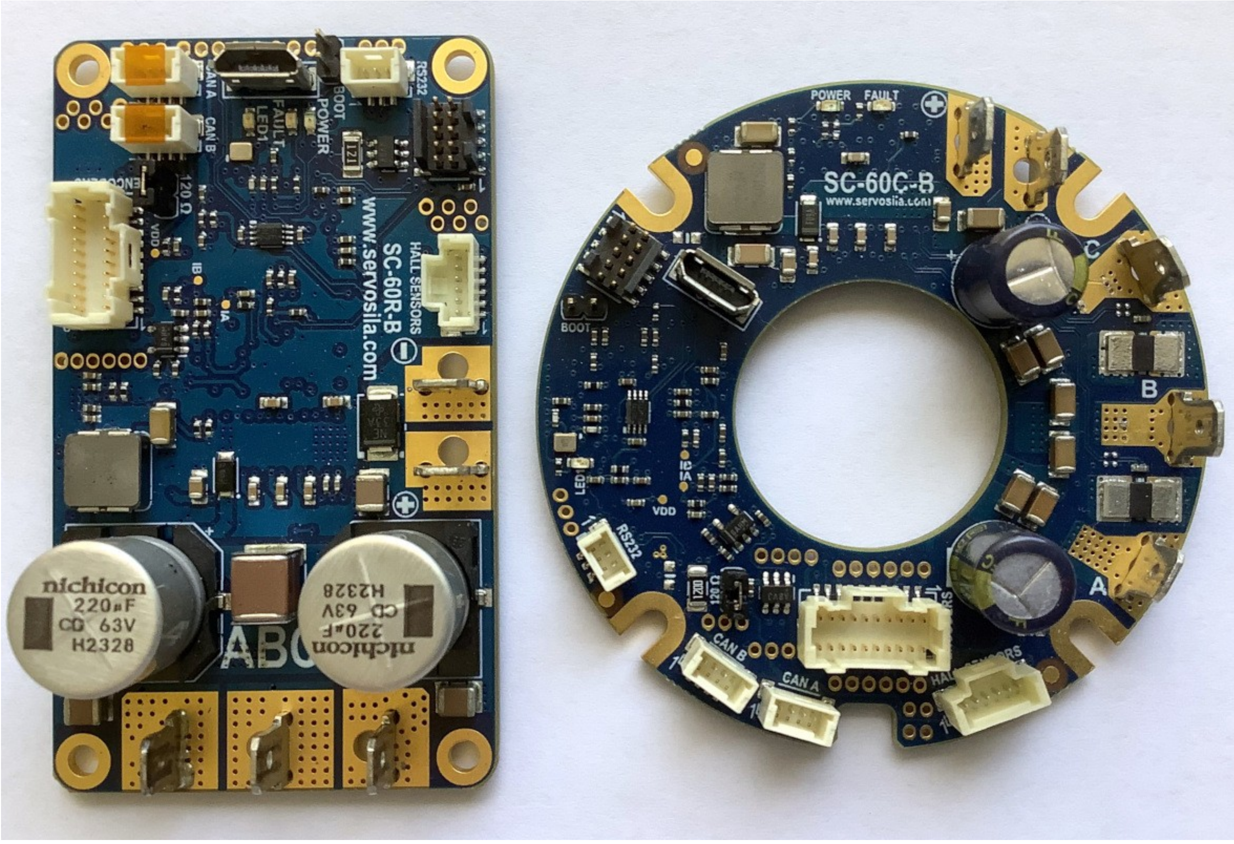
Using Servosila Brushless Motor Controllers as Starter-Generator Control Units

Application Note

Revision B



www.servosila.com/en/motion-control

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Introduction

Servosila Brushless Motor Controllers are efficient starter-generator control units for internal combustion engines or turbines. The "starter-generator control” is a built-in function of all models of Servosila brushless motor controllers. The rated DC power output is up to 850W for SC-series controllers (refer to the controllers’ datasheet).

