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# Topologies for Future Automotive Generators – Part II: Optimization

L. M. Lorilla, *Student member, IEEE,* T. A. Keim, *Member, IEEE,*
J. H. Lang, *Member, IEEE*, D. J. Perreault, *Member, IEEE*

*Abstract*-- **This paper compares the relative suitability of four different alternator topologies for use in an advanced automobile electrical system. The four candidate topologies are: the salient- and non-salient-pole wound-field synchronous alternators, the Lundell alternator, and the homopolar inductor alternator. In part I, each of the four alternators was modeled. Relative power and efficiency were evaluated based on hand calculations. Part II involves a more accurate optimization of each of these alternators for cost, subject to constraints on output and efficiency. The performance of each machine is determined both with a conventional diode rectifier bridge and also with a switched-mode boost rectifier. Mechanical finite element analyses are performed to evaluate stresses. The most cost effective machines are compared based on size, weight, and inertia. The results reveal that the Lundell and salient-pole wound-field synchronous alternators are the most cost effective. Most surprising is the finding that the Lundell is capable of meeting the challenging next-generation requirements of power and efficiency while meeting the mechanical constraints set on the machines. Also noteworthy is the fact that the switched-mode boost rectifier gives a decrease in cost of more than 10% for each of the least expensive machines.**

*Index Terms*-- **Automotive alternator, synchronous generator, switched-mode rectifier, non-salient wound-field alternator, salient wound-field alternator, Lundell alternator, homopolar inductor alternator , constant voltage load, generator lumped parameters**

## I. OPTIMIZATION

### A. Search for optimal machines

In order to verify the validity of the back of the envelope calculations made in part I, a cost optimization of each of the four alternators is performed, subject to the requirements of future automobiles. Each machine must provide at least 4 kW at 1200 rpm, and at least 6 kW at 12000 rpm; 12000 rpm is the maximum operating speed. Each must be at least 75% efficient while generating 3250 W and running at 3000 rpm. The power outputs stated here are net; gross power must include net power plus field winding loss, but no allowance is made for field winding power conversion inefficiencies. Maximum limits are set for the heat flux densities as discussed later in Section II.B.1. Saturation of the teeth and pole necks are avoided by requiring the flux densities to be less than 1.8 Tesla. The back iron thickness dimension is not a search variable, but is determined based on this same flux density limit.

Given these requirements, the machines are optimized for cost by using a grid search over the entire design space. The objective function is a very simple one. The cost of the copper windings is added to the cost of the active magnetic materials to determine a total cost. The volume of the windings is estimated from the geometry, with simple approximations for end turn volumes, and assuming a turns packing density which is constant for all machines. The mass of copper and then the dollar cost of copper is computed. The active magnetic materials included the stator stack and the magnetically active rotor (a stack or a solid object). The volume and mass of these components are computed, using a stacking factor of unity in the case of laminated structures. A constant price per unit mass is applied to the entire (rotor plus stator) iron mass. The specific costs assumed are $5/kg for copper and $1/kg for iron.

The most cost effective machines are further compared based on size, rotor inertia, and mechanical stresses. We want the best alternator to be the most cost effective alternator which should have other desirable properties such as small volume, low rotor inertia, and allowable mechanical stresses.

Unlike previous optimizations done on alternators [1]-[2], the load voltage seen at the output of the rectifier can be varied. This is the fundamental contribution of the switched-mode rectifier. For each of the operating points, the optimizer determines the minimum number of field ampere turns to generate enough power across effective output voltages less than or equal to 42 V. Thus, the machines are not necessarily operating at the load matched condition or peak of the power vs. voltage curves.

An exhaustive search is done on the number of armature turns. For each geometry and a given set of output voltages, the highest number of armature turns that meets the efficiency and heat flux limits is selected. This is done because the flux densities in the air gap tend to decrease with a higher number of armature turns and so the back iron thicknesses are allowed to decrease as well.

