Guide to UAV Power Systems

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Introduction

Electrical power systems are critical to a UAV's design and operation. But they don't operate in a vacuum. Their weight, operating temperature, and efficiency of the power components have a major influence on performance parameters such as flight duration, payload, operating ceiling, and range.

The choices involved in selecting an electric power system are dictated largely by the duration of continuous and peak power requirements. Unlike many other UAV subsystems, the power system supports both the platform and the payload. Depending on the mission, the payload will require different amounts of electrical power while in flight. This power demand can be tens or hundreds of watts for sensors or communications or tens of kilowatts for more complex payloads.

Power systems considerations include power generation, electronics, torque, battery packs, thermal managements, and how it all operates with an electrical motor or with an internal combustion engine (ICE)—in hybrid mode or otherwise. The sections below address these subjects in detail.

Power Generation

The performance of a generator is a complex combination of the material used, the physical design, and the manufacturing processes. An ideal generator will be lightweight but able to produce power reliably and efficiently to meet the mission parameters.

An electrical generator converts mechanical energy to electrical energy. Its basic parts are a **rotor** and a **stator**. The rotor is the magnetic field source while the stator contains the conductorwhere the electric motive force (EMF) is induced (generally the conductor is a coiled wire called windings). All generators operate on the same basic principle: a magnetic field cutting through conductors, or conductors passing through a magnetic field, to produce electricity. An electrical generator is the same basic design as an electric motor because its construction and working principles are based on the mutual induction between the rotor and the stator windings.

The rotor and stator are both key parts of the electrical machine, where the rotor rotates while the stator is stationary. In UAV applications, the stator mounts to the internal combustion engine drive shaft directly or connects mechanically through belts. The mounting system is a key component that affects the overall system reliability and performance. Integrated power-propulsion (shared-shaft) systems have higher efficiency, lower weight, and lower cost than indirect mechanisms like belts.

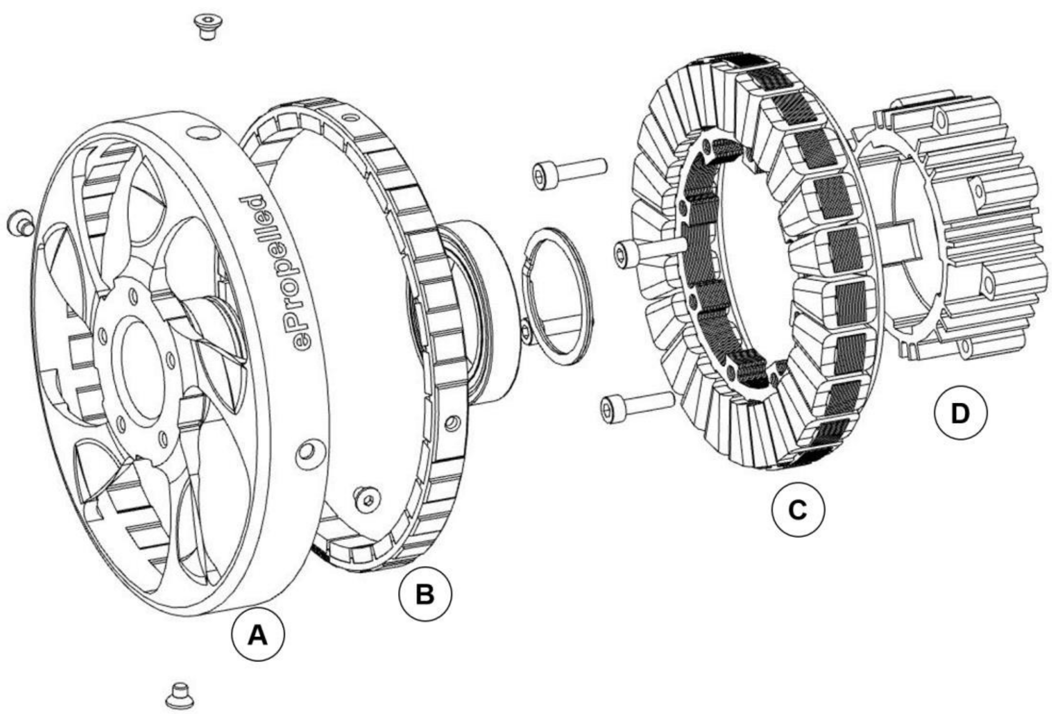

Figure 1: The Rotor (A) houses the magnets (B), while the stator has the windings (C) and uses a mount (D) to the UAV engine.

