

Speed and Directional Control of American Flyer Trains

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Version 2.0 of September 2012



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History

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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.

E-unit: An E-unit is a device, either electro-mechanic as with the original American Flyer e-units, or completely solid state with modern ones, used to control the direction of the engine.

1.2 System Description

With the exception of battery powered trains, the powering of an electric train motor can be broken up 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,

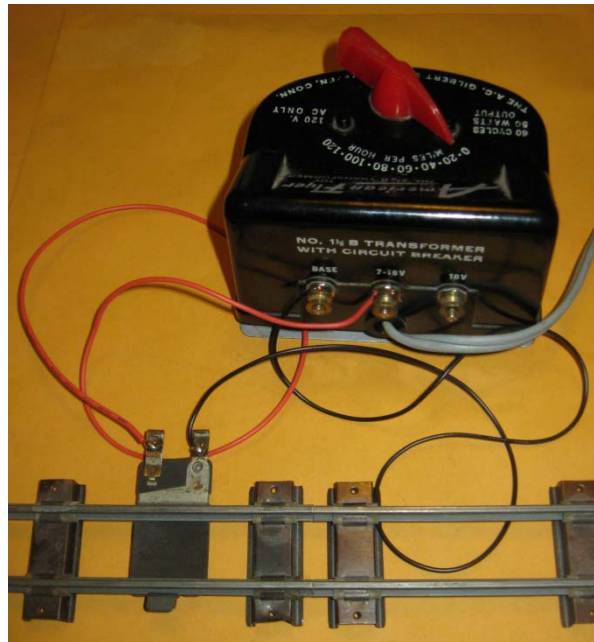


Figure 1: AC Transformer directly powering the track

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. As shown in Figure 3, these DC power sources typically also provide two posts for supplying a constant AC voltage to accessories.



Figure 2: DC Power Source connected directly to the track

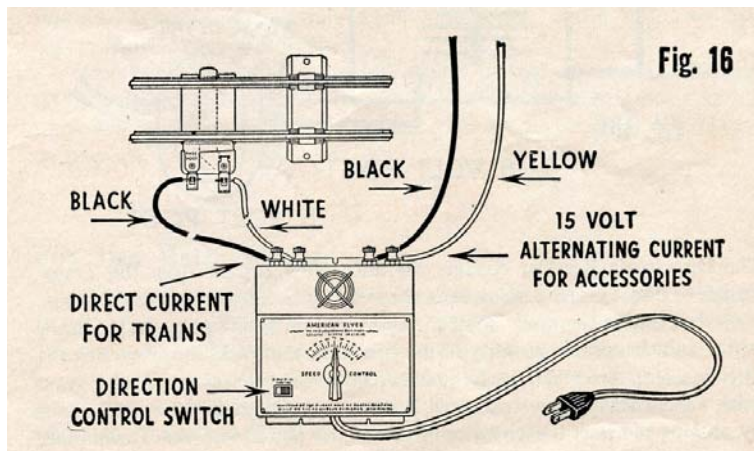


Figure 3: Hookup instructions for No 14 Electronic Rectifier²

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

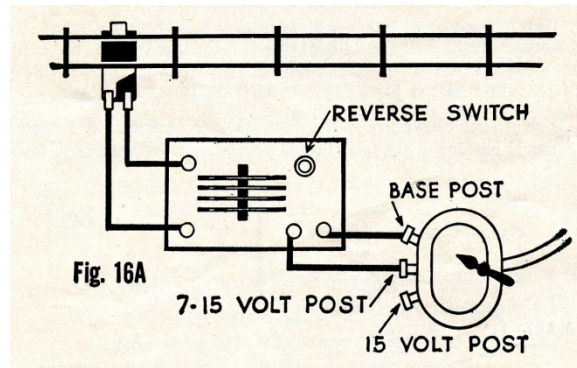


Figure 5: Hookup instructions for No 15 Directronic Rectifier³

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.

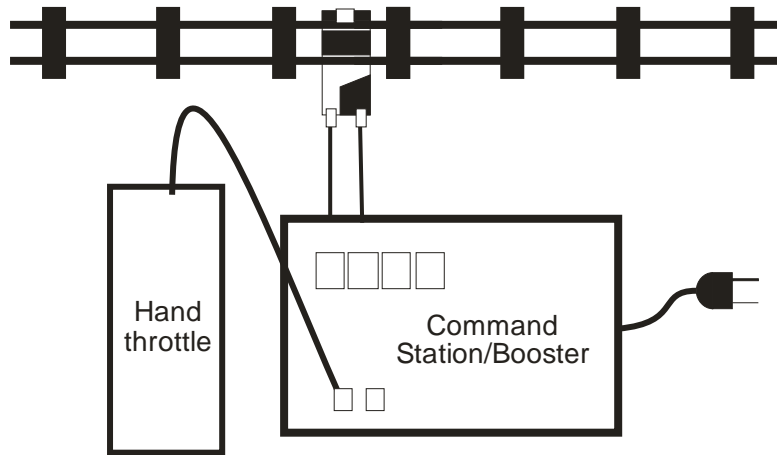


Figure 6: Simple Digital Command Control (DCC) system

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.

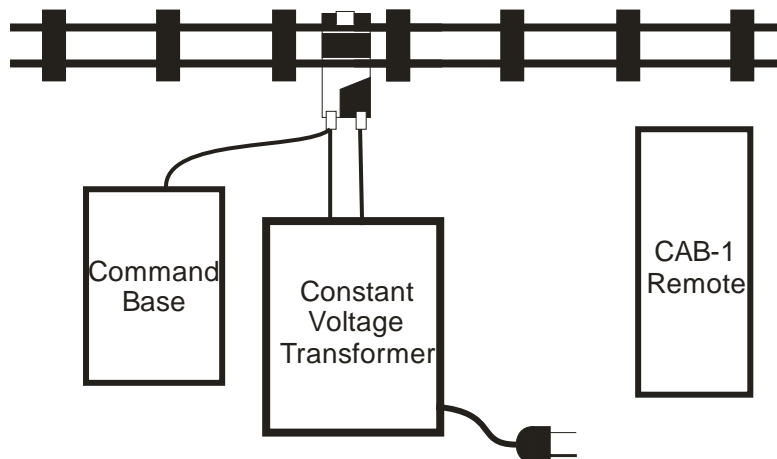


Figure 7: Simple Trainmaster Command Control (TMCC) wiring

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 E-Unit or electronic E-unit.

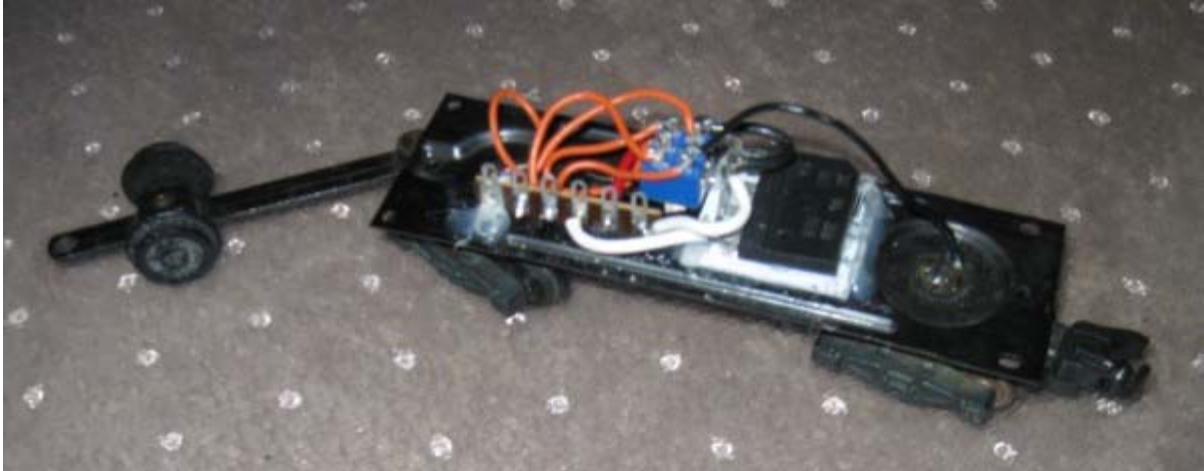


Figure 8: Rectifier and Reverse Switch in a tender

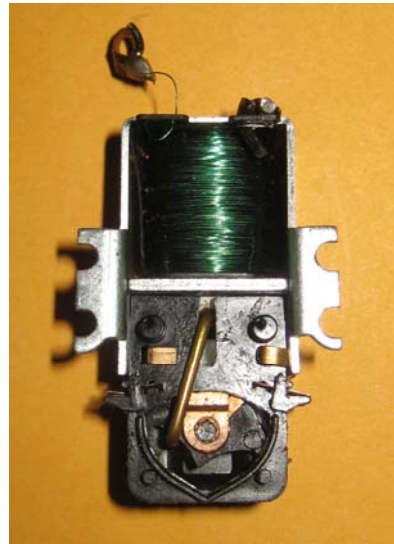
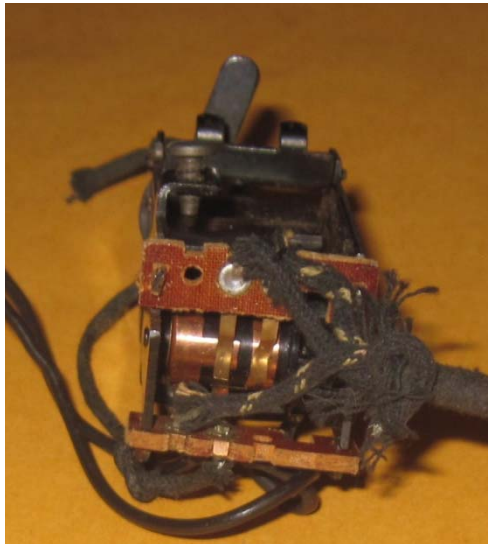


Figure 9: 4 position and 2 position Electromechanical E-Units



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 3 (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 E-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 E-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.

