Optimizing a Permanent Magnet Alternator for micro-hydro application

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Abstract

This article reports a procedure for modifying an existing permanent magnet alternator-rectifier system to achieve the maximum possible efficiency in the predetermined output power range at a given rotating speed. Several methods of altering performance of the alternator-rectifier system are discussed and compared. Methods that are practical and lead to high efficiency are identified, implemented and experimentally verified. The article demonstrates that a 1kW alternator-rectifier system can be intelligently modified to generate 100 Watts with 97% efficiency. The article also presents a simple and accurate method of measuring alternator efficiency.

1 Nomenclature

ω frequency of the output voltage rad/s
Ω rotating speed RPM
R_L load resistance per phase
R_a armature (windings) resistance per phase
$R = R_L + R_a$
i imaginary unit $i = \sqrt{-1}$
I amplitude of current
L Inductance
V_o no-load open circuit voltage
V_R voltage at R
V_L voltage at load R_L
P true power
P_{mech} mechanical input power
P_{CL} core loss (Watts)
P_{BL} bearing loss (Watts)
η efficiency
k experimental constant
k_o axial pole overlap ratio $0 \leqslant k_o \leqslant 1$
n effective number of turns per phase
r radial clearance (air gap size)

2 Objectives

One of the main objectives for the work presented in this article was to develop an efficient permanent magnet alternator-rectifier system for a micro-hydro application with the following specifications:

1. Rotating speed about 700 rpm, determined by the available water pressure and the size of the Pelton turbine rotor
2. Power output range from 100 to 300 W, determined by the available water flow and pressure ranges
3. Output voltage between 70-100 VDC, arising from the necessity of transmitting the generated power over 450m distance with acceptably small losses and limited from above by the battery charger specifications.
4. Good efficiency in the entire power range

The motivation for writing this article is to present some useful guidelines for modifying performance and improving the efficiency of similar systems.

3 Linear model of an alternator

Operation of a permanent magnet alternator can be explained using an equivalent circuit presented in Fig 1.The alternator

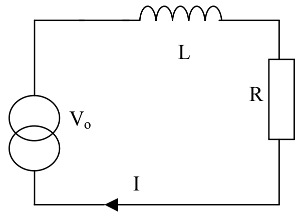

Fig 1. Equivalent circuit of a generator

windings produce voltage V_o that causes the current flow I through the circuit. L is the windings inductance and the resistance $R = R_a + R_L$ is composed from the armature (windings) resistance R_a and a useful load resistance R_L. In a symmetrically loaded 3 phase alternator it is sufficient to consider only one phase, since all phases behave in a similar way. When a sinusoidal current of amplitude I flows through the circuit in Fig 1 at frequency ω we can write that $V_o = IR + iI\omega L$. From this equation we can find the current amplitude I to be $I = \frac{V_o}{R+i\omega L}$ and the true power P at R to be

$$P = |I|^2 R = \frac{RV_o^2}{R^2 + \omega^2 L^2}. \tag{1}$$

It is important to note, that V_o can be directly measured when there is no load ($R_L \to \infty$) and hence it is called an "open circuit voltage". This voltage is usually proportional to the rotating speed of the alternator shaft.

4 Maximum power

Expression (1) for the true power P above reveals that the maximum theoretically possible true power $P_{\max} = \frac{V_o^2}{2\omega L}$ is delivered to R when $R = \omega L$. The voltage V_R at R is then $V_R = V_o/\sqrt{2}$. At any other voltage (and at any load other than $R = \omega L$) the true power extracted from the alternator is smaller that the maximum possible.

A few algebraic transformations yield expression for the output power ratio $P/P_{\max}$ (the ratio between actual and the maximum theoretically possible true output power) as a function of the voltage ratio V_R/V_o representing the voltage at which the true power is taken from the alternator.

$$\frac{P}{P_{\max}} = 2\frac{V_R}{V_o}\sqrt{1 - \left(\frac{V_R}{V_o}\right)^2} \tag{2}$$

The equation (2) and the corresponding diagram in Fig 2

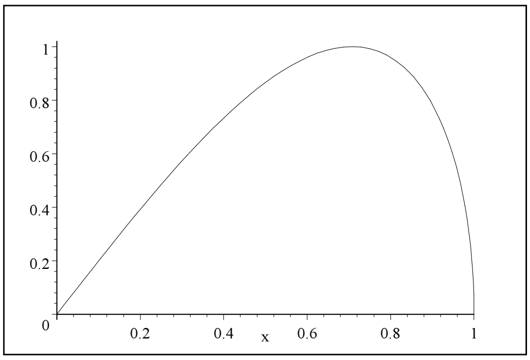

Fig 2. Power ratio $P/P_{\max}$ as a function of voltage ratio V_R/V_o

are non-dimensional and at the first gance seem applicable to any reasonable alternator operating at any reasonable rotating speed.

