting Power from the Track to the Motor

The train engines receive power from the track via metal wheels and/or electrical pickup shoes. The power can either be directly applied to the motor, or it can be "conditioned" to match the needs of the motor in order to implement the commanded speed and direction. The "conditioning" can be as simple as a reverse switch or rectifier (Figure 8), or as complex as an electronic digital control, electro-mechanical remote control unit or electronic "E" unit.



Figure 8: Rectifier and Reverse Switch in a tender

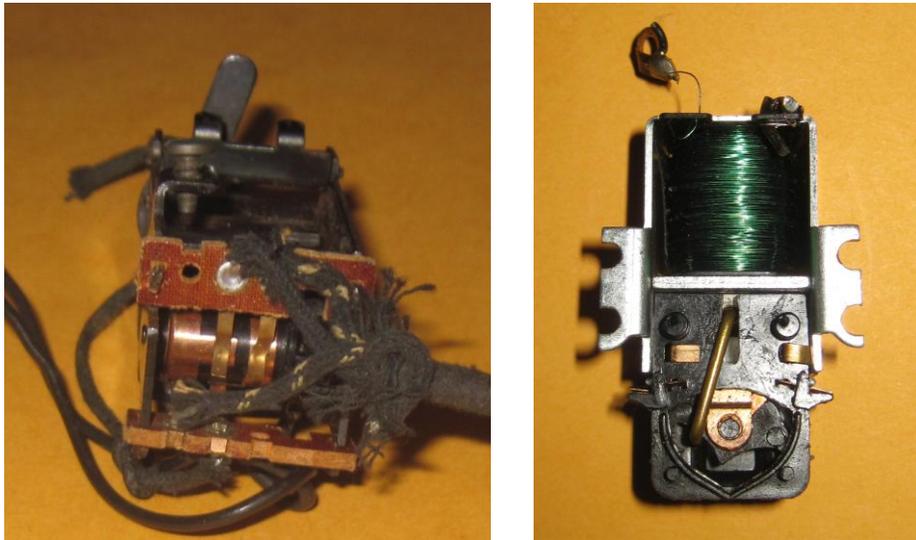


Figure 9: 4 position and 2 position Electromechanical Remote Control Units



Figure 10: Electronic E-Unit (Lionel American Flyer 6-48005)

2. Motors

Most toy train motors work by turning on and off as well as controlling the direction of current through the armature windings (typically via the commutator) to keep the magnetic fields on the rotor and stator out of alignment. By having the magnetic fields out of alignment, a torque is produced that will rotate the rotor to align the two magnetic fields; as soon as the fields are aligned, different sets of coils are energized to put the two fields back out of alignment. The way in which this is accomplished differentiates the different types of motors.

2.1 Universal Series Wound Motors

Most American Flyer trains use a universal series motor (or simply a "universal motor") having both field windings and armature windings. These motors will operate either on AC or DC power. A universal motor has a wire wound field coil on the stator, and an armature on the rotor. The armature typically has three (as with the American Flyer motors) or more coils. Current through the armature windings is controlled via a commutator and its associated brushes. (See appendix B) The armature (via its brushes) and the field are connected in series. The direction of rotation of the motor is determined by which wire end of the field winding is connected to the armature (the other end of the field winding is connected to the power supply, likewise for the other end of the armature). Direction of rotation does not depend on the direction of the current, hence the motor will work with either AC or DC power. To change the direction of rotation, the field winding (or alternately the armature winding) connections must be reversed. (The American Flyer remote control unit does precisely this)

The brushes are usually made out of a graphite / carbon based material and held in contact with the commutator with brush springs. The brushes are often held in place with a brush bracket assembly that many times also serves to hold the bearing supporting one end of the rotor.

In the parts list associated with many of the American Flyer engines, the rotor is also known as the armature assembly. Similarly, the stator is called either the magnet assembly, or the field assembly. Figure 11 shows the different parts of a universal motor for an American Flyer steam engine. Figure 12 shows a universal motor mounted on an engine chassis.

For the American Flyer motors, the voltage drop across the field winding will be much less than the voltage drop across the armature winding (Typically the voltage across the field is only a few volts at maximum track voltage). Consequently, many of the American Flyer steam engines with the remote control unit in the tender connect the smoke box and the headlight across the armature winding so that only four wires (2 for the field windings and 2 for the armature windings) are needed to connect the tender to the engine. A 5th wire is needed if full track voltage is desired for the headlight and smoke box.

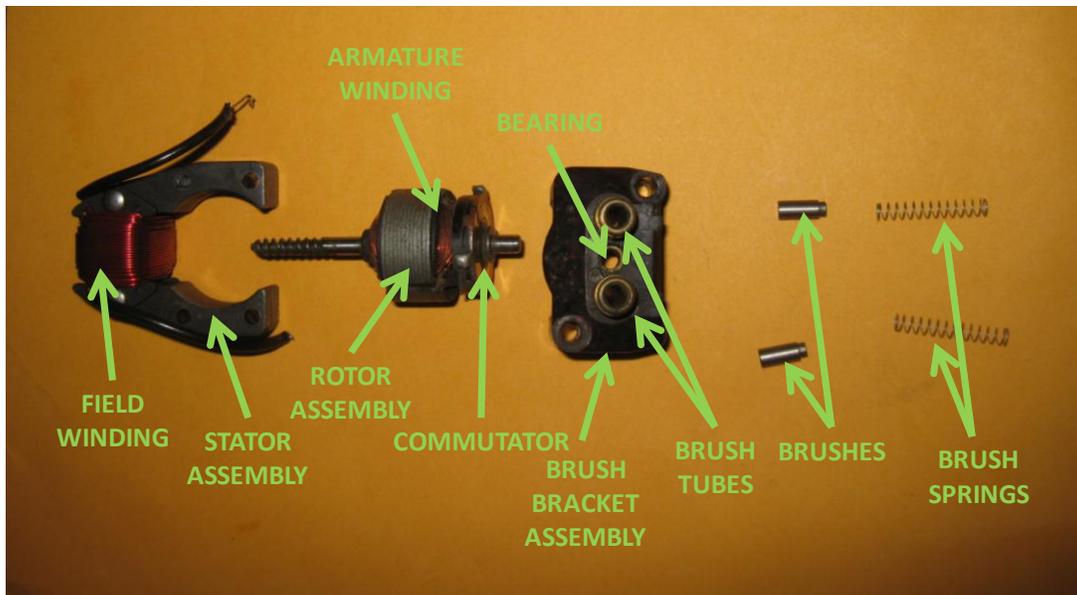


Figure 11: Parts of an A.C. Gilbert universal series wound motor for a steam engine.

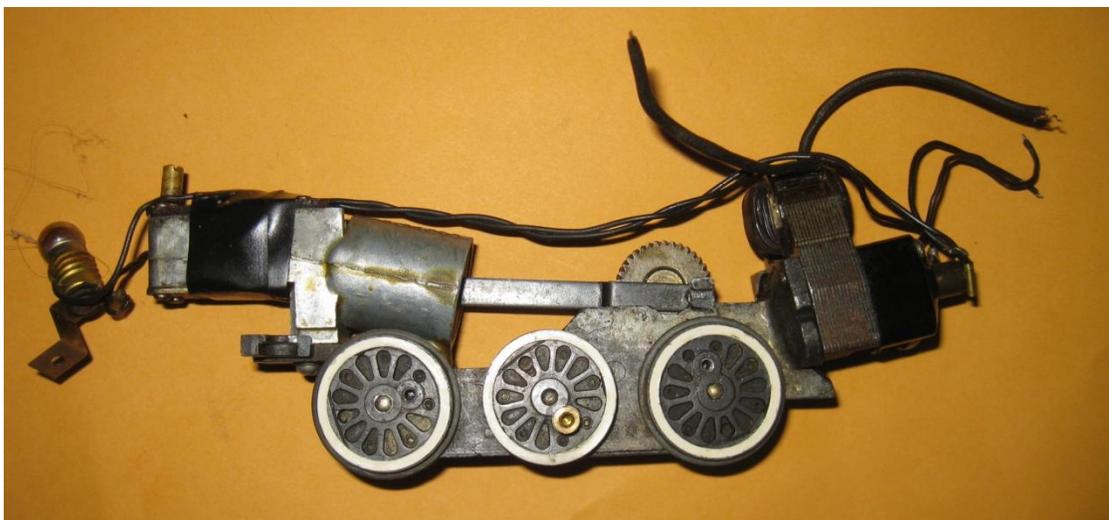


Figure 12: Open frame motor mounted on train engine chassis

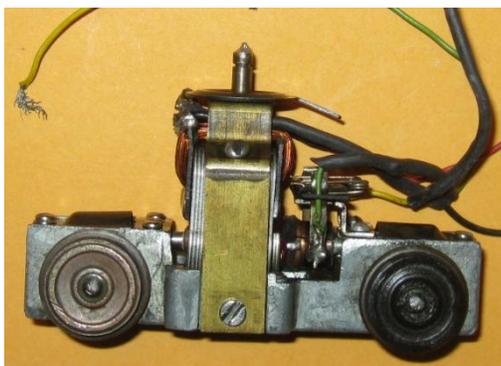


Figure 13: Open Frame motor for diesel engine

2.2 Open Frame DC Permanent Magnet Motors

An open frame DC Permanent Magnet Motor is similar to the universal motor, except the field winding is replaced with a permanent magnet. As a consequence, the direction of rotation is determined by the direction of current flow through the armature (via the commutator/brushes). Hence these motors will not work when connected directly to AC power.

The armature windings of a DC permanent magnet motor typically use more turns of thinner wire than an AC motor. One should not consider the rotor assemblies of open frame DC permanent magnet motors and universal motors to be interchangeable. If you use a rotor for AC operation with a DC permanent magnet field, the engine will attain a higher speed for a given track voltage. The armature coils on the rotor may overheat if you apply too high of a voltage.



Figure 14: Permanent magnet field for open frame DC motor

2.3 DC Can Motors

The only difference between the DC Can Motor and the Open Frame DC Permanent Magnet Motor is the method of construction. DC Can Motors are completely enclosed with the bearings for the rotor incorporated into the "can" housing.



Figure 15: Cam motor (with flywheel) for Lionel American Flyer Docksider

3. Track Power

The waveforms shown below were measured for an American Flyer Atlantic engine with headlight, smoke unit, and a 4 position remote control unit locked in the forward position. The engine was pulling a box car, gondola, tank car and caboose. The transformer was an American Flyer model 4B 100 watt transformer set for maximum voltage. A 10,000 uF filter capacitor was used for the filtered DC option. Current was determined by measuring the voltage across a 1 ohm resistor in series with the track.

3.1 AC variable voltage

The traditional method for powering most American Flyer engines is directly from a variable voltage AC transformer. The voltage varies from 7 volts AC to about 15 or 16 volts AC depending on the position of the throttle knob. As seen in Figure 16, the track voltage has a sine waveform with a minimal amount of distortion. The current waveform, shown in Figure 17, is not completely sinusoidal, but is relatively close. As the waveforms deviate from sine waves, the amount of energy converted to heat in both the transformer and the motor increases.

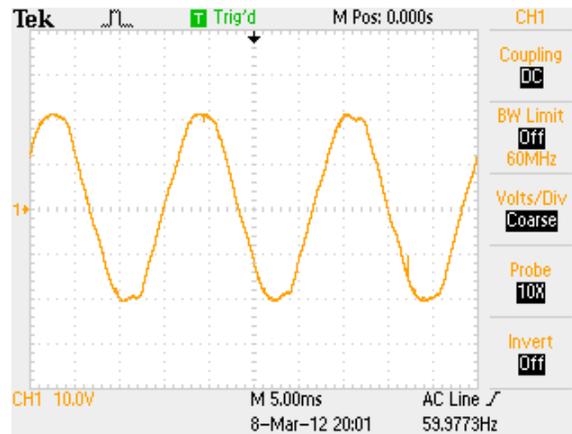


Figure 16: Track Voltage Waveform: AC transformer

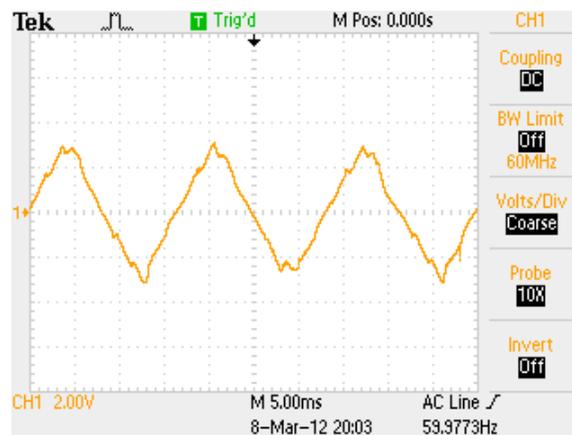


Figure 17: Transformer Current Waveform: AC transformer

3.2 DC variable voltage

DC power is generally created by rectifying AC power and then possibly filtering the power with a large capacitor. This section describes three different ways of producing DC power: Full wave bridge rectification, half wave rectification, and filtered DC.

3.2.1 Full Wave Bridge Rectified AC

A Full Wave Bridge Rectifier is a device consisting of 4 diodes connected as shown in Figure 18. A diode only allows current to flow in the direction of the arrow. When conducting current, a diode has a voltage drop of about 0.6 volts. The bridge rectifier connects the more positive of the two AC inputs to the DC + output, and the more negative of the two AC inputs to the DC - output. The resulting voltage waveform at the track is shown in Figure 19: The negative half of the input ac waveform is flipped so it too is positive. While the resulting waveform is not a pure constant voltage DC, the polarity of the track voltage is always the same. To reverse the polarity of the track, a double pole double throw (DPDT) switch is configured as a reversing switch as shown in Figure 20. The current waveform for the track power is shown in Figure 21. Note that while the current is not constant, it does not change polarity. As shown in Figure 22, the transformer current is an AC waveform, but it does exhibit more distortion than when supplying AC to the track.

The current rating of the rectifier should be based on the rating of the transformer. The rectifier should survive when supplying current equal to the maximum current the transformer can supply without tripping its circuit breaker. Most transformers have a circuit breaker that trips slightly above the rated current. The rated current can be approximated by dividing the power rating by the maximum voltage (typically 15 volts). I recommend the voltage rating for the rectifier should be at least 100 volts to ensure the rectifier survives voltage spikes.