Windings are the wire wound on the stator armatures to work as a conductor. The only physical difference between a single-phase generator and a multiphase generator is the additional coils with accompanying parts in the stator. But a multiphase generator is smaller, lighter, and less expensive than a single-phase generator with equal power. Each phase generates approximately equal amounts of energy. The generated energy is multiplied with the number of phase coils in the generator.

A three-phase AC generator, as the name implies, has three single-phase windings spaced so that the voltage induced in each winding is 120° out of phase with the voltages in the other two windings. The electromagnetic field is directly proportional to the number of coil turns. For example, in the case of a coil with 100 turns, the induced electromotiveforce will be 100 times higher than one in a single coil turn of conductor.

The rotor houses a **permanent magnet** made from a hard ferromagnetic material that creates a persistent magnetic field. Ferromagnetic materials include iron, nickel, cobalt, and some alloys of rare earth metals. Rare earths are a group of 17 chemically similar elements crucial to the manufacture of many tech products. Despite their name, most are abundant in nature but are hazardous to extract.

Permanent magnets do not require any power source and usually produce a powerful magnetic field compared to their size. The specification of the magnets is a critical aspect of the design.

Most starter generators use rare earth magnets for high power density. Compounds of rare earth materials and transition metals can have high Curie temperatures (the temperature above which its ferromagnetism disappears). They are ideally suited to applications that involve elevated temperatures (up to 300° C) and the need for high magnetic properties.

Electronics

Given the increased demand for electrical power for more complex missions, system designers have to provide higher currents and multiple supply rails. New and innovative power supply topologies are necessary to improve efficiency, reduce weight, minimize heat dissipation, and lower overall costs. Below is an example of an optimally-working system.

Starter generators produce three-phase AC voltages that vary with engine RPM and load. The AC output is be converted to DC voltage by a **power management unit (PMU) or an intelligent power system** (iPS) that uses active rectification and regulation to supply one or more DC voltage outputs from the variable AC input. The platform and payload needs determine thenumber of outputs and the appropriate DC voltages.

Figure 2: The iPS (PMU) takes AC inputs from the SG (right) and converts to DC outputs (left). The communications port is the CAN interface.

When the starter generator is used to start the internal combustion engine, an **electronic engine starter (EES)** device or function is needed. Once the engine is up to speed, the PMU or iPS would deliver regulated voltages. If, for any reason, the starter generator stopped working, a **backup battery** should automatically engage to provide regulated voltages for a fixed duration, depending on backup battery size. PMUs and iPSs must be designed to provide power over a wide RPM range. Weight, cooling, and high efficiency are all factors to minimize fuel consumption.

Data analytics is rapidly becoming critical to the operation of any system. As UAV missions become more complex, the demand for accurate, real-time system information continues to increase. The PMU/iPS should connect to a controller area network (CAN) via a standard (RS-485) interface to the onboard avionics. The CAN should monitor and report the following in realtime:

- System configuration
- DC voltage levels
- Current levels and limits reached
- Temperature of various modules
- RMS value of the input SG
- Active onboard or onshore batteries

Batteries

For platforms that run on internal combustion engines, energy storage is necessary to ensure a reliable supply of electrical power for onboard systems. This means batteries. But battery packs are more than a simpleconfiguration of cells. The main components of a battery pack are:

- the cells, which are the energy source and storage,
- a battery management system that provides the intelligence of the system,
- an enclosure, and
- external contacts or connectors.