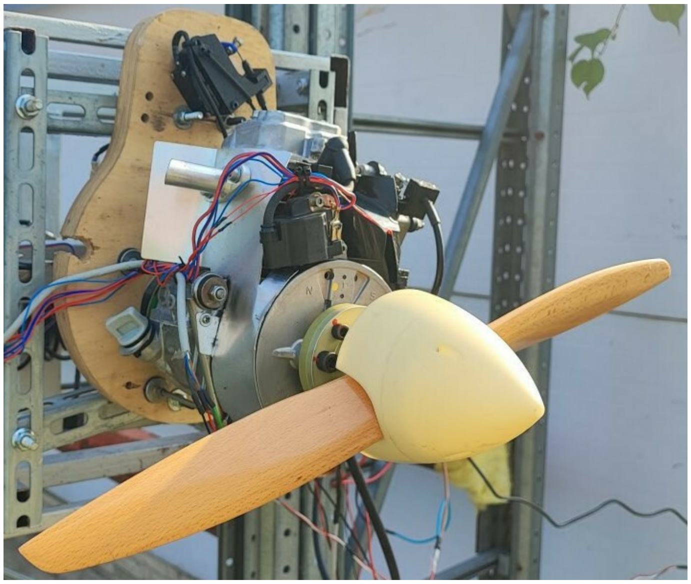


Figure 1: A sample converted Honda GX50 4-stroke internal combustion engine

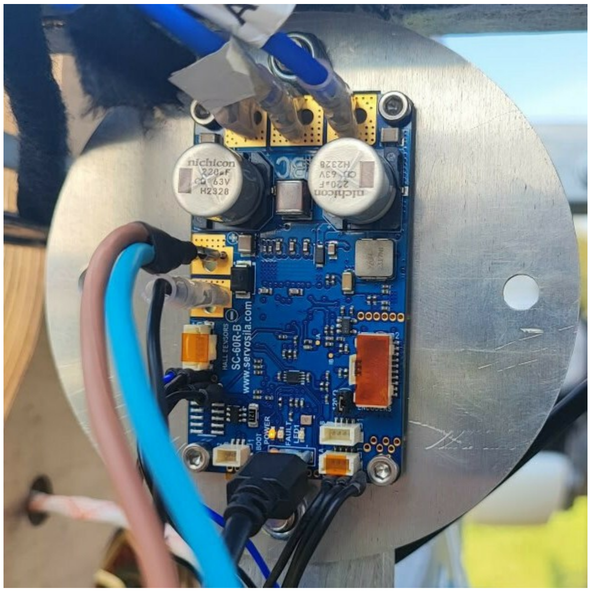


Figure 2: Servosila SC-60R Brushless Motor Controller

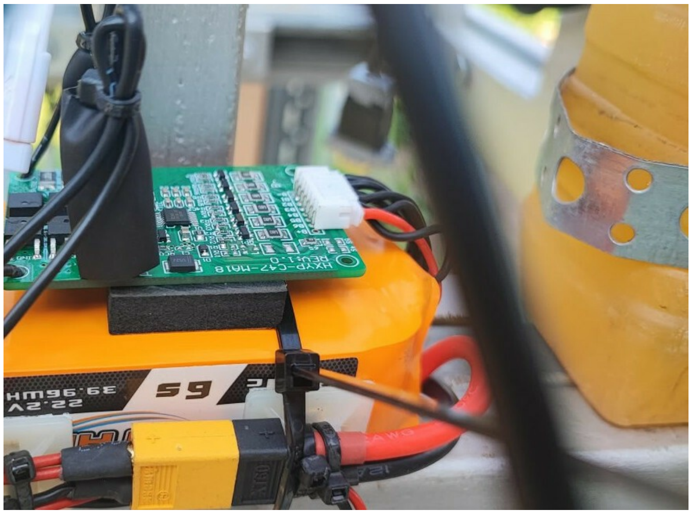


Figure 3: A 6S battery with a BMS

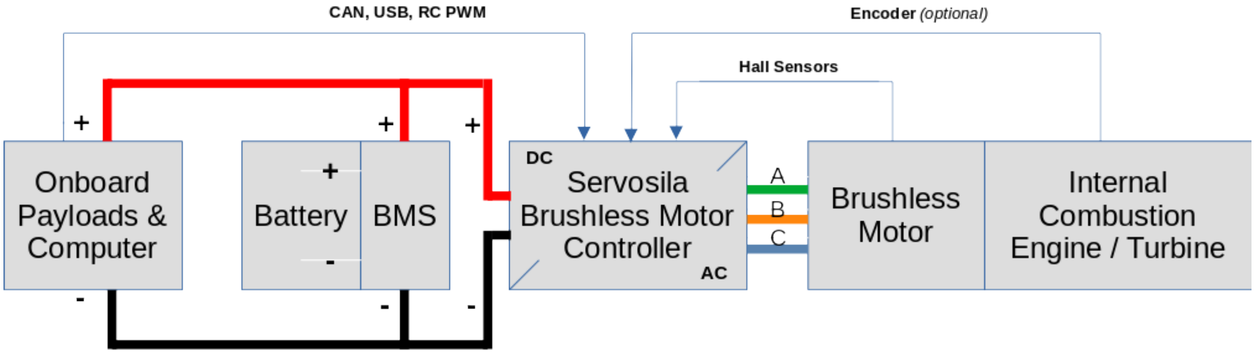
Figure 4: A brushless electric motor that acts a a stator and generator

Technical Specifications ("Starter-Generator" application)

Parameter	Description
Supported kinds of electric motors	Brushless Motors (PMSM) Sensored or Sensorless
Maximum Output Power	850 W
Battery Voltage	7-60 V DC
Maximum speed of internal combustion engine / turbine	72000RPM (up to 80000RPM with special tuning)
Auto configuration (system identification) function for brushless motors	Yes
Hall Sensors input (discrete)	Yes ("single-ended")
Interfaces to absolute position encoders	BISS-C (unidirectional), SSI, SPI, PWM, Quadrature with Index Signal ("single-ended")
Built-in network router	Built-in USB-to-CAN router («USB2CAN dongle»). Both 11bit and 29bit identifiers are supported by the routing function.
Control Interfaces	CAN bus with CANopen application protocol. USB 2.0, a virtual COM port, with SLCAN application protocol. RC PWM control interface
CANbus Terminal Resistor 120 Ohm	Yes (jumper controlled)
Supported CANbus bit rates	1 mbit/sec, 500 kbit/sec, 250 kbit/sec. 125 kbit/sec, 100 kbit/sec, 50 kbit/sec
CANbus ports	2 (parallel)
USB 2.0 ports	1
GPIO functions	2x Limit Switch inputs 1x Emergency Stop input 1x dedicated GPIO output (discrete or PWM signal) 1x dedicated GPIO input (discrete)
Software Simulator	Yes (included, free)