Table 1: Recommended Minimum Rectifier Current Rating

Transformer Rating (Watts)	Rectifier Minimum Current Rating (amps)
50 or less	4
60	5
75	6
100	8
125	10
150	12

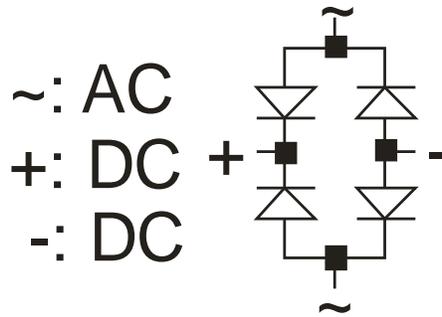


Figure 18: Full Wave Bridge Rectifier Schematic

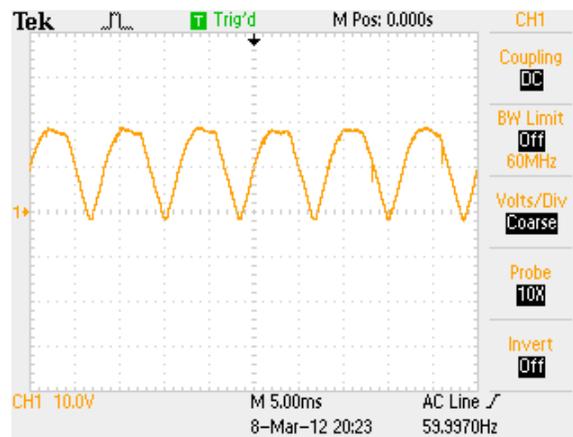


Figure 19: Track Voltage Waveform: Full Wave Bridge Rectified

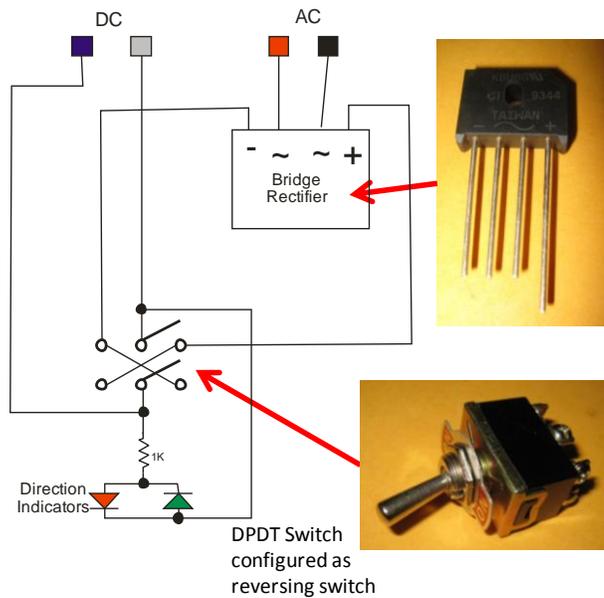


Figure 20: Circuit Diagram for Full Wave Bridge Rectifier

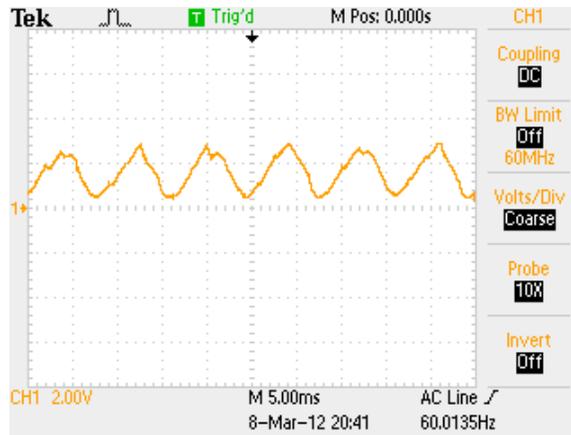


Figure 21: Track Current: Full Wave Bridge Rectifier



Figure 22: Transformer Current: Full Wave Bridge Rectifier

3.2.2 Half Wave Rectified AC

A half wave rectifier consists of a single diode that allows current to flow in only one direction. The resulting track voltage is shown in Figure 23. The diode is on during the entire positive half of the waveform, and dips below zero for a short time to "drain" the energy stored in the magnetic fields of the motor windings (motor inductor current). When the current through the diode is zero, the diode turns off and stays off until the input voltage waveform becomes positive again. To change the polarity of the track, a reversing DPDT switch is used to reverse the direction of the diode as shown in Figure 24. This circuit has the advantage that the base post of the AC transformer is connected to the base rail of the track at all times, allowing action cars to work normally. The disadvantage of this circuit is that the transformer current is definitely not sinusoidal (see Figure 25) and results in greater losses in both the motor and the transformer. If this circuit is used, I recommend avoiding overheating the transformer by using a transformer rated at least 100 watts for a single motor engine and at least 150 watts for a dual motor ALCO.

As with the bridge rectifier, the current rating of the diode should be based on the power capability of the transformer. Use Table 1 as guide for selecting the diode current rating. The reverse voltage rating of the diode should be at least 100 Volts.

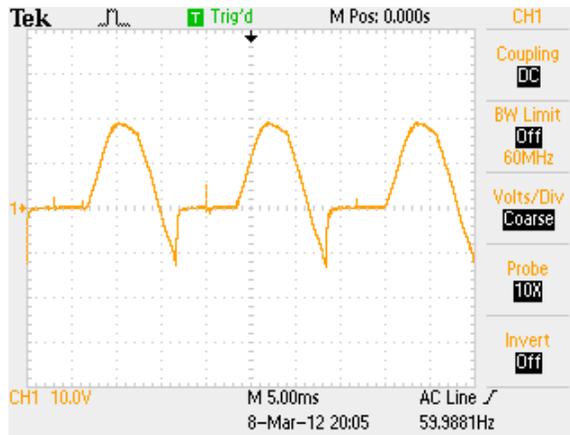


Figure 23: Track Voltage: Half Wave Rectifier

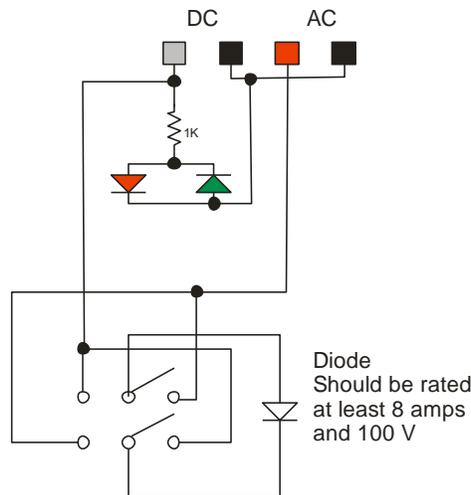


Figure 24: Circuit Diagram for Half Wave Rectifier

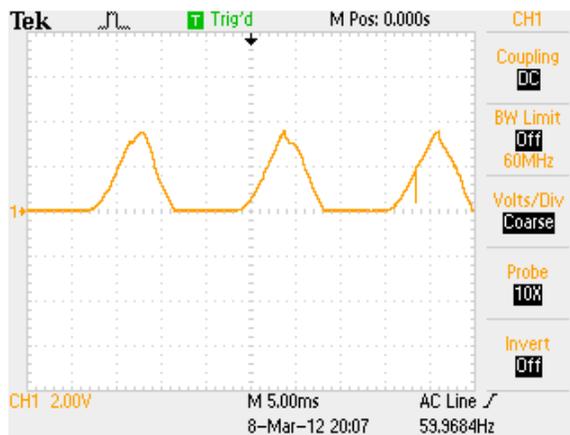


Figure 25: Track & Transformer Current: Half Wave Rectifier

3.2.3 Filtered DC

A closer approximation to constant voltage DC for the track voltage (Figure 26) can be obtained by inserting a capacitor across the output of the bridge rectifier as shown in Figure 27. Capacitors store

energy and can be charged and discharged very rapidly. In this application, the capacitor charges when the rectified AC waveform is near its peak, and discharges to fill the valleys between the peaks of the rectified AC. The resulting track current used by the engine is also nearly constant DC as shown in

Figure 28. On the other hand, the current provided by the transformer (Figure 29) is AC, but shows strong positive and negative pulses when the capacitor is charging.

An electrolytic capacitor is normally used in this application. For the several amps of current used by the motors, a capacitor with a capacitance of about 10,000 micro-farads or more should be chosen. The voltage rating of the capacitor should be at least 50 V to ensure its reliability in the presence of voltage spikes. Electrolytic capacitors of this rating are polarized, which means that one of its sides must always have a positive voltage with respect to its other side. This means that the capacitor should be connected across the rectifier output with the correct polarity, and before the reversing switch determines the polarity applied to the track.

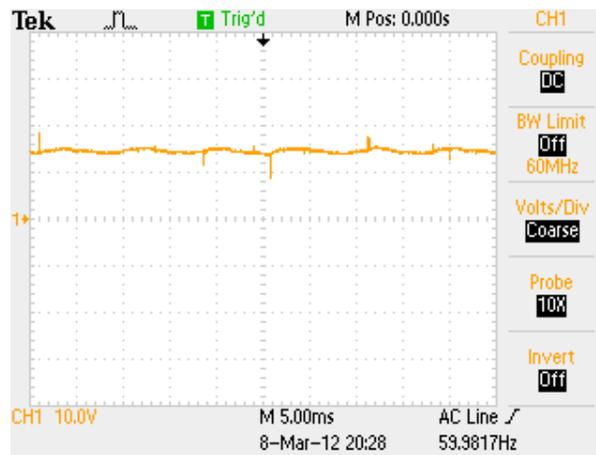
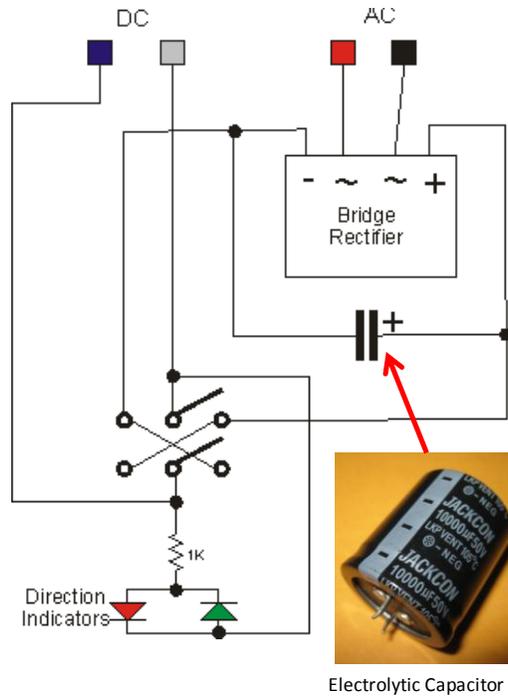


Figure 26: Track Voltage: Filtered DC



Electrolytic Capacitor

Figure 27: Circuit Diagram for Bridge Rectifier with Filter

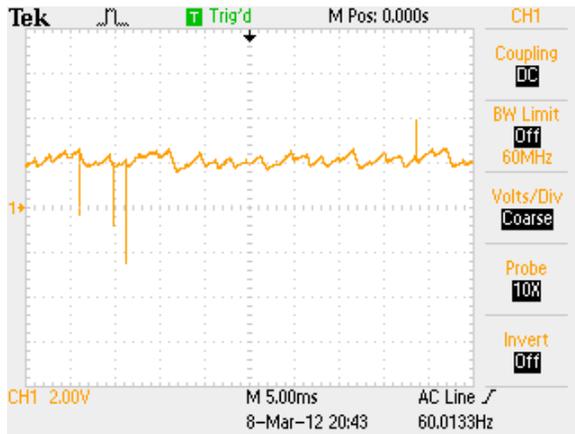


Figure 28: Track Current: Filtered DC

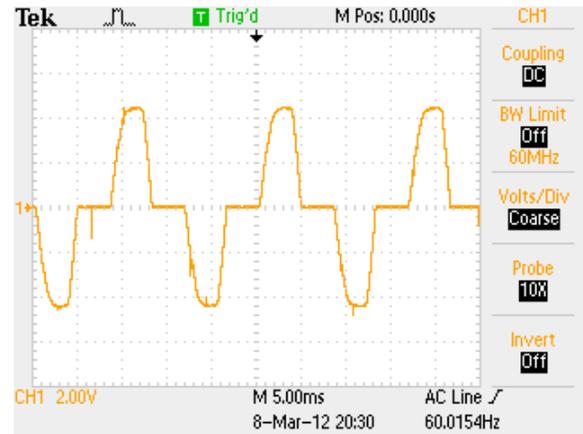


Figure 29: Transformer Current: Filtered DC

3.3 Pulse Width Modulation

Pulse Width Modulation (PWM) is a technique for controlling the average voltage through pulses of power. The average voltage is calculated by multiplying the "on" voltage by the fraction of the time the voltage is "on." PWM has the advantage of being easily controlled by a computer or microcontroller. With suitable power transistors and driver circuits, PWM can result in very low losses.

Figure 30 is an example of a test circuit for demonstrating PWM. A 20K variable resistor is used to vary the "on" time relative to the "off" time. When the "Gate Signal" is grounded, the output MOSFET turns on and applies the "on" voltage to the motor. This circuit was used to create the graphs in Figure 31. Note that at low speeds, the "on" voltage has a short duration compared to the "off" condition. Conversely, at high speeds, the "on" has a long duration compared to the "off" condition.

As shown in Figure 32, the track current has more of a DC characteristic because after the transistor turns off, motor inductor current continues to flow through the reverse biased "free wheeling" diode connected across the output as shown in Figure 30. The current provided by the rectifier however, does show the PWM characteristic as shown in Figure 33

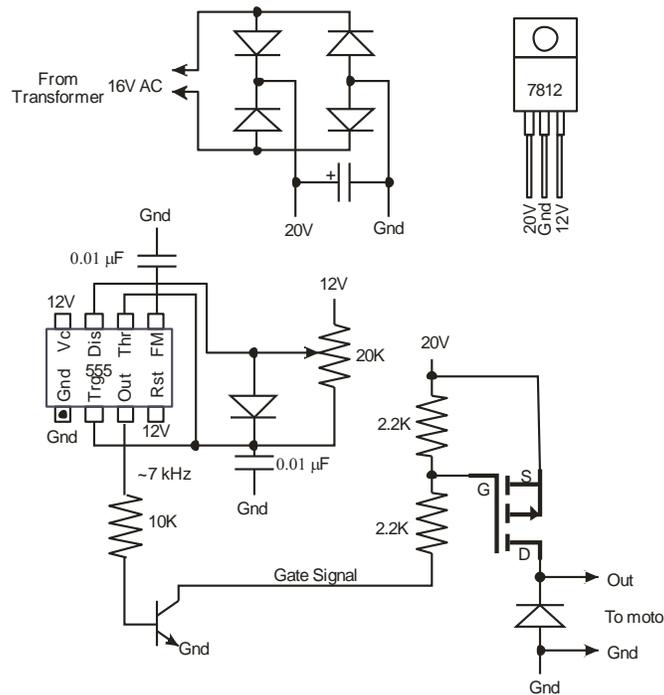
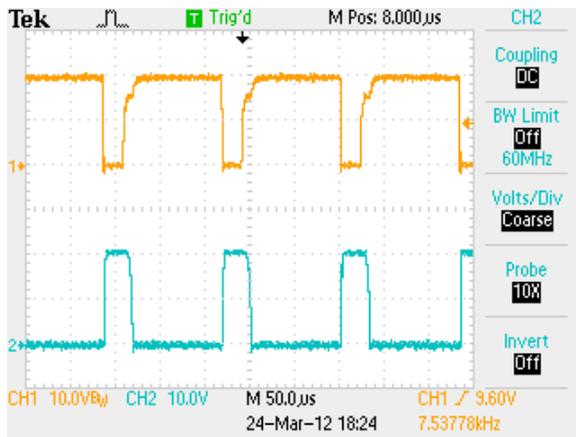
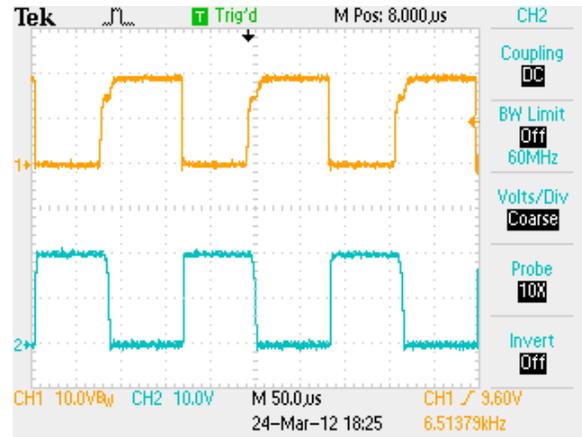


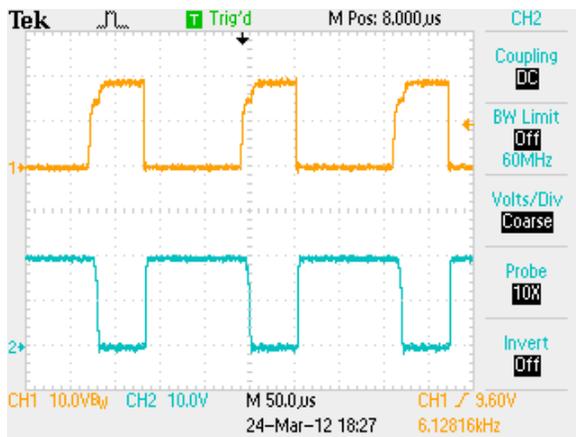
Figure 30: PWM Test Circuit



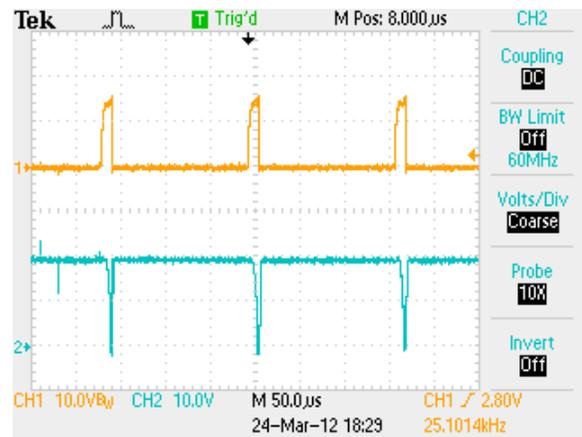
(a)



(b)

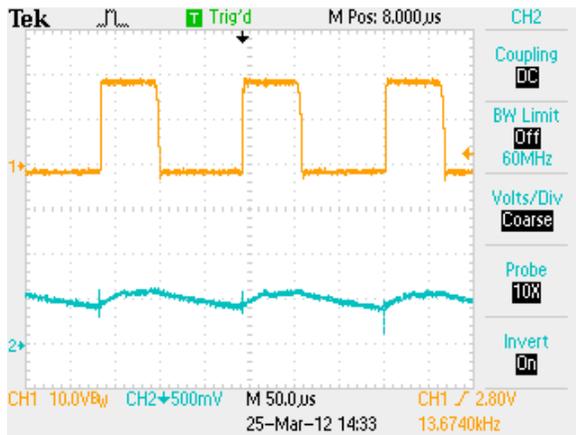


(c)

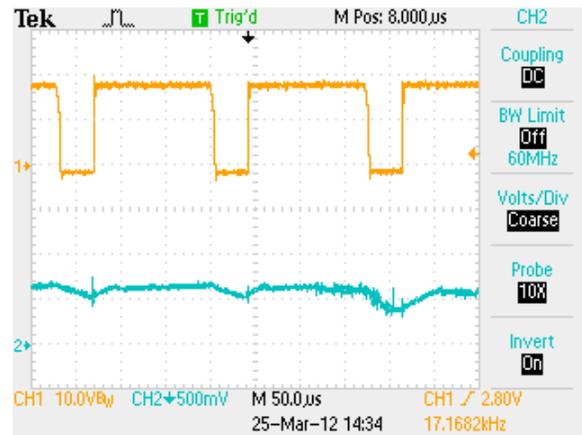


(d)

Figure 31: PWM waveforms (Top {orange} gate signal; Bottom {blue} motor voltage): (a) slow; (b) medium-slow; (c) medium fast; and (d) fast for unloaded Casey Jones universal motor with a rectified field.



