Introduction

Electrical and electronic systems have evolved over the years to become an essential element of modern off-road vehicles.

The earliest successful agricultural tractors, like the Froelich, used a battery and electric ignition system to start the engine.

A modern off-road vehicle typically incorporates an electrical system having its own power generation, storage, and distribution. Vehicle controls and diagnostics may have dozens of electronic computer-based controllers integrated into its systems.

Electrical Systems

Functions generally provided by the electrical system of a conventional off-road vehicle:
- Engine starting
- Ignition (spark-ignition engine)
- Lighting (work and safety)
- Sensing, display, and control
- Ventilation
- Accessory may include windscreen wiping, entertainment systems, radio, etc.
Electrical Systems con’t

- The charging system (power generation) is composed of an alternator and voltage regulator.
- Power storage system is typically a 12 V dc battery.
- The distribution system is composed of both the current distribution network and the current return loop.
- Overload protection commonly includes a fuse panel with a common conductor to the battery and individual fuses on each conductor to the loads.

Electrical Systems con’t

- The typical loads are engine starting, ignition, lighting, sensing devices, ventilation, entertainment systems, etc.
- The power control element might be an electronic control unit (ECU), which is an embedded computer-based controller. These devices might serve to regulate current to set the position of a solenoid controlled valve.

Components of an electrical system

![Components of an electrical system diagram](image-url)
Batteries
- 12 or 24 V dc batteries are the primary electrical energy storage elements in off-road vehicles.
- During each start-up to shut-down operating cycle of the vehicle, the battery undergoes a discharge and a re-charge cycle.
- The battery supplies large starting currents to the electrical engine starting motor.

Batteries con’t
- During vehicle operation, the on-board alternator provides current to recharge the battery, so the battery will be sufficiently re-charged to allow restarting.
- During vehicle operation, alternator generated current not required for vehicle electrical loads recharge the battery.

Batteries con’t
- Battery characteristics are critical in determining the capacity necessary for a particular vehicle. This figure depicts a cell in a lead-acid battery. This is the primary battery used in off-highway vehicles.

Figure 13.2: Diagram of a cell in a lead-acid storage battery during discharge.
During discharge, current flow is due to the chemical reactions that occur in the battery. A single cell in the battery develops a potential difference of slightly more than 2 V at full charge. 

At the positive plate, lead peroxide (PbO₂) combines with hydrogen that is ionized in the electrolyte of the battery in a reaction that consumes electrons and reduces the plate to lead, releases water, and causes the electrode to be more positive.

At the negative plate, lead gains electrons making the plate more negative.

Charging the battery reverses the reactions at both plates and increases the acid concentration in the electrolyte.

Voltage levels in a lead-acid battery depend on the acid concentration, temperature, and battery load. The internal resistance, Rᵢ, is a function of temperature and state of charge of the battery. Individual cells in the battery produce a voltage which depends on the state of the charge and cell temperature.
Batteries con’t
A typical 12 V lead-acid battery consists of six cells connected internally in series. The battery case is typically an ABS plastic. The battery plates are made of lead calcium alloy to minimize gassing, strengthen the plates, and minimize self-discharge.

Batteries con’t
A porous material, commonly a glass-fiber mat or polyethylene film, is used to separate the plates and provide strength and vibration resistance in the battery. Most modern batteries plates are designed to be low maintenance and incorporate lead-calcium alloys.

Batteries con’t
Several performance criteria are used to characterize batteries. Cold cranking current is the current that can be delivered by the battery for 30 seconds at the rating temperatures and provide an ending voltage of at least 1.2 V per cell.
Batteries con’t

Reserve capacity is the time that a fully charged battery can deliver 25 amperes of current in a 27°C ambient environment and provide a final cell voltage of at least 1.75 V per cell.

Sizing the battery

The starter imposes the most significant battery load. Other system loads generally have longer durations, draw lower current, occur while the engine and alternator are running and can generally be accommodated by the alternator without significant demand from the battery.

The battery must carry the starting load and be able to be recharged during the operating cycle to meet the next starting load.

Sizing the battery con’t

The alternator must carry all permanent, long, and short durations loads within the vehicle while also providing adequate current to recharge the battery during the operating cycle.
Sizing the battery con’t

- Energy efficiency of the battery, $e_b$, is the ratio of discharging energy to charging and is typically 75%.
  - $e_b = \frac{E_d}{E_c} = \frac{P_d t_d}{P_c t_c}$
  - Where $e_b$ = energy efficiency of the battery
  - $E_d$, $E_c$ = discharging and charging energy
  - $P_d$, $P_c$ = discharging and charging power
  - $t_d$, $t_c$ = discharging and charging time

Charging Systems

- The charging system consists of an engine-driven alternator and a voltage regulator.
- The alternator generally consists of a set of stationary coils, a stator, arranged in a toroid within which a rotating coil, or rotor, is spun.