Dimensions: - Model SC-60R (rectangular) - Model SC-60C (circular)	 68mm x 40mm x 16mm Outer diameter: 60 mm. Inner diameter: 24mm. Height: 16 mm.
Weight	~50 g
Power consumption when idling	120-180 mA depending on connected peripherals

Principle of Operation

Functional Description



A basic onboard setup consists of an internal combustion engine / turbine, a brushless electric motor attached to the engine directly or via a belt or a gearbox, an onboard battery with a battery management system (BMS) and a Servosila brushless motor controller acting as both the brushless motor's driver and an AC-DC power converter. The brushless motor is selected to match specifications of the internal combustion engine and the onboard payloads. The brushless motor needs to be equipped with either Hall sensors or an absolute encoder or both.

Upon receiving a command from a control computer/autopilot, the Servosila controller drives the brushless electric motor to start up the internal combustion engine. Once the engine is started, the electric motor becomes a three-phase AC electric generator driven by the internal combustion engine. The Servosila controller then receives a command from the control computer to turn itself into an inverter that converts the three-phase AC voltage into a regulated DC voltage for onboard payloads and for charging the battery. The Servosila controller maintains a commanded output DC voltage despite changing RPMs of the internal combustion engine and despite changing power consumption of the onboard payloads. The output voltage is usually set to match the battery’s optimal charging voltage, so that the battery is charged on-the-fly. The output voltage reference can be adjusted by the control computer at any time.

