Stator Regulator Simulations

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Introduction

The stator type of electrical generators is a popular type of electrical power source for small engines where there is a fairly well defined small electrical load. Typical applications are motorcycles, ATVs and yard equipment. It is usually preferred because it is easy to implement and low cost. For higher electrical loads, the alternator type of generator is preferred. The stator electrical generator does have a number of drawbacks which lead to reliability issues and wear on the battery supporting the electrical load. These are:

1)High ripple current on the battery

2)Poor regulation of the battery charge voltage

The theory of operation of the stator generator is straightforward. It just consists of a permanent magnet which is rotated by the engine and a stator which is in the magnetic field. The magnetic field is defined by the permanent magnet. The open circuit voltage out of the generator is defined by the equation:

$$e = -N\frac{d\Phi}{dt}$$

Where e is the voltage, N is the number of turns and dphi/dt is the rate of change of the magnetic flux. Some of the key things to note from this equation is:

-The open circuit voltage will depend on the engine speed.

-This voltage can be pretty high (up to 75V or more depending on the engine speed)

In the application, there will be current induced into the stator. This current will create a magnetic field that will oppose the magnetic field from the permanent magnet.

$$\Phi = \frac{Ni}{R}$$

Where Φ is the magnetic flux, N is the number of turns, i is the instantaneous current in the winding and R is the reluctance of the magnetic path.

The key things to note from this equation is that the maximum current in the winding is limited by the reluctance, the number of turns and the magnetic field of the permanent magnet. Since the current is limited by the design of the stator and the magnetic path, it is possible to stop the conversion of mechanical energy to electrical energy but just shorting the stator winding out.

For the simulation models, I will use the electrical system of a 1983 Suzuki GS400 motorbike. In tests, this stator system has an open circuit voltage of 75V AC at 4000RPM and a short circuit current of 10A. Modelling this with lumped element parts, we will use a 10A current source in parallel with a 7.5 ohm resistor. Since the voltage depends on the engine speed, the resistance (hence voltage) will change with engine speed.

For the simulation models, we are also going to use only a single phase. The same theory holds true for 3 phase systems.

Another important note is that the 7.5 ohm resistor is just for modelling purposes. In the open circuit configuration there is nothing that will be dissipating the power of the resistor (75W in the example). In reality what happens is that the engine is going to encounter physical resistance to the permanent magnet approaching the coil. When the magnet is moved away from the coil, the physical force will push the magnet away from the coil returning the energy to the mechanical source.

The next part is a bridge rectifier. For the simulations I will use an idealized bridge rectifier. There is the addition of a 10K resistor to ground. This will not impact the simulations but provides a ground reference for the calculations when the diodes are not conducting.

Now the load. Most of the electrical loads (lights, motors, etc) will look like a resistive load. I will use a resistive load of 50W at 12VDC in the model. This will look like a 2.88 ohm load. The circuit so far is shown in Figure 1. The voltage waveform is in Figure 2.