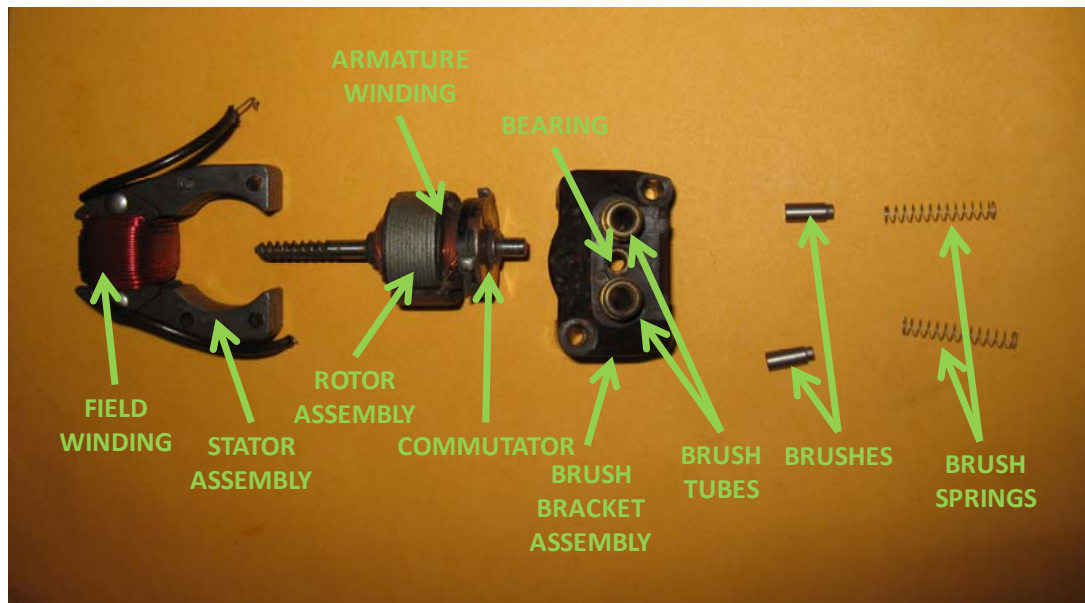


Figure 11: Parts of an A.C. Gilbert universal series wound motor for a steam engine.

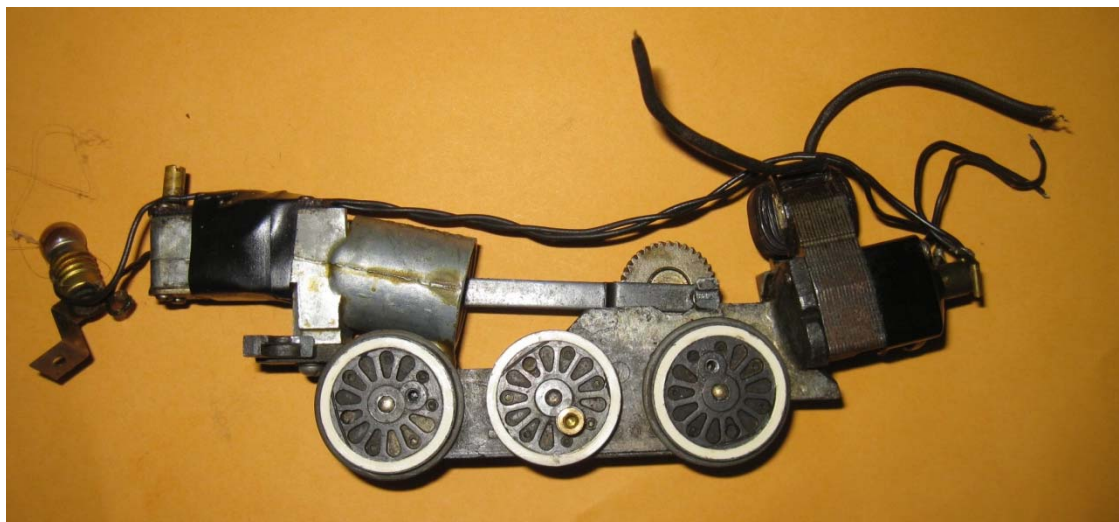


Figure 12: Open frame motor mounted on train engine chassis

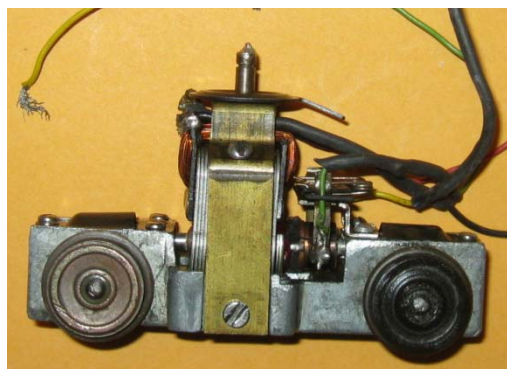


Figure 13: Open Frame motor for diesel engine

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 properly 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.



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

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3. Track Power

The waveforms shown below were measured for an American Flyer Atlantic engine with headlight, smoke unit, and a 4 position E-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.

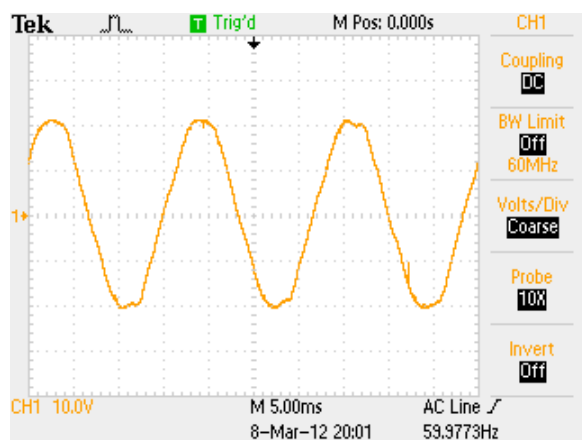


Figure 16: Track Voltage Waveform: AC transformer

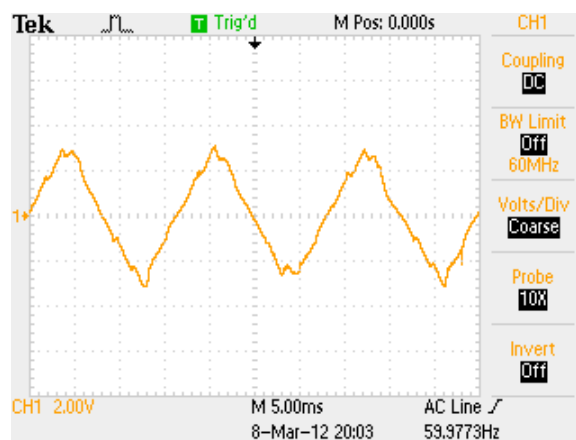


Figure 17: Transformer Current Waveform: AC transformer

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	5
60	5
75	8
100	8
125	10
150	12

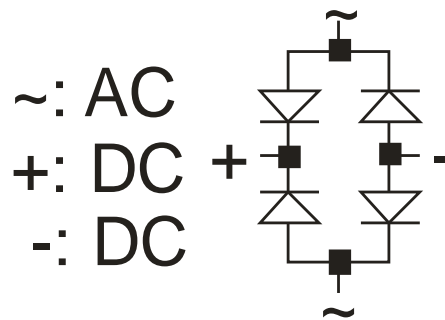


Figure 18: Full Wave Bridge Rectifier Schematic

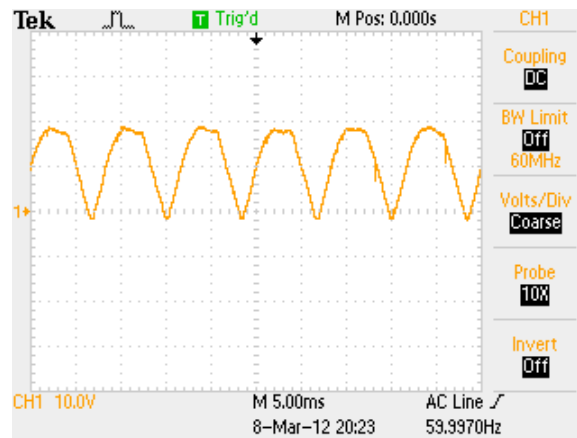


Figure 19: Track Voltage Waveform: Full Wave Bridge Rectified

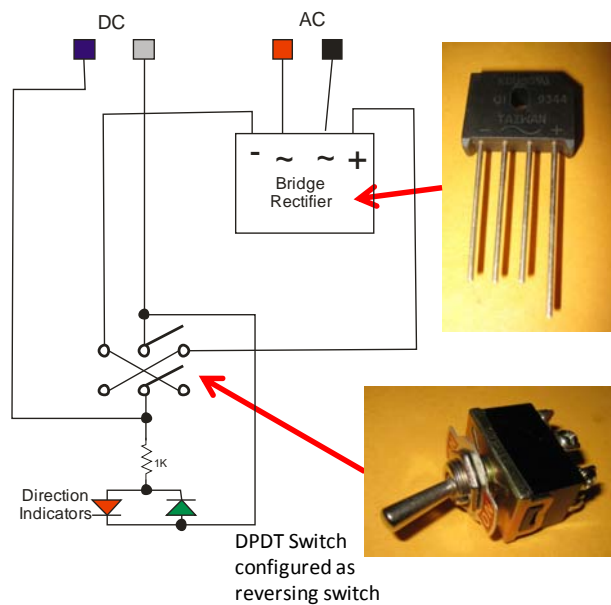


Figure 20: Circuit Diagram for Full Wave Bridge Rectifier

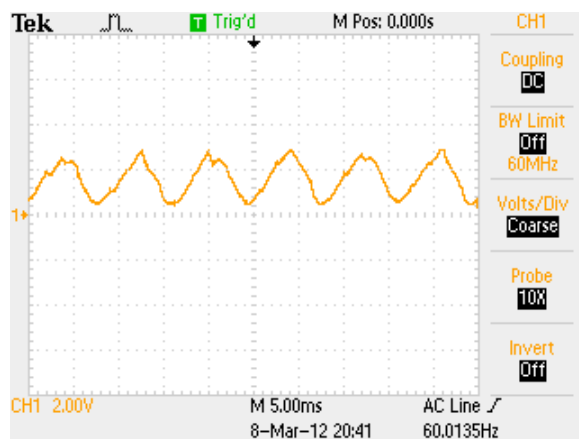


Figure 21: Track Current: Full Wave Bridge Rectifier

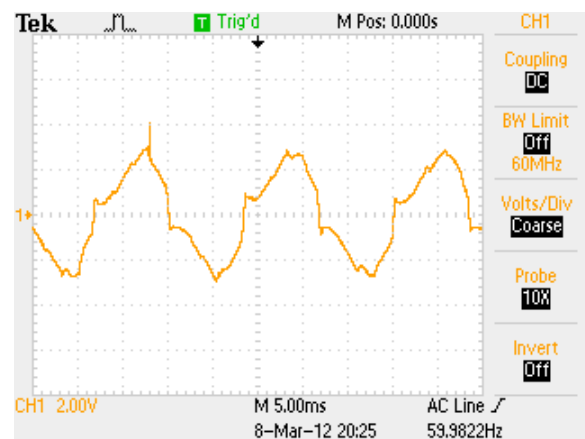


Figure 22: Transformer Current: Full Wave Bridge Rectifier

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.