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### *B. Details on properties subject to constraints*

#### *1) Heat transfer limits*

Candidate windings are evaluated on the basis of heat flux density, or heat flow per unit of cooling area. Machines with heat flux densities below the density limit are considered as candidates for the lowest cost machine; machines with heat flux densities above the limit are removed from further consideration.

The total heat flow from a winding is considered to be the ohmic loss within that winding, and all the heat flux is presumed to flow over a specified heat transfer area. In most cases, the area used is an approximation to the area exposed to air in the end turn structure of the machine. In Figures 1 through 4 of Part I, for example, the end turns are represented schematically by rectangular figures in the transverse section views. Each of these rectangular figures can be considered to represent the cross section of a ring of rectangular section, coaxial with the machine. One axial face of each ring is considered to abut the stator or rotor, as the case may be. Heat is presumed to enter the ring through this face. The remaining surface area of the ring is presumed to be available for heat transfer.

The radial dimension of the rings representing the end turns are the same as the slot dimensions for the winding in question, and the axial dimension is determined by a simple approximation. For example, the exposed area of the armature winding for each of the four machines is

$$A_a = 2\begin{pmatrix} p\left(R_{statslotbot}^2 - R_{statin}^2\right) \\ + 2p\left(R_{statslotbot} + R_{statin}\right)W_{endturn} \end{pmatrix} \qquad (1)$$

where $R_{statslotbot}$ and $R_{statin}$ are the stator slot bottom radius and stator inner radius respectively, and $W_{endturn}$ is the distance that an end turn extends from the edge of the stator.

The field windings of the homopolar and Lundell alternators do not have end turns in the same sense as the other windings considered here. In these cases, the complete winding is approximated as a ring (toroid) of rectangular cross section, and heat transfer is presumed to occur on only one surface with a radial normal, in particular the outer surface in the case of the Lundell alternator and the inner surface for the homopolar alternator.

It is acknowledged that the real heat transfer performance of an alternator is far more complicated than the situation depicted by this simple model, but the simplifications offered here are reasonable for the purpose of this study. The dominant cooling path for windings in automotive generators is convection through the end turns, and the temperature drop at the winding-to-air interface is generally dominant over other temperature drops in the cooling path. Other heat sources (iron loss, bearings, windage, etc.) and other heat paths (radial through the core, axial along the shaft, etc.) both exist, but the heat sources and coolant paths considered here are dominant over the others, especially in the performance-limiting conditions.

The thermal model presented here has the benefit that the limiting values for heat flux can be determined by observation of present-day design practice. In an automotive alternator, for example, the dimensions of the armature end-turn ring and of the field winding heat transfer surface can be measured, and the value of winding losses can be calculated from the rated current and the measured winding resistance. These inferred values have been applied directly to the machines in this study. This implies that for a machine in this study to be adequately cooled, it is necessary only that the ratio of actual effective end-winding heat transfer area to the area of its approximating ring be similar between the machine from this study and the alternator from which the measurements were taken, and further that the air flow and heat transfer coefficient be comparable in the two machines. Since both the required area and the required air flow and heat transfer coefficient have already been achieved in one case (the measured machine), it should not be impossible to achieve them in the relatively similar proposed new machines. The heat flux density limits used here are 7.28 x $10^4$ W/m$^2$ for the armature windings of all machines and field winding of the wound-field alternators and 6200 W/m$^2$ for the field windings of the Lundell and homopolar inductor alternators.

The heat flux density for the field winding can be expressed as

$$q_f = \frac{\left(R_f \big/ N_f^2\right)\left(N_f I_f\right)^2}{A_f} \qquad (2)$$

where $R_f$ is the field resistance and $A_f$ is the exposed area of the field winding. The partitioning of terms in (2) is not as capricious as it may first seem. The importance of the grouping $N_f I_f$ is well understood, and the grouping $R_f/N_f^2$ makes sense when one recognizes this as the resistance of a one-turn field winding occupying the available winding volume.