In reality - inductance L is non-linear due to the presence of the iron core that can saturate and hence introduce power limitations. It turns out that the practical (quantitative) applicability of the "linear" theory presented above is quite limited, because in realistic alternator designs the iron core limitations actually dominate and cannot be disregarded..

However, the linear theory highlights the fact, that for any alternator we should expect the maximum power to be achieved only at one particular set of operating conditions.

5 Modifying performance

The power loss in a real alternator is a sum of copper losses in the windings, magnetic core losses, friction losses in bearings and aerodynamic resistance losses. In a well-designed alternator all these loses should typically take a few % off the total output power when taken together. They can be estimated together at any rotating speed (and the corresponding frequency ω) by spinning an unloaded alternator and measuring the mechanical power used to spin it. Since all of these losses increase with the rotating speed, it is important to measure them at a suitable range of rotating speeds.

Preliminary measurements for unmodified Smart Drive Permanent Magnet alternators indicate that in the 540-995 rpm range the core losses P_{CL} are approximately 0.0954 W/rpm and bearing friction losses P_{BL} (for 2 new polymer sealed ball bearings) are approximately 0.0363 W/rpm. Aerodynamic losses were found negligible in comparison. Hence, at any rotating speed Ω these losses can be estimated as $P_{CL} \approx 0.0954\Omega$.and $P_{BL} \approx 0.0363\Omega$ respectively.

At 1000 rpm these losses total about 130 Watts, which is significant. Bearing losses can be reduced easily, but the core losses clearly demonstrate that unmodified Smart Drive alternators should not really be used for rotating speeds above 800 rpm, unless we have an excess energy to waste and heat up the core.

The methods of adjusting performance of the alternator are discussed below.

5.1 Adjusting magnetic flux

The voltage V_o induced in the alternator windings is proportional to the rate of change of the magnetic flux in alternator windings. For a sinusoidally variable flux (a reasonable assumption for not loaded alternator), the amplitude of this rate of change and hence the induced voltage V_o is proportional to the frequency of the magnetic flux changes ω as well as its amplitude B. The frequency ω in turn is proportional to the rotating speed of the alternator's rotor. The constant of proportionality depends on the number of poles and the number of permanent magnets. For a given set of magnets, the amplitude of the magnetic flux B depends on the geometry (mainly the size of an air gap and the axial pole overlap) between moving magnets and the stator core.

Hence, for practical purposes, in some limited range of parameters, V_o may be expressed as follows:

$$V_o \approx kk_o n\omega/r \tag{3}$$

where r is the radial gap between rotor and stator, n is the number of wire turns per phase, ω is the voltage frequency in rad/s, k_o is the axial pole overlap ratio (taking values from 0.5 to 1) and k is the experimentally determined constant, evaluated by measuring V_o for a set of known n, ω and r.

The relationship discussed above indicates a possibility of modifying V_o by changing the alternator air gap geometry. For a given set of magnets we can accomplish this by:

1. Increasing the radial size of the air gap r by grinding away the stator poles. This method leads to decreased magnetic flux in the windings, reduced V_o and hence reduced maximum power. According to expression (3), after doubling the size of the gap we can expect reducing V_o by a factor of 2 and reducing the maximum extractable power by a factor of 4.

2. Changing the axial alignment of the rotor with respect to the stator by installing suitably sized spacing washers on the shaft (reducing k_o to a value smaller than 1). This method is quite practical, but increases stray losses, ruins the pole symmetry with difficult to predict negative effects on the alternator efficiency. Hence, changes of axial alignment should be restricted to small range and used only in fine-tuning, troubleshooting and emergency if necessary. Preliminary experiments seem to confirm (3) that 50% axial pole overlap ($k_o = 0.5$) leads to reducing V_o by a factor of 2 and reducing the maximum extractable power by a factor of 4.