Cutaway Schematic of a Claw-pole Alternator

*Figure 18.4. Cutaway schematic of a claw-pole alternator.*

*Goering, Off-road Vehicle Engineering Principles, 2003*
Charging Systems con't

Voltage is applied to the rotating coil through the brush and slip ring assembly, causing current to flow and the rotating coil and claw poles to be magnetized.

The magnitude of voltage applied to the rotor coil controls the strength of the magnetism in the claw poles and the magnitude of the current induced in the stator coils.

Charging Systems con't

The current induced in the stator coils of the alternator is an alternating current. The alternating current must be rectified to DC current to charge the battery and supply vehicle electrical loads.

Charging Systems con't

This figure shows a schematic of a diode-bridge with a sinusoidal input current similar to that generated by one pair of stator coils of an alternator.

![Diagram of a diode-bridge with a sinusoidal input current similar to that generated by one pair of stator coils of an alternator.](image-url)
Alternator Sizing

- Alternator performance curves may be used when selecting an alternator for a particular application.
- Standardized test procedures are available to allow manufacturers to provide comparable test information. The full load current versus speed curve, for example, is produced by the standard test methods.

![Typical Performance Curve for Alternator](image)

Alternator Sizing con’t

- The range of load expected for the alternator must be determined to allow selection of a specific alternator.
- The speed range of the alternator is set by designing the gear ratio of the coupling of the alternator to the engine. The alternator is driven by a belt or gear drive.
Alternator Sizing con’t

The alternator provides power for all long-term or permanently connected loads while the vehicle is idling, including electric fuel pumps, headlamps, work lighting, instrument panel lamps, ignition systems, electronic control systems, and charging the battery.

Alternator Sizing con’t

The alternator should be able to provide 130 to 150% of the long-term or permanently connected loads at the engine idle speed for passenger cars. The alternator also provides the power to meet the sum of short-duration and long-term or permanently connected loads at the “normal” engine operating speed. The “normal” engine speed would be the average speed over the operating cycle.

A hypothetical calculation of alternator size.

<table>
<thead>
<tr>
<th>Source</th>
<th>Power, W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel pump</td>
<td>75</td>
</tr>
<tr>
<td>Alternator control (ECA)</td>
<td>15</td>
</tr>
<tr>
<td>Engine control</td>
<td>15</td>
</tr>
<tr>
<td>Transmission controller</td>
<td>35</td>
</tr>
<tr>
<td>Instrument control</td>
<td>15</td>
</tr>
<tr>
<td>HEUI controller</td>
<td>15</td>
</tr>
<tr>
<td>Headlight controller</td>
<td>15</td>
</tr>
<tr>
<td>Windshield wiper</td>
<td>10</td>
</tr>
<tr>
<td>Brake</td>
<td>100</td>
</tr>
<tr>
<td>Taillight</td>
<td>10</td>
</tr>
<tr>
<td>Parking lights</td>
<td>10</td>
</tr>
<tr>
<td>Total long-term or permanently</td>
<td>342</td>
</tr>
<tr>
<td>connected loads</td>
<td></td>
</tr>
<tr>
<td>Short-term or intermittent loads</td>
<td>46</td>
</tr>
<tr>
<td>Ventilation fan</td>
<td>46 0.25</td>
</tr>
<tr>
<td>Wiper Mechanism</td>
<td>40 0.25</td>
</tr>
<tr>
<td>Turn signal</td>
<td>40 0.25</td>
</tr>
<tr>
<td>Total short-term or intermittent</td>
<td>138</td>
</tr>
<tr>
<td>loads</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>480</td>
</tr>
</tbody>
</table>

Goering, Off-road Vehicle Engineering Principles, 2003
Alternator Sizing con’t

- At idle, the alternator should be able to provide $1.5 \times 362 \text{ W} = 543 \text{ W}$ or approximately $543 \text{ W} / 14 \text{ V} = 39 \text{ A}$.
- At the normal engine operating speed, the alternator in this example should be able to deliver $421 \text{ W}$ or $30 \text{ A}$.

Power Distribution

- Power within the vehicle is normally distributed from the battery to a fuse or circuit breaker system and then individual wires carry current to the individual loads.
- The distribution system must be designed for correct size fuses or circuit breakers, wiring size, and connectors to assure a safe, efficient, and economic design.