The Hall sensors are mostly needed for starting up piston engines. The sensors enable the electric motor to generate a stable torque near Top Dead Centers (TDC) of pistons, where the startup torque is at its highest, but the rotational speed is at its lowest. The Hall sensors might not be needed for turbines, since turbines do not usually have a pronounced torque fluctuations during startup. Thus, turbines might be started up using a sensorless control method.

An (optional) absolute encoder is either a replacement or a complement to Hall sensors that improves speed measurement and torque at low RPMs as well as enables a range of advanced functions found in hybrid power plants. It also allows propellor servo-positioning for engine-off landings.

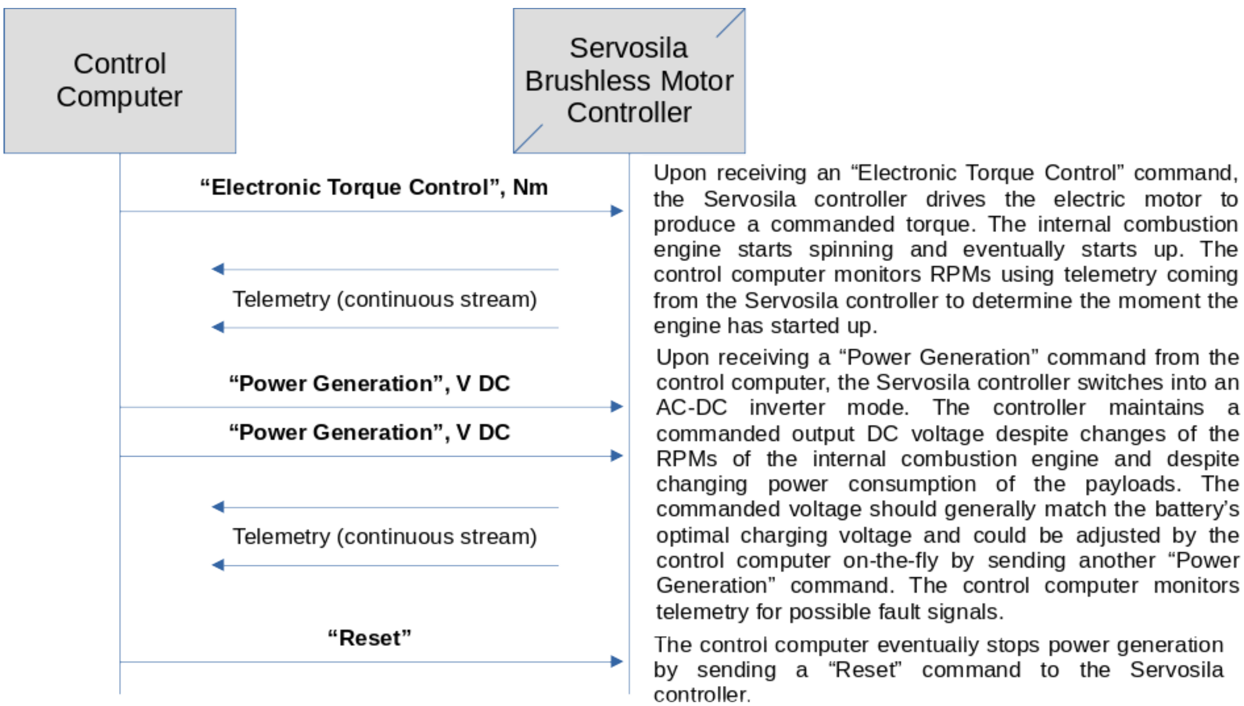
Note that the battery and the payloads are electrically connected in parallel in respect to the DC voltage supplied by the generator. This means that if the generated voltage drops below the battery’s voltage, the onboard payloads start drawing current from the battery until such time that the generator comes back online. Thus, the battery serves as a backup source of electric power in case of issues with the generator or its controller.