Designers need to understand their options in battery technology such as LiHV, $LiFePO_4$, Li-ion, NiCad, NiMH, and lead-acid batteries. A typical lithium-ion battery can store between 150 and 265 watt-hours of electricity per kilogram of battery. A NiMH (nickel-metal hydride) battery pack can potentially store 100 watt-hours per kilogram, although 60 to 70 watt-hours might be more typical. A lead-acid battery can store only 25 watt-hours per kilogram. Thus, most UAVs use lithium-based batteries.

Lithium iron phosphate ($LiFePO_4$) battery, also called LFP battery, is a type of Li-ion rechargeable battery for-high power applications.

- Individual $LiFePO_4$ cells have a nominal voltage of about 3.2 V or 3.3 V.
- The cells have greater cell density than lead acid, at a fraction of theweight.
- The cells have a lower cell density than lithium-ion. This makes them lessvolatile, safer to use, and offers an almost one-to-one replacement for lead-acid packs.
- The typical estimated life of a lithium iron phosphate battery is 1500-2000 charge cycles for up to 10 years.
- Typically, a lithium iron phosphate pack will hold its charge for 350 days.

Lithium-ion batteries are widely used in UAVs as well as laptops, PDAs, and cell phones. They're so common because, pound for pound, they're some of the most energetic rechargeable batteries available.

- Individual lithium-ion cells usually have a nominal voltage of 3.6 V or 3.7 V.
- Lithium-ion cells have a higher cell density than lithium iron phosphate. This means fewer of them can be used for the desired capacity. But higher cell density comes at the expense of greater volatility.
- The typical estimated life of a lithium-ion battery is two to three years or 300 to 500 charge cycles.
- Typically, a lithium-ion pack will hold its charge for 300 days.

Rapid industry growth has led to a substantial reduction in lithium-based energy costs from $1,000/kWh some 10 years ago, to only $200/kWh today. The prices are expected to decrease even further to less than $100/kWh by 2022.

Li-ion technology has started to reach its energy density limits of approximately 280 Wh/kg. In the last decade, researchers started to investigate new combinations of metals to increase their energy density. Specifically, there has been an increase in research of lithium-sulfur(Li-S) batteries due to the potential for storing more energy (approx. 500 Wh/kg).

But regardless of the battery used in the UAV, its charge and its use are going to influence mission parameters and final performance. Therefore, when designing UAVs, the importance of a battery management system cannot be overstated. A battery management system will:

- continuously monitor important battery parameters,
- handle the varying power demands of the many aspects of the UAV’s operation, and
- optimize the battery usage.

A battery management system can also protect the battery during charging, safeguarding against conditions such as overcurrent or overvoltage.

Starter Options

UAVs can have onboard or outboard starters. The starter generator must be able to create enough torque and speed for the internal combustionengine, and the battery must provide enough voltage and current. Therefore, an onboard electronic engine starter is a good option.

Some designers rely on ground-based starters to minimize onboard requirements and thus keep overall weight down. However, an onboard system has the advantage of being self-contained and may provide greater flexibility in the field. An EES can also be integrated into the PMU/iPS.

Figure 3: Electronic engine starter

When a starter generator is used to start the internal combustion engine, it is used as an electric motor. This requires the EES to convert the input from batteries to a modulated three-phase AC signal that is coordinated to the relative position of the rotor and stator in a process known as commutation.

Starting the ICE requires high torque which is produced by very high currents from the battery. Proper sizing of these components is crucial.

Hybrid Operation

Most large UAVs are still powered by internal combustion engines, while electric propulsion systems are more common in civilian micro and mini UAVs. Increasingly, high-performance electric motors make electric propulsion possible for larger commercial UAVs.

However, electric propulsion systems may be limited by a reasonably-sized battery pack. What's more, the noise produced by internal combustion propeller-driven UAVs can be a drawback, which can bepartially solved by installing an electric motor to drive the propeller. A hybrid propulsion systemfor UAVs addresses these issues.