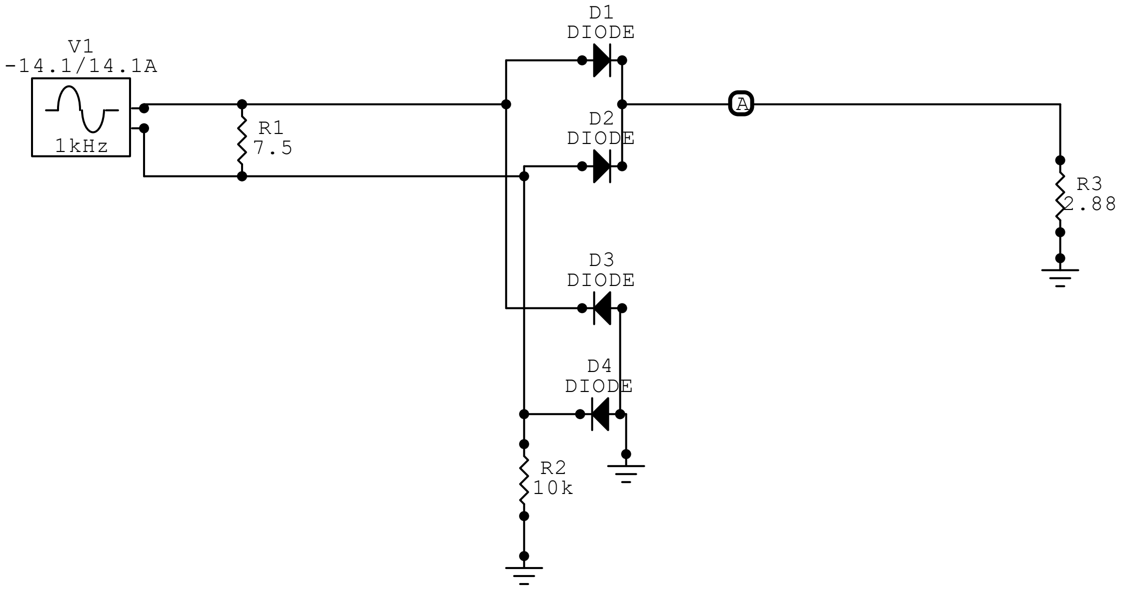

Figure 1 - Simulation circuit for stator and bridge rectifier

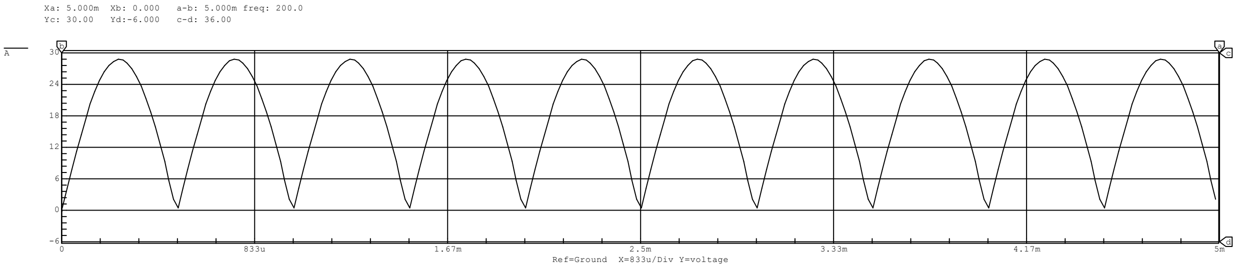

Figure 2 - Voltage waveform on the load

The DC average voltage on the load of the circuit is around 18.19VDC. This does not have a battery to smooth the voltage and is pretty ghastly. This might be useable for running light bulbs but not much else. The deep valleys would have difficulty providing enough voltage to fire the ignition system.

Battery Ripple Current

Now adding a battery to the circuit. The model for this is a voltage source in series with a resistor. I will use 12.6V for the nominal battery voltage and 0.1 ohms for the battery resistance. This resistance will change over the life of the battery and whether it is charged or discharged. The circuit is shown in Figure 3. It can be seen that the output voltage is much better behaved in Figure 4. This voltage is stable enough for the electrical system to function but there are still problems. As can be seen the battery current waveform, there is a large RMS current on the battery. The battery has a DC current caused by the error between the AC source and the battery. In reality, the DC current will just increase the internal pressure in the battery which increases the DC voltage of the battery and limits the current.