(a)



(b)

Figure 32: PWM Track Voltage and Track Current for (a) Medium, and (b) Fast speeds

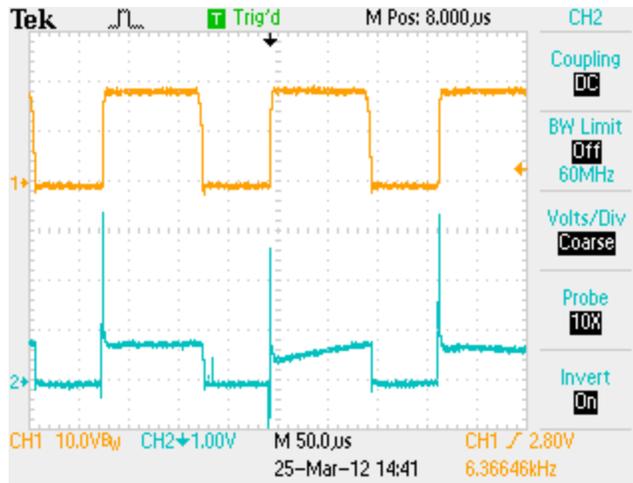


Figure 33: PWM Track Voltage and Rectifier Output Current

3.4 Fixed Voltage (AC or DC)

It is also possible to apply a fixed AC or DC voltage to the track and use some other means to communicate train direction and speed. For many engines, DCC can also be thought of as a fixed voltage of high (variable) frequency AC.

4. Communicating Direction

The following sections describe how an engine can be configured to respond to different methods of communicating direction.

4.1 Fixed Direction (Forward only)

In some cases, it may be desirable to have an engine only operate in the forward direction.

For universal motors, this can be accomplished by hard wiring the field coil and the armature in series such that the engine always goes forward. One end of the field coil is attached to one of the brushes for the armature. Track power is applied to the other end of the field coil and the other brush.

For DC motors, the easiest way is to use a bridge rectifier. The AC inputs in the rectifier are connected to the track pickups, and the DC outputs are connected to the DC motor in the polarity needed for the train to go forward. If desired, a filter capacitor can be placed across the DC output of the rectifier. This capacitor should be rated at least 50 Volts with a value greater than 1000 uF. In this configuration, the track can be powered with either AC or DC.

4.2 Manual switch on engine

If remote control of the train's direction is not required, a DPDT switch (either toggle or slide) mounted on the engine (or possibly in the tender) can be used to determine the engine's direction.

For universal motors, the field winding is connected to the input of a reversing switch circuit (Figure 34). The output of the reversing switch circuit is connected in series with the armature. One of the output connections of the reversing switch circuit is connected to one of the armature brushes. Track power is applied to the other reversing switch circuit output connection and the other brush. (Alternately you can connect the armature to the input of the reversing switch circuit, and connect the output in series with the field)

For DC motors, the inputs to the reversing switch circuit are connected to track power and the outputs of the reversing switch circuit are connected to the motor.

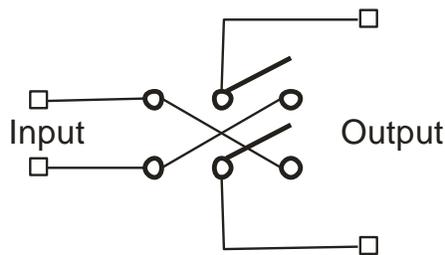


Figure 34: Reversing Switch Circuit

4.3 Time Sequence (American Flyer Remote Control Unit)

The original American Flyer Remote Control Unit (Figure 9 on the left and Figure 35) consists of a drum that rotates 1/8 of a revolution each time power is applied. This is accomplished by an electromagnetic actuator connected directly to the power pickups. This actuator pulls a pawl down on a sprocket attached to the drum, causing the drum to rotate 1/8 of a revolution. The surface of the drum has two copper patterns that if flattened, would look like those in Figure 36. Two sets of copper "fingers" make contact

with the drum surface. As the drum rotates with each application of power, the field coil is first connected for operation in one direction, then disconnected entirely, then connected for operation in the other direction, and then disconnected entirely again. This pattern is repeated as the drum rotates.

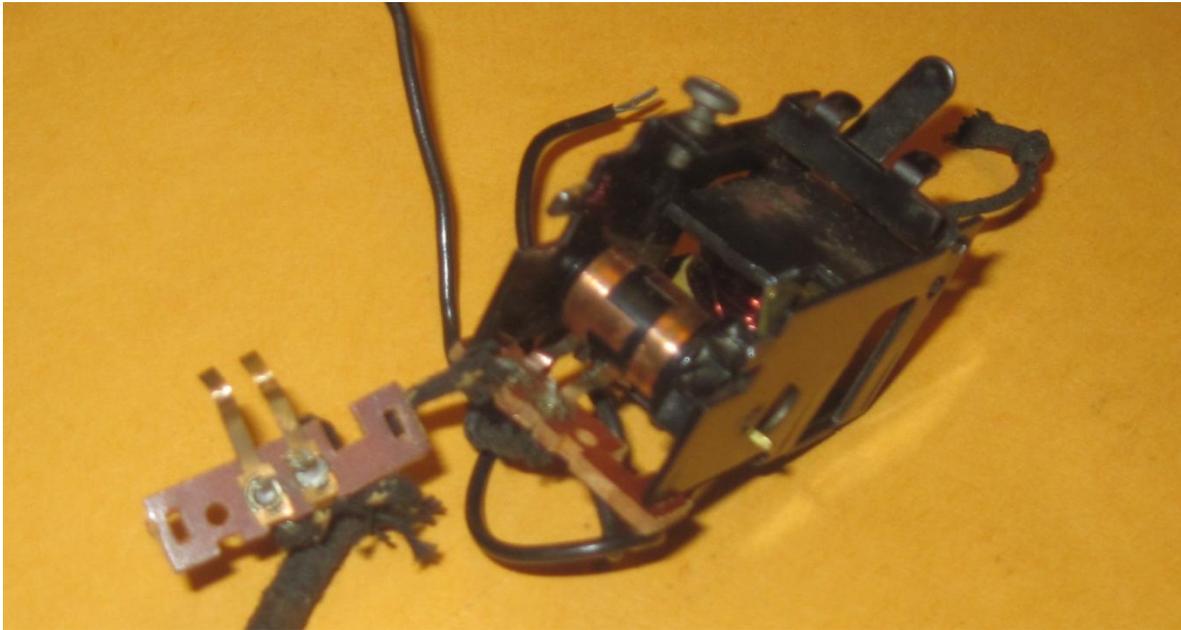


Figure 35: 4 position E-Unit with one set of fingers removed to reveal drum below.

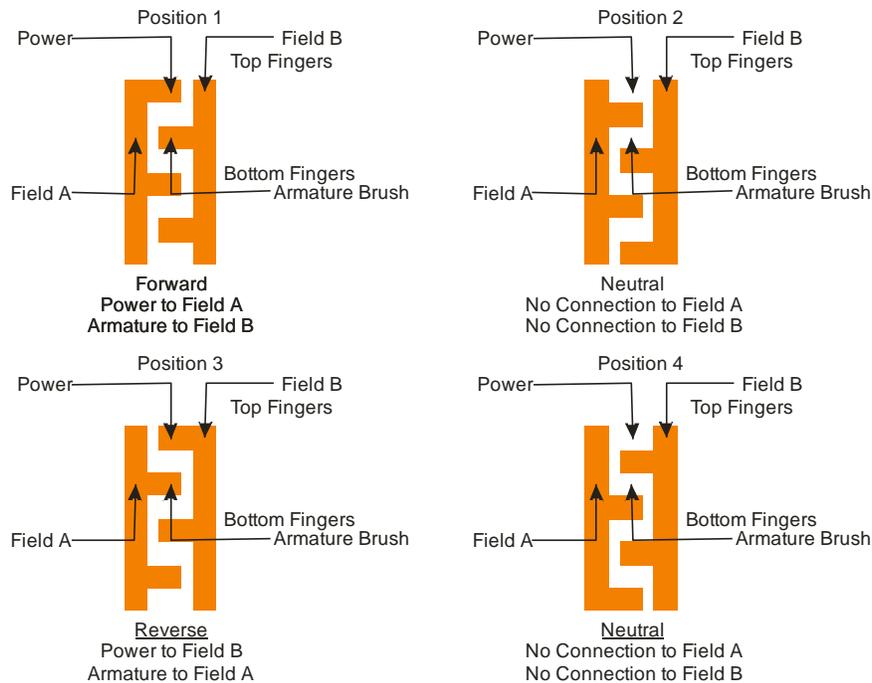


Figure 36: Gilbert American Flyer 4 position Remote Control Unit operation

A DC motor can also use the Gilbert Remote Control Units. The only difference is that the Remote Control Unit is wired as shown in Figure 37.

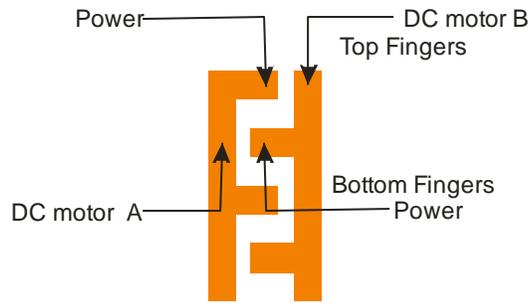


Figure 37: Connecting a Remote Control Unit to a DC motor

The later 2 position Remote Control Units (Figure 9 on the right) uses a solenoid that toggles a switch in one of two direction (Figure 38). This switch is configured as a reversing switch which alternately switches the connection of the field coil (Figure 39). When the power is off, the solenoid plunger is in the down position. The drum is shaped so that when power is applied and the solenoid plunger rises into the solenoid coil, the solenoid plunger also pulls up on the drum to rotate it slightly and change its position. Only two fingers are used; both connect to the field coil. The drum pivot points are also used for electrical connection to power and to the armature brush.

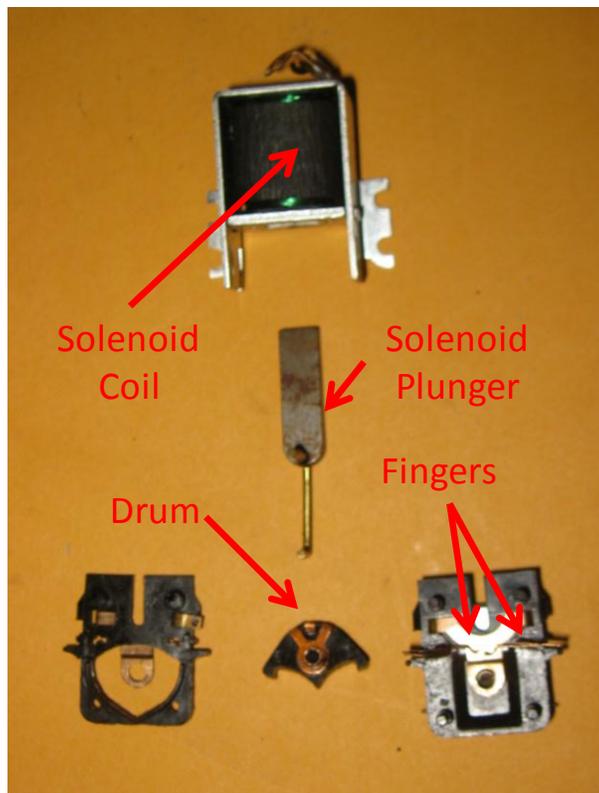


Figure 38: Gilbert American Flyer 2 position Remote Control Unit Disassembled

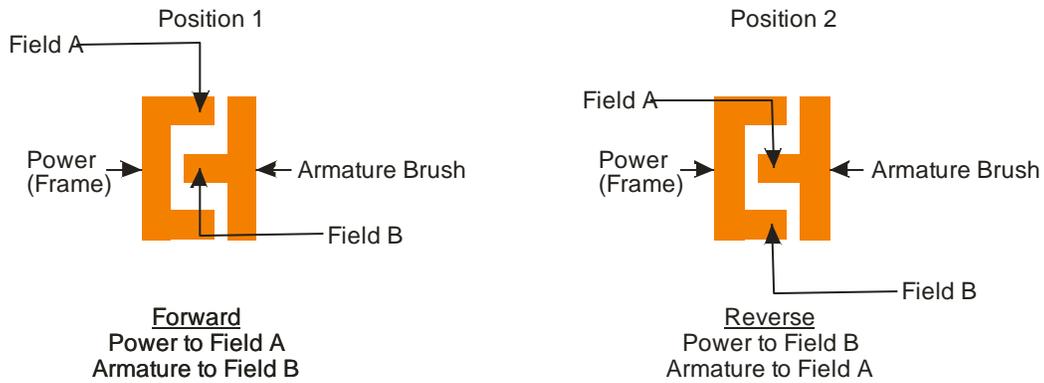


Figure 39: Gilbert American Flyer 2 position Remote Control Unit operation

The Gilbert American Flyer remote control units will work with DC track power. It has been reported that extended operation with DC power will cause the remote control unit to magnetize and stick. The generally accepted solution is to operate for a short time with AC track power to demagnetize the remote control unit. In my experimentation with operating the remote control units with DC, I found them to operate hotter for a given applied voltage; the current is higher because the coil inductance does not reduce the current at DC like it does with AC. In my discussions with others, no one has reported this to be a problem.

An engine with a Gilbert Remote Control Unit can be stopped without cycling the Remote Control Unit by inserting a resistor of about 10 ohms (as used in the American Flyer 709 Lockout Eliminator as shown in Figure 40) between the variable voltage terminal of the transformer and the track. This resistor will reduce the track voltage below that needed for the motor, but still high enough to keep the solenoid in the Remote Control Unit energized. Engines with modern can motors may still creep forward with only a 10 ohm resistor. I have found that 20 to 25 ohm resistors (two 10 ohm resistors in series or two 50 ohm resistors in parallel) will still work effectively to prevent the Remote Control Unit from cycling and will keep most trains from moving. The resistor should have a power rating of at least 5 watts. These resistors are also used in the Cow-on-Track, semaphore, and talking station accessories.



Figure 40: American Flyer 709 Lockout Eliminator

The more recent engines use an electronic "E" unit driving a DC can motor. The electronic "E" unit emulates the operation of the 4 position A.C. Gilbert Remote Control Unit. The only difference is that if the engine is off for a certain amount of time, then the sequence will begin with the train moving in the forward direction (or in reverse if so desired -- need only reverse the wires on the motor)

4.4 DC Polarity

With a DC motor, simply connecting the two motor wires to the track pick-ups will work. Alternately, installing a reversing switch between the track pick-ups and the motor will control which direction the train will move for a given position of the direction switch on the transformer / rectifier.

Using DC polarity to control train direction with a universal motor can be accomplished by using a bridge rectifier to keep the polarity on the field constant. The track polarity determines the polarity of the armature (rotor) and therefore the direction of movement. See Figure 41. The only downside to this conversion is that the engine will not operate on AC track power.

In Figure 41 a reversing switch is incorporated to establish which direction is forward for a given track polarity. This switch is optional. NMRA Standards S-9 Electrical established the convention that when the right hand rail (when looking forward) has a positive voltage with respect to the left hand rail, the locomotive should move forward.