As noted earlier, a starter generator and an electric motor are electric machines that use the same physical construction and components like magnets and windings. This allows the electric machine to generate electricity from the mechanical action of the ICE to power onboard electrical systems and store energy in the battery. The same electric machine can also be used as a propulsion motor that utilizes the energy stored in the battery in a hybrid application.

The key requirements for a hybrid application are the addition of a motor controller to the power system and the appropriate dual-purpose electrical machine called starter generator propulsion motor (SGPM). The motor controller converts DC from the battery to controlled three-phase AC so that the electrical machine can propel the UAV. There are simple mechanical modificationsto a starter generator to allow it to function in a hybrid application.

The electric motor is more efficient at producing torque and the combustion engine is better for maintaining speed. Having an electric motor also allows for more efficient engine design. A power assist or range extender feature helps reduce demands on a hybrid's internal combustion engine, which in turn can be downsized and more efficiently operated. The ICE would produce less power but when combined with electric motors, the system's total power could equal or exceed that of a conventional vehicle.

There are three main use cases for a hybrid system:

- Using a SGPM to provide sufficient power to assist the internal combustion engine during takeoff. This allows the internal combustion engine to be sized for a steady flight rather than sized exclusively for peak power requirements at takeoff.We refer to this as power assist.
- Battery power can be used to extend flight time. This provides a mechanism to use the battery power to land the aircraft in theevent of an emergency.
- Converting to electrical power temporarily for reduced noise.

Glossary

ALTERNATOR - A device that converts mechanical energy into electrical energy.

ALTERNATING CURRENT (AC) - A flow of electrons that reverses its direction of flow at regular intervals in a conductor.

AMBIENT TEMPERATURE - The temperature of the surrounding medium, such as gas, airor liquid, which comes into contact with a particular component.

AMPERE - A unit of measure for the flow of current in a circuit. One ampere is the amount ofcurrent flow provided when one volt of electrical pressure is applied against one ohm of resistance. The ampere is used to measure electricity just as "gallons per minute" is used to measure water flow.

AMPERE-HOUR - A unit of measure for battery capacity. It is obtained by multiplying the current (in amperes) by the time (in hours) during which current flows. For example, a batterywhich provides 5 amperes for 20 hours is said to deliver 100 ampere-hours.

ARMATURE - It is made up of conductors that rotate through a magnetic field to provide voltage or force by electromagnetic induction. The pivoted points in generator regulators are alsocalled armatures.

BRUSH - A device that rubs against a rotating slip ring or commutator to provide a passagefor electric current to a stationary conductor.

BRUSHLESS - A brushless DC motor (BLDC) is a synchronous electric motor that ispowered by direct-current electricity (DC) and has an electronically-controlled commutation system, instead of a mechanical commutation system based on brushes.

CHARGE - To restore the active materials in a storage battery by the passage of direct currentthrough the battery cells in a direction opposite to the discharging current.

CONDUCTOR - A type of material that allows the flow of charge (electrical current) in one ormore directions.

CURIE TEMPERATURE - A characteristic property of a ferromagnetic material, often used asa reference point for assessing magnet capabilities.

CURRENT - Movement of electricity along a conductor. Current is measured in amperes.

DIRECT CURRENT (DC) - A steady flow of electrons moving steadily and continually in thesame direction along a conductor from a point of high potential to one of lower potential. It is produced by a battery, generator, or rectifier.

EFFICIENCY (MOTOR) - the ratio of output to input (effectiveness of energy conversion).

ELECTROMAGNET - core of magnetic material, generally soft iron, surrounded by a coil ofwire through which electrical current is passed to magnetize the core.

ELECTROMAGNETIC FIELD - The magnetic field about a conductor created by the flow ofelectrical current through it.

ELECTROMAGNETIC INDUCTION - The process by which voltage is induced in aconductor by varying the magnetic field so that lines of force cut across the conductor.