Wiring, Fusing, and Connections

- Several factors must be considered when selecting cable sizes. The major factors are:
  - Mechanical strength
  - Temperature rise
  - Voltage drop
  - Connector requirements
- Circuit configuration must be specified, including the required current capacity, cable lengths, connector positions, and physical exposure requirements.
Wiring, Fusing, and Connections

- Wiring mechanical strength requirements constrain the minimum size that may be selected for a cable. Minimum cable sizes of 0.8 mm² in harnesses or 1 mm² in areas susceptible to physical damage are recommended to prevent failure due to inadequate mechanical strength.

Wiring, Fusing, and Connections

- To temperature rise in a cable during a short-circuit condition, the cable must be sized for circuit protection. The primary function of the circuit protection device is to protect the cable from failure during a fault. The circuit protection device may also provide some protection for the load device, but this is a secondary function.

This table is a portion of the requirements given in SAE 1614, which specifies methods for sizing cabling on off-highway vehicles.

<p>| Table 18.3: Cable size based on thermal circuit protection (SAE J1614). |
|---------------------------------|-----------------|-----------------|-----------------|
| 10% Load Operating Current,   | Circuit Breaker Rating, | Smallest Acceptable Cable Size, |</p>
<table>
<thead>
<tr>
<th>[A]</th>
<th>[A]</th>
<th>[mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.2</td>
<td>7.5</td>
<td>0.8</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>10.5</td>
<td>15</td>
<td>2</td>
</tr>
<tr>
<td>14</td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>21</td>
<td>30</td>
<td>5</td>
</tr>
</tbody>
</table>

Wiring, Fusing, and Connections

Requirements for temperature rise of the cable and voltage drop across the cable must also be within design constraints. SAE J1614 (SAE 1998b) specifies sizing methods for both steady and intermittent loads and shows a derivation of the equations for the calculations.

Wiring, Fusing, and Connections

For steady loads, and a 30°C rise for cables bundled in a harness or 10°C rise of a single cable in free air, the minimum cable sizes have been calculated and a partial extract is shown.

<table>
<thead>
<tr>
<th>Cable Size, mm²</th>
<th>Rating, A</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>7.5</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>14</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>29</td>
</tr>
</tbody>
</table>

Wiring, Fusing, and Connections

For intermittent loads of 90 s or less. This equation may be used. It estimates the cable size based on a 40°C ambient temperature and allowing the wire to rise to 150°C through resistive heating.

- \( I / A = 13.82 \)
- Where \( I \) = current, A
- \( A \) = conductor area, mm²
Wiring, Fusing, and Connections

Voltage drop in the cable should be evaluated using Ohm's Law to calculate voltage drop for the current requirement.

Resistivity can be used to calculate the resistance of a wire.

\[ R = \rho \left( \frac{1}{A} \right) \]

\[ r_s = R / l = \frac{\rho}{A} \]

Where:
- \( R \) = resistance, \( \Omega \)
- \( l \) = length, m
- \( \rho \) = resistivity, \( \Omega \)m
- \( r_s \) = specific resistance, \( \Omega \)m\(^{-1}\)
- \( A \) = area, m

Resistivities may be compensated for temperature using:

\[ r_t = r_{base} \left[ 1 + \alpha \left( T - T_{base} \right) \right] \]

Where:
- \( r_t \) = electrical resistivity at temperature \( T \)
- \( r_{base} \) = electrical resistivity at base temperature
- \( \alpha \) = temperature coefficient of electrical resistance
- \( T \) = temperature of material
- \( T_{base} \) = temperature of the material at which the base electrical resistivity, \( r_{base} \), is given

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This table provides basic resistivity per unit length of wire.

<table>
<thead>
<tr>
<th>Material</th>
<th>Electrical Resistivity(^{\text{a}}) ( \Omega )m or ( \mu )Ohm</th>
<th>Temperature Coefficient of Electrical Resistance, ( \alpha ) ( \text{K}^{-1} )</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure copper</td>
<td>16.7</td>
<td>0.00404</td>
<td>Pick and</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Christiansen, 1996</td>
</tr>
<tr>
<td>Copper-steinel</td>
<td>17.1</td>
<td>0.00797</td>
<td>Pick and</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Christiansen, 1996</td>
</tr>
<tr>
<td>Nickel</td>
<td>79.0</td>
<td>0.006</td>
<td>Lide, 2001</td>
</tr>
<tr>
<td>Gold</td>
<td>24.4</td>
<td>0.0014</td>
<td>Lide, 2001</td>
</tr>
<tr>
<td>Steel</td>
<td>104.0</td>
<td>0.009</td>
<td>Lide, 2001</td>
</tr>
</tbody>
</table>

\(^{\text{a}}\) Values given at 20°C.
Wiring, Fusing, and Connections

- Minimum wire size to meet a voltage drop constraint may be selected given the acceptable voltage drop, the current requirement, and the cable length. Specific resistance for the cable may be calculated using this equation as given in SAE J1614.