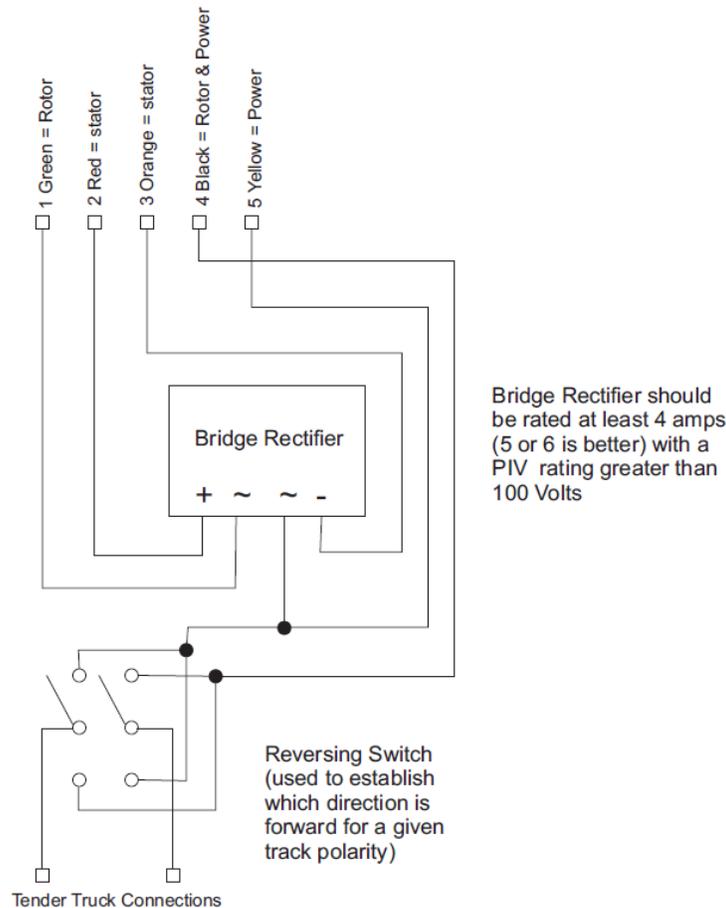


Figure 41: DC directional control with a universal motor

4.5 Digital Commands

Digital messages can also be used to signal an engine the desired speed and direction. This message can be communicated many ways including frequency modulation (such as DCC), radio frequency control (such as those used to control model airplanes), Infrared control (such as those used for remote control of televisions), and superimposing a signal on the track voltage (like TMCC).

Figure 42 shows how DCC used frequency modulation to send binary ones and zeroes through the track power. The complete specifications for DCC are available from the National Model Railroad Association (NMRA) through their web site (<http://www.nmra.org/standards/sandrp/consist.html>) The "Baseline Packet" that all DCC Command Stations and engine Digital Decoders is defined in NMRA standard S-9.2 and consists of a preamble byte (8 bits) and 3 data bytes. The three data bytes are an address data byte, instruction data byte and error detection data byte. The preamble byte is used as an indicator that data bytes will follow. The address byte contains the address of the digital decoder the message is intended; each decoder on a layout should have a unique address. The data byte contains 4 or 5 bits to indicated the ordered speed, as well as a direction bit to indicated the ordered direction. The final error detection data byte enables the decoder to determine if the first two data bytes were successfully received.

More extensive data can be communicated using extended packet formats that are defined in NMRA recommended practice RP-9.2.1.

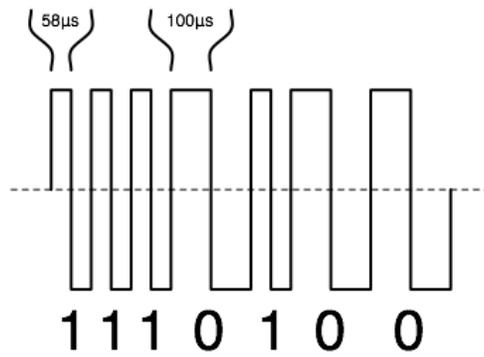


Figure 42: Voltage waveform for Digital Command Control (DCC)⁴

⁴ Tobin Richards, <http://en.wikipedia.org/wiki/File:DCCsig.png>

(This page left intentionally blank)

5. Communicating Speed

The following sections describe how an engine can be configured to respond to different methods of communicating speed.

5.1 Variable Voltage (AC or DC)

Varying the track voltage is the most common means for communicating speed. Universal and DC motors naturally increase speed when the voltage applied is increased. The precise speed however is also a function of the load placed on the motor; motors will slow down under load. The track voltage can also decrease due to voltage losses in the electrical connections between track sections. To keep train speed consistent on a floor layout, a track power connection should be provided within 4 track sections of the end of a block and spaced no more than 8 track sections apart within a block. For a permanent layout, more track power connections would be beneficial.

5.2 Digital Commands

Using digital commands, such as those used in DCC, can eliminate (to a degree) train speed variation due to track voltage losses. If the decoder uses speed feedback sensors, the speed of the train can be independent of load (to a degree) as well. Since many decoders can only decrease voltage from the tracks to the motor, the track voltage limits the highest speed achievable for a given load.

(This page left intentionally blank)

6. Action Car Considerations

American Flyer Action cars generally fall into one of the following categories:

- a. Mechanical Activation: No electrical power used. Examples include the Hay-jector and Tie-jector cars. These action cars are not dependent on track voltage and will not be discussed further in this document.
- b. Continuous action: Electrical power picked up from the tracks. Examples include floodlight cars, walking brakeman cars, and action caboose.
- c. Control Button Activated. Electrical power is provided via the "Base" rail and a pickup shoe engaging a special track section (Figure 43 and Figure 44). Examples include the TNT car, mail pickup car, log unloading car, truck unloading car, rocket launcher, operating stock car, and lumber unloading car.



Figure 43: Special Rail Section



Figure 44: Action car with power contact shoe

6.1 AC Track Voltage

The American Flyer electrically actuated action cars are designed to operate either on AC track voltage for those that are continuous action and on 15 volts AC for those that use the special track section and a control button. Figure 45 shows how the control button is wired to the special track section and the 15 volt accessory post on the transformer. The metal wheels on the action car must be on the rail connected to the base post of the transformer.

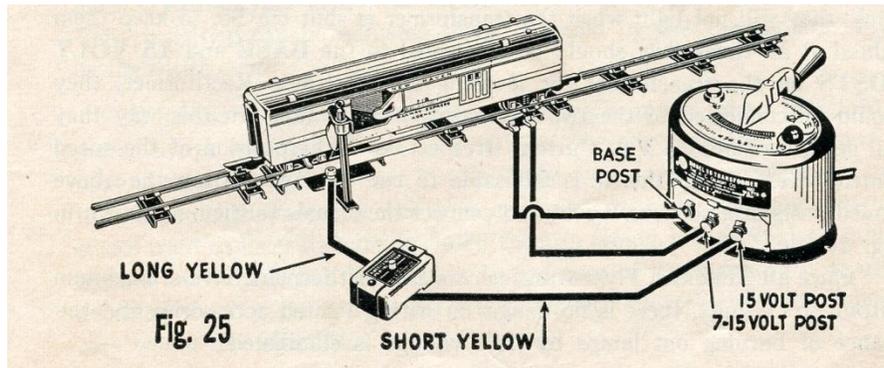


Figure 45: Wiring for an Action Car with an AC transformer⁵

6.2 DC Track Voltage

Some of the electrically actuated action cars that operate off the track voltage are incompatible with DC power. One examples is the Walking Brakeman car which uses a vibrating mat and requires AC power to function. Others, such as the floodlight car, and action caboose work well with DC power.

Special consideration must be made however, for action cars that use the "base rail" and the special track section. While many of the action cars will work correctly with DC power, the challenge is in providing a voltage difference of about 15 to 20 volts DC between the base rail and the special track section. The challenge is generally due to using a reversing switch to switch the polarity of the track voltage to control engine direction. If a common voltage source is used for both track power and the action car, then the voltage applied to the special track section must be adjusted when the polarity of the track power is changed. The following sections describe ways to deal with this challenge.

6.2.1 Separate Transformer

The simplest solution is to use a second AC transformer for the action cars as shown in Figure 46. The base post of this second transformer is attached to the "base rail" and the 15 volt post is connected via the control button to the special track section. Since the two transformer outputs are independent, the circuit for the track power is independent from the circuit through the special rail section, even though they share the "base rail." All action cars using the special rail section will work with this circuit.

⁵ *Instructions for Assembling and Operating American Flyer 3/16" Scale Trains and Equipment*, Developed at the Gilbert Hall of Science, 1949.

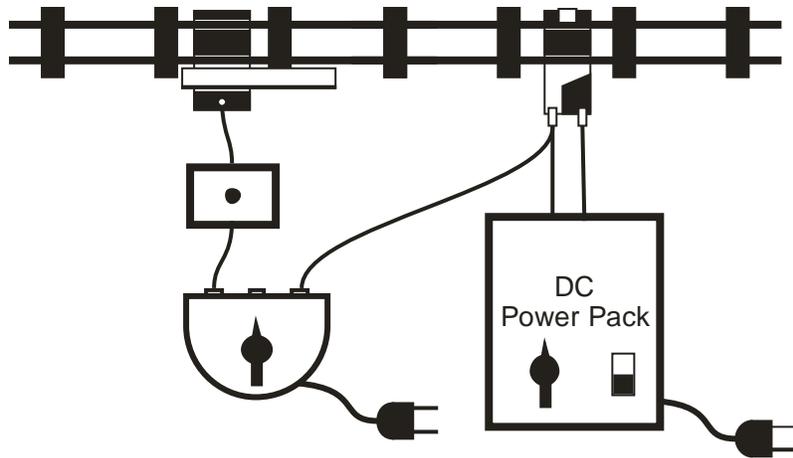


Figure 46: Use of Second Transformer for Action Cars

6.2.2 Double Pole Single Throw Pushbutton

For action cars that are only used when the train is "off," A double-pole-single-throw pushbutton can be used as shown in Figure 47 provided the transformer throttle is in the "off" position when the pushbutton is pressed. The rectifier may be damaged if the pushbutton is pressed and throttle is placed in an "on" position. Although this circuit was provided by the A.C. Gilbert company, it should generally be avoided to prevent accidental damage to the rectifier.

Note that the mail pickup car should not be used with this configuration because the mail pickup car requires the train to be operating when the pushbutton is pressed.

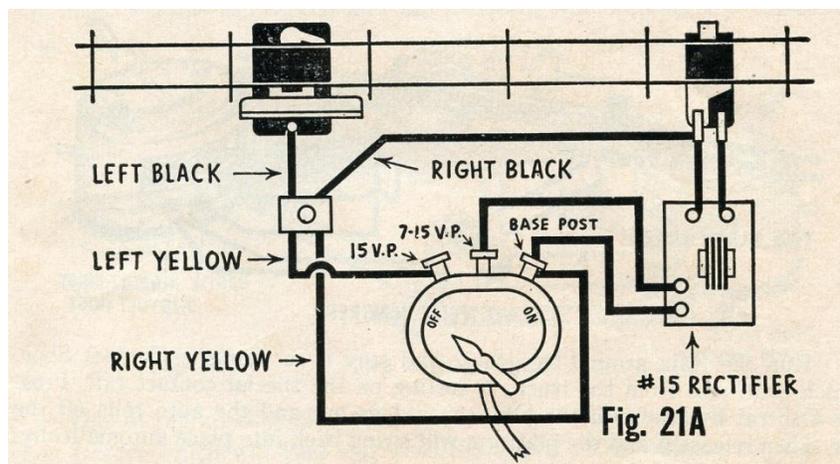


Figure 47: Double Pole Single Throw pushbutton for controlling Action Cars with DC⁶

6.2.3 Isolation Relay

Figure 48 illustrates how an isolation relay can be added to the circuit shown in Figure 47 to protect the rectifier from damage. Normally the relay is not energized and the normally closed contacts on the relay connect the track to the rectifier output. When the pushbutton is depressed, the relay is energized via a

⁶ *Instructions for Assembling and Operating American Flyer 3/16" Scale Trains and Equipment*, Developed at the Gilbert Hall of Science, 1949

half wave rectifier and a 7812 12 volt regulator. A capacitor provides filtering; its value may be adjusted to adjust for different relay coil currents. The base terminal on the transformer is connected to the base track rail via the relay. The control button also provides accessory power directly to the special track section.

Note that the mail pickup car should not be used with this configuration because the mail pickup car requires the train to be operating when the pushbutton is pressed. This circuit will stop the train when the pushbutton is pressed. This circuit will work with the other action cars that do not require the train to be in motion.

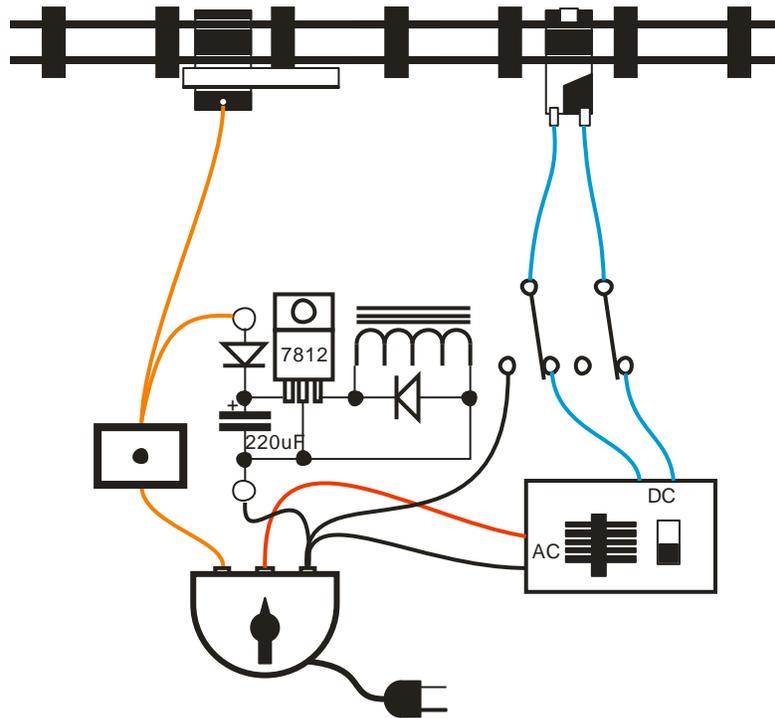


Figure 48: Isolation Relay

6.2.4 Half Wave Rectifiers

Figure 49 demonstrates the use of a half-wave rectifier to provide DC to the track while providing AC to the special rail section. Notice that the base rail of the track is always connected to the base post of the transformer. Note that the current drawn from the transformer from a half wave rectifier is not sinusoidal and the track voltage is not a constant DC (Figure 25 and Figure 26). A filtered half wave rectifier as described in A.2 may also be used to reduce the voltage and current waveform distortion.

All action cars employing the special rail section, including the mail pickup car will work with this circuit.

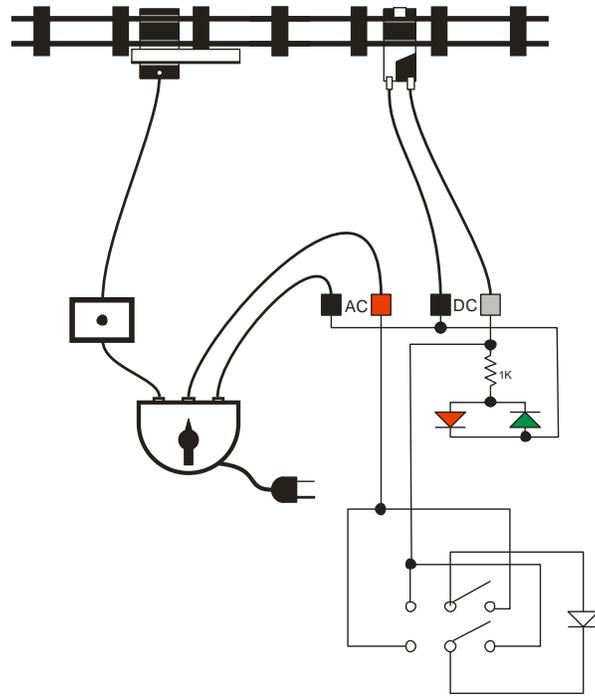


Figure 49: Half Wave Rectifier with special rail section

(This page left intentionally blank)

7. Sound Activation Considerations

7.1 Modulated Power

Most AC Gilbert air chime whistles (Figure 50) worked by superimposing a roughly 600 to 1000 Hz signal on the track power. This signal is created either with a vacuum tube in the case of the Electronic Whistle Control Box or through an electromagnetic vibrator in the case of an Air Chime Whistle Generator. Within the engine/ tender, a circuit similar to Figure 51 is used to drive the speaker. Although the sound quality is usually not considered very good, this circuit works with either AC or DC track voltage. Figure 52 shows the transformer and track voltage with the Air Chime Whistle Generator activated. See Thomas B. Barkers book (2012) for more details on the Electronic Whistle Control Box and the Air Chime Whistle Generator.