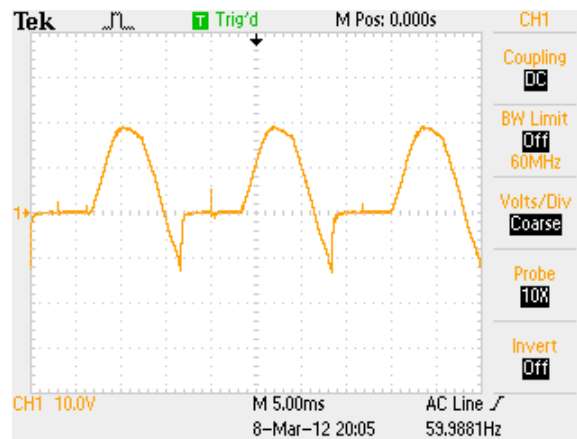


Figure 23: Track Voltage: Half Wave Rectifier

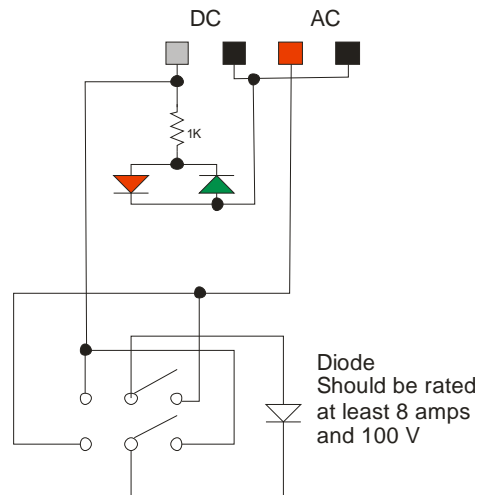


Figure 24: Circuit Diagram for Half Wave Rectifier

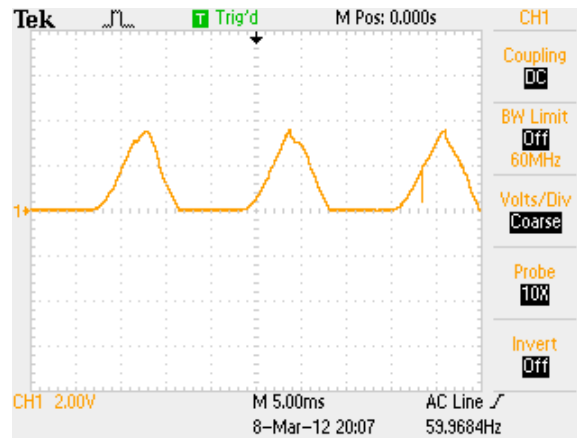


Figure 25: Track & Transformer Current: Half Wave Rectifier

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.

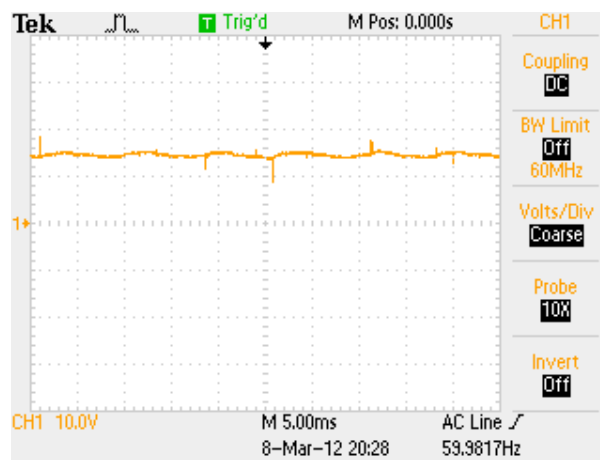


Figure 26: Track Voltage: Filtered DC

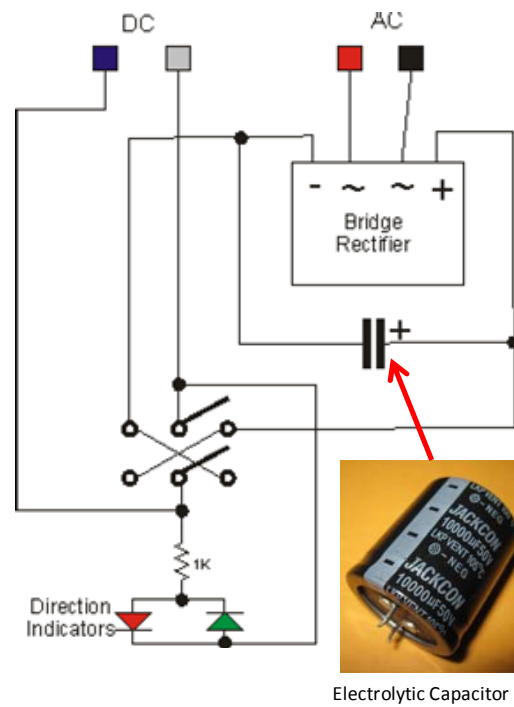


Figure 27: Circuit Diagram for Bridge Rectifier with Filter

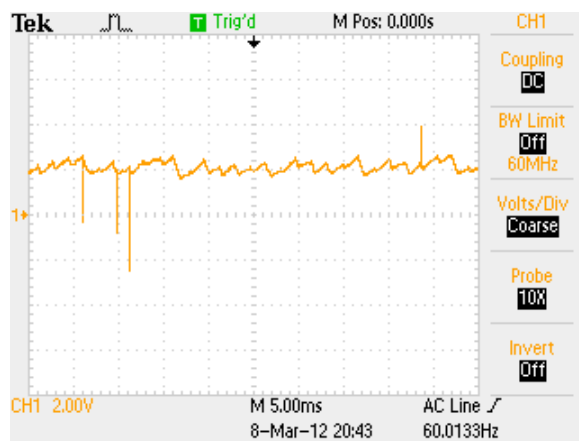


Figure 28: Track Current: Filtered DC

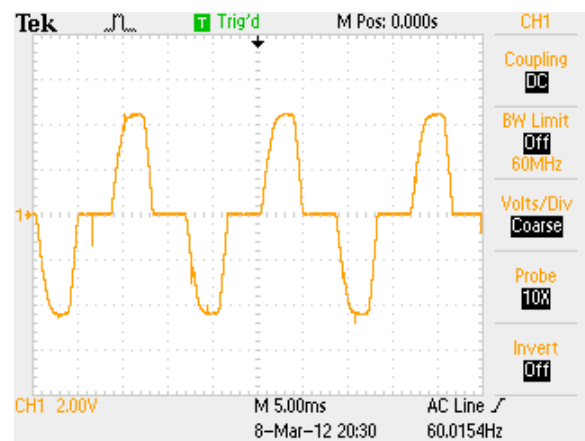


Figure 29: Transformer Current: Filtered DC

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 DC characteristic due to after the transistor turning off, motor inductor current continuing 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

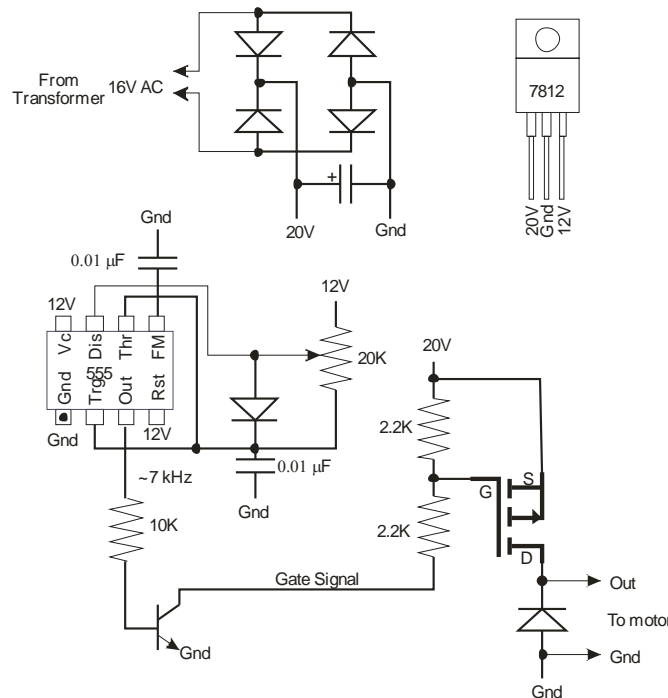
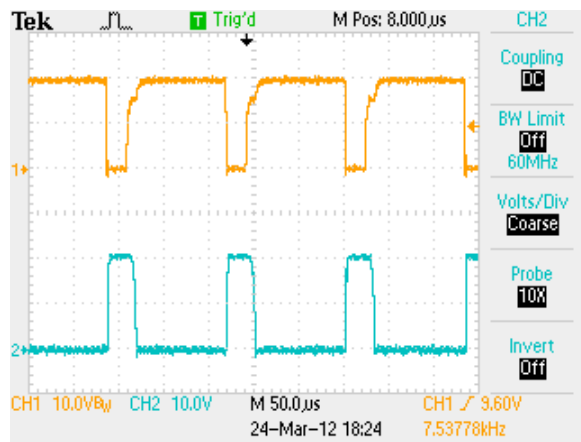
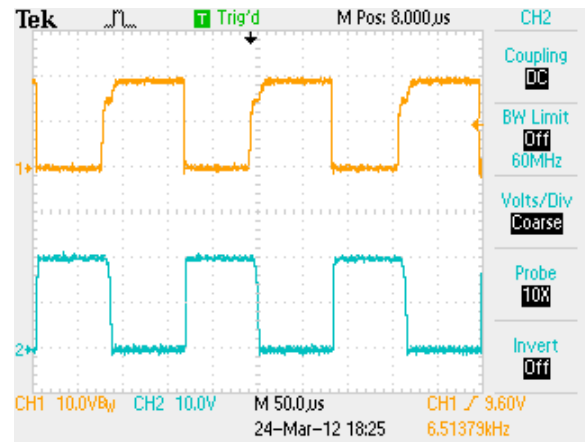


