

ALTERNATORS VERSUS GENERATORS / DYNAMOS.

H. Holden 2010, revised Sept 2012.

Why were Dynamos phased out and replaced by Alternators?

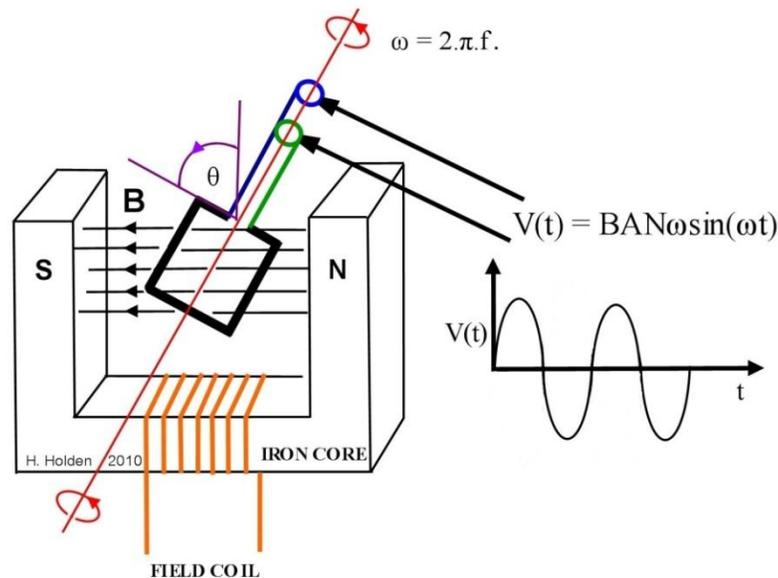
To answer this question we need to look at some fundamentals of a loop of wire or coil moving through a magnetic field. In both types of machine a voltage is generated in an output coil which is exposed to a varying magnetic field. Electric charges (electrons) in the coil experience a force from the varying magnetic field and this is how an electric voltage and current flow are produced.

In the case of the Dynamo the magnetic field is generated by the stationary field coil. The armature coil which we could call an “output coil” is rotating and therefore experiences a varying magnetic field. In the case of the Alternator the magnetic field is generated by the moving rotor coil which we will also call a field coil for this discussion. The output coil for the Alternator is the stator coil which experiences the varying magnetic field from the moving rotor coil. In the alternator example the stator is physically stationary to the observer, however if you were miniaturized and hitched a ride on the rotor then you could imagine the field coil(rotor) as being stationary and the stator or output coil revolving around the stationary rotor coil.

In either instance the output coil is exposed to a varying magnetic field. It is the *relative* motion between the field coil’s magnetic field and the output coil that is important. This generates the output voltage on the output coil due to the changing magnetic flux Φ passing through the output coils’ cross sectional area.

Referring to figure Z below for a 1 turn loop output coil (drawn as the thick black rectangle) in a magnetic field:

One turn loop of cross sectional area A rotating in a magnetic field B with an angular velocity of ω .



The magnetic flux Φ passing through the coil is measured in Webers and has units of Volt.Seconds. The magnetic field itself is denoted by B and often is drawn with vector lines between North and South poles of a magnet. B has units of Volt.Seconds per square meter and is measured in Teslas. Therefore the magnetic flux Φ passing through this single loop of coil is equal to the magnetic field B times the cross sectional area A of the loop; which is BA. The magnetic flux Φ via the loop decreases as the loop rotates because flux passing through the coil's surface area plane falls off with the cosine of the angle θ .

We can therefore write for any angle of the loop θ , the flux Φ passing through the 1 turn loop is:

$$\Phi = BA\cos\theta$$

With the loop spinning at some speed the angle of the loop is equal to 2π radians (or one cycle of rotation) times the frequency of the rotation f in cycles per second times the elapsed time t from zero to when the angle is measured. Therefore the angle θ at any time t is:

$$\theta = 2\pi ft = \omega t$$

Where ω is the angular frequency of the rotation and has units of radians per second.