Since the above described two methods of adjusting flux reduce the power output 2 times faster than they reduce core losses, they should be expecetd to reduce the overall alternator efficiency and hence they should be avoided if possible.

5.2 Reducing core losses

For a given core material the core losses in SD alternator may be considered aproximately proportional to the core mass, the operating frequency ω and the magnitude of the magnetic field B. Hence, in practical applications, core losses can be reduced by:

1. Reducing the rotating speed. Reduction in speed 2 times should reduce the core losses 2 times and $P_{\max}$ 2 times

2. Reducing the core mass. In an SD alternator this can be achieved by physically removing some stator poles. Reduc-

ing the number of stator poles (fingers) per phase by half (2 times) should nearly half the core losses and reduce the $P_{\max}$ 2 times.

3. reduce the frequency ω of stator pole re-magnetization for a given rotating speed Ω. This can be accomplished by reducing the number of magnet pairs in the rotor that are uniformly distributed on the rotor circumference. Reducing the number of magnet pairs 2 times should reduce both core losses and $P_{\max}$ 2 times.

From the above it is clear that reducing core losses in an existing machine is only possible when there is some power margin for our application - when the power that we plan to extract is smaller than the maximum power the alternator can provide at given Ω.

It is also clear that methods presented here are twice as effective for reducing core losses in proportion to $P_{\max}$ when compared with methods of adjusting the magnetic flux discussed earlier and hence they should be our preferred methods for reducing the power capacity of an alternator. Of those, the easiest of all is the method 1 - lowering the rotating speed at which the power is extracted, subject to Ω restrictions for our application. For this reason we should consider the method 1 first.

5.3 Reducing bearing losses

Measured bearing losses for 2 polymer sealed ball bearings installed in Smart Drive alternator casing are $P_{BL} = 0.363\Omega$. At $\Omega = 1000$ rpm these losses are about 36Watts. This power is converted to heat that heats up the polymer seal and causes it to expand. Before polymer seal wears out sufficiently, this thermal expansion can cause an additional friction resistance in the bearing. If the inner bearing ring is not attached to the shaft by an interference fit, the shaft is likely to spin in the bearing bush and wear out. From this point of view polymer sealed ball bearings should be avoided if possible, especially for low-power applications.

Bearing losses can be reduced as follows:

1. by a careful and conscious choice of bearings and seals. Commonly available not-contact metal seal ball bearings should be considered, if possible.

2. impregnating all bearing and seal contact surfaces with a teflon based lubricant. Teflon is known to bind to metal molecules and to reduce both the friction and wear significantly

Removing the polymer seals from default SD bearings and soaking bearings in a teflon based lubricant for a few minutes brought bearing losses down to negligible values at 1000 rpm. If we did it for a alternator working at 1000 rpm, we would have gained about 30 Watts of power.

6 Rectification

In a growing number of alternator applications their 3-phase outputs are rectified to provide a DC voltage source. As it turns out, rectification is another strongly non-linear part of the system that introduces complications difficult to disregard.

During 3-phase rectification, rectifier diodes are switched on and off at non-zero voltage and non-zero current. The effect of this is a sudden "step loading" of each phase source. When a 3-phase source has a very low impedance (like a 3-phase grid) repetitive step loading does not disturb the source much and it is possible to derive a simple algebraic relationship between the fixed AC source input and the DC output from the rectifier.

The case of rectifying the output of a small 3-phase alternator however, is not quite as simple. The alternator windings have significant resistance (R), inductance (L) and capacitance (C) that form RLC circuits. Each step-loading of such a RLC system (6 times per period) excites its natural oscillations. The frequency of these oscillations is typically too high for the alternator core material (iron) to handle and hence these oscillations become choked (i.e dissipated) by the core. So, in reality, rather than oscillations, at each diode switching we observe a voltage spike followed by an exponential decay (Fig 3). Choking of the step-load induced oscillations introduces additional core losses and significantly reduces the power capacity of the alternator-rectifier system. It was found that in the case of SD alternator family such a reduction can be as high as 50%.