- A voltage drop constraint must be set based on the particular situation.
  - \( r_s = \left( \frac{\Delta V}{L \cdot I} \right) \cdot 10^6 \)
  - \( r_s \) = specific resistance, \( \mu \Omega/mm \)
  - \( \Delta V \) = acceptable voltage drop, V
  - \( L \) = cable length, mm
  - \( I \) = current, A

Electronic Systems

- Manufacturers of agricultural equipment are increasingly turning to electronics to provide products with improved functionality, productivity, and performance to customers.

- Electronic control units combined with sensing and actuation elements make up the fundamental components of modern electronic systems.

Electronic Control Units

- ECUs are microcontrollers which interface inputs and outputs to various components of the equipment.

- These computer-based modules run a program which use digital (on/off) and analog (continuously variable) input and output signals. The program interprets the inputs to the ECU and makes decisions which will effect outputs that control the operation of the vehicle.
Electronic Control Units con’t

◆ The ECU can then produce digital outputs to set the position of a hydraulic valve or turn a motor ON or OFF, or analog outputs to control a proportional or servo-valve.

◆ ECUs have limited computational speed which limits the rate at which ECUs can input information, process the information, and produce an output.

Electronic Control Units con’t

◆ Digital outputs are typically used to drive valves, actuators, and indicators. Many different types of circuits are used. A common driver circuit for a digital output would drive a solenoid or motor coil.

Electronic Control Units con’t

◆ Signal conditioning is employed to scale analog inputs (voltages or currents) to voltage ranges appropriate for analog to digital (A/D) converters.

◆ A/D converters convert voltage inputs into binary numbers used within the microcontroller, and are often integral to the controller device.
Electronic Control Units con’t

- Typical A/D converters provide 8-, 10-, or 12-bit resolutions. These resolutions provide scaled numbers with resolutions of 1 part in 256, 1024, and 4096 respectively.
- Analog signals may be a voltage level referenced to the ground (the negative battery terminal) or may be a differential voltage, without reference to ground. The former is known as a single-ended signal, and the latter as a double-ended signal.

Sensors

- Sensors are a critical component in embedded electronics. Inputs to the embedded electronics include those provided directly by the operator and those provided by external sensors.
- The common form of signal communication from the sensor to an ECU are through analog, frequency, or a digital signals. Analog voltage or current signal levels are commonly proportional to the parameter being measured. While digital signals can be discrete on/off, or encoded representations of the sensor status. Frequencies are typically encoded.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sensor Type</th>
<th>Signal Type</th>
<th>Typical Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Thermo-voltage</td>
<td>Voltage</td>
<td>Water temperature, air temperature</td>
</tr>
<tr>
<td></td>
<td>Solid-state above</td>
<td>Single-ended</td>
<td>Water temperature, air temperature</td>
</tr>
<tr>
<td></td>
<td>Solid-state below</td>
<td>Single-ended</td>
<td>Water temperature, air temperature</td>
</tr>
<tr>
<td>Pressure</td>
<td>Piezoelectric</td>
<td>Voltage</td>
<td>Accelerometer, pedal position</td>
</tr>
<tr>
<td>RPM</td>
<td>Motor speed encoder</td>
<td>Frequency</td>
<td>Engine speed, wheel speed</td>
</tr>
<tr>
<td>Linear position</td>
<td>Potentiometer</td>
<td>Voltage</td>
<td>Engine fuel and air position</td>
</tr>
<tr>
<td>Linear position</td>
<td>Digital encoder</td>
<td>Frequency</td>
<td>Engine fuel and air position</td>
</tr>
<tr>
<td>Level</td>
<td>Potentiometer</td>
<td>Voltage</td>
<td>Fuel level</td>
</tr>
<tr>
<td>Fire</td>
<td>Smoke detector</td>
<td>Voltage</td>
<td>Dust sensing</td>
</tr>
</tbody>
</table>
Sensors con’t

Devices that produce current generally derive power from the external power source. These devices usually regulate the current flow proportional to the parameter being measured. These current devices are desirable when it is important to eliminate the effect of voltage drop and noise in connectors or wiring.