Then the flux passing through the loop at any time t is:

$$\Phi = BA\cos(\omega t)$$

When a loop is moving in a magnetic field the voltage induced on the loop's terminals (the green and blue wires in the diagram) is proportional to the rate of change of magnetic flux Φ with time, this is symbolised as $d\Phi/dt$ or "rate of change of flux with time" This is Faraday's law of induction.

Differentiating the equation above to find the rate of change of flux with time and therefore the voltage generated on the loop with time V(t) yields:

$$d\Phi/dt = V(t) = BA\omega\sin(\omega t)$$

If there is more than one turn of the loop, say N turns, then:

$$V(t) = BAN\omega\sin(\omega t)$$

The above equation in the box is the basic equation for a single pole pair Alternator or the AC generator output voltage and applies to the Dynamo too. To simplify this further, the sine function has a peak value of 1 when the surface area of the plane of the coil is aligned with the magnetic field lines and $\theta = 90$ degrees or $\pi/2$ radians, and the rate of change of the flux Φ with time is at its greatest. Therefore the peak voltage produced by this system is:

$$V_{(\text{peak})} = BAN\omega.$$

In addition we can replace the angular velocity with an rpm (rpm of the armature or rotor) value:

$$2\pi f = \omega$$

Where f is the frequency of rotation in cycles (rotations) per second, therefore:

$$f = (\text{rpm}) / 60$$

Therefore:

$$\omega = 2\pi(\text{rpm})/60$$

$$\omega = 0.1(\text{rpm}) \text{ approx.}$$

So reformatting of the basic equation gives:

$$V_{(\text{peak})} = 0.1BAN(\text{rpm})$$

So we can learn from the equation above that the output voltage peak amplitude increases with the speed of rotation (rpm) and increases with the size or geometry of the output coil (larger cross sectional area A) and the number of turns N on that coil.

The term BA is the field flux density area product which is simply the magnetic flux Φ . So the equation for the dynamo's peak output can simply be written:

DYNAMO:

$$V_{(\text{peak})} = 0.1N\Phi(\text{rpm})$$

It is very interesting to compare this with the equation for the output voltage of the alternator:

This equation is essentially the same as that for a transformer except for span and breadth factors related to the stator winding placement. The rms voltage per phase of an alternator is: From Applied Electricity, A.W. Hirst, Blackie & sons (1959)

$$V(\text{rms}) = 4.44kb.k_sNp\Phi. (\text{rpm})/60$$

kb and ks are span factors & breadth factors related to the fact that the stator windings for each phase are not exactly space one pole pitch apart. This is done to make the output voltage more sinusoidal in the case of the alternator. The $kb.k_s$ product might be in the order of 0.7 to 0.9.

(The rpm/60 is the frequency of shaft rotation F in revolutions per second and the flux reversals experienced by the stator, or the frequency of these, relates to the number of magnetic pole pairs p on the rotor. So that frequency f of flux reversals is F.p. Therefore $f = F.p$ where p is the number of magnetic pole pairs. The standard equation for a transformer is $4.44N.\Phi.f$ volts for example where f is the frequency of the alternating current applied to the transformer)

Φ is the magnetic flux per pole.

The peak voltage is about 1.4 times the rms value.

Modern "claw pole" auto alternators have 6 pole pairs on the rotor, so to simplify the alternator equation then the peak voltage per phase of a 6 pole alternator is approximately:

$$V_{(\text{peak})} = 4.44N6\Phi(\text{rpm})/60$$

Therefore for the alternator:

ALTERNATOR:

$$V_{(\text{peak})} = 0.44N\Phi(\text{rpm})$$

Repeating the dynamo equation:

DYNAMO:

$$V_{(\text{peak})} = 0.1N\Phi(\text{rpm})$$

We can now see that a 6 pole pair alternator for example has about 4 times the output voltage of the single pole pair dynamo for the same rpm and field flux and number of turns on the armature or stator.

Therefore the main reason why the alternator has a higher output voltage at any rpm is that it has a larger number of pole pairs than the typical dynamo all other proportions being approximately equal.

One utility of the alternator therefore is to produce a good output voltage at lower alternator shaft rpm's. This is further enhanced by having a smaller pulley to run the alternator at a higher shaft speed than the dynamo.