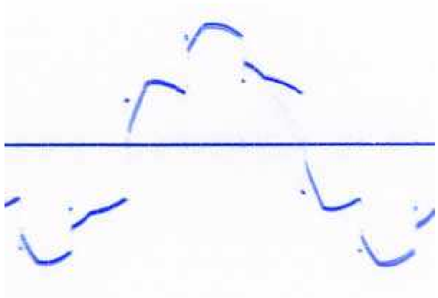

Fig 3. Typical analog oscilloscope trace of AC phase voltage of a permanent magnet alternator loaded via 3 phase rectifier. Note spikes at each diode switching followed by exponential decay.

What can be done to improve the power capacity of the alternator-rectifier system? One of the simplest solutions is to de-tune the RLC system so that its natural frequency becomes low and oscillations don't have a chance to develop because they are too slow in comparison to ω. This can be accomplished by loading the output of each phase by a capacitor. The presence of such a capacitor, however, increases the current through the winding and will therefore increase copper losses. Since this capacitor can reduce core losses to some degree and increases the copper losses in the same time, there should be some optimal capacitance for a given application.

Since the theory of non-linear alternator-rectifier system circuitry is quite difficult to present in a brief article, I decided to determine the effects and the optimal value of phase-to-phase capacitance experimentally and report results.

7 Efficiency measurement

Since the purpose of experiments is to observe the power generation efficiency - an accurate efficiency measurement is of key importance.

The efficiency of an alternator-rectifier system is determined from the formula:

$$\eta = \frac{P}{P_{mech}} 100\% \quad (4)$$

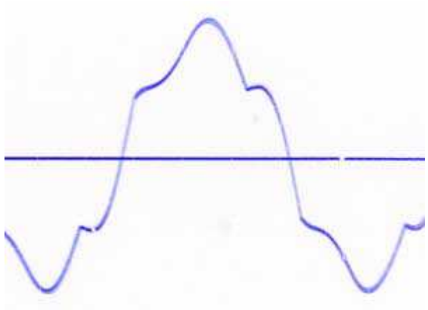

Fig 4. Effect of phase-to-phase capacitors. Voltage spikes are eliminated and both peak and RMS value of the AC phase voltage are increased.

where P is the true DC output power of the alternator-rectifier system and P_{mech} is the input mechanical power to the alternator. Measuring P is easy, but accurately measuring P_{mech} is not. The most direct way to measure mechanical power in rotating machinery is to measure the torque transmitted by the spinning shaft. This, however requires a special sensor and a system of transmitting data from this spinning sensor.

I decided to determine the mechanical power P_{MECH} from measued electrical power P_{em} consumed by the electric motor of a bench drill used to spin the alternator shaft. This decision originated from the fact, that during my power efficiency research I acquired a very good and inexpensive (@A$200) microprocessor based instrument for measuring the AC power called "Sparometer".

The basic idea was to perform a differential measurement of the power used by the electric motor - loaded by the alternator and disconnected from it (running pulleys and the free spindle only). Using the power difference I was able to estimate the mechanical power taken by the alternator. This method required detailed knowledge of the efficiency of the electrical motor. Fortunately, efficiency of single-phase AC motors is a well-studied subject and I could easily find an accurate efficiency curve for a 4-pole single phase 3/4 HP motor [1] that I used to spin the alternator. I have fitted a 3-rd order parabola to the motor efficiency curve from the reference [1] and was able to determine the mechanical power P_{mech} , delivered by the motor on the basis of the electrical power P_{em} the motor consumed, from the following expression:

$$P_{MECH} = P_{em} \left(\begin{array}{c} 0.2293 + 0.88 \frac{P_{MECH}}{559.2} \\ -0.525 \left(\frac{P_{MECH}}{559.2}\right)^2 \\ +6.141\,4 \times 10^{-2} \left(\frac{P_{MECH}}{559.2}\right)^3 \end{array} \right) \quad (5)$$

To use this method in practice I wrote the right-hand side of this equation in a single cell of a spreadsheet and installed the necessary solver module to handle circular references.

Two electrical power readings of P_{em0} and P_{emL} for motor disconnected from the alternator (running the belts and the drill spindle only) and for the motor loaded with the alternator produced 2 corresponding mechanical power values, P_{MECH0} and P_{MECHL}. The efficiency of the alternator was then determined as

$$\eta = \frac{P}{P_{MECHL} - \frac{\omega_{Load}}{\omega_o} P_{MECH0}} \quad (6)$$

where ω_{Load} and ω_o are fundamental alternator phase frequencies in two cases: loaded by the alternator and free spinning and the factor $\frac{\omega_{Load}}{\omega_o}$ is a correction for the fact that P_{MECH0} and P_{MECHL} are determined at slightly different rotating speeds. Preliminary error analysis of the above procedure indicated that efficiency measurement with accuracy better than 1% should be possible.

