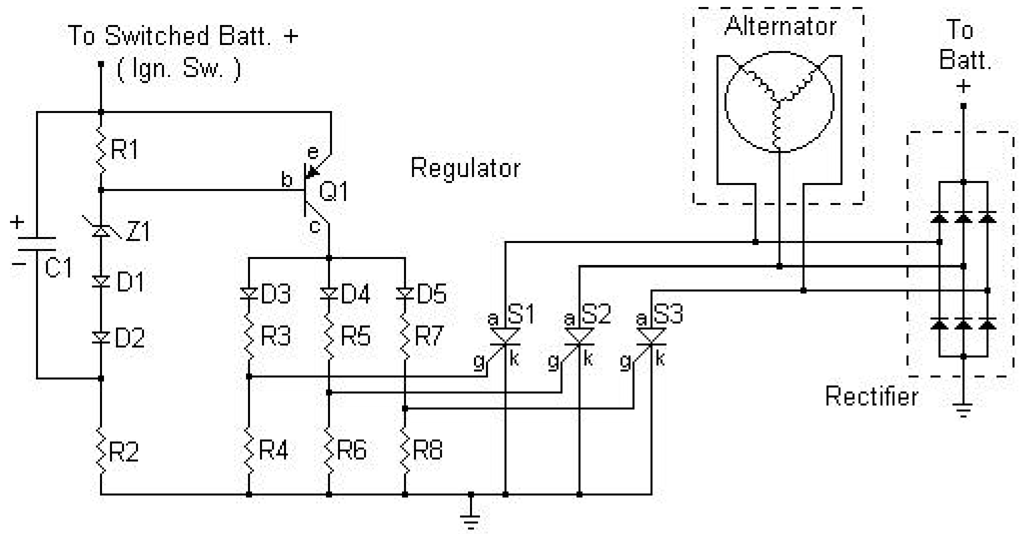
Introduction:

This design is a voltage regulator for a 3-phase, permanent-magnet alternator typically found on modern motorcycles. The same design can be used for single-phase alternators simply by eliminating some parts. This project only describes the regulator, even though a rectifier is typically integrated into the unit.



Circuit Analysis:

Please refer to the circuit diagram during the analysis of the circuit.

Overview:

The way this type of regulator controls the alternator's output voltage is by simply shorting out the stator winding for one cycle of the ac waveform. This is called shunting. This is done because it is much easier to short-circuit an inductor (the stator winding is an inductor) than to open-circuit an inductor. Very high voltages are induced when an inductor circuit is opened. This may cause a breakdown in the winding's insulator.

The device used to shunt one cycle of one phase is an SCR. A silicon-controlled rectifier acts as a diode when triggered at its gate. It stops conducting when the current drops below a very low threshold value. Once it stops conducting, it will not conduct again until it receives another gate signal.

A voltage detection circuit is used to trigger the gate on each of the three SCRs. The threshold voltage to trigger the gate is selected as 14.6volt (on the motorcycle's system-voltage). This is when the gate would trigger if there were no capacitor as described in the next paragraph.

Since the voltage from an alternator fluctuates, the detection circuit will trigger during a peak in the waveform of one of the phases, but this causes the average voltage to be too low. To raise the average system-voltage without increasing the detection threshold, a simple capacitor is used to delay the triggering of the SCR gates. The capacitor acts as a filter to reduce the ac ripple going to the detection circuit. If the system voltage was strictly DC voltage (with no ripple) the gate would trigger at 14.6v and the average voltage would be 14.6v. In reality, the average voltage is always less than the threshold voltage and only approaches it as the ripple reduces. The actual trigger voltage is higher than 14.6v, but the average voltage is lower than 14.6v. As the ripple reduces, the average and trigger voltages approach 14.6v.

R1, Z1, D1, D2, and R2 make up the detection circuit. R1 allows for an "idle" current to flow through the detection circuit so the Zener diode Z1 and regular diodes D1 and D2 are in the linear portion of their operating range. As the motorcycle's electrical system-voltage increases past a set threshold, Q1 starts conducting. This sends current to the gates of the SCRs. D3-

D5 act to isolate the gates from each other. R3, R5, and R7 act as current limiting resistors for the gates. R4, R6, and R8 act as drains for any possible leakage in Q1.

To determine the values of the components, it is probably best to start at the output and work toward the input.

Selecting S1-S3:
S1 through S3 must shunt a large amount of current to reduce the alternators output voltage. Typically this may approach 15 or 20 amps for short periods of time. The typical forward voltage-drop on the SCRs will be around 1 or 2 volts. This results in significant power that must be dissipated by the SCR. The SCRs will be selected as 25 amp devices that can surge up to 300 amps. They will have to be heat-sinked with thermal gel to handle the power.