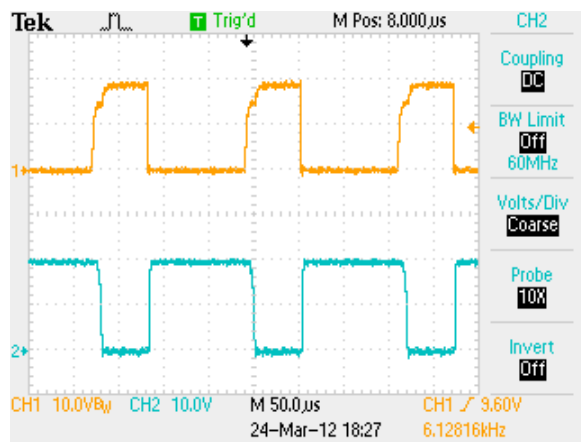
Figure 30: PWM Test Circuit



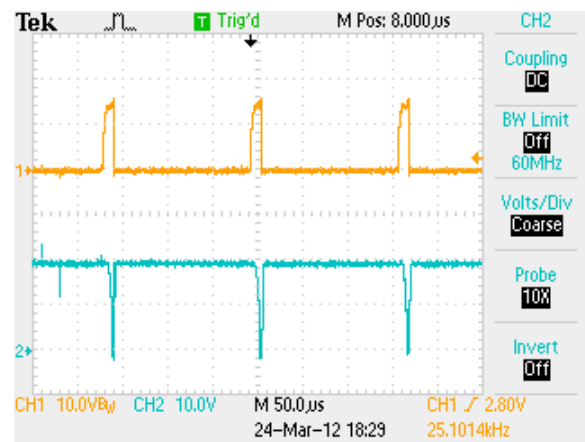
(a)



(b)

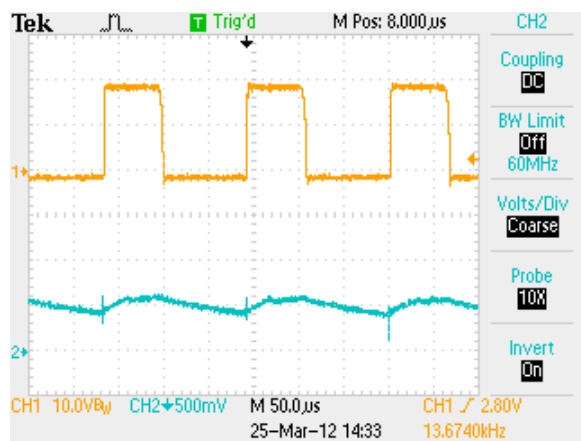


(c)

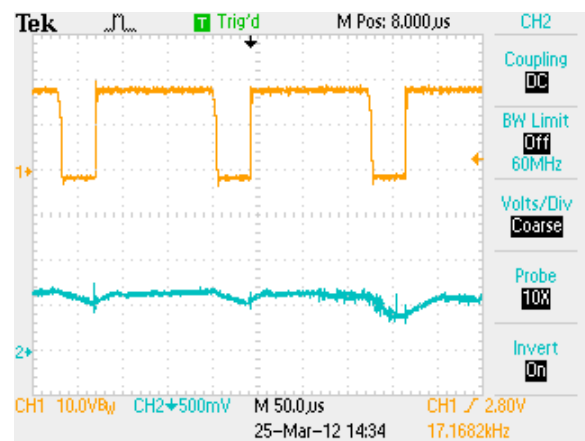


(d)

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

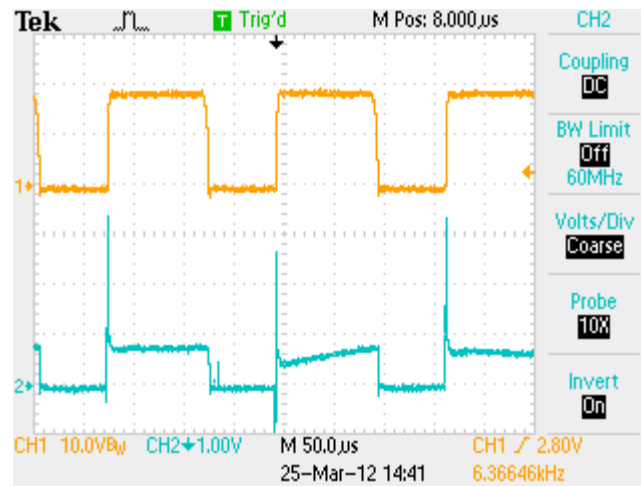


Figure 33: PWM Track Voltage and Rectifier Output Current

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.

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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 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.

4.2 Manual switch on engine

If remote control of the trains direction is not required, a DPDT switch (either toggle or slide) mounted on the engine can be used to determine the engines 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 field coil. One of the output connections of the reversing switch circuit is connected to the field coil. Track power is applied to the other reversing switch circuit output connection and the other brush.

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

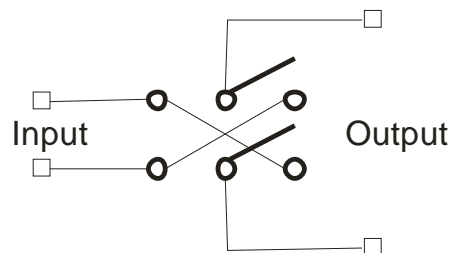


Figure 34: Reversing Switch Circuit

4.3 Time Sequence (American Flyer E-Units)

The original American Flyer E-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.

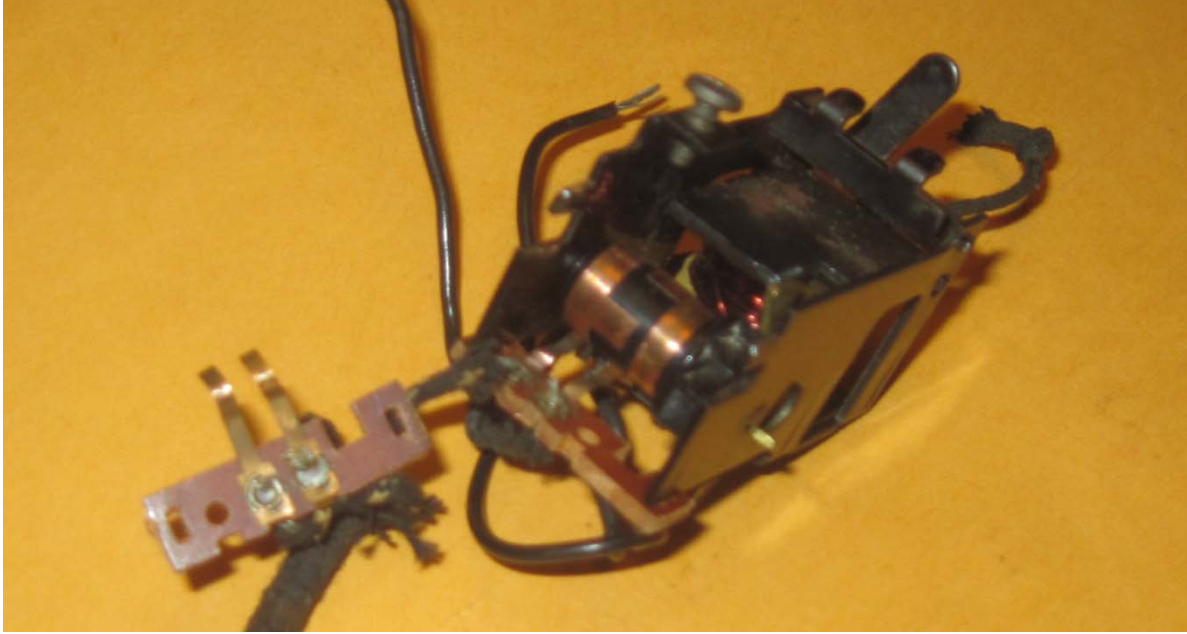


Figure 35: 4 position E-Unit with one set of fingers removed to reveal drum below.

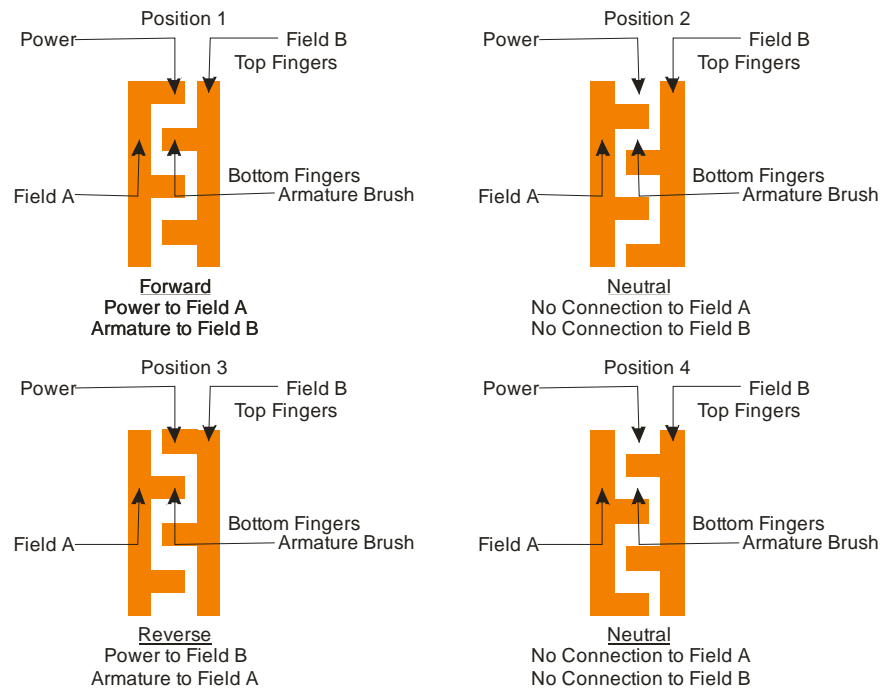


Figure 36: Gilbert American Flyer 4 position E unit operation

A DC motor can also use the Gilbert E-Units. The only difference is that the E-unit is wired as shown in Figure 37.

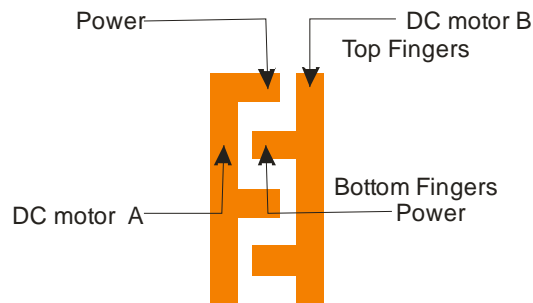


Figure 37: Connecting an E-Unit to a DC motor

The later 2 position E-Unit (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 which connect to the field coil. The drum pivot points are also used for electrical connection to power and to the armature brush.