Control Protocol

Servosila Brushless Motor Controller receives commands from a control computer and returns telemetry back via the following network interfaces:

- a CAN/CANopen interface (primary),
- a USB interface, a virtual COM port with a text protocol, or
- via an RC PWM interface.

A typical protocol message flow is as the following:



There are several applicable CANopen commands that allow an autopilot/control computer to manage a Servosila controller that plays a role of a "starter-generator" control unit:

- The **"Electronic Torque Control"** command that takes a torque reference in N*m as a parameter, is used to initiate the engine start up routine. The commanded torque should be sufficient to start up the internal combustion engine under every practical condition. Upon receiving an "Electronic Torque Control" command, the Servosila controller starts driving the electric motor to produce the commanded torque. The internal combustion engine starts spinning and eventually starts up. The control computer should monitor the RPM telemetry coming from the Servosila controller to determine the moment the engine has started up. Alternatively, the control computer might use other means of determining the moment when the engine starts up.

- The **“Power Generation”** command that takes a DC voltage reference in volts (V) as a parameter, is used to switch the Servosila controller into an AC-DC conversion and voltage regulation mode. Upon receiving a “Power Generation” command from a control computer, the Servosila controller starts maintaining the commanded DC voltage output despite of changes of the RPM of the internal combustion engine and despite of changes in power consumption by the onboard payloads. The commanded voltage should generally match the battery’s optimal charging voltage and could be adjusted by the control computer on-the-fly by sending another “Power Generation” command. The voltage should in most cases be slightly higher than the battery voltage, so that the onboard payloads to not draw current from the battery. The control computer is expected to monitor voltage telemetry and fault signals and react to irregularities.
- The **“Reset”** command disables “Power Generation” mode. The control computer can stop power generation at any time by sending a “Reset” command to the Servosila controller. It is allowed to send a “Reset” command to temporarily stop power generation, and then restart it again by issuing a new “Power Generation” command. While the power generation is stopped, the onboard payloads draw current from the onboard battery.

Note that “Electronic Torque Control” and “Power Generation” commands need to be sent **continuously**. Otherwise, the controller assumes there is a failure in either the control computer or the CAN network, and shuts off as a safety measure.

Servosila controllers come with built-in overcurrent and short-circuit protections that shut off their inverters whenever the output current goes above a hardware limit. The controllers can be restarted “in flight” after such a fault by sending a “Reset” command, followed by a new “Power Generation” command.

Refer to the brushless motor controller’s “Programming Guide” and “Device Reference” documents for a complete list of supported commands and telemetry parameters and to get binary message formats.

Voltage Regulation

Brushless electric motors come with coils in their stators. Servosila Brushless Motor Controllers use the motors’ coils for boosting output DC voltage via a method similar to “boost converter” or “step-up converter” method. The key principle that drives a boost converter is the tendency of an inductor to resist changes in current by either increasing or decreasing the energy stored in the inductor's magnetic field. The Servosila controller employs the inductance of stator coils to generate a current that charges a network of capacitors at the output side of the controller. The “step-up converter” method is known for its overall efficiency.

The Servosila controller comes with a voltage regulator that keeps the capacitors charged to a commanded output DC voltage. The voltage regulator is activated by the “Power Generation” command that takes a voltage reference as a parameter. Typically, the commanded output DC voltage is maintained slightly above the battery's voltage, so that the battery is charged while also supplying power to onboard payloads and a control computer.

Note that Servosila controllers regulate the output voltage, but not the output current or power. Given the voltage, a steady-state output current is defined by an internal resistance of the battery and its BMS as well as by an effective resistance of the onboard payloads (via Ohms Law). Servosila controllers come with built-in overcurrent and short-circuit protections that shut off their inverters whenever the output current goes above a hardware limit.