The commercial part number is NTE5460 or ECG5460. These are the most expensive components in the project and are not available at Radio Shack. They can be obtained through Newark or MCM.

Selecting D3-D5:
D3 through D5 are simply to isolate the three SCRs from each other. It is not known how significant the diodes are to the circuit, but they were put in just as a precaution. They are selected as small signal diodes. The commercial part # is 1N4148. There is no significant current or power to concern with.

Selecting R3, R5, R7:
These three resistors act to limit the current to the SCR gates. The specs for the SCR place .040 amps as the limit for the gate current. The resistors will be selected to limit the current to .019 amps. The gate voltage is approximately .8volt. The voltage on R3 can be found as follows:

R3voltage = system voltage – Q1 voltage – D3 voltage – gate voltage
R3 voltage = 14.6v - .1v - .7v - .8v = 13v

The value of R3 can be found now that the current and voltage are known:

R3 = R3voltage / R3current
R3 = 13v / .019 amp
R3 = 684 ohms

The power in R3 is found:
R3power = R3voltage * R3current
R3power = 13v * .019amp = .247watt

For safety, a .5watt resistor will be used.

R5 and R7 are found the same way as R3.
R3, R5, and R7 will be selected as 680 ohm, .5watt resistors.

Selecting R4, R6, R8:
These three resistors are to drain any possible leakage there may be in Q1. They will be selected such that they will drain about .001amp just as the gate is triggering. The gate's voltage is the same as the voltage on R4. Therefore, R4 is found:

R4 = gate voltage / .001amp
R4 = .8v / .001amp = 800 ohms
Since it is not critical, for convenience, R4, R6, and R8 will be selected as 680 ohms to match R3, R5, and R7.
The power in R4 is found:
R4power = R4voltage * R4current
R4power = .8v * .0012 = .00096watt

R4 can be a .25watt resistor safely, but to use the same part as R3, R5, and R7, it can also be .5 watt.
R6 and R8 are found the same as R4.
R4, R6, and R6 will be selected as 680 ohm, .5watt resistors.

Selecting Q1:
Q1 is a PNP transistor. Since each of the three gate circuits will draw .02 amps, the transistor must supply .06 amps. For reasons of availability and reliability, Q1 will be selected as a TIP42 transistor. The transistor can handle 10 amps and has a power rating of 65 watts. This far exceeds the requirements of Q1. Therefore, the transistor will not even need a heat sink at all. The minimum gain is 20 for a TIP42, but typically they have a gain closer to 100. It will be assumed, therefore, the gain is at least 50 in this application.

Detection Circuit:
Z1, D1, D2, R1, and R2 make up the voltage detection circuit. R1 determines what the idle current will be before Q1 conducts. The idle current ensures that Z1, D1, and D2 are operating in their linear range before Q1 starts to conduct. The idle current needs to be about .013 amps to accomplish this.

The emitter-base junction of Q1 reaches about .6v before it conducts. That voltage will be used to determine the value of R1 to obtain the desired idle current. The voltage on R1 will always be the same as the e-b junction on Q1, so it will never go much higher than about .6 volt.

R2 is the current limiting resistor in case the system voltage runs high or a battery charger or some other voltage source is applied to the system. R2 should be made as small as possible so that the detection circuit's threshold voltage will not be affected much by the current in the detection circuit. R2 will be selected to make the final adjustment to the threshold voltage while still maintaining its current-limit function.

Z1, D1, and D2 should have a relatively constant voltage drop which is relatively unaffected by a change in current. Normally, one would use a single Zener diode to maintain the necessary voltage drop. However, in this case, the required voltage is not found in a readily available Zener diode, at least it's not readily found at Radio Shack. Because of this, D1 and D2 are necessary to raise the overall voltage drop. If Z1 were a higher voltage Zener, D1 and D2 could be eliminated.

Before any current can flow in Q1, the system voltage must be higher than the sum of the voltages on R1, Z1, D1, D2, and R2 while the idle current is flowing.

Selecting R1:
Knowing the idle current, the value of R1 can be determined. The voltage on R1 will be .6v and the idle-current will be .013 amps.

R1 = R1voltage / idle current
R1 = .6v / .013a = 46.2 ohm

The power dissipated in R1 can be found:
R1power = R1voltage * R1current
R1power = .6v * .013a = .0078

R1 will be selected as a 47 ohm, .25watt resistor.

Selecting Z1:
For availability, Z1 is selected as a 12v, 1watt Zener diode. The commercial part number is 1N4742a. Since it is 1 watt, the maximum current in Z1 can be found:

Z1max current = 1watt / 12v
Z1max current = .083 amp

The maximum current allowed in Z1 is .083 amps.
The actual voltage on the Zener diode at the idle current (.013 amp) is about 11.7 v. This value can vary from diode to diode. The value can range from about 11.55v to 11.95v. Therefore, the threshold voltage may vary by that same range (about .4 volt). However, the design will be built around 11.7v as the typical value for the Zener diode.