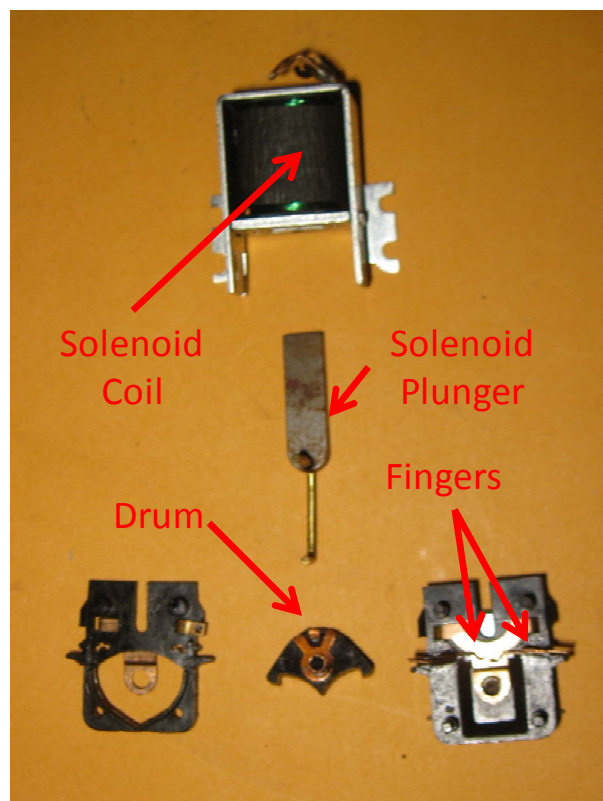


Figure 38: Gilbert American Flyer 2 position E-Unit Disassembled

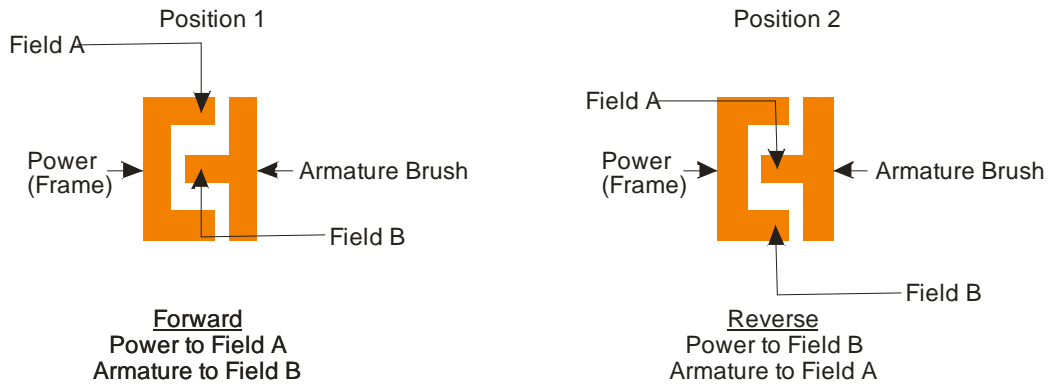


Figure 39: Gilbert American Flyer 2 position E-Unit operation

An engine with a Gilbert E-Unit can be stopped without cycling the E-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 E-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 E-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 E-Unit emulates the operation of the 4 position A.C. Gilbert E-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.

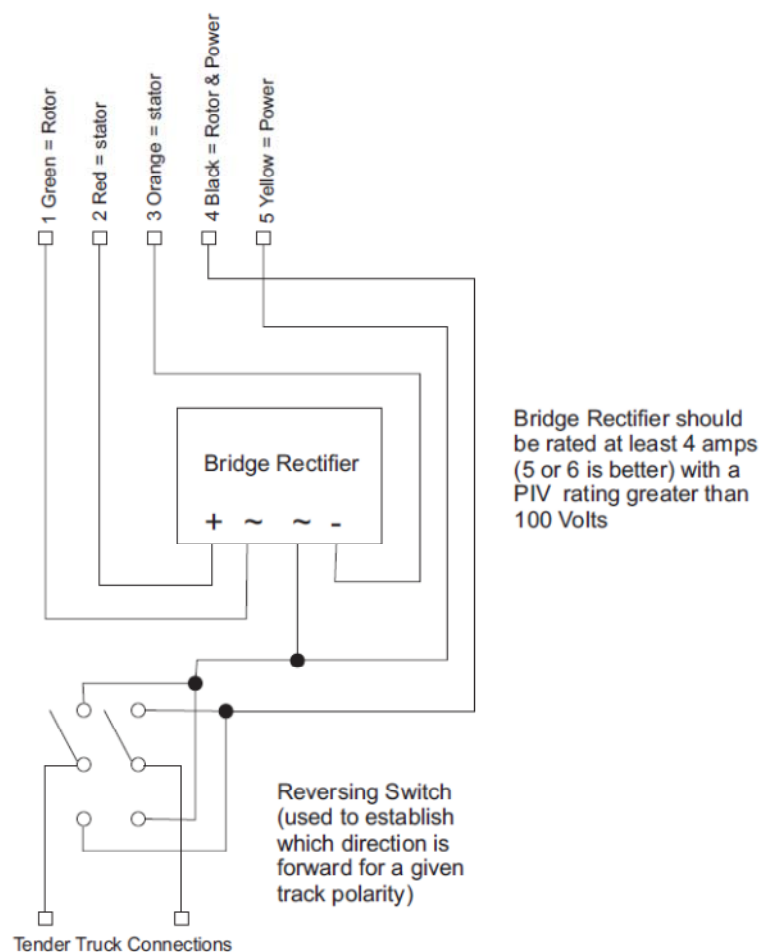


Figure 41: DC directional control with a universal motor

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.

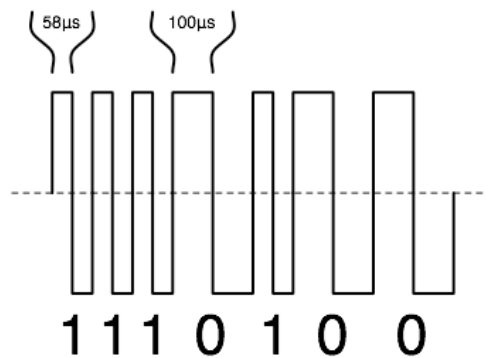


Figure 42: Voltage waveform for Digital Command Control (DCC)⁴

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

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) trains 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.

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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.

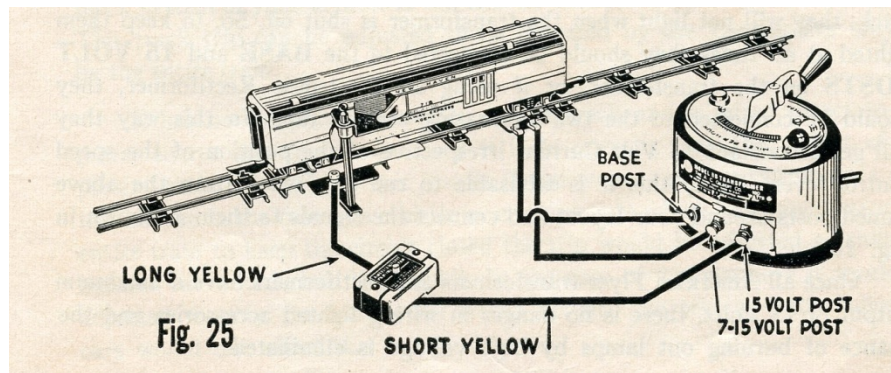


Figure 45: Wiring for an Action Car with an AC transformer⁵

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.

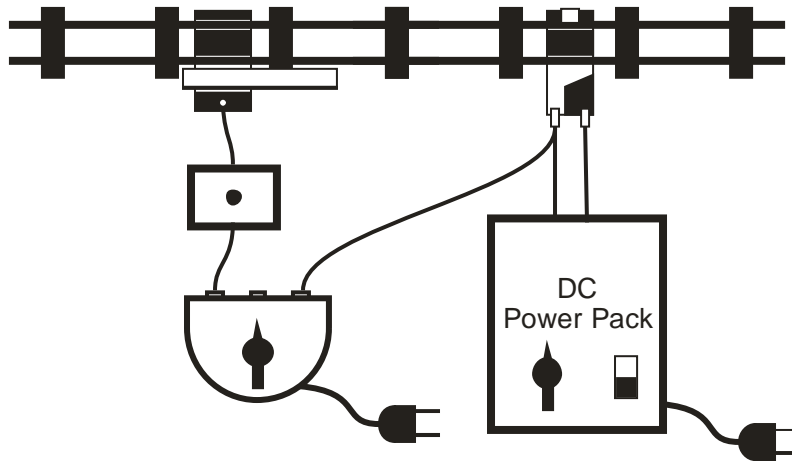


Figure 46: Use of Second Transformer for Action Cars

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.

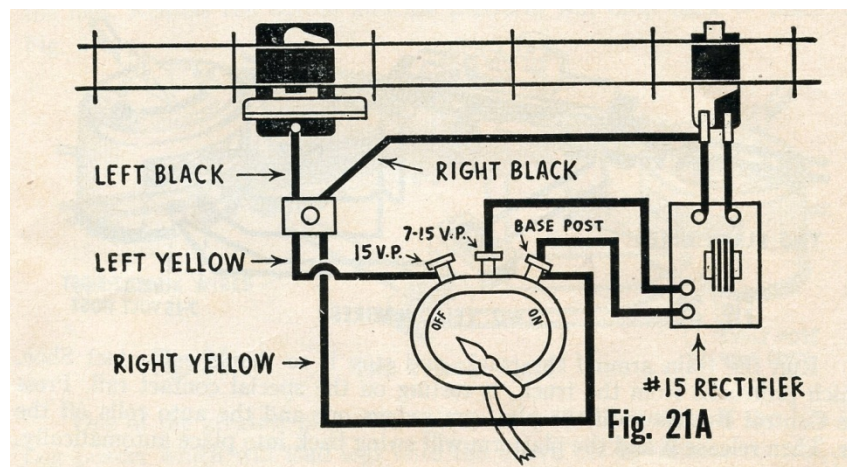


Figure 47: Double Pole Single Throw pushbutton for controlling Action Cars with DC⁶

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.