Selection Criteria for a suitable Brushless Electric Motor

Most off-the-shelf brushless motors equipped with Hall sensors or Encoders can be used in the starter-generator application. In practice, however, the selection is significantly narrowed down due to the need to match the brushless motor to a given internal combustion engine as well as to a consumption profile of the onboard payloads.

Here is a set of rules that help select a suitable brushless electric motor.

Rule #1: The brushless motor must be compatible with the Servosila Brushless Motor Controller.

Refer to the Servosila controller's datasheet document to verify if a given brushless motor can be driven by the controller. *We are not going to copy the verification rules from the datasheet into this document. Just check for those rules in the datasheet. Then come back to this document to continue with further verifications specific to the "starter-generator" application.*

Rule #2: The "no-load" speed of the brushless motor, a datasheet value, MUST be higher than the maximum speed of the internal combustion engine. Otherwise, the electric motor is not suitable.

For example, if the maximum speed of an internal combustion engine is 8000RPM and the "no load" speed of a brushless motor at the onboard battery's voltage is 10000RPM (higher with a margin), then this brushless motor is suitable for use with the given engine.

There is a catch to watch out for, related to the input voltage at which the "no-load" speed is given in the motor's datasheet. In general, the "no load" speed of a brushless motor is (nearly) proportional to the input voltage; the higher the voltage, the higher the "no load" speed is. For use with this verification rule, the "no load" speed must be measured at the input voltage that is equal to the voltage of the onboard battery. Otherwise, the "no-load" speed taken from the motor's datasheet, must be adjusted.

To adjust the datasheet value, use a simple proportion rule. For example, lets say, a brushless motor's datasheet says that at 24V input the "no-load" speed is 10000RPM. However, a chosen onboard battery has a different voltage of 28V (note the 28V vs. 24V difference). So, it is required to adjust the "no-load" speed proportionally as the following: (28.0V / 24.0V) * 10000RPM = 11667 RPM. This adjusted "no-load" speed needs to be used for comparison against the maximum speed of the internal combustion engine.

An alternative method, using Kv constant:

The "no load" speed can also be computed using Kv constant of the motor, another datasheet value, as the following: **RPM_no_load = Kv * Voltage_battery** For example, if Kv constant is 450RPM/V and the onboard battery voltage is 28V, then the "no load" speed is 450RPM/V*28V = 12600RPM.

Some brushless motors' datasheets do not provide information about their "no-load" speeds. Instead, a datasheet might provide an alternative value, such as a maximum speed of the brushless motor with some standardized load such a propellor of a particular size. Since a "no-load" speed would always be higher than a speed with a load, it is safe to use the "loaded" motor's speed for comparison against the RPMs of the internal combustion engine.

Piston engines experience sudden accelerations (jolts) during power stokes, when fuel is burnt, and significant decelerations during fuel mixture compression strokes. It is important to use the engine's peak momentary RPMs achieved during power strokes (vs. average RPM) when comparing against the brushless motor's "no load" speed. If in doubt, pick a brushless motor with a significant margin in its "no load" speed in relation to the internal combustion engine's maximum RPM.

If a belt or a gearbox is used to amplify the torque of a brushless motor, the datasheet's "no load" speed of a selected brushless motor must be higher than the highest speed the internal combustion engine can ever accelerate the brushless motor to, when acting through the belt or gearbox.

What happens if the "no load" speed is exceeded, is that the Servosila controller is no longer capable of regulating the output DC voltage, so over-current hardware protections kick-in, the inverter circuitry shuts-off, and power generation stops.

To summarize, in the generator mode, the brushless motor should never exceed or even closely approach its "no load" speed, so that controllability of the DC voltage output is maintained.

Rule #3: Electrical Speed Limit

The following relation MUST hold:

(RPM_max/60) * (Poles/2) < 1200 Hz (or up to 1400 Hz with some special tuning),

where **RPM_max** is the maximum speed (RPM) of the internal combustion engine, and **Poles** is the number of rotor poles of the brushless motor, a datasheet value.