Selecting D1 and D2:
Diodes D1 and D2 are selected to give additional, constant voltage drop in the detection circuit. Diodes are used since their voltage does not vary (much) with a change in current. (As opposed to a resistor whose voltage varies proportionally with current).
D1 and D2 will be small-signal diodes. The commercial number is 1N4148.
At .013 amps, the forward voltage drop on each diode is about .7v.
There is no significant power dissipation in these diodes.

Selecting R2:
R2 is the one resistor whose value may be changed to alter the output voltage of the regulator. It also protects the Zener diode from an over-voltage condition caused by an external voltage source such as a car alternator or battery charger.

In order to protect Z1, it must limit the current to .083 amps. The protection must be provided up to a system voltage of 17 volts. At 17 volts, the detection circuit can have no more than .083 amps flowing. At .083 amps, Z1 will have about 12.5 volts on it. D1 and D2 will each have about .8 volts on them. R1 will have about .8 volts on it.

At a system voltage of 17 volts and .083 amps in the detection circuit, the voltage on R2 can be found.

R2voltage = system voltage – R1voltage – Z1voltage – D1voltage – D2voltage
R2voltage = 17v - .8v – 12.5v - .8v -.8v
R2voltage = 2.1v

From this, the minimum value of R2 can be found.

R2minimum = R2voltage / R2current
R2minimum = 2.1v / .083a = 25ohm

R2 can't be any less than 25 ohms. Since R2 will be a higher value, as will be discussed below, the circuit will be protected to a much higher voltage.

The actual value of R2 will be determined by the requirements of the detection circuit. The threshold voltage will be selected as 14.65 volts. The idle current was set at .013 amps. At .013 amps, Z1 voltage is 11.7v, D1 voltage is .7v, D2 voltage is .7v, and R1 voltage is .6v. The idle voltage on R2 is found as follows:

R2idleVoltage = System voltage – Z1voltage – D1voltage – D2voltage – R1voltage
R2idleVoltage = 14.65v – 11.7v - .7v - .7v - .6v
R2idleVoltage = .95v

The value of R2 can then be found:

R2 = R2voltage / idle current
R2 = .95v / .013a = 73 ohms

The power dissipation in R2 will be highest when the over-voltage of 17 volts occurs. Therefore the power factor will be calculated with this in mind.

At a system voltage of 17 volts, the voltage on R2 may reach 3 volts. The power is found as follows:

R2power = ((R2voltage)^2) / R2

R2power = ((3v)^2) / R2
R2power = (9v^2) / 73 ohms
R2power = .123 watt

For safety, a .5watt resistor will be used.

For availability, R2 will be selected as a 75ohm, .5watt resistor.
Most likely, R2 will be comprised of two 150ohm, .25watt resistors in parallel.

Selecting C1:
C1 is used to raise the average system voltage. C1 delays the triggering of the SCRs, thus allowing the instantaneous system-voltage to exceed the threshold voltage while the average system-voltage remains below the threshold voltage. As the load on the electrical system drops, the average system voltage will approach the threshold voltage.

The value for C1 was determined experimentally rather than being calculated.

C1 is selected as a 10 microfarad, 35volt (minimum) electrolytic capacitor.

It is possible that different alternators may require different values for C1. However, 10uF should probably be adequate. If the capacitor is too large, oscillations may occur. If the capacitor is too small, the average system-voltage will remain too low. A capacitor should be selected which gives a maximum average voltage between 14.0v and 14.6v.

Notes:
It should be noted that the system-voltage could have up to 2 volts (or more) of ripple as measured on an oscilloscope depending on the engine RPM and electrical load.

To convert this regulator for single-phase use, simply leave off D5, R7, R8, and S3.

What is the difference between a thyristor (SCR) and a MOSFET based R/R?

The switches in the Regulator part can be either MOSFET (Metal-Oxide Field-Effect Transistor) or SCR (Silicone Controlled Rectifier), but they both do the same thing. They rapidly turn on and off, short-circuiting power to ground to keep voltage constant. This is called "Shunting", and almost every type of motorcycle R/R used now is made this way.

Every time you short circuit something, it creates heat. That applies equally to both types, but the difference is in *how you switch!*

On a thyristor (SCR) based R/R the most heat isn't generated because of the short-circuit, it's caused during the switching. A thyristor is basically a diode with a separate leg (gate) acting as a switch, but the switch has a delay. The thyristor relies on the current flowing through it, to keep it open.