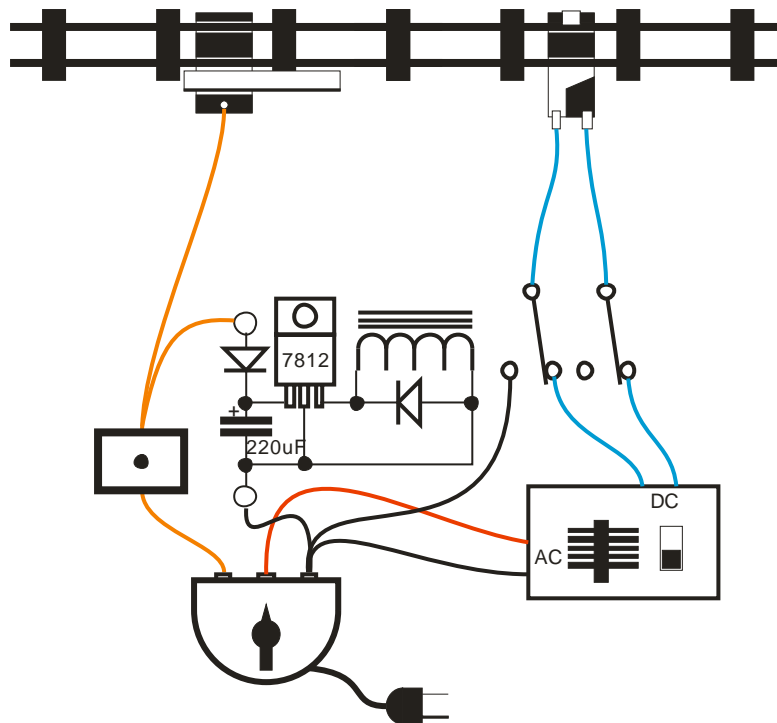


Figure 48: Isolation Relay

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.

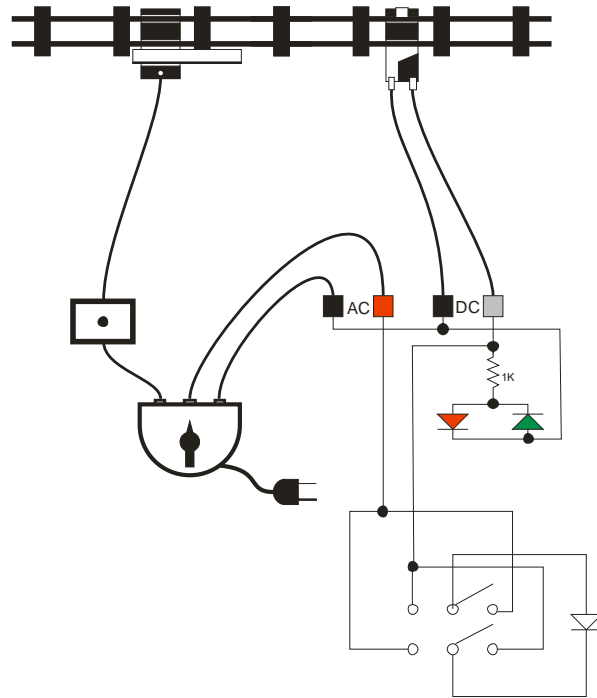


Figure 49: Half Wave Rectifier with special rail section

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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.

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.

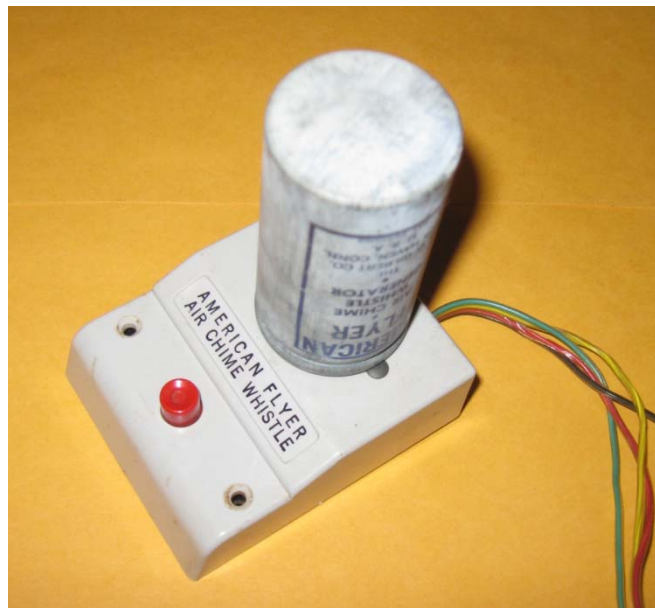


Figure 50: American Flyer Air Chime Whistle

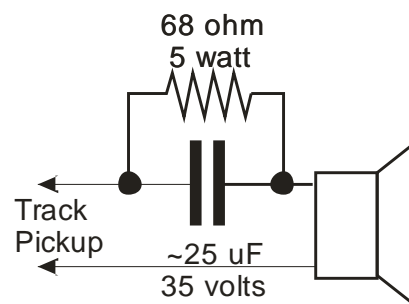


Figure 51: Engine / Tender Air Chime Whistle circuit

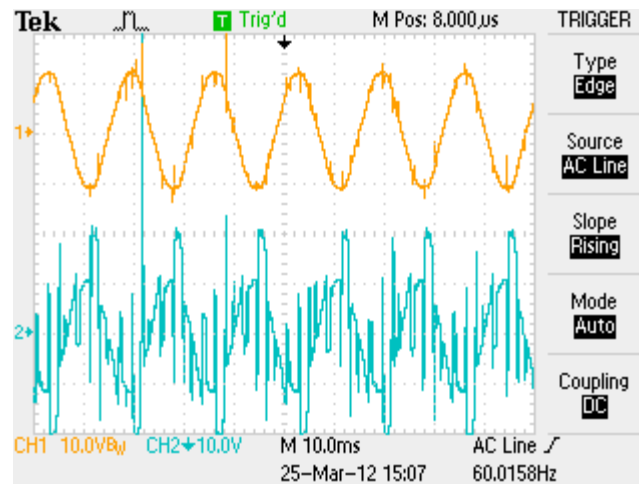


Figure 52: Transformer Voltage (top) and Track Voltage (bottom) with Air Chime Whistle Generator on.

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

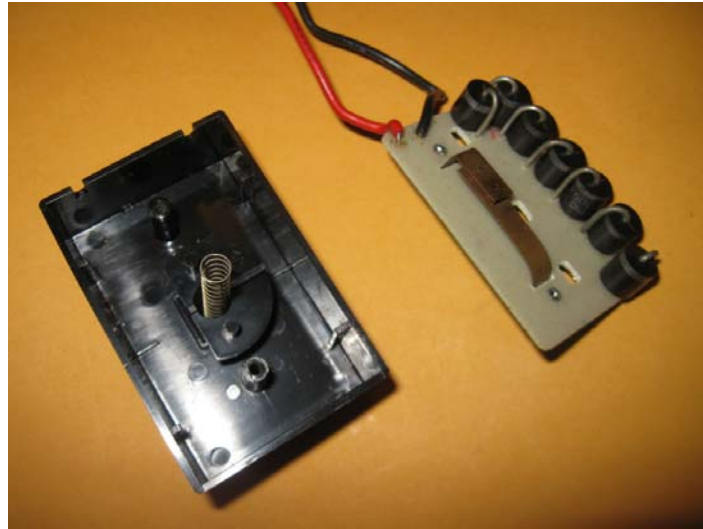


Figure 54: Lionel 6-5906 Sound Activation Button internals

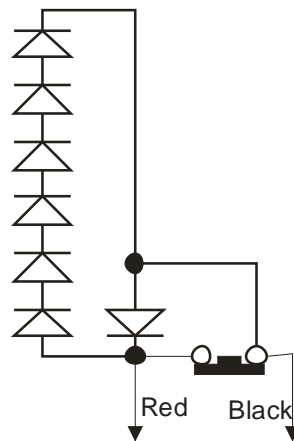


Figure 55: Schematic of Sound Activation Button

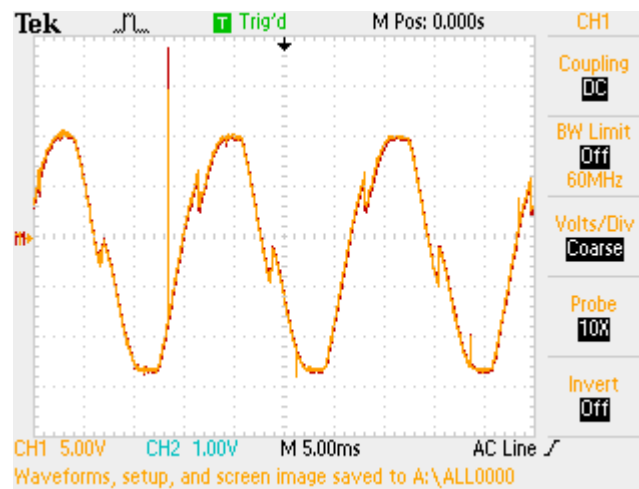


Figure 56: Track Voltage when powering an unloaded universal motor and with Sound Activation Button pressed

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

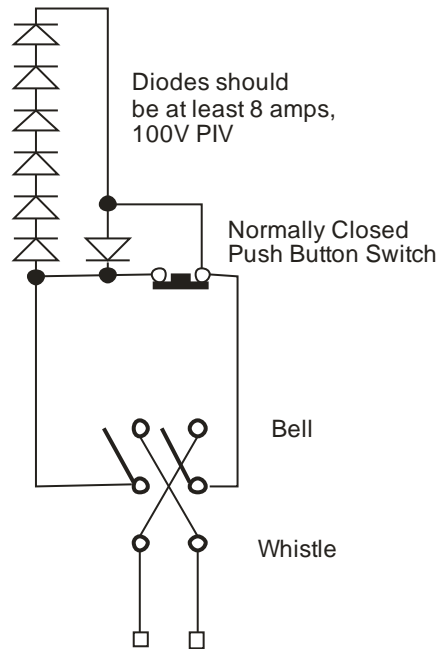


Figure 57: Use of reversing circuit to control both a bell and whistle with same push-button

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

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.

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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.