This relationship tells that **higher-speed internal combustion engines require brushless motors with smaller number of rotor poles**. The faster the internal combustion engine is, the smaller the number of poles a matching brushless motor should have. This limit is imposed mostly by a finite performance of an embedded CPU used by Servosila Brushless Motor Controllers.

Note that the smallest possible number of rotor poles is 2, which implies that the maximum RPM limit is about 80000RPM.

Rule #4: The brushless motor's torque must be sufficient to startup the internal combustion engine.

Starting a piston engine might require much torque. The brushless motor should be able to generate enough torque to rotate a piston engine through its Top Dead Centers (TDC), where the startup torque is at its highest, but the rotational speed is at its lowest. *For example, it takes about 0.85Nm of torque to start up a Honda GX50 4-stroke engine.*

Note that higher torque often implies a higher number of rotor poles or/and a lower "no load" speed because of lower Kv constants. However, there is a limit on the number of rotor poles due to a limit on the maximum electrical speed (see a rule above) and a limit on how low the "no load" speed could be as compared to the maximum RPMs of the internal combustion engine (see another rule above). These trade-offs might significantly narrow down the selection of applicable brushless motors.

Note that it is usually allowed to push a higher short-term peak current through the brushless motor to temporarily increase its torque. Torque is proportional to the current.

It might sometimes be required to use a belt or a gearbox as a means of increasing the torque.

Rule #5: Use a brushless motor with a sinusoidal Back-Emf form. Avoid using BLDC motors with trapezoidal Back-Emf forms.

Many brushless electric motors have a sinusoidal Back-Emf form. However, some motors, usually called "BLDC motors", have a trapezoidal Back-Emf form. Avoid using such BLDC motors for the starter-generator application. Find a suitable brushless motor with a sinusoidal Back-Emf form.

Rule #6: Sufficient Output Power

The brushless motor draws power from the internal combustion engine. The brushless motor needs to be sized properly, so that it draws enough power for onboard payloads and for charging the battery at the same time. As the mechanical power is converted into electrical power, the physic's law of power balance governs the formulae for sizing of the brushless motor as the following:

The following relationships MUST hold **with a margin**:

I_requirement < (P_at_idle_rpm / V_battery) * 0.90

I_requirement < (P_at_max_rpm / V_battery) * 0.90

where

P_at_idle_rpm, in **Watts**, is a peak mechanical power output of the brushless motor measured at RPMs equal to RPMs of the idling internal combustion engine. *Note that the power is the one of the brushless motor, but the RPMs are the ones of the idling internal combustion engine.*

P_at_max_rpm, in **Watts**, is a peak mechanical power output of the brushless motor measured at RPMs equal to maximum RPMs of the internal combustion engine. *Again, the power is the one of the brushless motor, but the maximum RPMs are the ones of the internal combustion engine.*

I_requirement = I_charging + I_payloads, in **Amps**, is a maximum total current requirement of the battery, when charging, and the onboard payloads.

V_battery, in **V DC**, is a nominal voltage of the onboard battery. *This is also the nominal output DC voltage produced by the Servosila controller.* Note that the output DC voltage is tightly regulated by the controller and is usually set to be slightly higher than the voltage of the onboard battery.

Sample power computations:

Peak current requirement is 7A (payloads + battery charging). The battery voltage is 28V DC.

Internal combustion engine's range of RPMs is 2500RPM (idling) to 8000RPM (max).

Mechanical power output of the brushless motor at 2500RPM is 300W, a datasheet power curve value.

Mechanical power of the brushless motor at 8000RPM is 480W, a datasheet power curve value.

7A < (300W / 28V) * 0.90 **[OK with a margin]**

7A < (480W / 28V) * 0.90 **[OK with a margin]**

Note that a maximum of mechanical power produced by a brushless motor varies with RPMs. The power output initially grows with RPMs, but eventually decays to zero at the “no load” speed of the brushless motor. This is another reason why the “no load” speed of the brushless motor should be significantly higher than the maximum speed of the internal combustion engine (see a rule above).