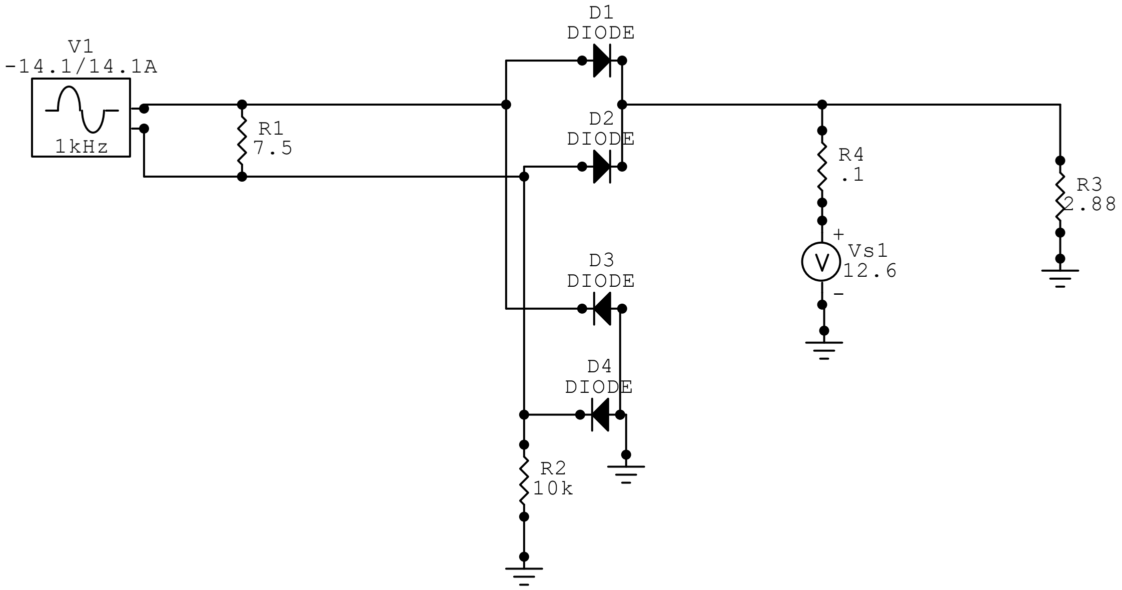

Figure 3 - Circuit with the battery in it

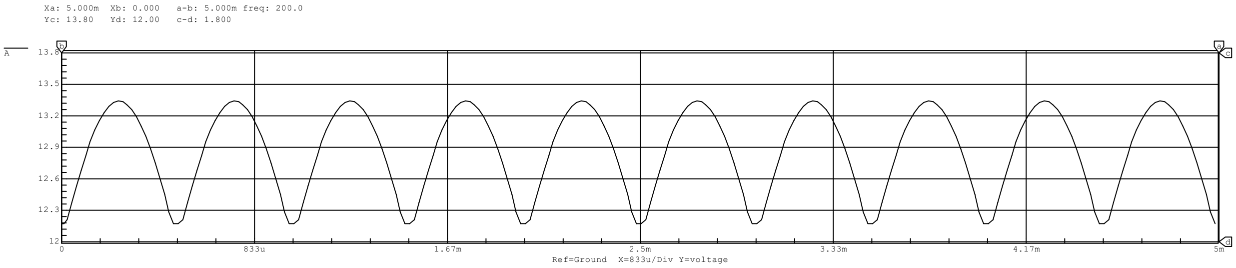

Figure 4 - Battery voltage

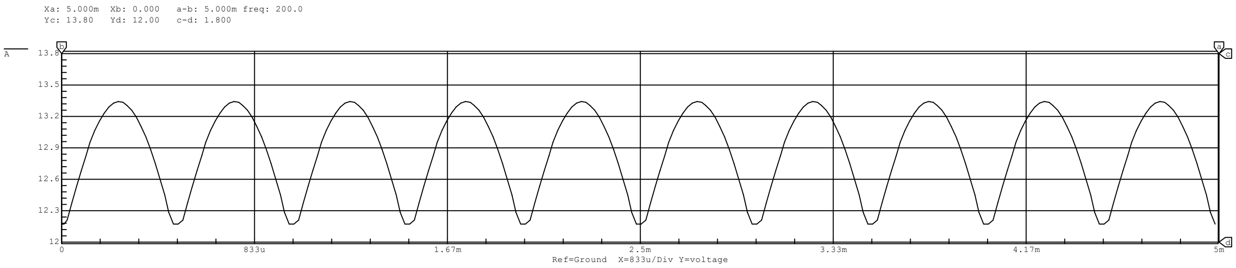

Figure 5 - Battery current

In this circuit the battery has to support the external accessories during the drops in the output from the bridge rectifier with a ripple current of 3.973A RMS. This ripple current will heat the battery and wear out the chemistry in the battery reducing the service life.

This regulator is similar to circuits used in the 1960s era motorbikes with flooded lead acid batteries. They are high maintenance because the water in the battery needs to be topped up as it evaporates.

To summarize, the deficiencies with this circuit are:

- Regulation provided by the electrolysis of water which makes the system high maintenance.
- High ripple current on the battery reduces its service life.

Single phase SCR regulator

To address the battery over charging issue, an SCR/Triac circuit is added to short out one of the stator windings. This is implemented with the voltage controlled switch. There are some additional parts added to get the simulation to run. The high transition speed of ideal switches tends to cause the simulation to fail. C10 addresses the reverse recovery of the bridge diodes. R5/C2 low pass filters the input to the switch so it does not bounce and oscillate on high frequency noise.

The circuit is in figure 6.