In practice, the main nuisance turned out to be the belt-pulley system of the drill that varied its own efficiency slightly as the belt was warming up. A simple remedy was to perform the 2 necessary differential measurements in a very short time interval (less than 5 seconds apart) so that the condition of the belt was the same for both measurements. With this remedy, errors in day-to-day repeatability and reproducibility of the efficiency measurements using the above described procedure were less than 0.3%, even though the electrical power readings differed by as much as 5%.

The obvious improvement for the method would be to eliminate the belt drive. Since the efficiency of the belt drive is likely to reduce for higher loads, it is hence likely that the above method underestimates the alternator efficiency somewhat for loads above 300 Watts.

Fig 5. Experimental rig for efficiency measurement. The bench drill drives the alternator shaft. Electrical power consumption of the drill motor is measured by Sparometer, a white instrument between voltmeters. Note the removed poles of the alternator stator.

The experimental setup is shown in Fig 5. The left digital voltmeter measures the frequency ω in Hz and the right voltmeter measures DC voltage at the resistive load. Analog oscilloscope monitors the phase voltage transients.

8 Experiments

On the basis of measurement results kindly provided by

EcoInnovation in NZ I have chosen to modify a Smart Drive alternator by Fisher and Paykel.

The linear theory presented first in this article seems to suggest that an efficient alternator should have the minimal possible winding inductance and resistance in each phase while providing the necessary output voltage V_o. For a given set of rotor magnets and a given air gap, the requirement for V_o determines the required number of wire turns per phase. In order to achieve the minimum possible inductance, these turns should be evenly distributed among all poles in each phase. The requirement for the minimum possible turns per phase effectively forces a "star" configuration. The minimum possible winding resistance requires the wire of maximum possible diameter.

The above requirements pointed to 100S (1mm wire diameter, 44 turns per finger, 14 fingers per phase version of SD) as a prime candidate for modifications. Requirement for V_o indicated that only 7 fingers per phase were needed, so that 21 fingers were physically removed from the stator and the remaining 21 poles were re-connected in star configuration, 7 in each phase. The modified 21 pole alternator rotor was spun at 713 RPM using the bench drill. Four 1kW resistors were used to load the DC output of the alternator: 66.8, 43.5, 23.4 and 15.4 Ohms respectively.

Six sets of experiments are reported later on in this article:

1. Set of tests with no phase-to-phase capacitors
2. Set of tests with $1\mu F$ phase-to-phase capacitors (delta configuration)
3. Set of tests with $3.3\mu F$ phase-to-phase capacitors (delta configuration)
4. Set of tests with no phase-to-phase capacitors with added $100\mu F$ DC filtering capacitor
5. Set of tests with $1\mu F$ phase-to-phase capacitors (delta configuration) with added $100\mu F$ DC filtering capacitor
6. Set of tests with $3.3\mu F$ phase-to-phase capacitors (delta configuration) with added $100\mu F$ DC filtering capacitor

9 Experimental results

Fig 6 demonstrates the power capacity of the 100S version of SD modified to 7 poles per phase. Significant effect of phase-to phase capacitance is evident. The phase-to-phase capacitance significantly increases both the power output power and the voltage at which this power is generated. The 3.3 μF capacitance limit arose due to the limited power of the drill motor. With $10\mu F$ phase-to-phase capacitors V_o was above 150 VDC, well above the target specifications for our alternator. DC characteristics of the alternator-rectifier system is shown in Fig 7. Measurements indicated that for each combination of capacitance, including zero external capacitance, there exists an output voltage (and the corresponding output power) for which the alternator operates with maximum efficiency. This voltage does not coincide with the voltage at which the maximum possible power is generated.