Although the generated voltage from the alternator is high for the rpm, the alternator is an "AC machine" and the output current is limited by the leakage reactance of the stator windings, which one could regard as a significant inductance (impedance) in series with the alternator's output (see below). This is quite different from the dynamo where the internal impedance or internal resistance of the unit is mainly Ohmic in character due to the DC resistance of the armature copper coils and commutator & brushes. The reactance of the armature in the DC machine instead results in commutator arcing.

Due to the increasing electrical energy consumption in the modern car charging at idle speeds became essential, especially so for cars stuck in city traffic. Unfortunately this caused an added complication of sudden loads causing rough idling or even engine stalling as simple conventional alternator voltage regulators respond quickly to a change in electrical load. Therefore a complex system of alternator voltage regulation was devised called LRC (load response control) see below.

In addition the mass of the armature in the dynamo limits the dynamo rpm as the forces to hold the dynamo armature windings and commutator together, without flying apart, increase with the square of the rpm and linearly with the mass of the rotating objects. Alternators with the smaller physical mass of the rotor can be run with smaller pulleys at a higher shaft rpm's further assisting the voltage and power output at low engine rpm.

The output voltage of a Dynamo or Alternator is controlled by altering the average field coil (or rotor) electrical current, because this controls the average magnetic field strength B. This is the job of the dynamo or alternator's voltage regulator unit. The average voltage is controlled by the field coil being switched on and off at variable duty cycle. This conserves energy in the regulator module than if it were variable DC control. The inductance of the rotor (or field coil) and the magnetic properties of the stator (or armature) help to smooth out the switching events so only a negligible ripple is present at the output. These switching events usually occur, depending on the control system at between 25 to 300 cycles per second in alternator and dynamo regulators.

With regards to the number of wire turns N of course, the more you increase the number of turns with thinner wire (in a fixed space) the higher the electrical resistance so there is a limit to the number of turns on an Alternator stator or a Dynamo armature you could practically use without making the assembly physically bigger. As the resistance increases there is more voltage drop under current load and heat generated in the windings raising the internal resistance of the unit which beyond a certain margin is unfavorable.

When no current is being taken from the rotating loop as shown in figure Z, the loop would turn freely with little resistance. When current is being taken work is done and the loop becomes more difficult to turn, consuming more mechanical energy. So when the Alternator or Dynamo is under electrical load this consumes more power from the engine. The Alternator or Dynamo behaves as a device to convert mechanical energy into electrical energy. The Alternator is around 50% to 65% efficient at this task. At say 20 amps output the power output delivered is around $14V \times 20A = 280$ watts, so at least 500 watts of power would be taken from the engine to support this.

Rectification of $V(t)$, which is an AC sine-wave voltage, is achieved mechanically in the Dynamo by the commutator which acts as a mechanical rectifier by essentially selecting the correct output voltage polarity from the multiple armature windings. The armature windings providing the output reside in one place in the field and are merely replaced by other coils with rotation. As a result there is no rotating field in this DC machine. See the article on the C40 Dynamo and its Armature on www.worldphaco.net to learn how the process of commutation works.

In the Alternator rectification is done with silicon power rectifiers with a full wave three phase rectifier containing 6 silicon power diodes in most machines. Some of the power losses in the Alternator are in the rectifiers. At 50 Amps output each rectifier diode is dropping around 1 volt

and at any one time two of the total of the six rectifiers are in conduction (there are two rectifiers per phase). So this means the power loss from the rectifier system is around 100 watts at 50 amps which is quite significant albeit a small proportion of the $50A \times 14v = 700W$ output at that load.

When dynamos were first invented such silicon power diodes were not available, later there were selenium units and vacuum tube and mercury vapor rectifiers however these were large and cumbersome with poor performance at high currents compared to the modern silicon rectifier. The only practical solution at that time was mechanical rectification. Mechanical rectification can produce more voltage spikes and transients if the brushes and commutator are not in good order, but it doesn't have the forward voltage drop and power loss of the silicon rectifier, so there is a small advantage there for the Dynamo.

Also the full power output of the Dynamo must come via the mechanical brushes, so the entire current and power output must come via the brushes and the physical size of these and their connections can limit the power that can be transferred. There is also the issue of wear for the commutator not present in the Alternator.

