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Technical Note 010: Lessons Learned, Why are Fuses and Solenoid Disconnects So Important in EV's?

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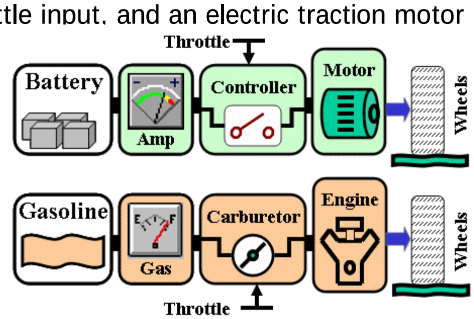
Overview

Gasoline driven vehicles have a century worth of design evolution, from increasing performance to meeting safety requirements. Electric vehicles are still, relatively speaking, a new and infant market. Many lessons are learned when rebuilding EV cars such as wrong motor & controller combination, old or worn motor brushes, stock wiring used with a 600 amp controller, or a hunting buggy plowing through the bog with stock gearing and large tires.

In electric vehicles, when we change design parameters – we can stress other components. It's like putting a Chevy 454 in a Chevy Nova with a stock transmission, high way gearing inside a weak 10 bolt rear axle. Of course it will work – for a while…and then "an event" occurs and something fails or lets loose.

Electric vehicles provide "motive power" in a different way; they utilize a large battery pack as the source of power (fuel), controlled by a DC motor controller to modulate power (carburetor) based on throttle input, and an electric traction motor (engine).



Large amounts of current are required to operate an electric vehicle, especially a modified EV with larger tires, stock gear ratios, or pulling heavy loads. If something goes wrong, the batteries are capable of unleashing potentially large currents. It is very important to have the right combination of components when increasing performance or capabilities.

Equipment Design:

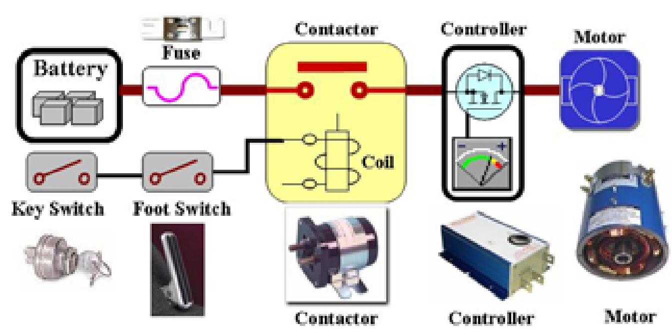
We mentioned the stock Chevy car, so let's talk about original equipment designs for electric cars such as golf carts, boats, or industrial equipment and how safety devices are designed to protect our investment.

This technical note will discuss each component and safety device for a more reliable and safer design.

- **FUSE** interrupts battery power during a short circuit situation. Main purpose to protect the wiring and batteries, with secondary protection for controller or motor failure (direct short).
- **CONTACTOR** (sometimes called a solenoid) is controlled by the throttle footswitch. If the motor or controller fails, the operator removes the throttle which opens the contactor and disconnects battery current. Since the arc current is well below the main fuse current, the only defense is using the contactor as the protection device to disconnect the arc or plasma event.
- **DIODE** is a protection device across the contactor coil. The contactor coil is a magnetic device. When the contactor is turned off, the magnetic field collapses causing a "voltage spike" that can damage the controller. The diode safely clamps this energy.
- **PRE-CHARGE RESISTOR** is a device that slowly charges the capacitors within the electronic controller. Without this resistor, closing the contactor would generate large amounts of current and arc the contacts.

Interlock Diagram:

The Key Switch and the throttle footswitch control power to the contactor coil.



Detailed Discussion:

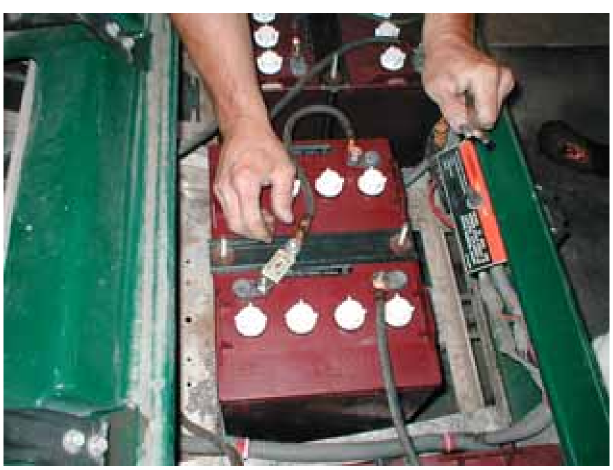
Lets discuss the details of each component for the fuse, contactor, pre-charge resistor, and coil diode. We will also briefly discuss wiring, batteries, and terminations.