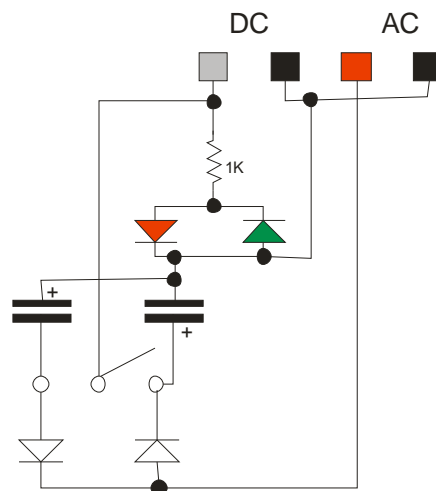


Figure 58: Filtered Half Wave Rectifier

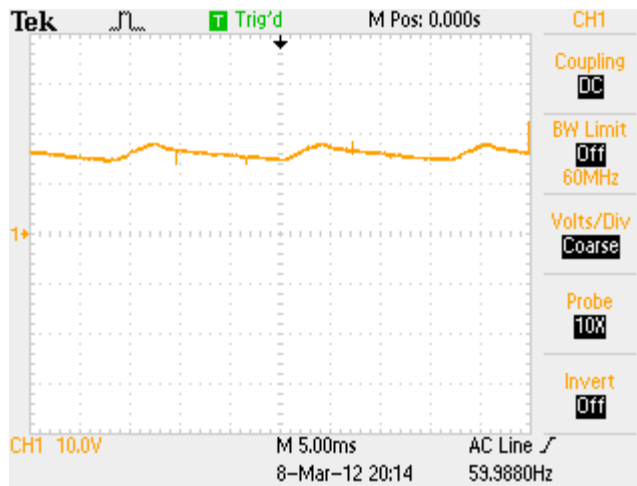


Figure 59: Track Voltage: Filtered Half Wave Rectification

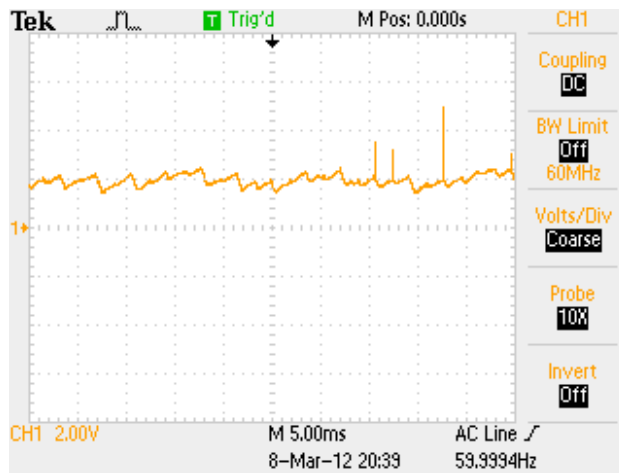


Figure 60: Track Current: Filtered Half Wave Rectification

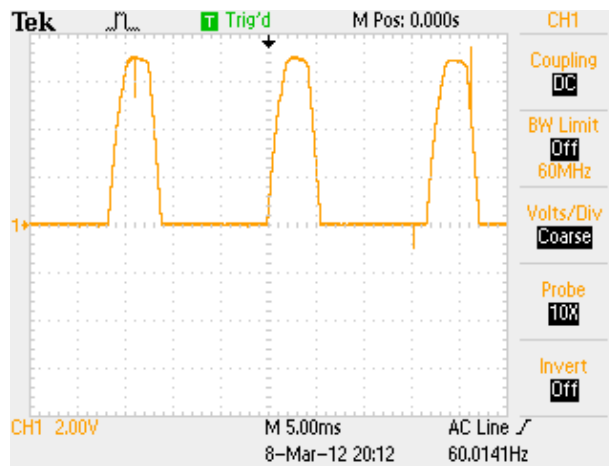
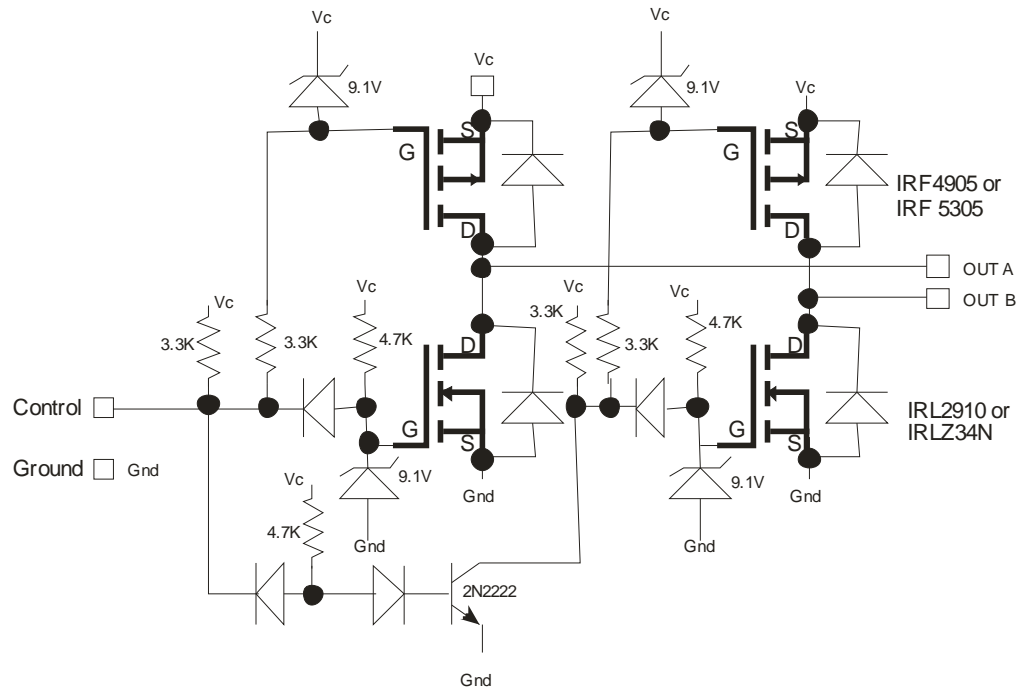


Figure 61: Transformer Current: Filtered Half Wave Rectification

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

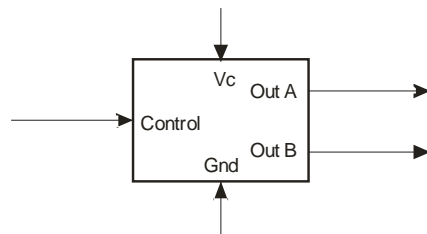


Figure 63: Functional representation of polarity reversing circuit

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 circuit 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.

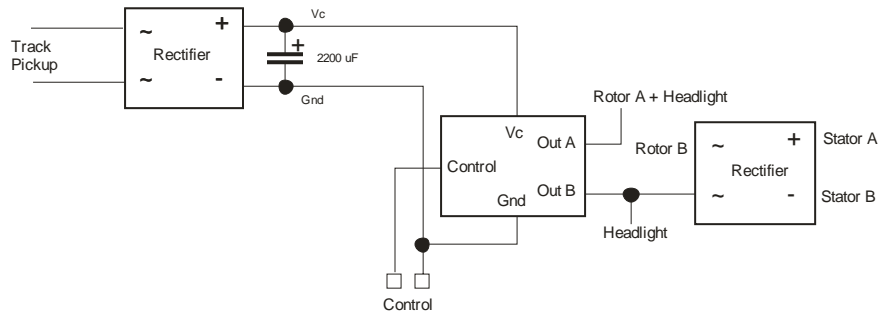


Figure 64: Reversing a Universal Motor with power FETs

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.

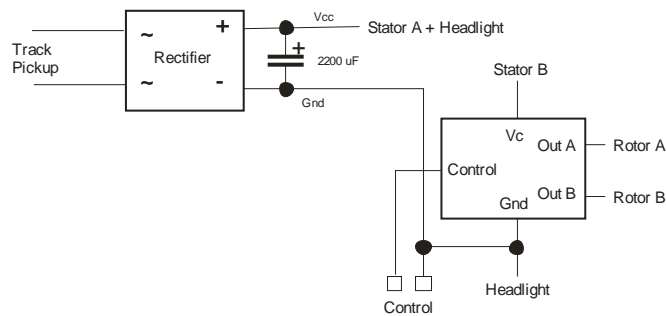


Figure 65: Alternate FET circuit for reversing a Universal Motor

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.

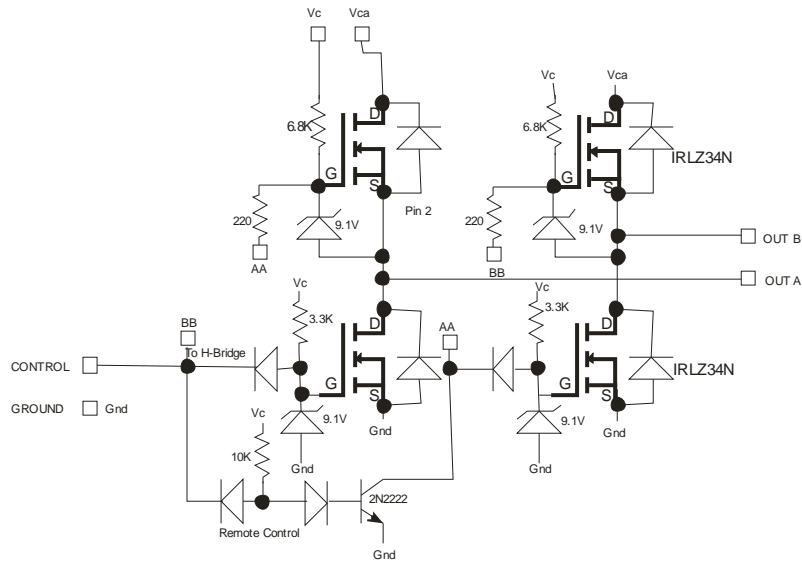


Figure 66: All N-FET circuit to reverse polarity

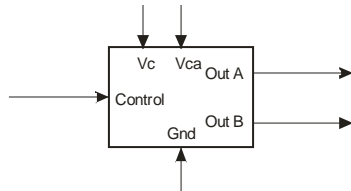


Figure 67: Functional Representation of N-FET circuit

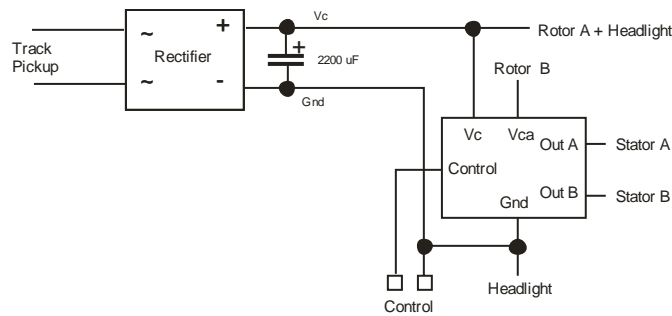


Figure 68: Circuit for reversing a Universal Motor using N-FETs

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.