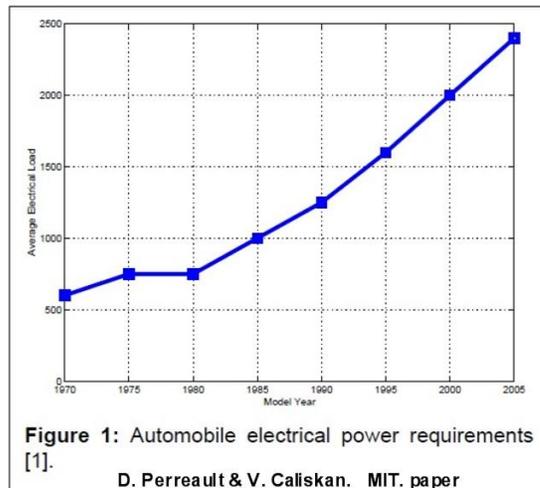
In the Alternator the output power comes directly from the stator via the rectifier diodes. The current supply to the alternator's rotor via the slip rings is only around 2 or 3 amps to create the B field and there is less stress on them, even with a high current output Alternator. This is why it has been possible to build fairly compact alternators with 70 to 100 amps output capability.

If a 3 phase AC voltage is applied to the stator, which essentially has 3 windings spaced 120 degrees apart, this produces a rotating magnetic field which will induce rotation in a magnet placed in that field. Nicola Tesla discovered this in the mid 1880's. This creates a synchronous AC motor. Therefore if you powered an Alternator stator with 3 phase AC and excited the rotor coil with DC then you would have a synchronous motor. So in this sense an Alternator is in fact a synchronous motor used in reverse to become a generator. In the case of a Dynamo you could regard it as a brush DC motor with a field coil electromagnet (rather than a permanent magnet seen in most DC motors) and used in reverse to become a generator.

A Dynamo with a 70 to 100 amp output would require a massive armature and large elaborate commutator assembly. The compact Lucas C40 Dynamo in the TR4A car for example has a modest 22 amp maximum output.

Initially many early alternators had the rectifier packs and regulator modules remote from the Alternator and ultimately they were added to the Alternator body. Some early units inside alternators were prone to failure as the components were not up to the harsh conditions of heat and vibration on the rear of the Alternator.

Over many years the electrical energy consumption in the average car has increased dramatically. In 1970 the power requirement was 600 watts, by the year 2005 it had increased to nearly 2500watts.The following is a graph pasted from an interesting MIT article on alternators:



2000-01-C084

The 1966 TR4A has a power requirement of only 300 watts.

Any electrical energy consumption in the car has to be supplied by the Alternator, on the average at least, or the battery would discharge with use of the vehicle. Energy recovery systems such as regenerative braking can help but again the complexity is increased. Changing over to electronic engine management with electric fuel injectors and electrical rather than mechanical fuel pumps have added to this burden. It has increased further with the addition of many auxiliary electrical systems such as air con systems controllers, Abs braking, gearbox controllers, cruise control, high powered stereos, security systems, heated windows, in some cases active suspension controllers, electric radiator cooling fans etc, and the list of additions goes on and on. One obvious thing with this is that the efficiency can drop off as all the added electrical gear needs electrical supply from the Alternator which is 50 to 65% efficient in the conversion of mechanical to electrical energy.

To add to this problem the conversion of petrol to mechanical energy is only at best 40% efficient. Therefore the conversion from fuel to electrical energy is only 0.65×0.4 or about 26% efficient.

On top of that the fact that the car's electrical demand became so high it required battery charging at idle speeds, which was not required before 1970. It became possible for a sudden electrical load such as switching on high beam headlamps to stall the idling engine or cause transient rough running. This problem had to be addressed by using more sophisticated

Alternator regulator control systems called Load Response Control or LRC. This grossly increased the complexity of the alternator's regulator circuitry from two or three transistors, to IC's containing hundreds of transistors to execute the pulse width modulation control to achieve LRC. See article on the Dynamo & Alternator Emulator on www.wordphaco.net section on LRC.