Fuses:

Any application where there is a battery pack, a fuse must be installed. Anyone who has dropped a wrench on battery terminals or accidentally touched the positive and negative battery wires together knows the importance of a fuse. Batteries store a lot of energy and in the case of a direct short the results can be pretty dramatic.

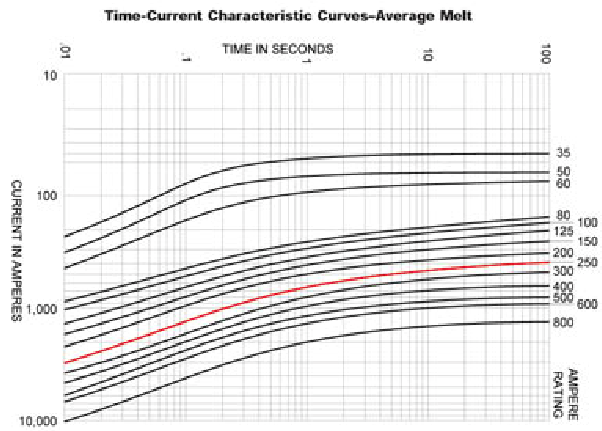
A fuse will open the battery circuit and prevent any serious damage from occurring. Without a fuse, the shorted battery string will continue to supply power until a battery explodes or one of the connections melts. By then it is too late and the vehicle will probably have burned to the ground. *A properly rated fuse must be on each battery pack in all applications.*

It should be mounted on the battery terminal inline with either the positive or negative battery cable going to the controller. (See drawing Doc100-016-A_OP-Fuse-Install-Guide.pdf for more information on installing a fuse).



Fuses have a set behavior called the *Time-Current Curve*. This curve shows how much current the fuse can handle for a given amount of time before it fails.

The fuse time current curve shown below. An example highlighted in red is the ANN250 fuse. The curve shows the fuse can handle 3000Amp for 1/100th of second and about 400Amp for 1 second and 250Amp continuous amount of time.



The table below shows the size of fuse used with Alltrax controllers. The fuse may be of either an ANN or ANL type.

Controller Amperage	Fuse Rating
400A or less	250A
450A or more	400A

During a controller or motor failure, the current level may not be sufficient to open the fuse. When a controller fails there is typically not a direct short circuit taking place between the B+ and B- of the battery pack. The typical failure is the MOSFETs "popping", where the MOSFET material separates from the housing. In the event the conductor can not separate, a plasma arc may form at the transistor.

When a motor fails, the plasma may also be generated - but not always cause a direct short circuit.

Plasma arcing can be sustained by a fairly low current and may not blow the large main battery fuse. As long as there is battery power available the arc or plasma event will be sustained. Once the energy from the batteries is disrupted, the plasma arc will self extinguish. That is the purpose of the contactor (solenoid) which disconnects (breaks) this power in the event something went wrong.

Contactors (called Solenoids)

A contactor is basically an "electromagnetically driven switch" capable of carry large amounts of current. Inside the contactor are a set of fixed contacts and a set of moving contacts. When the coil is energized, a magnet either pushes or pulls a metal rod and the contacts against the current carrying components.

Contactors used in EV applications:

The contactor must be wired so it is *only energizes when the throttle pedal is depressed.* Once the contactor is energized, battery current can flow to the controller. When the throttle is off in the "rest position", the throttle switch opens and the contactor turns off, thereby removing battery power to the controller. This prevents the cart from moving until the operator is ready. AXE and DCX controller products handle this function differently which will be described later.

The contactor also functions as a primary disconnect in an emergency... If something happens, the driver's first instinct is take their foot off the throttle and step on the brake. When the contactor is wired through the throttle (foot switch), the contactor is very fast and will open long before the driver's foot actually touches brake pedal.

To ensure the proper operation of the contactor, its ratings are very important:

- Coil Voltage
- Carry Current (continuous current)
- Break current (or called disconnect current)
- Contact material and plating (the durability of the contact surface)

The **coil** of the contactor is a electromagnet device which provides a strong enough field to keep the contacts closed while the vehicle is being jostled around. When turned off, the return spring in the contactor must be strong enough to "break" the current flow in case something goes wrong.