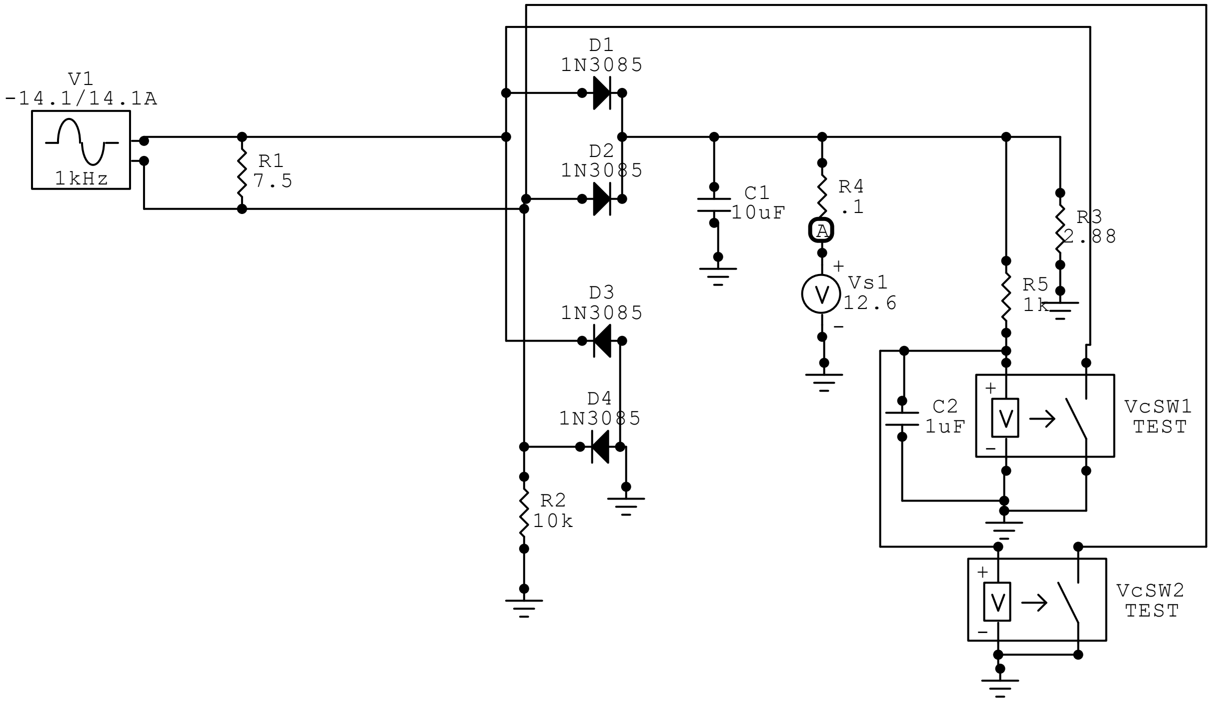

Figure 6 - Circuit with regulator

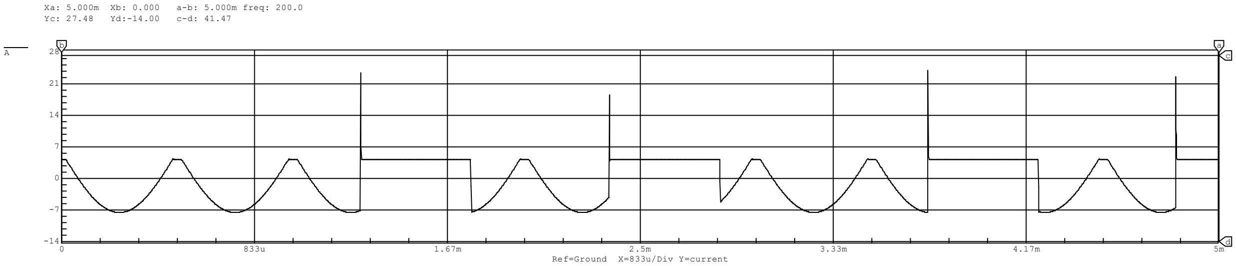

Figure 7 – Current waveform

The current waveform for the battery is shown in figure 7. There are a few things to note. When the switches fire, all of the current of the load is supplied by the batteries. With 3 phase systems the AC RMS current on the battery due to rectifying the AC waveform is much lower but the RMS current for riding through the time where the shunt switches are on will remain the same. In this example the RMS current of the rectified AC is 3.973A and the total RMS of the circuit is 4.701A. This will result in an RMS current on the battery of 2.51A just due to having to support the load when the stator windings are being shunted. What this means is that there is significant stress on the battery which reduces the service life.