If PWM is used for speed control and the switching frequency is in the audio range, then it will likely be heard continuously through the speaker. Either the switching frequency would have to be raised above the audio range, or the speaker would have to be disabled.

DCC which switches between 5 kHz and 10 kHz will probably be heard continually as well. With DCC, it may be desirable to disconnect the air chime whistle.



Figure 50: American Flyer Air Chime Whistle

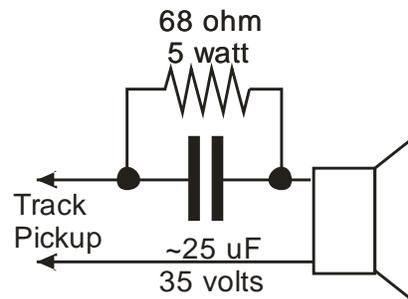


Figure 51: Engine / Tender Air Chime Whistle circuit

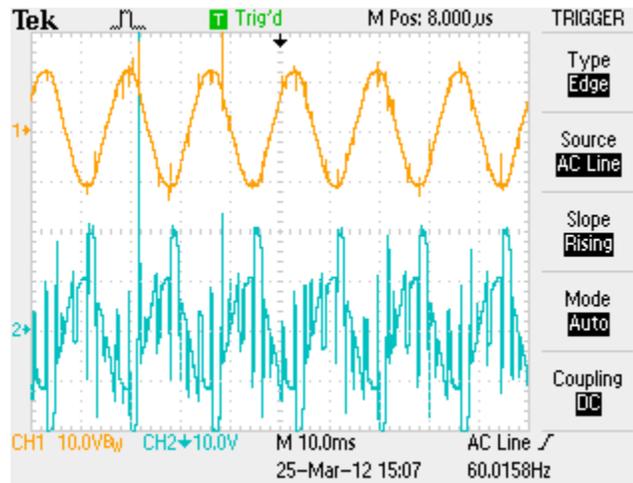


Figure 52: Transformer Voltage (top) and Track Voltage (bottom) with Air Chime Whistle Generator on.

7.2 DC Offset ("Railsounds")

The 314AW engine and later engines with "Railsounds" compatible sound operate by superimposing a DC signal on AC power. The Lionel 6-5906 sound activation button (Figure 53 and Figure 54) accomplishes this by placing in series with the track, one diode in anti-parallel with six diodes as shown in Figure 55. The push button is normally closed and thereby bypasses the diodes. When the button is depressed and opens the switch, the voltage drop across the 6 diodes in one direction is between about 3.5 and 4.0 volts DC and the voltage drop across the single diode in the other direction is between about 0.6 and 0.65 volts DC. The impact of depressing the sound activation button on the track voltage is shown in Figure 56. Note that the peak value in the positive direction is about 3.5 to 4.0 volts less than the peak in the negative direction. The sound board /relay in the engine / tender senses this difference to activate a whistle or bell.

Because this method of signaling relies on a difference in the peak voltage of the positive and negative half-waves, the method only works with AC track power.



Figure 53: Lionel 6-5906 Sound Activation Button

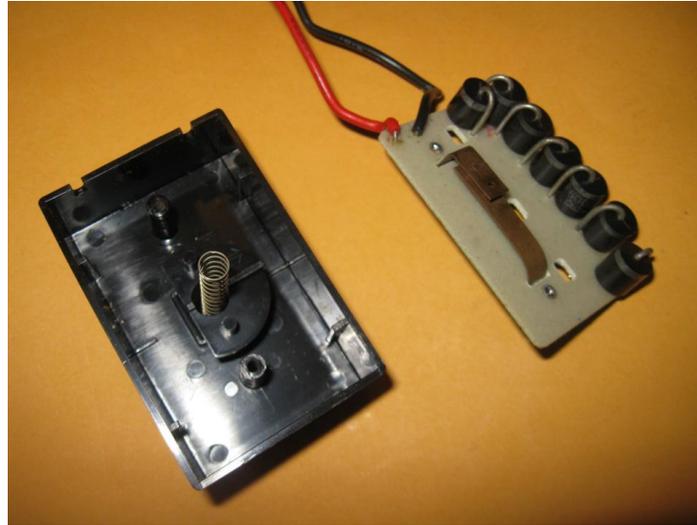


Figure 54: Lionel 6-5906 Sound Activation Button internals

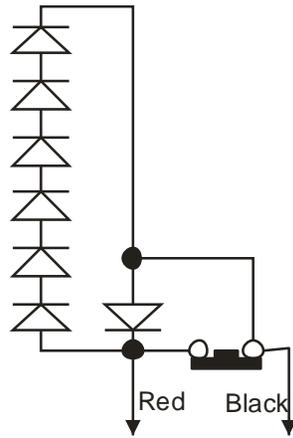


Figure 55: Schematic of Sound Activation Button

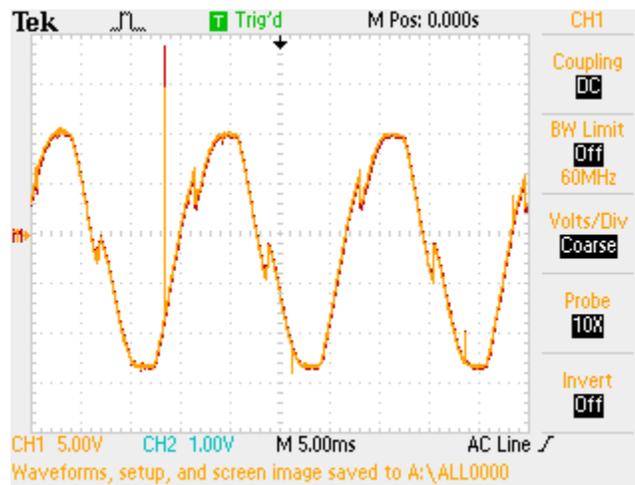


Figure 56: Track Voltage when powering an unloaded universal motor and with Sound Activation Button pressed

The 314AW control box employed a circuit different from Figure 55. A description of this circuit can be found in Thomas B. Barker's book (2012).

While the 314AW engine is not sensitive to the polarity of the DC offset, many Railsounds equipped engines will sound a bell with one polarity and a whistle with the other. One could hook up two controllers like those in Figure 55 such that the two red wires are connected together, and the black wires are connected to the 7-16 Volt post on the transformer, and to the track. Alternately, the circuit shown in Figure 57 can be used. One terminal is attached to the 7-16 volt post on the transformer and the other to the track. The reversing switch controls whether the bell or the whistle is activated by the pushbutton

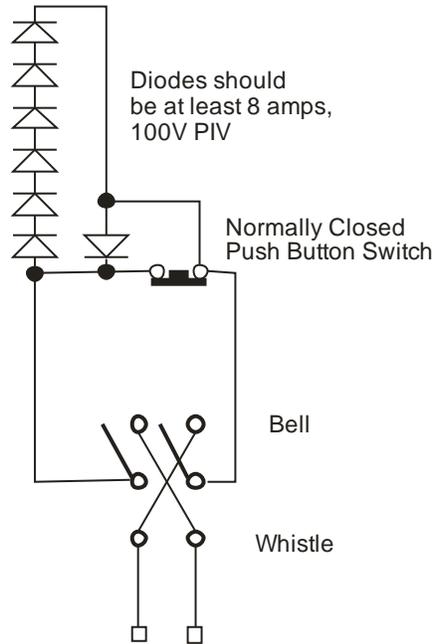


Figure 57: Use of reversing circuit to control both a bell and whistle with same push-button

7.3 Digital Control

Digital messages can also be used to activate engine sounds. As with engine directional and speed control, this message can be communicated many ways including frequency modulation (such as DCC), radio frequency control (such as those used to control model airplanes), Infrared control (such as those used for remote control of televisions), and superimposing a signal on the track voltage (like TMCC).

8. Bibliography

Barker, Thomas B., *Gilbert American Flyer S Gauge Operating and Repair Guide*, Third Edition, printed on demand by CreatSpace, an Amazon Company, 2012.

Overall outstanding reference that explains the operation and repair of American Flyer engines, action cars and accessories.

Hannon, Robert A., *A.C. Gilbert's Postwar American Flyer S-Gauge Reference Manual, Locomotives, Rolling Stock & Accessories*, First Edition, CrowsNest Publishing, Clarksville, MD, 2001.

This book provides detailed specifications and pictures for almost all the electro-mechanical devices in the A.C. Gilbert postwar product line. For example, if you have a burned out armature winding, this book will tell you what wire to use, how many turns, which direction to make the turns, and how to tie off the wire ends.

National Model Railroad Association, *NMRA Standards S-9 Electrical*, of August 1984

This standard provides electrical conventions for DC operation on a two rail system.

(This page left intentionally blank)

Appendix A: unusual technologies

A.1 Brushless DC Motors

A brushless DC motor has the permanent magnet field on the rotor, with the armature on the stator. Some type of position sensor is used to determine which of the armature coils should be energized and which polarity to use. This sensor is typically a solid state "Hall Effect" sensor that detects the magnetic field created by the field magnet. The armature coils are switched on and off using transistors. As a consequence, the commutator/brushes are eliminated. Since the life of a typical motor with brushes is limited by the brush/commutator wear, brushless DC motors can have a significantly longer service life.

A.2 Filtered Half Wave rectification for DC Directional Control

Figure 58 is a schematic of a filtered half wave rectifier for DC directional control. The advantage of this circuit over the unfiltered half wave circuit is that track voltage (Figure 59) and current (Figure 60) are much closer to a constant DC. The transformer current (Figure 61) however, still has considerable distortion. This circuit can be used with the special track section to provide ac power to action cars. One disadvantage to this circuit is that it requires two filter capacitors (unless one can find a non-polarized capacitor of sufficient capacitance). These capacitors typically have a value on the order of 10,000 uF with a voltage rating of 50 volts and can be expensive. I also recommend that the rectifiers be rated for at least 8 amps with a reverse voltage rating at least 100 Volts.

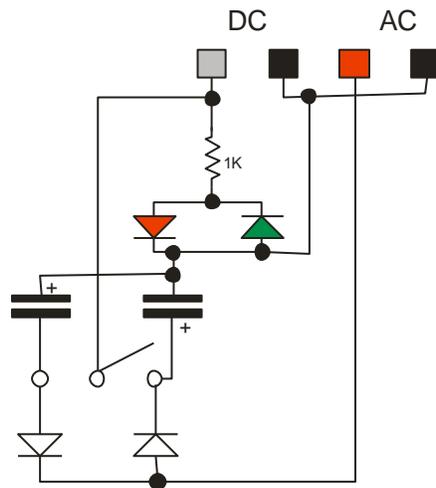


Figure 58: Filtered Half Wave Rectifier

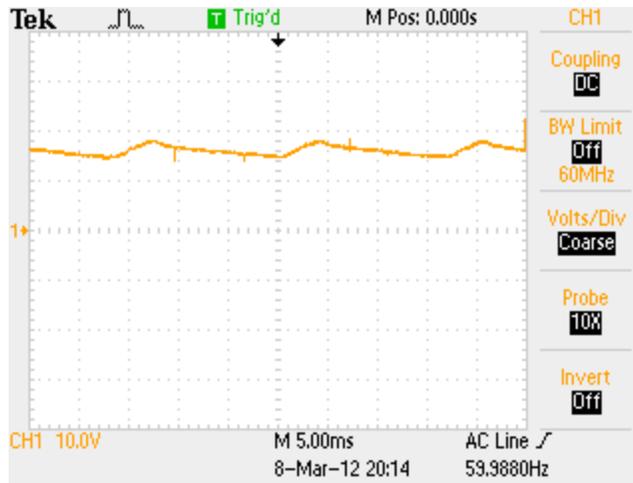


Figure 59: Track Voltage: Filtered Half Wave Rectification

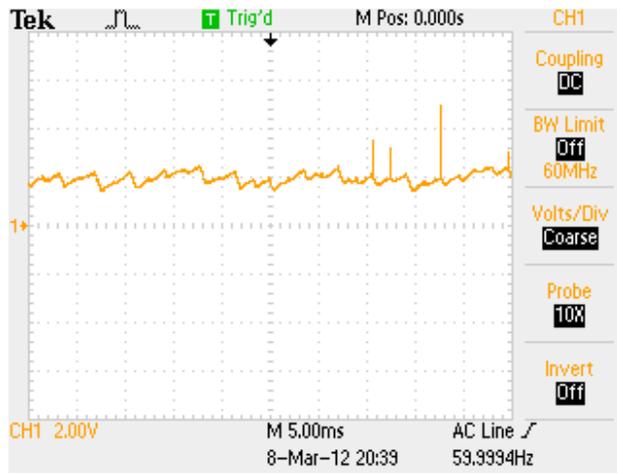


Figure 60: Track Current: Filtered Half Wave Rectification

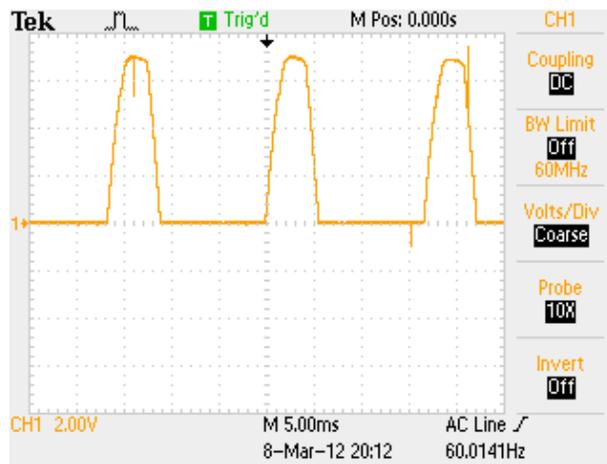
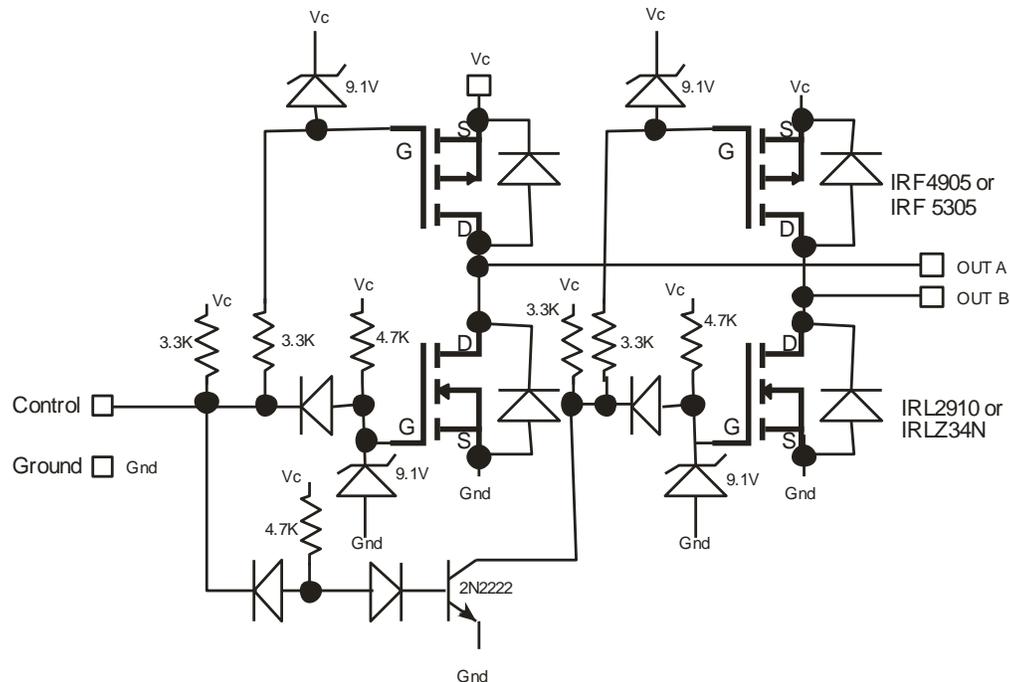


Figure 61: Transformer Current: Filtered Half Wave Rectification

A.3 Power FETs to control DC polarity and motor direction

Figure 62 is a schematic for a fully solid state circuit that will change the polarity of the output terminals when the control input is shorted to ground. Normally, with the control input not shorted to ground, the OUT A terminal is grounded and the OUT B terminal is at the supply voltage V_C . With the control input grounded the OUT A terminal is at V_C while the OUT B terminal is grounded. This circuit requires a supply voltage above about 6 volts to work well; hence it cannot be used to reverse the polarity on the field (stator) winding which typically has a voltage drop of less than 3 volts. The circuit described in Figure 62 can be functionally represented by Figure 63.