The **coil voltage** rating is important – use the correct contactor voltage rating! Using 24 volts to drive a 48 volt coil does not generate the required force necessary to hold the contacts in place during operation. Too much voltage will burn – or cook - the coil wiring of which the contacts may not separate when turned off. Contactor plunger binding or self arcing will cause controller failure.

Choosing the correct **current rating** of a contactor is just as critical as choosing the right size wire for the motor and battery connections. The carrying current is determined by the size and plating of the contacts inside of the contactor.

Why are Contactor Ratings So Important?

OEM style cars are very cost conscience and use lower current ratings and fairly small copper contacts without the costly contact plating material on the contacts. Adding a 500 amp controller to a stock OEM 70amp contactor will cause controller failure and could weld the contacts closed causing severe damage.

When the foot pedal is released, the contactor MUST open. If it fails to open, the battery current will continue to be fed to the controller. In the case of a controller failure or the motor commutator flashes over – a small or undersized contactor may weld closed and not open when the foot switch is opened, thereby continuing to feed the plasma arc.

- AXE controllers (for Series wound motors), closing of the foot switch activates the controller and the contactor.
- DCX controllers, (for Shunt wound motors), the foot switch switches applies pack voltage to pin 5 and the controller applies a ground to pin 7 and energizes the contactor.

Contactor Design:

Lets discuss the contactor ratings, physical design, and differences between Stock OEM and Performance (or called Heavy Duty) contactors.

Stock 70 amp contactor

Stock OEM 100 amp contactor

Performance 200Amp Contactor

Heavy Duty 400Amp Contactor

Breaking current is the “maximum disconnect current” the contacts can handle and still able to separate the contacts.

In high performance or modified EV applications using larger controllers, motors, or heavy duty pulling or mud buggies, you must use oversized contactors. A contactor that is undersized not only affects performance but is a safety hazard! If the contactor is overloaded and can not handle the current, it will weld itself together and the contacts will not be able to separate in case of an emergency.

Stock OEM 70amp or 100amp contactors typically use plain copper contacts without any plating material. These contactors are susceptible to arcing, carbon deposits, or contact pitting when used with high current controllers and motors.

OEM –Vs- Performance contactors (see example below) utilize larger contacts than the stock OEM 70amp versions. Performance and Heavy duty contactors use special plating material on the contact surface called silver-cadmium oxide (AgCdO) alloy. This helps prevent pitting and carbon deposits during arcing and increases the amount of current the contact can make or break.

Stock 70 amp contactor

Performance 200Amp Contactor

Contactor Analysis

The Prestolite **SBC-4801B** (Also Ametek) contactor was used in an application with a 500 amp controller. The contactor welded closed and the arcing during that event caused the controller to fail. The welded contactor could not disconnect and subsequently, the vehicle burned. The stock OEM contactor, the Prestolite, SBC-4801B was made for 75 amp controllers (Curtis 1204 with 75amp continuous run current).

Prestolite SBC-4801B – an inside view.

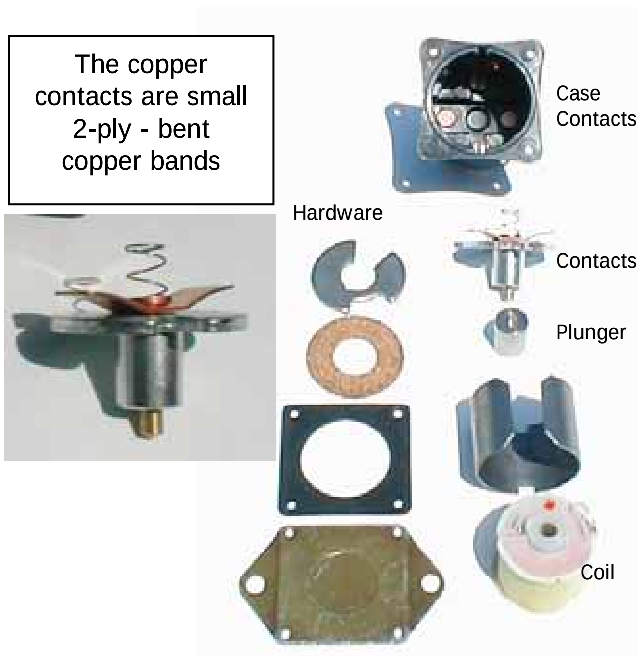
The contacts shown below are made of standard copper and copper alloy, prone to arcing under conditions outside their rated capacity. The break current rating (i.e. the current the contactor can safely disconnect) is rated as 75amps, but with higher temperatures, this rating is obviously reduced with plain copper contacts. (See manufacturing data)