Brushless motors as well as internal combustion engines have their distinct power efficiency curves in respect to RPMs with pronounced efficiency peaks. Whenever possible, it is best to select (or design if budget permits) a brushless motor with an efficiency peak closely aligned to an efficiency peak of the given internal combustion engine / turbine.

There is also as hardware limit on the maximum output power for Servosila Brushless Motor Controllers.

Rule #7: Hall Sensors or Encoder

Choose a brushless motor with Hall Sensors or an Encoder if a given internal combustion engines has significant ripples in startup torque.

Soldering, Cables, Connectors & Enclosures

Due to high levels of vibration inherent in the “starter-generator” application, it is recommended to solder brushless motor phase leads as well as DC power leads directly to the PCB, rather than using its connectors. Furthermore, in high-current applications, much heating happens in the phase connectors, so, from the thermal management point of view, it is also recommended to eliminate the connectors and solder the wires directly to the blades or to the PCB itself. When using the power connectors, make sure the connectors are tightly snapped in the blades.

Consider adding a heat sink. There are 2 large ICs at the back of the board (a CPU and a driver chip) and 6 MOSFET transistors. Those 2+6 chips should be connected to a heat-sink via thermal paste.

In vehicle-mounted applications, it is almost necessary to add an enclosure with vehicle-grade connectors, and solder internal wires directly to the PCB, while exposing the enclosure’s vehicle-grade connectors to the outside. The enclosure could also serve as a heat-sink. A Servosila Brushless Motor Controller can be seen as a module component designed for building such vehicle-mounted systems.

Simulation

Servoscope, a software tool that accompanies all Servosila controllers, comes with simulation capabilities related to the “starter-generator” application. The tool helps profile an brushless electric motor that matches an internal combustion engine as well as onboard payloads.

Advanced Features

If an absolute encoder is available in the setup, a range of advanced applications becomes available. For example, in a hybrid power application, an electric motor could be used to assist a piston engine during fuel-mixture compression strokes, while extracting the power during fuel burning strokes.

It becomes possible to rotate the propeller into a safer position for engine-off landings.

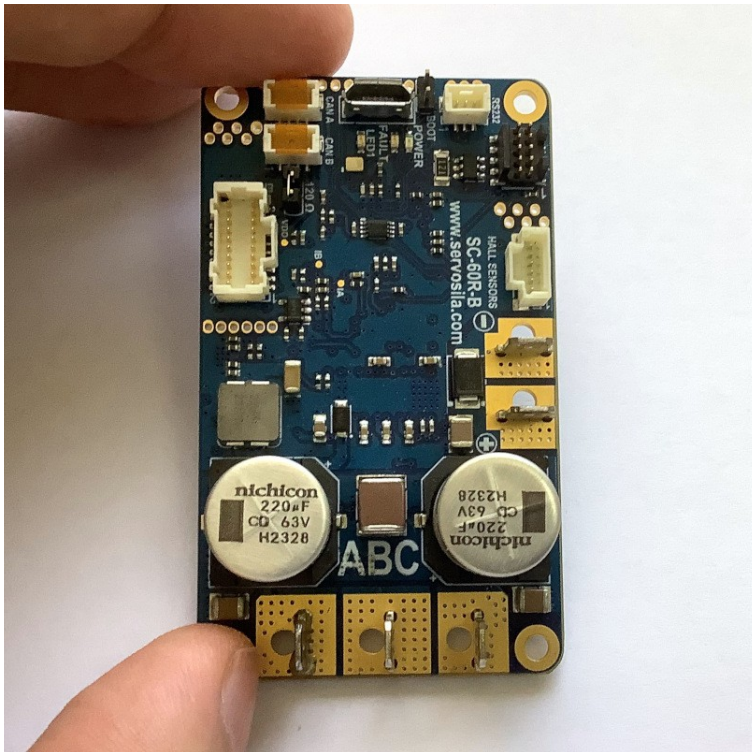


Figure 5: Servosila SC-60R Brishless Motor Controller

YouTube: http://www.youtube.com/user/servosila

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