As prediced, except for small capacitance values (below $1\mu F$), the phase-to-phase capacitance has detrimental effect on alternator-rectifier system efficiency. However, as can be seen from the measured data presented in Fig 9, a 10% compromise

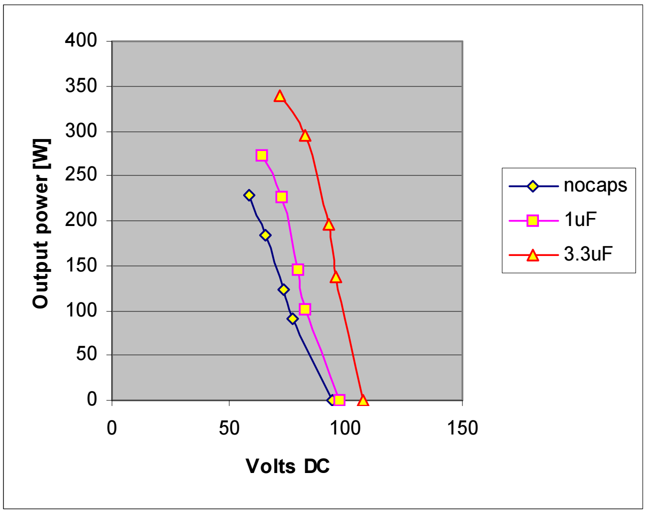

Fig 6. Output power of the alternator-rectifier system as a function of output DC voltage and phase-to-phase capacitance

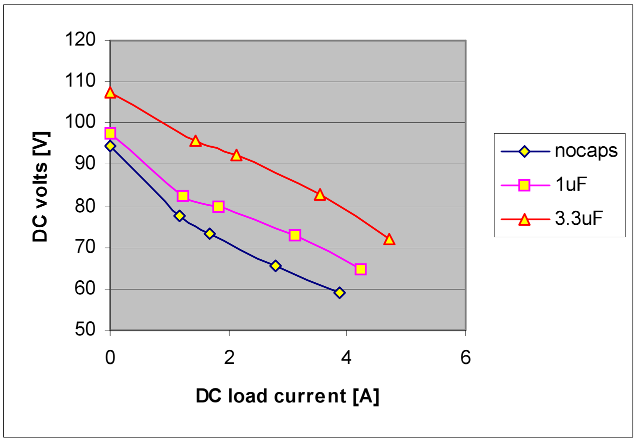

Fig 7. DC characteristics of alternator-rectifier system

in efficiency (from 95% to 85%) can result in more than doubling the output power capacity of the alternator-rectifier system.

Since phase-to-phase capacitance causes the DC power to be generated at higher voltages this may not be any compromise at all, because the reduced efficiency is partly compensated by the reduced power transmission losses.

In terms of the output voltage, the maximum efficiency seems to occur for $0.72V_o$ with no phase-to-phase capacitors. $1\mu F$ phase-to-phase capacitors shift the maximum efficiency point to $0.82V_o$ and $3.3\mu F$ capacitors to $0.87V_o$.

The point of maximum practicably available DC power (extractable with reasonable efficiency) is $0.62V_o$ with no phase-to-phase capacitors and around, $0.67V_o$ when phase-to-phase capacitors are installed.

The above results indicate that the point of maximum efficiency does not occur at the maximum power that the alternator-rectifier system can deliver at given RPM with reasonable efficiency. The point of maximum efficiency is closest to the point of maximum extractable power when no phase-to-phase capacitors are present. This point is remarkably close to the optimal output voltage $V_o/\sqrt{2} = 0.71V_o$ predicted by the simplified linear theory of an alternator presented earlier in this article.

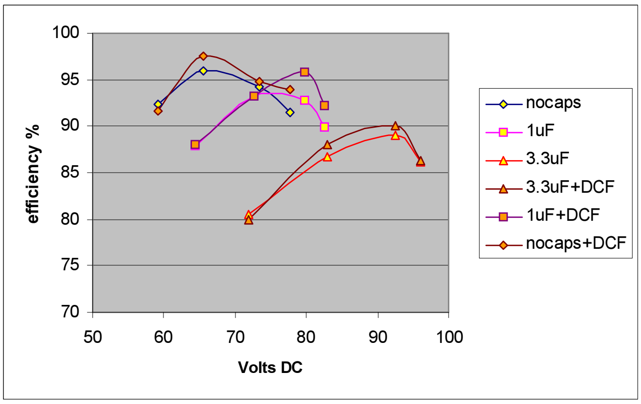

Fig 8. Effect of phase-to-phase capacitance and DC filtering on alternator-rectifier efficiency. DC filtering has a small positive effect on efficiency, but only when alternator operates near the peak efficiency.