Prestolite continued:

The Single Pole, Single Throw contact ratings are:

Prestolite SBC-4801B	**Ratings:**
Voltage	48 VDC
Continuous Current	100 Amps
Inrush Current	Not rated (0-amps)
Break Current	75 Amps
Typical voltage drop at 175A)	150mV
Electrical Life	60,000 cycles
Contact Bridge Material	Copper Alloy
Stationary Contact Material	Copper
Terminal material	Copper

The copper contacts are small 2-ply - bent copper bands



Contactor Comparison:

Although there are many variations and manufactures of DC contactors, three basic models are compared based on the current rating. The purpose of this discussion is to identify the failure mode of the contactor and why the contacts could not open, resulting in a failure experienced by a customer.

As shown above, the contactor used in this application is the Prestolite SBC-4801B. This contactor is clearly undersized and was in a stock OEM Club Car application for 3 years, then changed to the White Rogers Type 71 (or equiv) (See right of page).

White Rogers Type 71 – 80Amp for OEM applications.

The contacts are two side mounted thick copper bars with silver plate, and a thick copper plate. The ratings are shown below. Although the copper plates are still prone to arcing and deposition, because of the thick copper plate and larger spring, the heat can be dissipated and handles more breaking current.

Most golf car OEMs today utilize the White Rogers style (or equivalent) as shown below for 3.0 HP to 4HP. The 5HP and above motors use larger 200 or 300 amp contactors as shown on the next page.

White Rogers 70 & 71	**Ratings:**
Voltage	36-48VDC
Continuous Current	80-50 Amp
Inrush Current	400-200 Amp
Break Current	80 Amp
Electrical Life	100,000 operations
Contact Bridge Material	Copper Alloy
Stationary Contact Material	Copper Silver clad
Terminal material	Copper

Note: This contactor is not rated for use with any Alltrax controller above 300amp

White Rogers Type 586 - 200 Amp contactor:

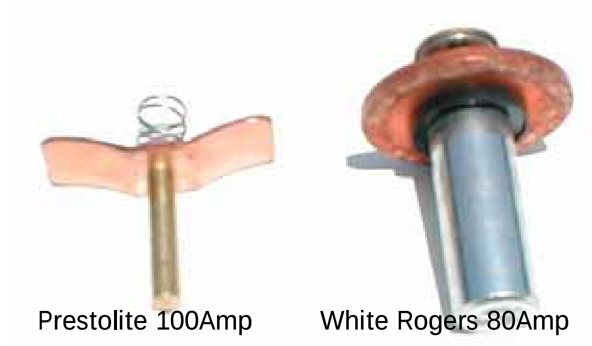
The contacts are post case mounted with Copper Clad AgCd silver cadmium material. The thick copper contact bar is also Copper Clad, AgCd Silver Cadmium contacts. These are rated for high current applications with high surge and break current capabilities without deposition issues.

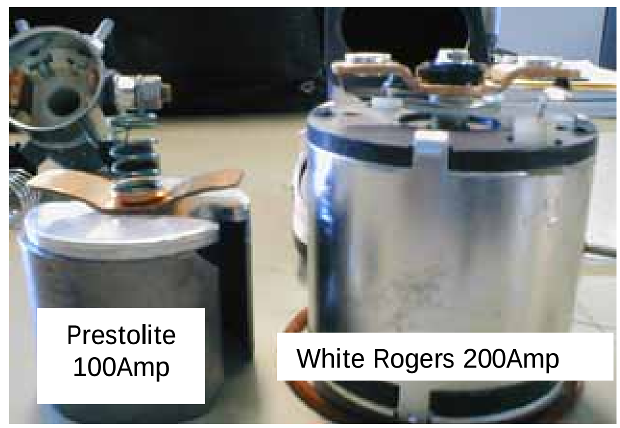
White Rogers 586	Ratings:
Voltage	36-48VDC
Continuous Current	200 Amp
Inrush Current	600 Amp
Break Current	200 Amp
Electrical Life	100,000 operations
Contact Bridge Material	Copper Clad AgCd
Stationary Contact Material	Copper Clad AgCd
Terminal material	Copper

Note: This contactor is rated for use with the Alltrax 300 and 400 Amp controllers (Standard duty)

Side By Side Comparison:

The contactors OEM verses Performance comparison.