This leaves one wondering if adding any kind of unnecessary electrical accessory to a petrol powered vehicle is a good idea. One also wonders whether in fact the truth might be that the petrol powered cars of yesteryear are superior and more energy efficient than the modern petrol powered car because they have low electrical energy requirements by making better use of rotating engine shafts for energy dependent activities. The older cars are also very simple to manufacture, repair, maintain & recycle compared to the modern vehicle? Many of the electrically powered bells & whistles in the modern vehicle that diminish the efficiency were the result of manufacturers attempting to gain ground in sales & marketing by "out-featuring" their competitors, not because they were making more efficient vehicles.

Other differences between Dynamos & Alternators on Overload:

Under overload conditions the voltage regulator becomes inactive and the field coil (or rotor) remains switched on.

On overload and running at some fixed rpm and the dynamo powering its own field winding the output voltage falls due to the resistance of the armature windings and brushes and due to the fact that armature current generates a magnetic field in the armature that opposes the magnetic field of the field windings. This is called "armature reaction". The field is twisted and weakened by this effect.

With enough load, after a peak output is reached, the output progressively fall as the field current reduces further. With a shorted out Dynamo there is a form of self protection as the field current is very low as there is little voltage to supply it. However at the point before the output voltage folds back significantly from this effect the output current may be very high and rpm dependent. Therefore an overloaded Dynamo is vulnerable to increasing rpm causing severe overload and overheating of the armature unless there is some current limiting or a fuse.

This is why the Dynamo's control system always has a *current and voltage* limiter inside the control box.

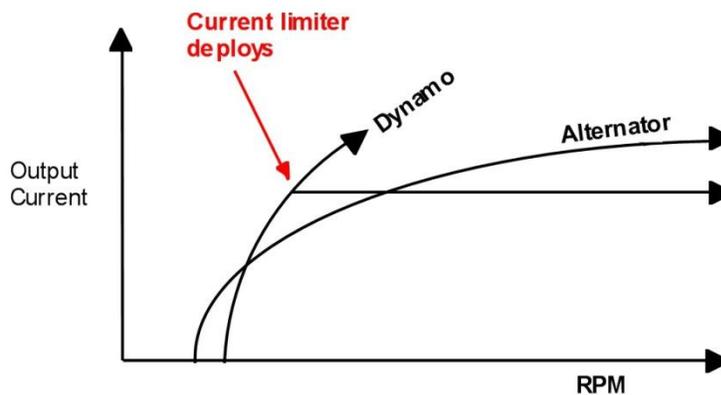
On the other hand Alternators have a different kind of "armature reaction" and it could be called stator reaction too. The armature (stator) reaction results in a rotating magnetic field generated by stator currents which follow the rotor around at synchronous speed. Also because there is leakage inductance (as a result of lines of magnetic field that do not link the magnetic circuits of

all of the stators turns) the output from any phase of the stator winding acts as if it had a relatively large value of inductance in series with it. In this AC machine the inductance impedes alternating current and also causes a phase lag where the AC current lags behind the voltage. This causes the magnetic field of the stator reaction to further reduce the rotor's magnetic field.

Therefore under load the armature reaction and leakage reactance both act to limit the output current. These are often lumped together as one term called "Synchronous Reactance" as from an experimental point of view they are difficult to separate and have the same effect. The stator also has some DC resistance too. So the synchronous reactance and the DC resistance result in current limiting. In a sense the Alternator acts as a high AC voltage generator with a large reactance in series with it. On the DC side after the rectifiers, this effect results in the output voltage falling with load or reduced regulation compared to the dynamo. And it results in current limiting as the rpm increases.

The net effect is that as the rpm increases and when the voltage regulator is inactive on overload *the current levels out* to a safe maximum value. This is why alternators generally do not have current limiters, only voltage regulators. Often a manufacturer will show the Alternators output current graph with increasing rpm and with an output clamped to 12V. (In this state the voltage regulator is inactive as it only activates at around 14V and above to limit the field).

The graph below summarizes the differences in that the dynamo's output current keeps rising with RPM requiring current limiting while the alternators current levels off:



It is still possible for alternators to fail due to continuous heavy loads in hot conditions. The rectifiers are a possible source of failure as their fusing currents are often lower than the stator windings.