For example, when the sensor is a long distance from the ECU, a signal that is current-based is not susceptible to voltage drop in the circuit.

Sensors con’t

Transmitted frequency signals is another method that allows elimination of the interference of voltage drops across sensor circuits. Frequency signals are commonly a square wave with nominal voltage levels of 0 and 5 volts. The frequency of the square wave conveys the value of the signal. This type of signal is insensitive to voltage drops and electrical noise.

Frequency signals can be interfaced with microcontrollers through a digital input port and then simple pulse counting can be used to reduce the signal to a numerical value.

Sensors con’t

Double-ended voltage signals are typically produced by sensors using elements in a wheatstone bridge arrangement. The figure illustrates a bridge with resistive elements. Changes in the resistance of any of the elements causes a voltage difference at the output.

[Diagram: Wheatstone Bridge]

Goering, Off-road Vehicle Engineering Principles, 2003
An advantage of the bridge is that equal changes in adjacent elements, such as line length, or temperature change, result in no net change in output. This effect thus compensates for temperature or other interferences. The adjacent elements are both exposed to the interference, temperature for example, and only one of the pair is exposed to the effect of interest, strain for example.

These devices are often used in strain-based transducers including pressure and draft. An important characteristic of a double-ended signal is that neither of the output conductors is at ground potential and the information in the output signal is the voltage difference between the conductors.

Smart sensors and actuators employ microcontrollers directly within the sensor. The microcontroller converts the sensor signal into a digital encoded message that is sent to the ECU.
Sensors con’t

- The sensor data are sent as a serial digital bit-stream to the ECU similar to that shown in the next figure.
- The reverse process occurs in a smart actuator.

Controller Area Networks

- A natural outcome from adding multiple electronic sensors and ECU’s to agricultural equipment is the creation of inter-component communication. A hitch controller on a tractor, for example, may communicate with a transmission and engine controller optimize performance.

Controller Area Networks con’t

- Communication between major systems components can be used to coordinate vehicle and implement operation, allow information to be shared among components of a vehicle, and allow control system tasks to be distributed across several components of a vehicle.
Proprietary Networks

Multiplex wiring has evolved to provide cost-effective communications among ECUs. In this wiring scheme, a single pair of wires (a bus) is shared among controllers and used to carry a serial-bit stream as shown.

Groups of bits are sent as messages with the first bits of the message forming a message identifier and the latter composing data.

The protocol embedded into the ECUs requires the ECU to check the bus to assure no other ECU is using it prior to transmitting their message.

Multiplexed wiring systems which use proprietary designs have been employed in off-road equipment for many years.

Standardized Communication Networks

The need for standardized communication networks for off-road vehicles was obvious once networks became popular.

Standardized networks allow different manufacturers’ ECUs to communicate and function on a common network.
Standardized Communication Networks con’t

- Engine, transmission, hitch controllers, etc. from different manufacturers are integrated into a single vehicle creating a need for common protocols.
- With different implements from various manufacturers often connected to tractors from different manufacturers, a standardized communication network system becomes an obvious requirement.

ISO 11783 Overview

This figure shows in schematic form a simplified ISO 11783 network superimposed on an agricultural tractor and implement background. A network with no master controller has been defined. The network is composed of 2 communication busses, a tractor bus, and an implement bus.

ISO 11783 Overview con’t

The implement bus spans the tractor, crosses the hitch, and spans implements. The implement is shown in this schematic with an implement sub-network. The busses are interconnected with network interconnection ECUs: the tractor ECU, implement ECU, and implement bridge.
ISO 11783 Overview con’t

◆ The task controller is an ECU, which normally resides on the tractor and is used to provide commands to implements to accomplish some task. An example might be to provide the commands of a prescription in a precision farming operation.

◆ The management computer gateway portion of the task controller and management computer gateway contains an interface that is compatible with the management computer and allows data to be exchanged between the task controller and the management computer.

ISO 11783 Overview con’t

◆ Standardized communications are defined between the task controller and implements; and between the task controller interface and applications software on the management computer.

◆ The interface between management computer and task controller is not standardized.

ISO 11783 Overview con’t

◆ The network has messages defined to allow communications between any of the components.

◆ An example might be communication between the task controller and the GPS ECU. Navigational messages are defined and allow positional information to be received by the task controller.

◆ Messages are defined to allow the engine ECU to provide a current torque curve to the transmission.
ISO 11783 Overview con’t

- The tractor ECU filters messages between the tractor and implement bus.
- This filtering prevents heavy traffic on either bus from overloading each other.