Also notice the larger return spring on the White Rogers 200Amp (see below). The spring compression is significantly stronger than the Prestolite, required to break the contact arc as quickly as possible.

Internal Contact Post Comparison – Prestolite 100Amp -to the- White Rogers 200Amp:

Prestolite 100Amp

White Rogers 200Amp

Albright SW180 andSW200 Series Contactors

The contacts robust design mounted to a large cross bar provides an excellent heatsink to keep the contacts cool. The contacts include thick silver alloy plating material. The ratings are shown below. The larger contacts, silver plating, and the larger return spring handles more breaking current. We have not seen this style of contactor fail (when used properly).

When larger controllers are used, the continuous current and breaking current are very important to keep the voltage stable and clean to the controller. It also has to break the large current should a motor or controller fail.

- **The SW180:** 200Amp continuous used with Alltrax 400 and 450 Amp controllers
- **The SW200:** 400Amp continuous used with Alltrax 500 and 650 Amp controllers

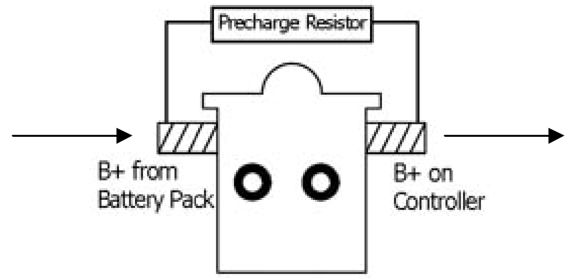
Albright SW200	Ratings:
Voltage:	24-72VDC (72V with magnetic blowoffs)
Continuous Current	400 Amp
Inrush Current	800 Amp
Break Current	1400 Amp @48VDC
Electrical Life	100,000 operations
Contact Bridge Material	Copper Silver alloy
Stationary Contact Material	Copper Silver alloy
Terminal material	Copper / HH brass

Note: This heavy duty contactor is rated for use with **Alltrax 500amp through the 650amp controllers**

Note: Top cover option available to enclose contact area

Pre-Charge Resistor:

The resistor, typically seen across the big terminals on the contactor, pre-charges the filter capacitors in the controller. This minimizes the voltage across the contactor to reduce arcing on the contacts as they close.



Closing the contactor without a pre-charge resistor causes arcing on the contact surface and they can become pitted. Plain copper contacts suffer the worst as they cannot tolerate peak inrush currents. Excessive pitting over time causes the contacts to weld together or not make a good contact.

The pre-charge circuit draws little or no power. Its purpose is to maintain the capacitors at battery pack voltage so when the contactor is closed, no arcing occurs. Resistor value is determined by pack voltage.

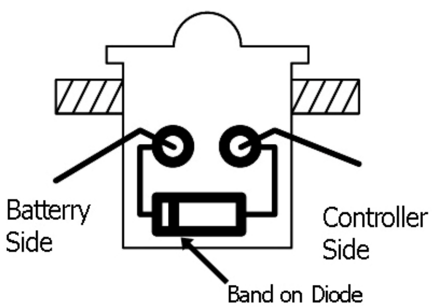
Battery Pack Voltage	**Resistor Value**
12V-36V	250 Ohm 10W
48V	470 Ohm 10W
72V	1000 Ohm 10W

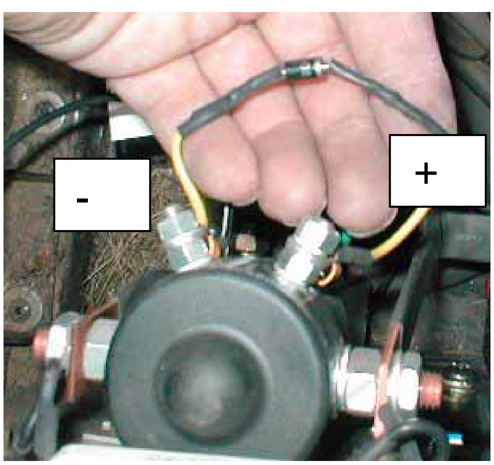
Contactor Coil Diode:

A contactor (as described before can be called a solenoid), is basically a electromagnetic switch. When the contactor is energized, a magnetic field is created that pulls or pushes a movable bar or plate to make a connection with a set of fixed contacts.