When the Control inputs are shorted together, the polarity of the Output switches.

Figure 62: Power FETs to control DC polarity

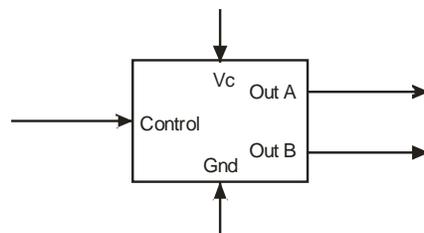


Figure 63: Functional representation of polarity reversing circuit

With the outputs of this circuit connected to a DC motor, the direction of the motor is determined by whether the Control input is connected to ground or not. The speed of the DC Motor is determined by the value of V_C . Figure 64 can be used to control the direction of a universal motor. The first rectifier converts the track power to DC, the polarity reversing circuits switches the polarity of the power coming from the rectifier if needed (based on the control input). The second rectifier keeps the polarity on the

stator (Field winding) constant while the polarity on the rotor (armature) is reversed. This circuit can be used to drive two motor ALCO locomotives; each motor would have its own stator (field) rectifier.

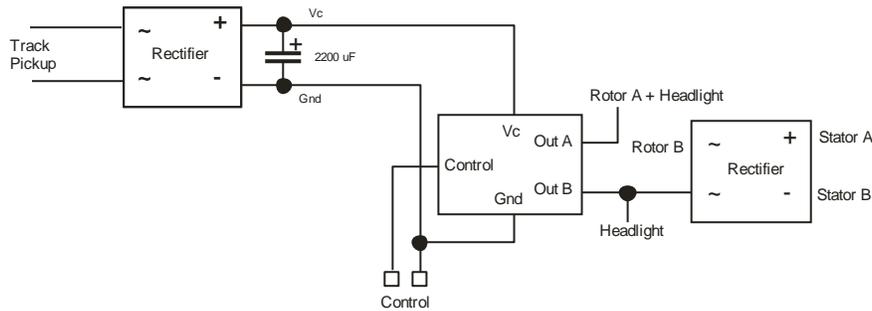


Figure 64: Reversing a Universal Motor with power FETs

Figure 65 is an alternate circuit that eliminates one of the rectifiers. For locomotives that power the smoke box and light using full track power, the locomotive wiring will require disconnecting a wire to one of the brush caps (armature / rotor) and soldering it to one of the field winding (stator) wires. Locomotives that connect the smoke box and headlight to both brush caps do not require modification. For this circuit the polarity of the stator (field) is constant while the polarity of the rotor (armature) is reversed.

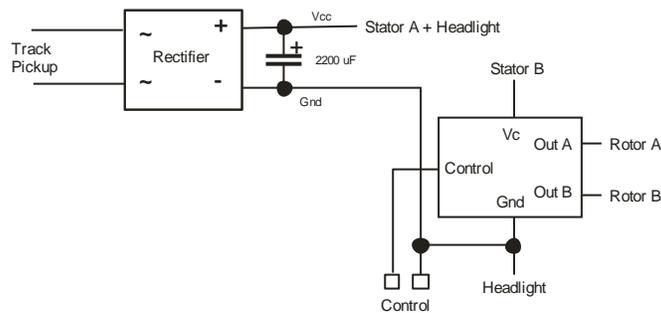


Figure 65: Alternate FET circuit for reversing a Universal Motor

Figure 66 depicts a schematic of another circuit for reversing polarity. This circuit however, requires two different supply voltages, V_c and V_{ca} . For this circuit to work properly, V_c must be at least 5 volts higher than V_{ca} . The output voltage is V_{ca} . The functional representation of this circuit is shown in Figure 67. Figure 68 shows how to use this circuit to reverse a universal motor. In this case the polarity on the rotor (armature) is held constant while the polarity on the stator (field) is reversed.

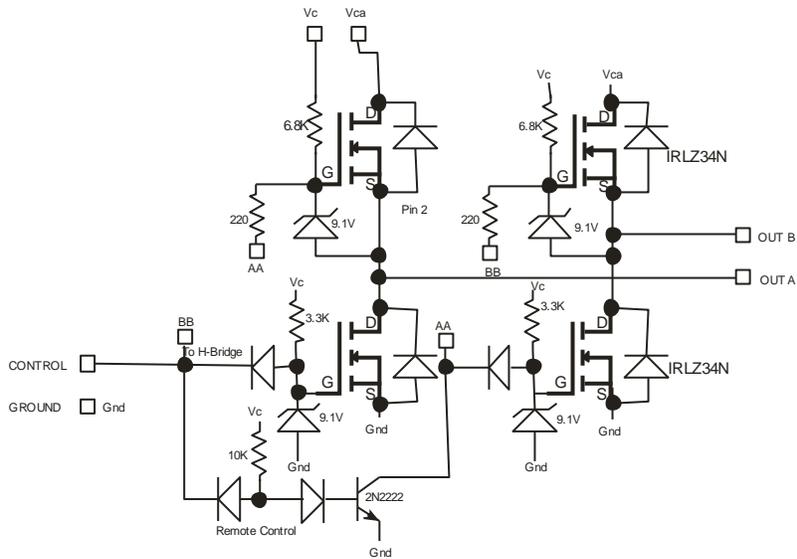


Figure 66: All N-FET circuit to reverse polarity

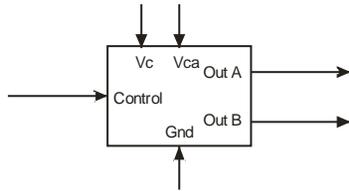


Figure 67: Functional Representation of N-FET circuit

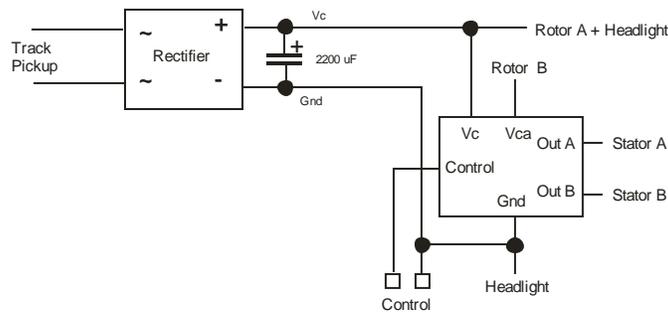


Figure 68: Circuit for reversing a Universal Motor using N-FETs

A.4 Control Circuits for Reversing

The previous section provided several alternatives for reversing the direction of a universal motor based on a control input. This section will provide several circuits for generating that control input. This section assumes that the rotor and stator windings are connected such that if the control input is not connected to ground, the locomotive will move in the forward direction. If the control input is grounded, then the locomotive will move in the reverse direction.

Figure 69 is an example of an AC-DC Reversing Control Circuit that will result in the locomotive moving forward if either AC is provided, or DC of one polarity. If DC of the other polarity is provided, the locomotive will move in the reverse direction. Hence this circuit will work on either AC or DC layouts.

The double pole double throw reversing switch determines which polarity of DC on the track will result in the train moving in reverse.

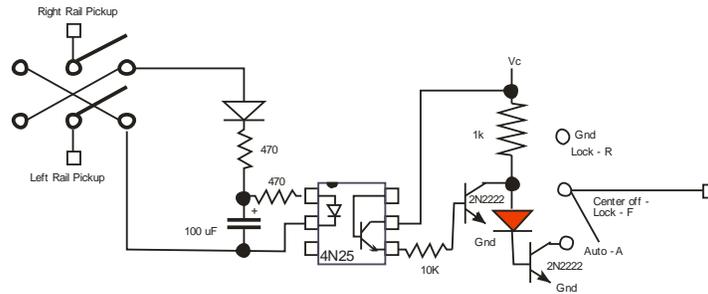


Figure 69: AC-DC Reversing Control Circuit

Figure 70 is a circuit for a reversing switch controller that is wired between the transformer and the track. The base post on the transformer is connected to the base rail at all times to enable action cars to use the 15V accessory post with the special rail section. The single pole double throw switch connects the track to either the transformer Variable voltage post, or to the output of a filtered half wave rectifier.

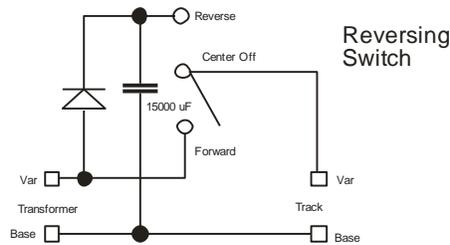


Figure 70: AC-DC Reversing Switch Controller

Figure 71 is an alternate AC-DC Reversing Control Circuit. With the switch in Auto mode the locomotive travels forward when provided AC without a DC offset, AC with a DC offset, or pure DC of one polarity. The locomotive reverses when provided DC power or AC with a DC offset of the opposite polarity. Hence a Railsounds controller (Figure 55 or Figure 57) can be used to reverse the locomotive.

As an aside, this circuit can also be used to activate many other locomotive or action car electrically activated mechanisms or circuits using a Railsounds controller.

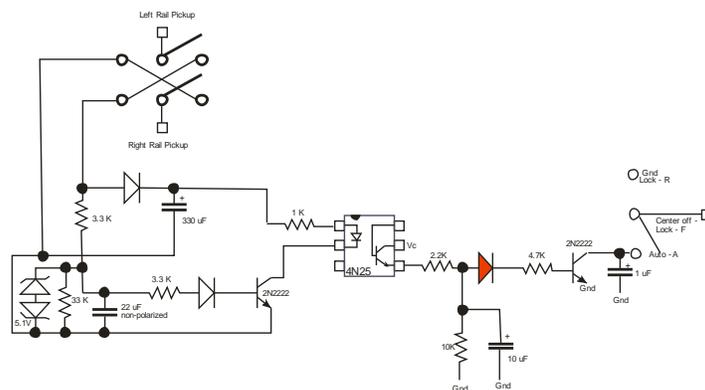


Figure 71: AC-DC Reversing Control Circuit for use with Railsounds controller

A.5 Relay Based Reversing

Figure 72 provides a schematic for a relay based remote control unit. One of the challenges with using a relay is that the range of track voltages that the circuit can experience is greater than the range for which most relays will successfully operate. Most relays capable of switching up to 5 amps of current have 12 VDC rated coils. While many of these relays will operate down to about 9 volts, track voltage can fall below this value. This circuit solves the problem by creating a regulated 5 volt DC supply, which is possible over the track voltage range, then converting the 5 volts to 12 VDC using a DC to DC converter. The VBSD1-S5-S12-SIP converter used in circuit is available from Digi-Key Corporation for about \$5.00 (in 2013). The relay is available from Jameco Electronics for under \$3.50 (in 2013).

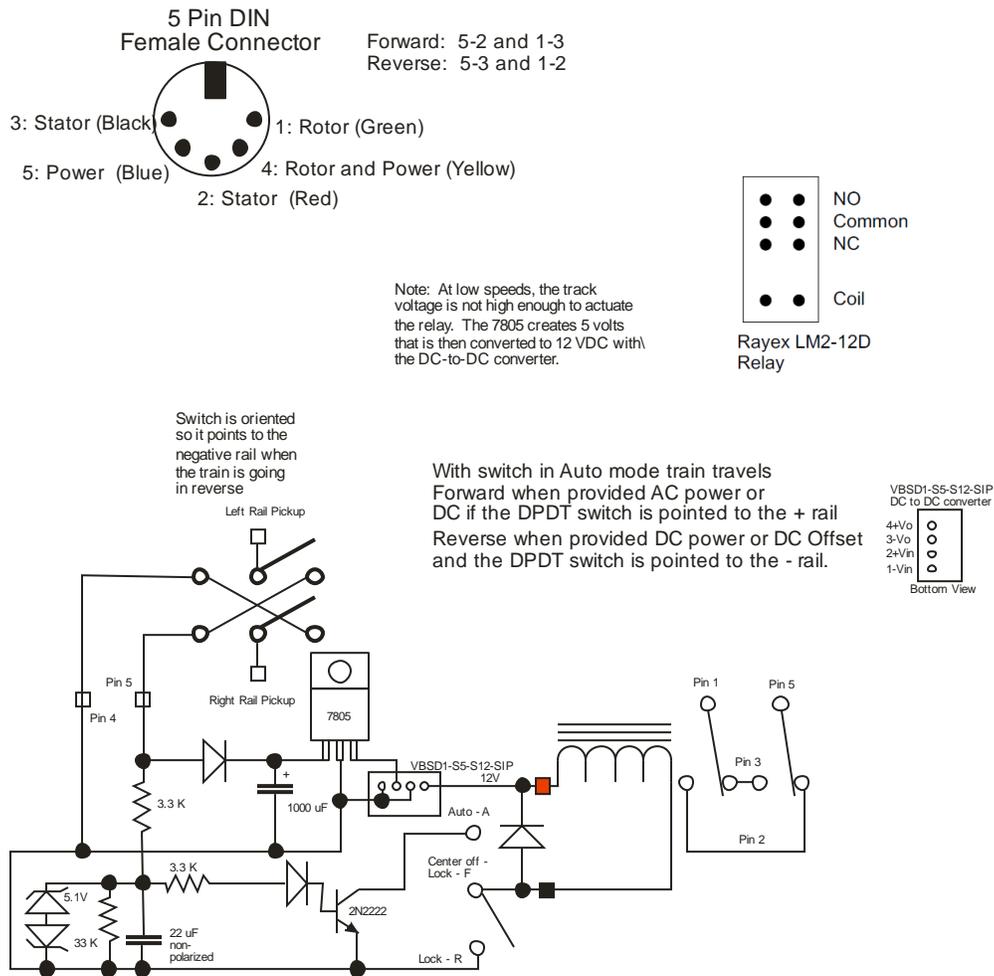


Figure 72: AC-DC Reversing Control Circuit using a relay

Figure 73 are pictures of circuits built to the schematic above (only difference is that a different DC to DC converter was used).

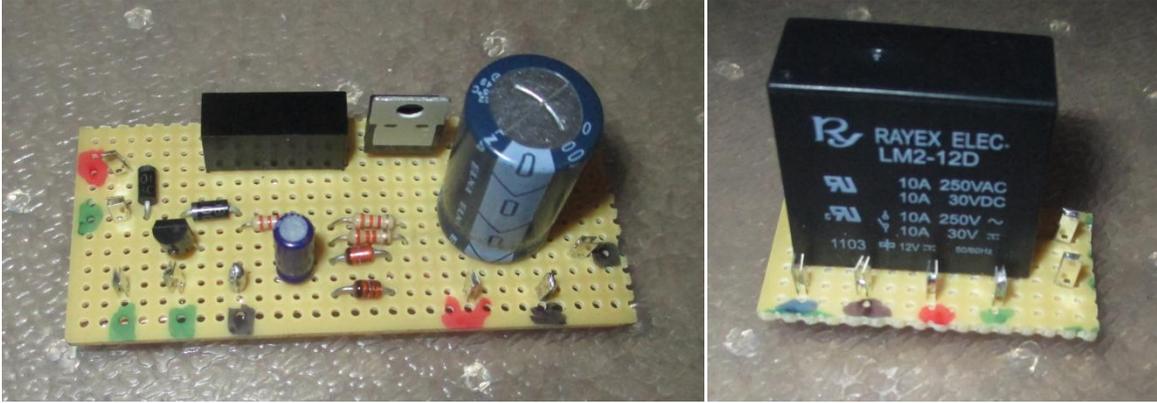


Figure 73: Example circuits built for an ALCO

Appendix B: How a Commutator Works

A commutator is a mechanical rotary switch used to control current through the armature (rotor) windings on a DC or universal motor. As shown in Figure 74, The armature consists of a shaft, commutator, and armature windings around multiple poles. The goal of the commutator is to connect the proper windings on the armature to keep the magnetic fields from the field and armature as close to 90 degrees out of phase as possible to maximize the motor torque.

The wires from each of the windings can be connected in two different methods. In the Common Tie-Off method, one end of each winding are connected together and not to the commutator. The "other" end of each winding is connected to a specific commutator segment. In the End-to-End Tie-Off method, the windings are connected into a big loop; the connection between windings is also connected to a specific commutator segment.

For both tie-off methods, the commutator segments are carefully aligned with the brushes to ensure the proper windings are energized for any rotation angle of the armature. For the Common Tie-Off method, the gaps between commutator segments nearly line up with the gaps between the poles. For the End-to-End Tie-Off method, the gaps between the commutator segments line up with the center of the pole.

Most (but not all) A.C. Gilbert open frame DC and universal motors have 3 poles and use a common tie-off.