ELECTRONIC CONTROL UNIT (ECU) - General term for any electronic controller.

ENGINE CONTROLLER - The electronic module that controls fuel delivery, diagnosticoutputs, back-up operation, and communications with other electronic modules.

GENERATOR - A device that converts mechanical energy into electrical energy.

INDUCTANCE - The property of an electric circuit by which an electromotive force (voltage)is induced in it by a variation of current either in the circuit itself or in a neighboring circuit.

INDUCTOR - A coil of wire wrapped around an iron core.

INVERTER - A device with only one input and one output; it inverts or reverses any input.

(MAGNETIC) LINES OF FORCE - Invisible lines that conveniently illustrate the characteristics of a magnetic field and magnetic flux about a magnet.

MAGNET - A body that has the property of attracting iron or other magnets. Its molecules are aligned.

MAGNETIC FIELD - The area near a magnet in which its property of magnetism can be detected. It is shown by magnetic lines of force.

MAGNETIC FLUX - The flow of magnetism about a magnet exhibited by magnetic lines offorce in a magnetic field.

MAGNETIC INDUCTION - The process of introducing magnetism into a bar of iron or othermagnetic material

MAGNETIC MATERIAL - Any material to whose molecules the property of magnetism canbe imparted.

MAGNETISM - The property inherent in the molecules of certain substances, such as iron, tobecome magnetized, thus making the substance into a magnet.

MOTOR - A device that converts electric energy into mechanical energy.

MUTUAL INDUCTION - Occurs when changing current in one coil induces voltage in asecond coil.

NATURAL MAGNET - A magnet that occurs in nature, such as a lodestone. Its property of magnetism has been imparted by the magnetic effects of the Earth.

PERMANENT MAGNET - A magnet that retains its property of magnetism for an indefiniteperiod.

POLARITY - A collective term applied to the positive (+) and negative (-) ends of a magnet orelectrical mechanism such as a coil or battery.

POLE - One or two points of a magnet at which its magnetic attraction is concentrated.

POWER DENSITY - The power to weight ratio of a motor.

PRINCIPLE OF TURNING FORCE - Explains how magnetic force acts on a current -carrying conductor to create movement of an armature, such as in an electric motor.

RECTIFIER - A device (such as a vacuum tube, commutator, or diode) that converts alternatingcurrent into direct current.

REGULATOR - A device that controls the flow of current or voltage in a circuit to a certaindesired level.

ROTOR - The rotating part of an electrical machine such as a generator, motor, or alternator.

SENSOR - A small coil of fine wire in the distributor on electronic ignition systems. The sensordevelops an electromagnetic field that is sensitive to the presence of metal. In monitors and controllers, they sense operations of machines and relay the information to a console.

STARTER MOTOR - A device that converts electrical energy from the battery into mechanicalenergy that turns an engine over for starting.

STATOR - The stationary part of an alternator in which another part (the rotor) revolves.

STORAGE BATTERY - A group of electrochemical cells connected together to generate electrical energy. It stores the energy in a chemical form.

VOLTAGE REGULATOR - A device that controls the strength of a magnetic field produced by a generator or alternator. It prevents the battery from being over or undercharged during high- or low-speed operation of the generator or alternator.

WATT-HOUR - A unit of electrical energy. It indicates the amount of work done in an hour by a circuit at a steady rate of one watt. That is, watthours = ampere - hours x volts.

WINDING - The coiling of a wire about itself or about an object. Often identified as a series winding, a shunt winding, etc.

About ePropelled:

ePropelled designs intelligent motors, motor controllers, and generators that help reduce energy consumption and improve system efficiency at a lower cost in the UAV, EV, and pump markets. We are a leader in magnetics engineering, and our patented technology and innovative smart power systems are equally at home in the air, on the road, and under water, defining the future of electric propulsion.

ePropelled has offices in the United States, Europe, and India and works with manufacturers of various types and sizes around the world. For more information, visit epropelled.com

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