The heat flux density equation for the stator winding is

$$q_a = \frac{\frac{3}{2} I_s^2 R_a}{A_a} \qquad (3)$$

where $I_s$ is the peak armature phase current, $R_a$ is the armature resistance and $A_a$ is the area of the exposed armature winding.

#### *2) Efficiency*

In calculating the efficiencies, only the field and armature winding losses and diode losses are included. The Lundell and homopolar inductor alternators are expected to have higher efficiencies since the number of field ampere turns do not have to increase with an increase in pole count. As indicated in the discussion above, we acknowledge that other losses exist and are important in some cases, but for this study, only the winding losses and diode losses are included.

### 3) *Saturation*

In order to compare the alternators in terms of saturation, the flux densities in the air gap are determined. Only the average and fundamental components are used. The flux density in the air gap is related to the flux density in the stator, and, if relevant, the rotor teeth and also to the flux density in the stator return iron by geometric constants.

### 4) *Inertia*

The rotor inertia for each of the four machines is determined using simplified approximations of rotor geometry. All the tooth and pole boundaries with a large radial component are modeled as purely radial. The main factors that contribute to inertia will be the air gap radius and machine length. Optimization of machines will result in machines with different air gap radii and machine length. The machines that create air gap fluxes most effectively are expected to have the smallest radii and lowest inertia. The ordering from best to worst in terms of output from a fixed geometry with a fixed number of field ampere turns is likely to apply as well to rotor inertia.

## II. RESULTS

### *A. Optimization results using switched-mode rectifier*

The optimization is performed to obtain the least expensive machines that meet the requirements. A satisfactory machine will have a combination of radii, active length, air gap width, and slot depth that allows it to generate enough power while meeting the efficiency, heat flux, and saturation limits.

The four optimal machines are shown in Figures 1-4. For ease of comparison, the machines are drawn to the same scale. The inductor alternator optimized to the largest dimensions. This is due to saturation limitations since the flux in the air gap is the sum of the alternating flux and average flux. Thus, instead of increasing the number of required field ampere turns to generate the required power, the dimensions of the machine must be increased. The large dimensions cause this machine to be the most expensive.

The non-salient wound-field alternator is the next most expensive machine, followed by the salient-pole wound-field alternator and finally, the Lundell, which is the least expensive alternator. The salient version of the wound-field alternator performs better than the non-salient type because of the field winding factor which is less than one for the non-salient alternator. This diminishes the output power of the non-salient type machine.

In agreement with the simplified analysis in Part I is the result that the Lundell alternator is the most effective in generating power. Looking back at the simplified analysis, given the same output power, the Lundell alternator has the largest field-armature mutual inductance which contributes to efficiency. In fact, looking at Table I, the efficiency of the optimal Lundell alternator is around 83%, which is far from the limit of 75%.

The limitations for the Lundell alternator are saturation of the rotor structure and the field heat flux limit. The Lundell alternator rotor structure is limited by saturation since the flux entering all the south poles for example, have to enter the supporting disk (also known as flux plate) through the end of the poles and return axially in the steel beneath the field winding. These require minimum thicknesses for both pieces of steel. Thus the rotor radius can not be reduced further. As a consequence, the field ampere turns do not have to be increased to the point where the efficiency is close to 75%.

As reported in Section II.B.1, the field winding heat flux density limit for the Lundell alternator was lower than that used for the wound-field machines, consistent with our observations of an automotive alternator. Table I shows that the heat flux density limit was reached before the efficiency limit. It is plausible that our observation is generally correct, in that it is credible that it will be harder to extract heat from a cylindrical surface, shielded from high velocity air flow by the claw pole structures, than from a finely subdivided end turn structure in the direct path of the flow from a radial fan. Since the field currents are lower for the Lundell and homopolar inductor alternator, the lower heat flux limit does not severely limit their capabilities compared to the wound-field alternator.