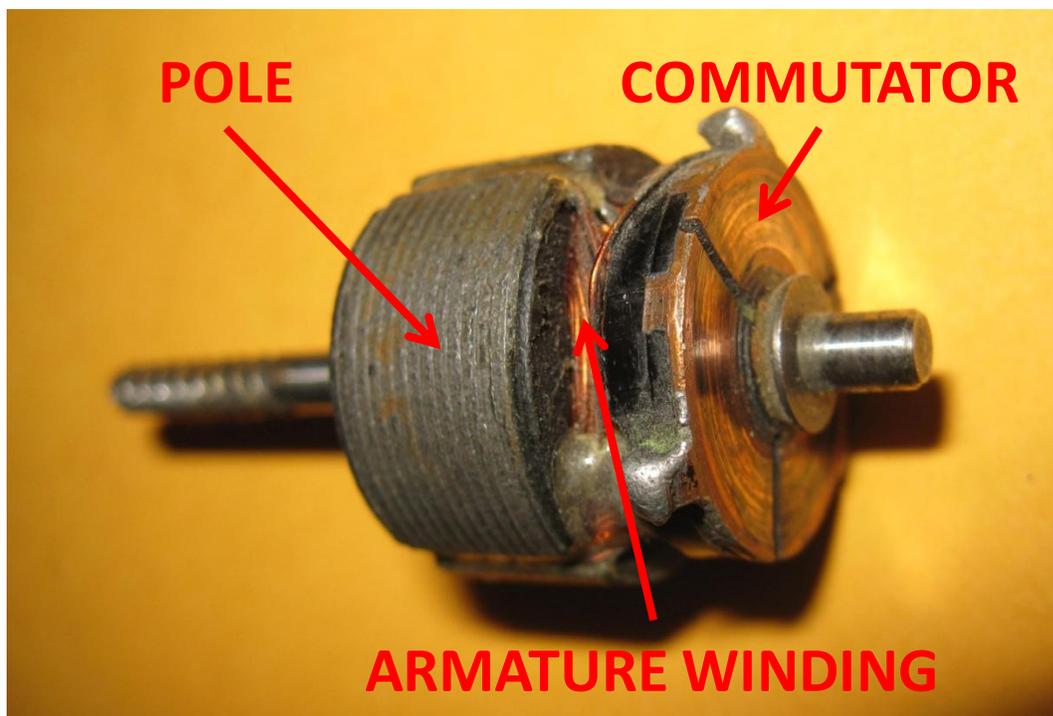


Figure 74: Armature

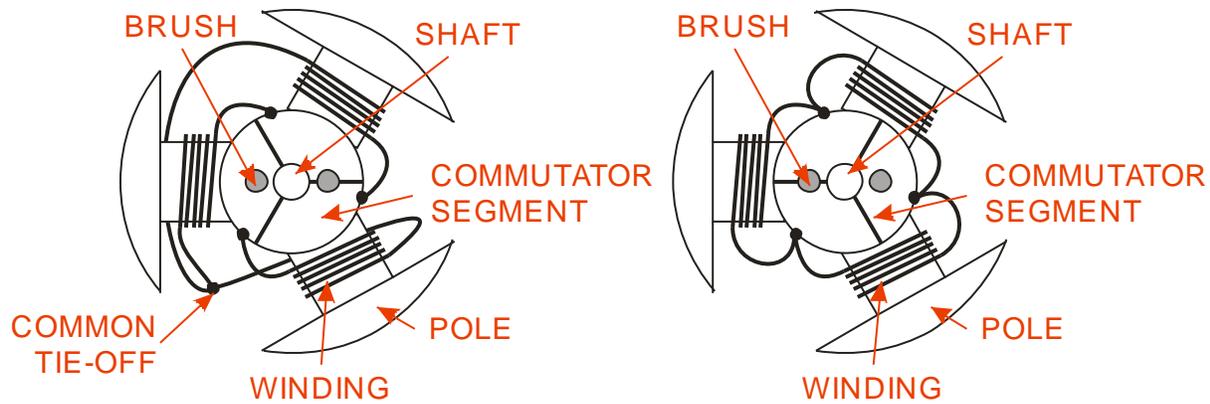


Figure 75: Common Tie-Off and End-to-End Tie Off Armatures

B.1 Common Tie-Off

Figure 76 shows how the commutator and brushes energize the rotor windings to produce a torque in the forward direction. The green and red bars on each side of the rotor symbolize the magnetic field polarity created by either the field winding or permanent magnet. In interpreting the figure, one could assume that the green bar symbolized a North magnetic pole and the red a South magnetic pole. Similarly, windings connected to the green brush result in a North magnetic pole and winding connected to the red brush result in a South magnetic pole. Figure 76 is representative of the rotor from an American Flyer steam engine. Note that the gaps between the commutator segments is rotated somewhat from the gap between the poles. This was likely done to improve forward operation without penalizing reverse operation significantly. Figure 77 shows reverse operation.

In examining Figure 76, note that at 0° rotation, winding 3 has the "green" polarity and winding 2 has the "red" polarity. Winding 1 is not energized. Since winding 3 is green and near the red pole, the magnetic force tends to rotate the rotor in the clockwise direction. Likewise, winding 2 is red and also near the red pole, hence the magnetic force is repulsive, but will still tend to rotate the rotor in the clockwise direction. At 30° rotation, the commutator has shifted supplying current from winding 3 to winding 1. This shifting of supplying current from one winding to another is called commutation. At 60° rotation, winding 1 is still green and repulsed from the green field pole and winding 2 is red and attracted to the green field pole. At 75° rotation, commutation is underway. Both winding 2 and 3 are red while winding 1 is green. Winding 3 is repulsed from the red field pole, winding 2 is attracted to the green field pole, and winding 1 is repulsed from the green field pole. At 90° rotation, commutation is complete and winding 2 is no longer energized. The situation at 120° rotation is identical to 0° with the poles all having rotated 120° .

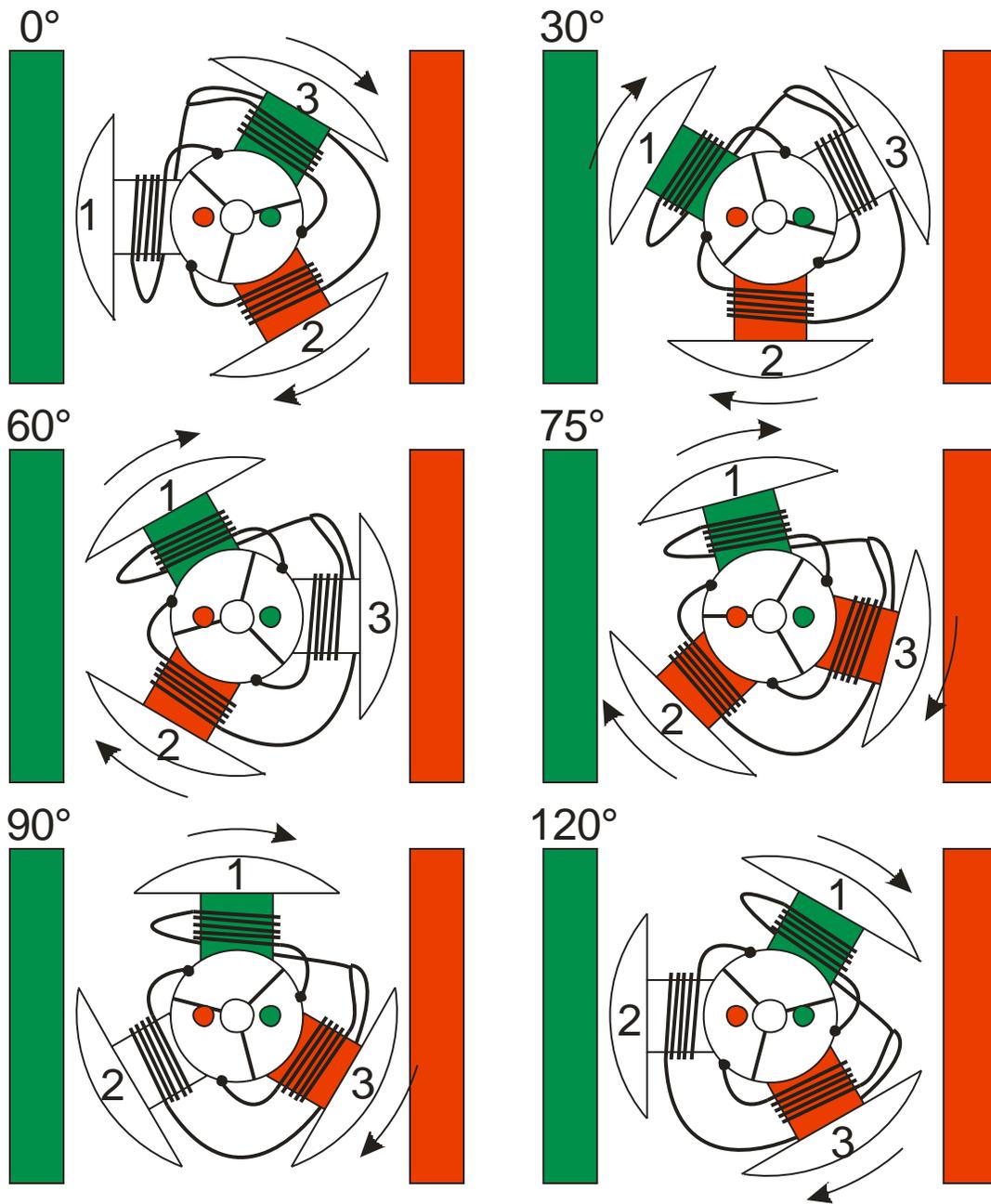


Figure 76: Common Tie-Off Rotor Forward Direction

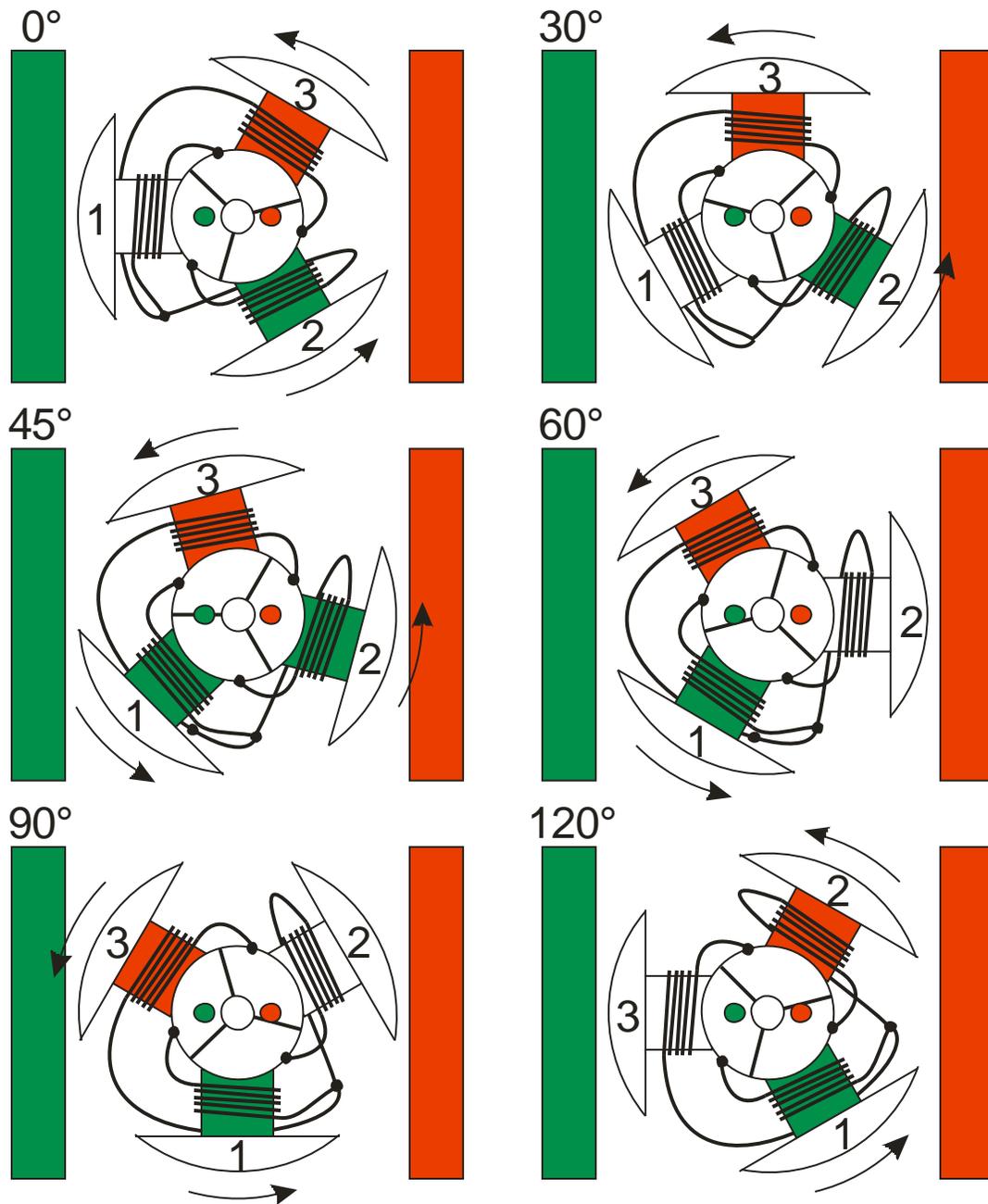


Figure 77: Common Tie-Off Rotor Reverse Direction

B.2 End to End Tie-Off

For American Flyer motors, the end-to-end tie-off is not as common. One example is the XA15B024 armature for the 21158 Docksider (As described by Hannon 2001). Note that other Docksider armatures use the common tie-off.

Figure 78 shows how the commutator works for the end-to-end tie off method. When a winding approaches one of the field poles, the brush nearest the field pole shorts out the winding. The remaining two armature windings produce torque. When the armature rotates to the 30° position, windings 1 and 3

are in series and in anti-parallel with winding 2. Hence windings 1 and 3 are green while winding 2 is red.

DC or universal motors with more than three poles typically use the end-to-end tie-off method because except for the windings near a field pole that are being commutated, all of the other windings are energized and producing torque.

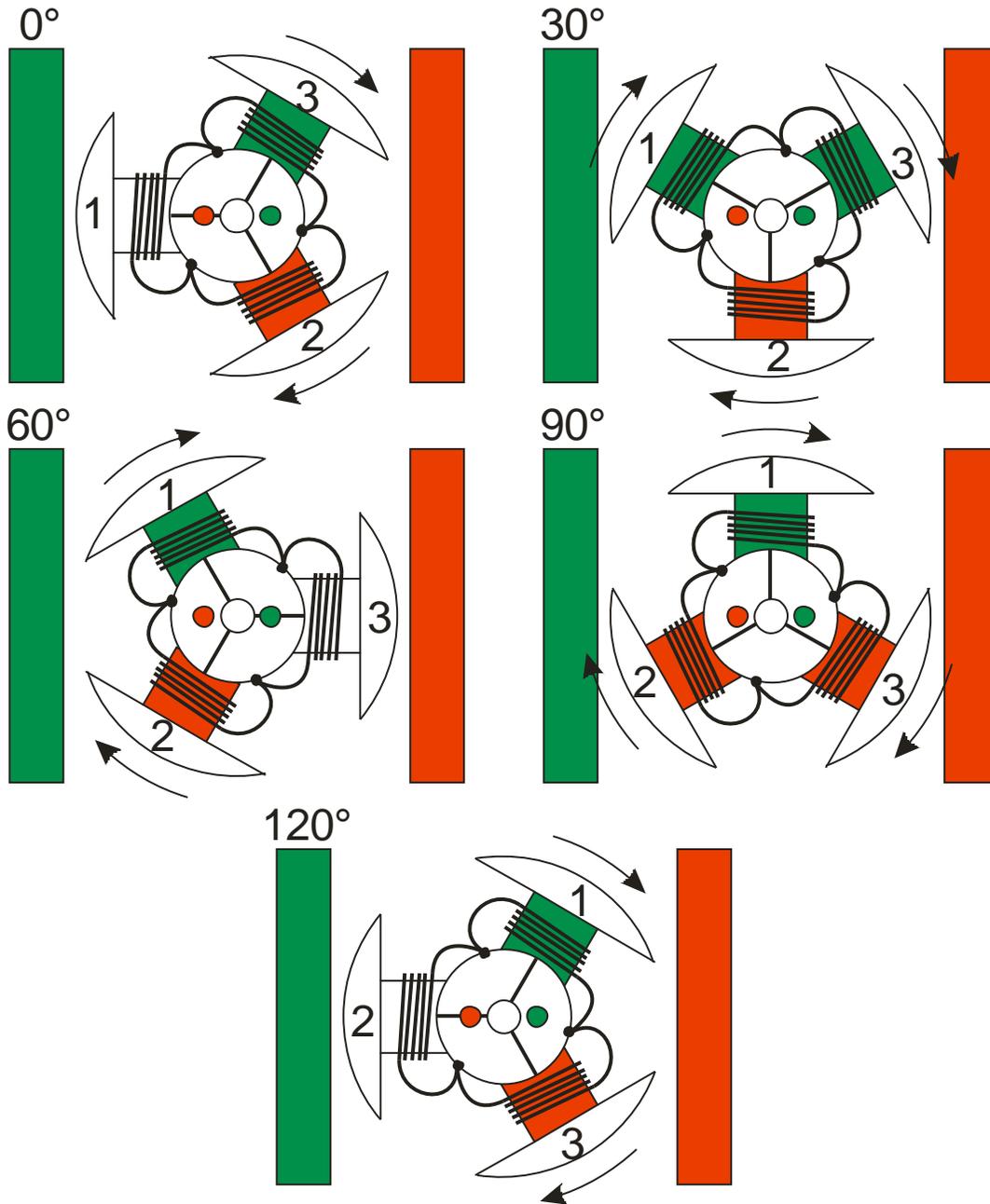


Figure 78: End-to-end Tie Off Rotor Rotation

(This page left intentionally blank)

Appendix C: GNU Free Documentation License

Version 1.3, 3 November 2008

Copyright © 2000, 2001, 2002, 2007, 2008 Free Software Foundation, Inc. <<http://fsf.org/>>

Everyone is permitted to copy and distribute verbatim copies of this license document, but changing it is not allowed.