This circuit is typical of regulators designed for specific vehicle electrical systems. You may notice there may be additional wiring between the stator and the rectifier to limit the range of loads this circuit will see in the application. In 3 phase systems, the circuit only regulates over a load variation of approximately 66% to 100% of full load with a single SCR. The control circuit is usually just a zener diode which triggers the SCR at a specific voltage.

Efficiency of this circuit is not very good as the forward diode losses of the rectifiers runs at about 1.1V. The SCRs have a forward drop of 2V. This means that for a 10A load, you are looking at having to dissipate 22W in the rectifiers. This is why many rectifier/regulators have heat sinks on them with lots of fins for cooling. The heat also prevents temperature compensation for the battery temperature because the regulator will be a lot hotter than the battery. It would require an external temperature sensor to get an accurate battery temperature.

To address the regulation range problem, it is common to have SCRs on multiple phases so they can all be disabled if the battery voltage is high. This provides regulation from 0 to full load. This type of circuit tends to be used for the regulators that are for multiple

To summarize, the deficiencies of the multiple SCR circuit are:

- High dissipation/No temperature compensation
- High battery AC current stress

The deficiencies of the simple control circuit are:

- It can be damaged if the battery voltage is higher than the regulator set point. This can be from boosting the equipment, charging the battery from an external charger, or anything else that brings the battery voltage above the regulating voltage. Most of these conditions can be fixed with the addition of a few extra parts.
- Cannot compensate for battery resistance or temperature.

Most of the low cost universal regulators (the $10.00 to $20.00 parts on amazon) are of this type of design.

Control Circuit Issues

The next stress that decreases the battery life is the set point of the charge voltage. The detectors typically used for the switches in Figure 6 are almost always just a zener diode hanging off an SCR/Triac gate. This is a peak detector. The charging of the battery depends on the average voltage of the battery. As the battery gets older or discharges, the resistance will go up. This means that the actual voltage charging the battery will go down. In the example, the battery is replaced by a 1mF capacitor and the trigger setpoint are both at 14.4V. The reason for changing to a capacitor is that the battery voltage will eventually settle on the voltage as determined by the regulator and the system will stabilize at this voltage. The electrical model of the switches shown in Figure 6 is not accurate in that the switches release when the battery voltage drops off where with the SCRs, the switch will fire and stay on until the end of the cycle. This means that we have to use a model that includes this effect. To do this an SCR was added to the circuit.

Resistance	Average voltage
0.02	14.21
0.05	14.31
0.1	14.00
0.2	13.23
0.3	12.62
0.4	11.92
0.5	11.30
0.6	10.58

The effect of this would be that as the battery gets older or discharged, it will have a higher resistance which will prevent the battery from charging. This problem is a positive feedback loop which causes older batteries to become unuseable. If the system is set to 14.2V for fast float charge on a new battery with 120 amp capacity, when it gets down to 30% capacity (0.3 ohms) it will only see an effective charging voltage of 12.62V. This will not effectively charge the battery, break down sulphate crystals, or maintain the battery in a good state. Placing the battery on a smart charger will recover it to some degree, but it will eventually fall into the positive feedback loop and strand the rider (especially on short commuter trips).