When a small current is applied to the gate, the switch opens the door a crack, and then waits for the current to crash into the door, slamming it open. Closing it is similar; you slowly push the door closed enough until the current looses power and can't hold the door open and it slams shut.

As a result, the thyristor is horribly inexact and inefficient. It takes time to switch, and it creates huge amounts of heat during this delay.

The MOSFET is a bit more intelligent, it doesn't rely on the current for opening the door and it doesn't try to close it slowly. Instead the switch is really a fast. Switching it on means it starts to conduct fast, and switching it off means it stops almost as fast and that results in a lot less heat and makes it more precise.

Finding an MOSFET R/R.
The "easy" way of knowing if a R/R is MOSFET based, is to look at the markings.
Almost all motorcycle R/R's for are made by Shindengen and they supply all the manufacturers: Honda, Kawasaki, Yamaha and Suzuki and others.
MOSFET R/R's are marked FH-***. The numbers give the specific output. (FH for "FET or MOSFET)

Older thyristor R/R's are marked SH-*** , numbers indicate the output (SH stands for shunt).

Here is a list of known MOSFET based R/R's

Code:

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Kawasaki
ZX-6R 2007-> Cut-n-splice. Either solder, or get both connectors from eastern beaver.
ZX-10 2004->
ZX14 2006->
Concours 2008-> Both MOSFET and non-MOSFET available, beware! (And the
tyristor based one seems to need a larger load than the VTR to work)

Yamaha
FZ1 2007->
YZF-R1 2007->
YZF-R1 2004-2006 - Works, but has large fins, making it hard to fit.
FJ1300 2007->
Wildstar 1300 2007->

Honda
CBR 1000RR 2004-2007 - Both MOSFET and non-MOSFET available, BEWARE! Cut-
n-splice
CBR 1000RR 2008-> Odd connectors, no plugs available, use spade connectors.
CBR 600RR 2003-2006 - Both MOSFET and non-MOSFET available, BEWARE! Cut-
n-splice
CBR 600RR 2007-> Cut-n-splice
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All the Yamaha R/R's use waterproof connectors that are available from www.easternbeaver.com .

Why old R/R's and new batteries don't mix well.

A typical thyristor (SCR) based R/R will produce 13.5-14.5V if it's healthy. and in semi healthy condition usually 13.2-14.8V. But depending on the temperature on the R/R, RPM and how fast the RPM changes it can swing wildly between these values.

A MOSFET new R/R usually provides 13.5-14.5V, and in semi healthy condition (which takes about 20-30 times longer than the SCR to age) the same 13.2-14.8V.

But. And that's a pretty important but. The MOSFET R/R tends towards the middle voltage at just off idle RPM, and then towards lower voltage at high RPM, with only small peaks towards higher voltage usually when the RPM's change. Also the swings are slower, more controlled.

A Sulphuric-Lead-Acid (SLA) battery wants 13.8-14V or so to charge, a GEL usually wants 14.1-14.2V to charge. Most SLA's "boil" and get reduced lifetime if they spend too much time above roughly 14.2V, same goes for GEL's at 14.5V. Drop too low and they simple stop charging. Just below optimal charging and you get "maintenance mode" as in most chargers.

This means that as long as the battery is in good condition it has no problems coping with a semi reliable R/R of either type, but a thyristor based R/R will age sooner, and then it can give problems.

A MOSFET based R/R keeps the battery in good condition longer and keeps the voltage more constant, which is good for the ECU/CDI, the electronics in the gauges, the fuses and your headlight bulb since it likes a tad over 14V to generate peak light output (provided you have decent wiring to it).

Both types will generate fire and smoke if the battery boils over in the event that a diode in the rectifier decides to go open circuit, and both will stop charging the battery if they fail. But a MOSFET regulator takes a very, very long time to degrade sufficiently to create the heat needed to damage the rectifier diodes. Corroded connectors are obviously something that will increase resistance and thus generate heat.

Now for the Lithium-Iron Batteries (LiFePo's). They like to be charged at 13.6-14.4V, and specifically at around 13.8V. They really dislike going above 14.4V since that charges them very rapidly with no real way for them to dissipate the heat, and charging to much at lower than 13.4V will build up internal resistance which reduces their service life.

So a thyristor based R/R in peak condition will work decently, but *only* in peak condition. A MOSFET based R/R will work even in half decent condition since it rarely peaks and if it does it's only for a short time. It might reduce lifetime, but it's unlikely to blow stuff up.

The LiFePo's are no more volatile than an SLA or GEL battery when they go *poof.* In fact they tend to cause less damage since the chemicals don't eat through aluminium, and because they are physically much smaller, they contain much smaller volumes of chemicals. But the margin for error is a smaller.