0. PREAMBLE

The purpose of this License is to make a manual, textbook, or other functional and useful document "free" in the sense of freedom: to assure everyone the effective freedom to copy and redistribute it, with or without modifying it, either commercially or noncommercially. Secondly, this License preserves for the author and publisher a way to get credit for their work, while not being considered responsible for modifications made by others.

This License is a kind of "copyleft", which means that derivative works of the document must themselves be free in the same sense. It complements the GNU General Public License, which is a copyleft license designed for free software.

We have designed this License in order to use it for manuals for free software, because free software needs free documentation: a free program should come with manuals providing the same freedoms that the software does. But this License is not limited to software manuals; it can be used for any textual work, regardless of subject matter or whether it is published as a printed book. We recommend this License principally for works whose purpose is instruction or reference.

1. APPLICABILITY AND DEFINITIONS

This License applies to any manual or other work, in any medium, that contains a notice placed by the copyright holder saying it can be distributed under the terms of this License. Such a notice grants a world-wide, royalty-free license, unlimited in duration, to use that work under the conditions stated herein. The "Document", below, refers to any such manual or work. Any member of the public is a licensee, and is addressed as "you". You accept the license if you copy, modify or distribute the work in a way requiring permission under copyright law.

A "Modified Version" of the Document means any work containing the Document or a portion of it, either copied verbatim, or with modifications and/or translated into another language.

A "Secondary Section" is a named appendix or a front-matter section of the Document that deals exclusively with the relationship of the publishers or authors of the Document to the Document's overall subject (or to related matters) and contains nothing that could fall directly within that overall subject. (Thus, if the Document is in part a textbook of mathematics, a Secondary Section may not explain any mathematics.) The relationship could be a matter of historical connection with the subject or with related matters, or of legal, commercial, philosophical, ethical or political position regarding them.

The "Invariant Sections" are certain Secondary Sections whose titles are designated, as being those of Invariant Sections, in the notice that says that the Document is released under this License. If a section does not fit the above definition of Secondary then it is not allowed to be designated as Invariant. The Document may contain zero Invariant Sections. If the Document does not identify any Invariant Sections then there are none.

The "Cover Texts" are certain short passages of text that are listed, as Front-Cover Texts or Back-Cover Texts, in the notice that says that the Document is released under this License. A Front-Cover Text may be at most 5 words, and a Back-Cover Text may be at most 25 words.

A "Transparent" copy of the Document means a machine-readable copy, represented in a format whose specification is available to the general public, that is suitable for revising the document straightforwardly with generic text editors or (for images composed of pixels) generic paint programs or (for drawings) some widely available drawing editor, and that is suitable for input to text formatters or for automatic translation to a variety of formats suitable for input to text formatters. A copy made in an otherwise Transparent file format whose markup, or absence of markup, has been arranged to thwart or discourage subsequent

modification by readers is not Transparent. An image format is not Transparent if used for any substantial amount of text. A copy that is not "Transparent" is called "Opaque".

Examples of suitable formats for Transparent copies include plain ASCII without markup, Texinfo input format, LaTeX input format, SGML or XML using a publicly available DTD, and standard-conforming simple HTML, PostScript or PDF designed for human modification. Examples of transparent image formats include PNG, XCF and JPG. Opaque formats include proprietary formats that can be read and edited only by proprietary word processors, SGML or XML for which the DTD and/or processing tools are not generally available, and the machine-generated HTML, PostScript or PDF produced by some word processors for output purposes only.

The "Title Page" means, for a printed book, the title page itself, plus such following pages as are needed to hold, legibly, the material this License requires to appear in the title page. For works in formats which do not have any title page as such, "Title Page" means the text near the most prominent appearance of the work's title, preceding the beginning of the body of the text.

The "publisher" means any person or entity that distributes copies of the Document to the public.

A section "Entitled XYZ" means a named subunit of the Document whose title either is precisely XYZ or contains XYZ in parentheses following text that translates XYZ in another language. (Here XYZ stands for a specific section name mentioned below, such as "Acknowledgements", "Dedications", "Endorsements", or "History".) To "Preserve the Title" of such a section when you modify the Document means that it remains a section "Entitled XYZ" according to this definition.

The Document may include Warranty Disclaimers next to the notice which states that this License applies to the Document. These Warranty Disclaimers are considered to be included by reference in this License, but only as regards disclaiming warranties: any other implication that these Warranty Disclaimers may have is void and has no effect on the meaning of this License.

2. VERBATIM COPYING

You may copy and distribute the Document in any medium, either commercially or noncommercially, provided that this License, the copyright notices, and the license notice saying this License applies to the Document are reproduced in all copies, and that you add no other conditions whatsoever to those of this License. You may not use technical measures to obstruct or control the reading or further copying of the copies you make or distribute. However, you may accept compensation in exchange for copies. If you distribute a large enough number of copies you must also follow the conditions in section 3.

You may also lend copies, under the same conditions stated above, and you may publicly display copies.

3. COPYING IN QUANTITY

If you publish printed copies (or copies in media that commonly have printed covers) of the Document, numbering more than 100, and the Document's license notice requires Cover Texts, you must enclose the copies in covers that carry, clearly and legibly, all these Cover Texts: Front-Cover Texts on the front cover, and Back-Cover Texts on the back cover. Both covers must also clearly and legibly identify you as the publisher of these copies. The front cover must present the full title with all words of the title equally prominent and visible. You may add other material on the covers in addition. Copying with changes limited to the covers, as long as they preserve the title of the Document and satisfy these conditions, can be treated as verbatim copying in other respects.

If the required texts for either cover are too voluminous to fit legibly, you should put the first ones listed (as many as fit reasonably) on the actual cover, and continue the rest onto adjacent pages.

If you publish or distribute Opaque copies of the Document numbering more than 100, you must either include a machine-readable Transparent copy along with each Opaque copy, or state in or with each Opaque copy a computer-network location from which the general network-using public has access to download using public-standard network protocols a complete Transparent copy of the Document, free of added material. If you use the latter option, you must take reasonably prudent steps, when you begin distribution of Opaque copies in quantity, to ensure that this Transparent copy will remain thus accessible at the stated location until at least one year after the last time you distribute an Opaque copy (directly or through your agents or retailers) of that edition to the public.

It is requested, but not required, that you contact the authors of the Document well before redistributing any large number of copies, to give them a chance to provide you with an updated version of the Document.

4. MODIFICATIONS

You may copy and distribute a Modified Version of the Document under the conditions of sections 2 and 3 above, provided that you release the Modified Version under precisely this License, with the Modified Version filling the role of the Document, thus licensing distribution and modification of the Modified Version to whoever possesses a copy of it. In addition, you must do these things in the Modified Version:

- A. Use in the Title Page (and on the covers, if any) a title distinct from that of the Document, and from those of previous versions (which should, if there were any, be listed in the History section of the Document). You may use the same title as a previous version if the original publisher of that version gives permission.
- B. List on the Title Page, as authors, one or more persons or entities responsible for authorship of the modifications in the Modified Version, together with at least five of the principal authors of the Document (all of its principal authors, if it has fewer than five), unless they release you from this requirement.
- C. State on the Title page the name of the publisher of the Modified Version, as the publisher.
- D. Preserve all the copyright notices of the Document.
- E. Add an appropriate copyright notice for your modifications adjacent to the other copyright notices.
- F. Include, immediately after the copyright notices, a license notice giving the public permission to use the Modified Version under the terms of this License, in the form shown in the Addendum below.
- G. Preserve in that license notice the full lists of Invariant Sections and required Cover Texts given in the Document's license notice.
- H. Include an unaltered copy of this License.
- I. Preserve the section Entitled "History", Preserve its Title, and add to it an item stating at least the title, year, new authors, and publisher of the Modified Version as given on the Title Page. If there is no section Entitled "History" in the Document, create one stating the title, year, authors, and publisher of the Document as given on its Title Page, then add an item describing the Modified Version as stated in the previous sentence.
- J. Preserve the network location, if any, given in the Document for public access to a Transparent copy of the Document, and likewise the network locations given in the Document for previous versions it was based on. These may be placed in the "History" section. You may omit a network location for a work that was published at least four years before the Document itself, or if the original publisher of the version it refers to gives permission.
- K. For any section Entitled "Acknowledgements" or "Dedications", Preserve the Title of the section, and preserve in the section all the substance and tone of each of the contributor acknowledgements and/or dedications given therein.
- L. Preserve all the Invariant Sections of the Document, unaltered in their text and in their titles. Section numbers or the equivalent are not considered part of the section titles.
- M. Delete any section Entitled "Endorsements". Such a section may not be included in the Modified Version.
- N. Do not retitle any existing section to be Entitled "Endorsements" or to conflict in title with any Invariant Section.
- O. Preserve any Warranty Disclaimers.

If the Modified Version includes new front-matter sections or appendices that qualify as Secondary Sections and contain no material copied from the Document, you may at your option designate some or all of these sections as invariant. To do this, add their titles to the list of Invariant Sections in the Modified Version's license notice. These titles must be distinct from any other section titles.

You may add a section Entitled "Endorsements", provided it contains nothing but endorsements of your Modified Version by various parties—for example, statements of peer review or that the text has been approved by an organization as the authoritative definition of a standard.

You may add a passage of up to five words as a Front-Cover Text, and a passage of up to 25 words as a Back-Cover Text, to the end of the list of Cover Texts in the Modified Version. Only one passage of Front-Cover Text and one of Back-Cover Text may be added by (or through arrangements made by) any one entity. If the Document already includes a cover text for the same cover, previously added by you or by arrangement made by the same entity you are acting on behalf of, you may not add another; but you may replace the old one, on explicit permission from the previous publisher that added the old one.

The author(s) and publisher(s) of the Document do not by this License give permission to use their names for publicity for or to assert or imply endorsement of any Modified Version.

5. COMBINING DOCUMENTS

You may combine the Document with other documents released under this License, under the terms defined in section 4 above for modified versions, provided that you include in the combination all of the Invariant Sections of all of the original documents, unmodified, and list them all as Invariant Sections of your combined work in its license notice, and that you preserve all their Warranty Disclaimers.

The combined work need only contain one copy of this License, and multiple identical Invariant Sections may be replaced with a single copy. If there are multiple Invariant Sections with the same name but different contents, make the title of each such section unique by adding at the end of it, in parentheses, the name of the original author or publisher of that section if known, or else a unique number. Make the same adjustment to the section titles in the list of Invariant Sections in the license notice of the combined work.

In the combination, you must combine any sections Entitled "History" in the various original documents, forming one section Entitled "History"; likewise combine any sections Entitled "Acknowledgements", and any sections Entitled "Dedications". You must delete all sections Entitled "Endorsements".

6. COLLECTIONS OF DOCUMENTS

You may make a collection consisting of the Document and other documents released under this License, and replace the individual copies of this License in the various documents with a single copy that is included in the collection, provided that you follow the rules of this License for verbatim copying of each of the documents in all other respects.

You may extract a single document from such a collection, and distribute it individually under this License, provided you insert a copy of this License into the extracted document, and follow this License in all other respects regarding verbatim copying of that document.

7. AGGREGATION WITH INDEPENDENT WORKS

A compilation of the Document or its derivatives with other separate and independent documents or works, in or on a volume of a storage or distribution medium, is called an "aggregate" if the copyright resulting from the compilation is not used to limit the legal rights of the compilation's users beyond what the individual works permit. When the Document is included in an aggregate, this License does not apply to the other works in the aggregate which are not themselves derivative works of the Document.

If the Cover Text requirement of section 3 is applicable to these copies of the Document, then if the Document is less than one half of the entire aggregate, the Document's Cover Texts may be placed on covers that bracket the Document within the aggregate, or the electronic equivalent of covers if the Document is in electronic form. Otherwise they must appear on printed covers that bracket the whole aggregate.

8. TRANSLATION

Translation is considered a kind of modification, so you may distribute translations of the Document under the terms of section 4. Replacing Invariant Sections with translations requires special permission from their copyright holders, but you may include translations of some or all Invariant Sections in addition to the original versions of these Invariant Sections. You may include a translation of this License, and all the license notices in the Document, and any Warranty Disclaimers, provided that you also include the original English version of this License and the original versions of those notices and disclaimers. In case of a disagreement between the translation and the original version of this License or a notice or disclaimer, the original version will prevail.

If a section in the Document is Entitled "Acknowledgements", "Dedications", or "History", the requirement (section 4) to Preserve its Title (section 1) will typically require changing the actual title.

9. TERMINATION

You may not copy, modify, sublicense, or distribute the Document except as expressly provided under this License. Any attempt otherwise to copy, modify, sublicense, or distribute it is void, and will automatically terminate your rights under this License.

However, if you cease all violation of this License, then your license from a particular copyright holder is reinstated (a) provisionally, unless and until the copyright holder explicitly and finally terminates your license, and (b) permanently, if the copyright holder fails to notify you of the violation by some reasonable means prior to 60 days after the cessation.

Moreover, your license from a particular copyright holder is reinstated permanently if the copyright holder notifies you of the violation by some reasonable means, this is the first time you have received notice of violation of this License (for any work) from that copyright holder, and you cure the violation prior to 30 days after your receipt of the notice.

Termination of your rights under this section does not terminate the licenses of parties who have received copies or rights from you under this License. If your rights have been terminated and not permanently reinstated, receipt of a copy of some or all of the same material does not give you any rights to use it.

10. FUTURE REVISIONS OF THIS LICENSE

The Free Software Foundation may publish new, revised versions of the GNU Free Documentation License from time to time. Such new versions will be similar in spirit to the present version, but may differ in detail to address new problems or concerns. See <http://www.gnu.org/copyleft/>.

Each version of the License is given a distinguishing version number. If the Document specifies that a particular numbered version of this License "or any later version" applies to it, you have the option of following the terms and conditions either of that specified version or of any later version that has been published (not as a draft) by the Free Software Foundation. If the Document does not specify a version number of this License, you may choose any version ever published (not as a draft) by the Free Software Foundation. If the Document specifies that a proxy can decide which future versions of this License can be used, that proxy's public statement of acceptance of a version permanently authorizes you to choose that version for the Document.

11. RELICENSING

"Massive Multiauthor Collaboration Site" (or "MMC Site") means any World Wide Web server that publishes copyrightable works and also provides prominent facilities for anybody to edit those works. A public wiki that anybody can edit is an example of such a server. A "Massive Multiauthor Collaboration" (or "MMC") contained in the site means any set of copyrightable works thus published on the MMC site.

"CC-BY-SA" means the Creative Commons Attribution-Share Alike 3.0 license published by Creative Commons Corporation, a not-for-profit corporation with a principal place of business in San Francisco, California, as well as future copyleft versions of that license published by that same organization.

"Incorporate" means to publish or republish a Document, in whole or in part, as part of another Document.

An MMC is "eligible for relicensing" if it is licensed under this License, and if all works that were first published under this License somewhere other than this MMC, and subsequently incorporated in whole or in part into the MMC, (1) had no cover texts or invariant sections, and (2) were thus incorporated prior to November 1, 2008.

The operator of an MMC Site may republish an MMC contained in the site under CC-BY-SA on the same site at any time before August 1, 2009, provided the MMC is eligible for relicensing.