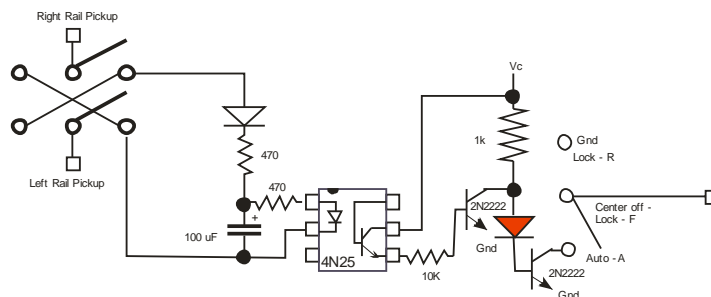


Figure 69: AC-DC Reversing Control Circuit

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.

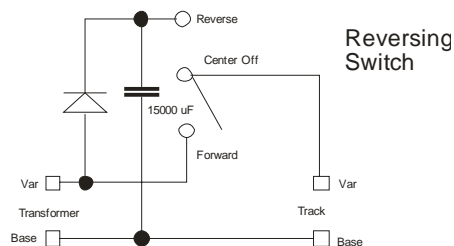


Figure 70: AC-DC Reversing Switch Controller

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.

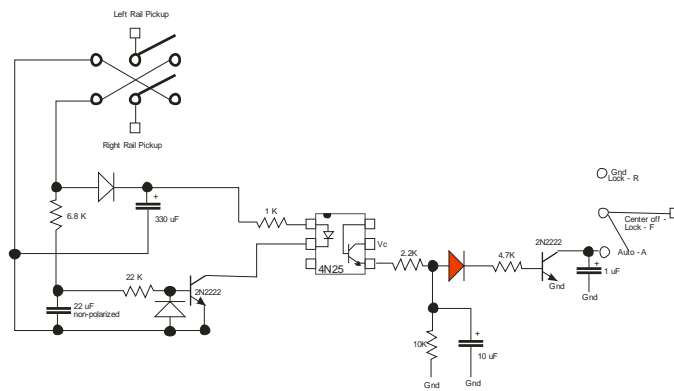


Figure 71: AC-DC Reversing Control Circuit for use with Railsounds controller

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 72, 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.

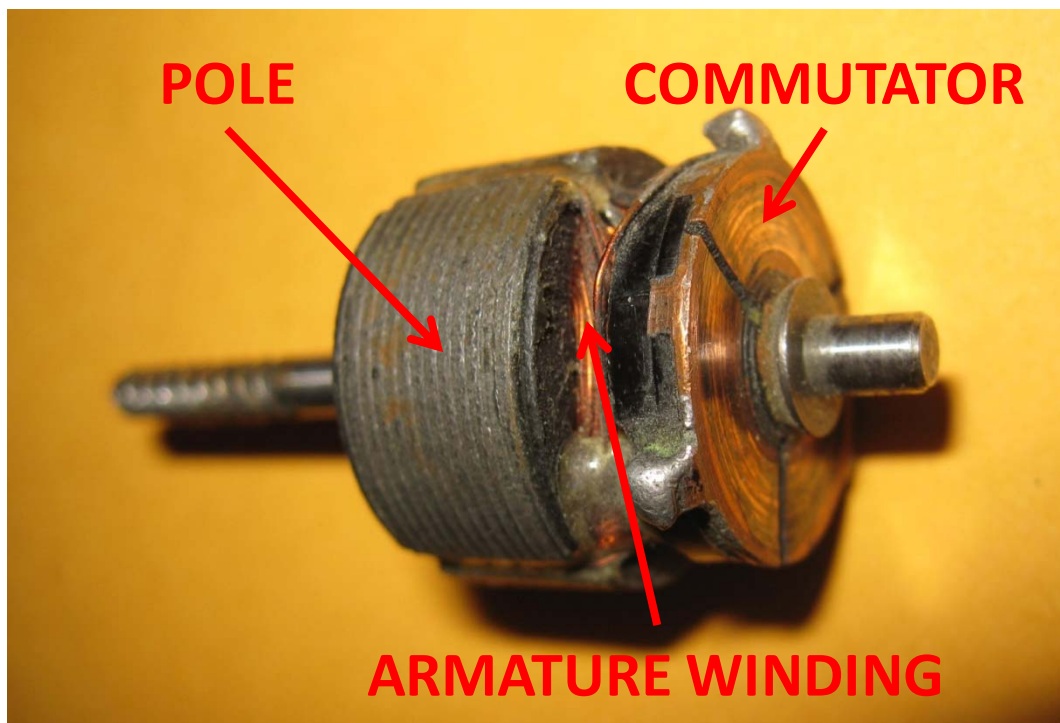


Figure 72: Armature

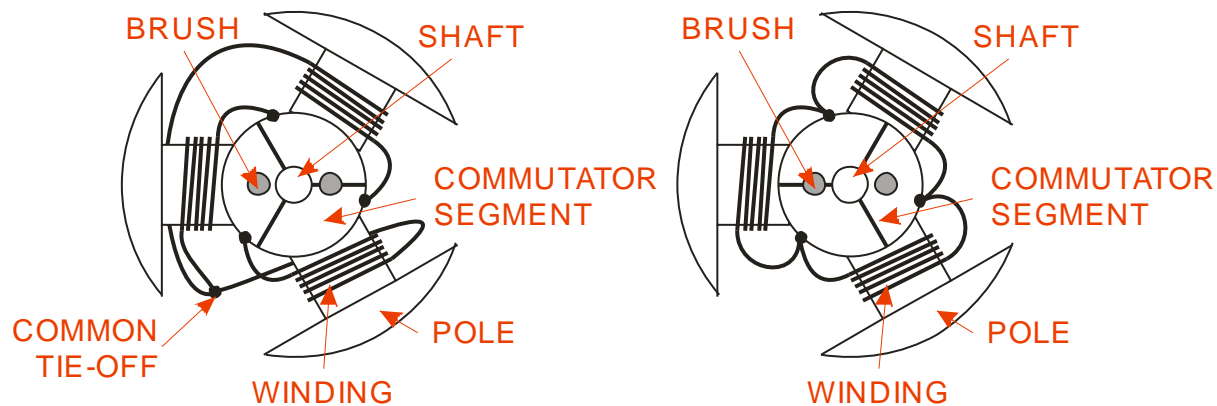


Figure 73: Common Tie-Off and End-to-End Tie Off Armatures

B.1 Common Tie-Off

Figure 74 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 74 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 75 shows reverse operation.

In examining Figure 74, 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 75: 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 76 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.

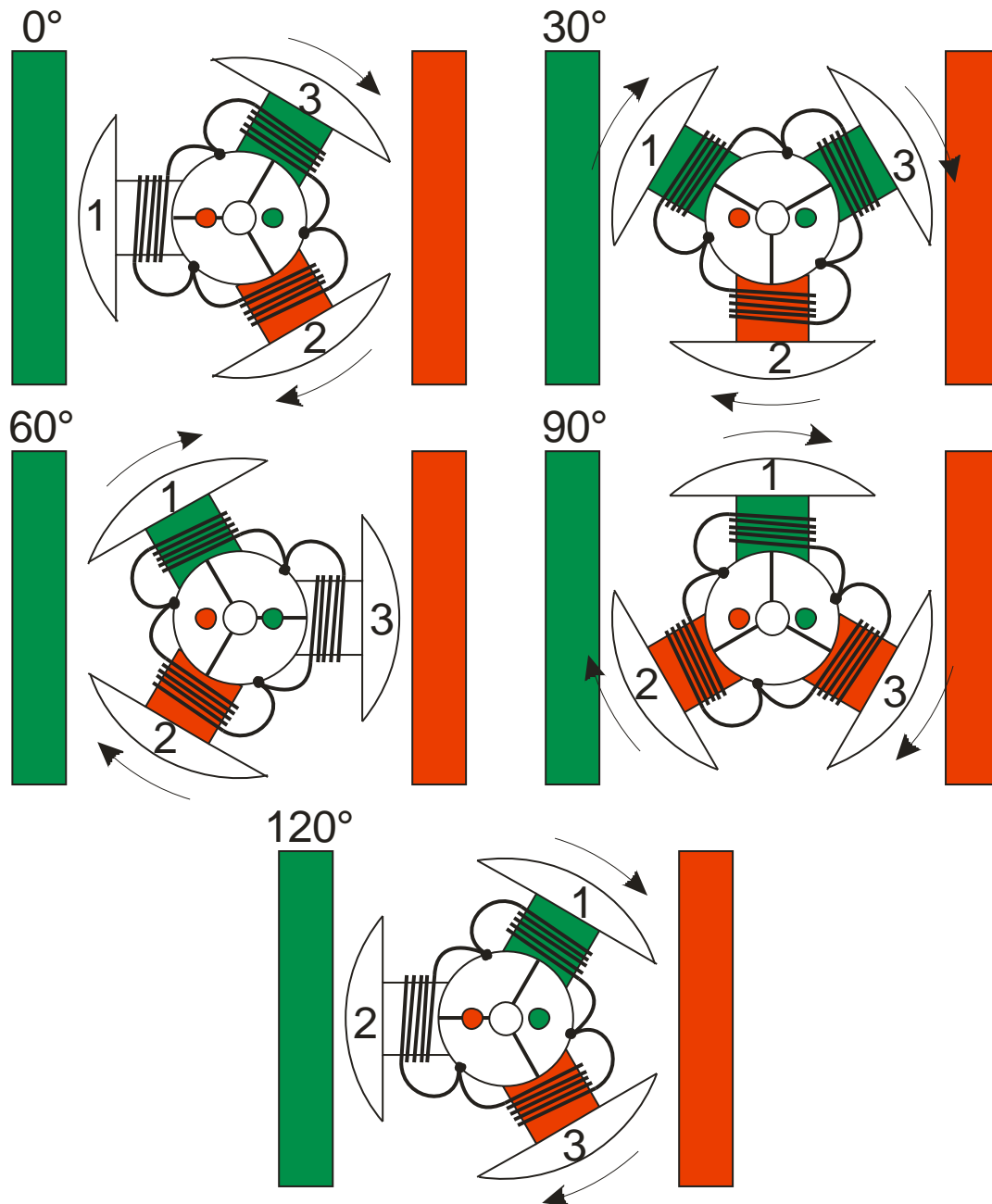


Figure 76: End-to-end Tie Off Rotor Rotation

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