To create this magnetic field, a current is passed through a coil of wire. As long as there is current flowing through the coil, the magnetic field remains. When the current stops, the magnetic field collapses releasing this energy in the form of a “fly-back voltage”. This voltage can be in excess of 150volts. If this voltage is not dissipated – it will be transferred back into the controller and cause permanent damage.

The diode across the coil terminals safely dissipates this energy. Vehicles with ITS throttles without diodes have been known to jump or jitter from contactor coil generated spikes.





The type and size of the diode used is dependant on the size of the contactor. On larger contactors, the coil is much larger and stores more energy. Larger coils therefore require more energy to be dissipated when the electromagnetic field collapses.

Contactor Size	Diode	Diode Current
Stock OEM 70-100Amp	1N4004	1A
200A and up contactors	1N5408	3A

Wire:

Wiring in an electric vehicle is a very important and sometimes is overlooked during performance upgrades. Customers who updated the car but not the wiring - ended up with poor performance, overheating terminals, and decreased life on the controller. Here are some “basic guidelines” but obviously, when it comes to wiring, err on the heavy side. Larger wire is absolutely better than smaller wire. Rule of thumb, “If its hot – its too small.”

Controller	Min wire AWG Standard Duty	Min Wire AWG Heavy Duty
300 Amp	Stock OEM – 6AWG	4AWG
400 Amp	4 AWG	4 AWG
450 Amp	4 AWG	2 AWG
500 Amp	2 AWG	2 AWG
600 Amp	2 AWG	1/0 AWG
650 Amp	2 AWG	1/0 to 2/0 AWG

Standard duty – flat lands with speed and torque with slight or moderate performance expectations

Heavy duty – maximum performance, high speed, maximum torque, pulling loads, hilly terrain, or hunting buggies

Batteries:

Batteries are the source of power used to drive the electric car. Weak, older, or mixed batteries (i.e. old & new batteries mixed together) offer low performance, can decrease your range, or be damaged by high loads and weak interconnections.

Common failure mode is battery neglect. We are really dealing with a “chemical engine”; charging causes the chemicals to separate into acid and positive and negative plates. Discharging the battery basically turns the acid into water. Undercharging a battery is the #1 killer of the battery plate material as the plates become sulfated and water causes plate corrosion. In a charged state the batteries a returned back into the chemical (acid) state preventing plate sulfation.

How to Increase Battery Lifetime?

- Keep all the terminal clean
- Charge the batteries after heavy use, do not let them sit overnight in a discharged state.
- Use an approved charger. Some chargers have a very high "finish charge voltage" that might be ok to use in short – high current charge cycles, but daily use will burn off the batteries liquid and eat away plate material
- NEVER add tap water, the minerals in tap water will plate the lead surfaces. Remember, it's a chemical engine, garbage in = garbage out. Only use distilled or de-ionized water for refilling batteries.
- Keep terminals tight and clean, use a good battery terminal spray to minimize corrosion
- Using 10 year old batteries with a 650 amp controller is asking for trouble. The high impedance of the battery can cause battery failure possibly damage the controller or motor.
- Don't TAP off a 12V battery in a multi battery string. Drawing 12V off one battery changes how its discharged. When a charger is connected, the battery charge rate will gas and burn out the other batteries in the series string. Use a DC-DC converter rated for the pack voltage to create the 12 volt output for accessories.

Conclusion:

The objective to hop-up the electric hot rod, golf car, or weekend warrior hunting buggy is to have fun, enjoy the work, and appreciate its performance. Missing the smallest details can lead to damaged components, frustration, lack of performance, or catastrophic damage to eh car or cause bodily injury.

Follow these guidelines and ask questions from those in the industry, web sites, technical notes, etc.

Whether it is a golf car, a NEV/EV or an industrial application, the fuse, diode and resistor play big a part in safety and longevity.

- The fuse will protect the vehicle and operator in the case of a direct short of the battery pack.
- The contactor to disconnect the batteries must have current ratings equal to - or higher - than the controllers ratings
- The pre-charge resistor increases the life of the contactor, by keeping the pitting of the contacts to a minimum.
- When the contactor is turned off, the diode across the contactor coil dissipates this energy and protects the controller.
- The wire size is important to carry the current
- The Batteries are your source of power, make the investment in a good pack, show them some love, and enjoy the fun!

References:

1. Electric Vehicles USA: http://www.electricvehiclesusa.com/product_p/ct-sw180-3.htm
2. Albright Contactors: www.curtisinstruments.com
3. White Rodgers Contactors: www.white-rodgers.com