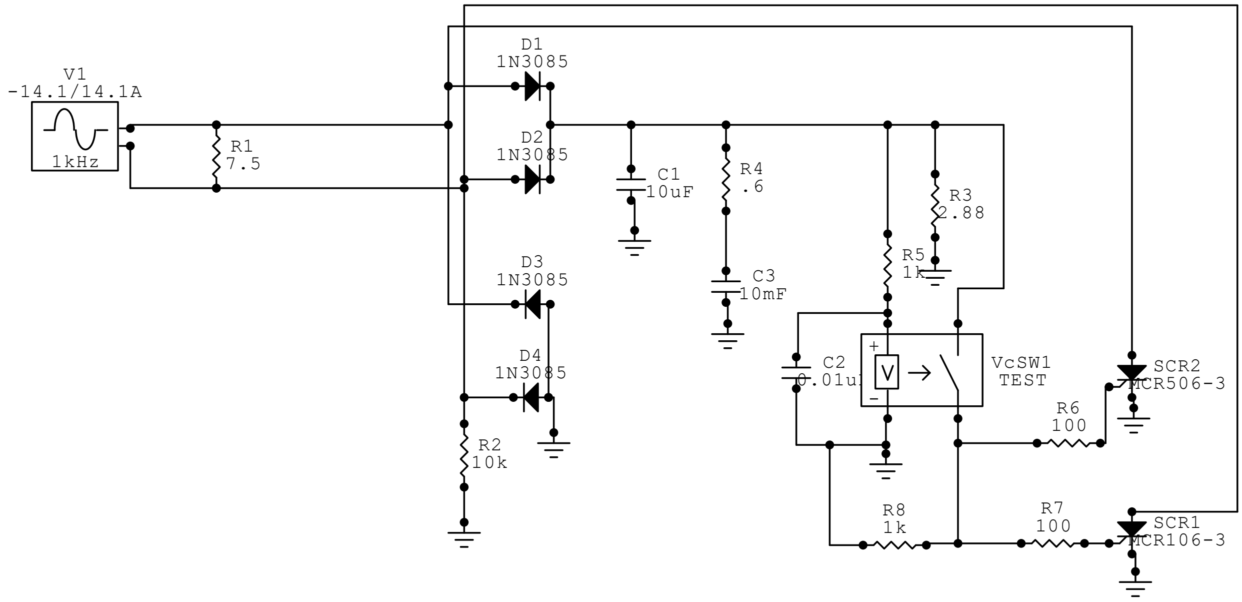

Figure 8- Regulator circuit with SCRs

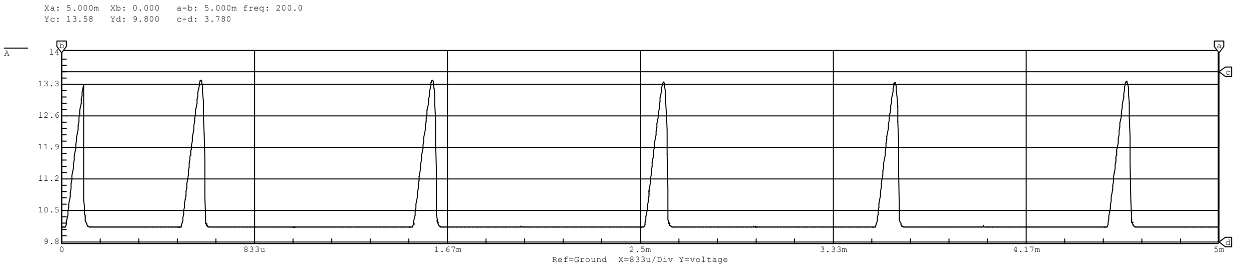

Figure 9 - Battery Charging voltage

Temperature Compensation

The existing regulator solutions also do not include features such as temperature compensation and smart charging. The temperature compensation keeps the battery charged properly whether it is in cold use (for snowmobiles) or high temperature applications (like motorbikes in the summer). At 50C, the charge voltage should be 13.85V+/-0.3V. At -20C the charge voltage needs to be 16.32V+/-0.3V. Needless to say, a regulator designed for low temperatures needs to be at a different voltage than one used at high temperatures.

The smart charging features are useful for breaking down sulphate crystals that will develop in the battery during long periods of storage or non use.

MOSFET Rectifiers

To address the issue of heat dissipation, MOSFET rectifiers can be used. In this case, the rectifying elements and the SCRs are replaced with mosfets and a control circuit. The VREGxx series of rectifier/regulators uses this type of design. In that case, the losses of the mosfets are now I^2*Rds. For a 4 mohm mosfet at 10A, the power dissipation is 0.4W per device (or about 0.8W for a bridge). In shunt mode, the current is a bit higher but only in one of the devices for a total power of 0.9W.

This is the type of design most “Mosfet Rectifier” rectifier regulators use. They can also add compensation for temperature and some compensation for battery resistance in the control loop.

Output DCDC converter

By using a capacitor on the output of the rectifier and a DCDC power converter, the high ripple current of the shunt regulators can be handled by capacitors. Capacitors can handle the stress much better than a battery. The output of the capacitors is fed into a DCDC converter. This provides a steady state DC voltage to the battery and the rest of the charging system.

Summary

This approach is used in the VREGxx series of regulators to provide a steady DC voltage with compensation for temperature. Compensation for battery ESR is not needed since it is a DC output. It also supports an automatic fast charge(for breaking down sulphate crystals) and a float charge (for reduced battery internal pressure).

The resulting feature set is:

- High efficiency (losses less than 6W for the VREG20
- Temperature compensated for wide temperature application
- Long battery life
- Useful in many applications (recreation vehicles, marine, and many others)
- Small, light design (no heavy heat sinks)
- Easy to install

Document Revision

Revision	Change
1.0	Initial release