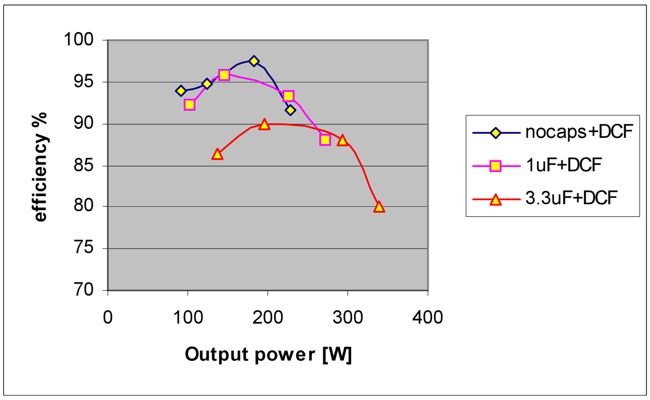

Fig 9. Efficiency of the altenator-rectifier system as a function of output power

A common guideline for the point of maximum efficiency can be established in terms of the ratio of the output power and the maximum practicaly extractable DC power. The maximum efficiency seems to occur in all cases when the output power is around 50% of the maximum practically extractable DC power.

10 Conclusions

For any permanent magnet alternator-rectifier system, defined by its design and operating parameters, there exists a load for which the maximum power generation efficiency is obtained. There also exist another load, for which the maximum power can be extracted from the alternator-rectifier system.

In general, the above two loads are not the same. The point of maximum efficiency seems to occur for loads that extract about 50% of the maximum practically extractable power.

Changing any of the design or operating parameters of the alternator-rectifier system influences both its output power and its efficiency.

It seems that many apparent "inefficiencies" in alternator applications are caused by the improper loading of the alternator: efforts to extract the true power at some arbitrary non-optimal voltage with some arbitrary load far away from the optimal load.

In order to improve the efficiency of any alternator-rectifier system it seems necessary to match the actual power extracted from the alternator with its "optimal" output power at which the alternator has the maximum possible efficiency. This can be achieved either by modifying alternator design parameters or its operating conditions. Of all alternator-rectifier system parameters - the easiest to adjust is the rotating speed and hence this parameter should be adjusted first, if possible.

In most cases, good efficiency is obtained when the voltage at which the power is extracted from the system is $V_o/\sqrt{2}$ or slightly greater.

When the power that we plan to extract is much lower than the maximum power that the alternator can deliver it is necessary to reduce the alternator core size in order to achieve higher efficiency of power generation. Smart Drive alternators are known for their poor efficiency at powers lower than 100Watts.

This article demonstrated that by reducing the core size it is possible to generate 100Watts with 97.1% efficiency at a voltage of our choice.

3-phase rectification excites undesirable transients in alternator windings. Small phase-to-phase capacitors were found to be quite useful in reducing these undesirable distortions. Phase-to-phase capacitors were found to have the potential to increase the output power capacity of alternator-rectifier systems by as much as 200% while raising the DC output voltages sigificantly as well.Significant phase-to-phase capacitance reduces the power generation efficiency.

Presented results indicate that it is possible to find an optimal phase-to-phase capacitance that noticeably improves the power characteristics (the output power and the output voltage) of a permanent magnet alternator-rectifier system without reducing its power generating efficiency. For the alternator-rectifier system presented in this article the value of this capacitance was approximately $1\mu F$.

It seems that installing phase-to-phase capacitors is the second-easiest method of improving the performance of permanent magnet alternator-rectifier systems.

Since phase-to-phase capacitors increase the power capacity of permanent magnet alternator-rectifier systems - it is possible to connect them automatically, when the power output demand increases. Such an automated capacitor switching offers an easy and attractive way of extending the operating power range of permanent magnet alternator-rectifier systems. In the case of the alternator-rectifier system presented in this article,capacitor switching would extend its power range to 70-350 Watts while providing power generation efficiency between 80 and 97%.

11 References

[1] ENGINEERING DATA (Aerovent, TC Ventco, Fiber-Aire, Twin City Fan & Blower, TC Axial, Clarage): Single-Phase AC Induction Squirrel Cage Motors, http://tcf.com/TCFBlower/pdfs/engr_data/ED1100.pdf