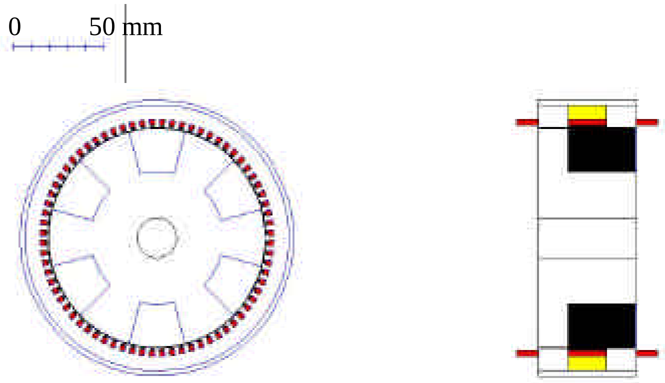

Fig. 1. Homopolar inductor alternator

Fig. 2. Wound-field non-salient pole alternator

Fig. 3. Wound-field salient pole alternator

Fig. 4. Lundell alternator

TABLE I
COMPARISON OF OPTIMAL MACHINES

| Feature | WFNS | WFS | Lundell | HIA |
|---|---|---|---|---|
| Cost ($ steel+$ copper) | 16.2 | 12.0 | 11.8 | 40.3 |
| Outer radius (m) | 0.0949 | 0.0832 | 0.0771 | 0.1393 |
| Outer length (m) | 0.055 | 0.05 | 0.0784 | 0.099 |
| Max Stress ($10^8$N/m$^2$) | 0.8 | 0.4 | 3.45 | 1.2 |
| Inertia (kg.m$^2$) | 0.0245 | 0.0072 | 0.0077 | 0.0686 |
| Efficiency (3000 rpm) | 0.7598 | 0.7582 | 0.8267 | 0.8064 |
| Field heat flux density at 1200 rpm (W/m$^2$) | 53261 | 41005 | 6184 | 6024 |
| Field heat flux density at 3000 rpm (W/m$^2$) | 9512 | 9698 | 1721 | 2090 |
| Field heat flux density at 12000 rpm (W/m$^2$) | 31806 | 57680 | 5472 | 5937 |
| Armature heat flux density at 1200 rpm (W/m$^2$) | 61455 | 60643 | 53820 | 17023 |
| Armature heat flux density at 3000 rpm (W/m$^2$) | 10779 | 14567 | 15307 | 7432 |
| Armature heat flux density at 12000rpm (W/m$^2$) | 43502 | 71968 | 52789 | 25835 |
| Flux density at 1200 rpm (T) | 1.758 | 1.753 | 1.788 | 1.783 |
| Flux density at 3000 rpm (T) | 0.777 | 0.758 | 0.881 | 0.776 |
| Flux density at 12000 rpm (T) | 0.333 | 0.293 | 0.566 | 0.489 |
| Output voltage at 1200 rpm (V) | 30 | 31 | 28 | 35 |
| Output voltage at 3000 rpm (V) | 42 | 42 | 42 | 42 |
| Output voltage at 12000 rpm (V) | 42 | 42 | 42 | 42 |

The last three rows in Table I show the effective voltage for each machine at each operating point. The action of the switched-mode rectifier makes it possible for a machine to run at an effective voltage anywhere at or below the nominal bus voltage of 42 volts. It is evident that the optimizer found it beneficial to use switched-mode operation of the rectifier only at the high-torque low-speed design point. The entries of 42 volts imply no switched-mode action. These operating points could be achieved with a simple diode rectifier. Since active switches are indicated for low-speed operation, it seems probable that they would be used in synchronous rectifier mode, wherever boost mode is not indicated.

Perhaps the most remarkable finding is not that the Lundell alternator was found to be least expensive, but that, given the huge difference seen in Part I, the difference between the Lundell and its closest competitor is as small as it is. Given the many approximations and inaccuracies remaining in the process to produce Table I the fairest conclusion is probably that the competition for lowest cost is a dead heat between the Lundell alternator and the wound-field salient alternator.

### *B. Stress Analysis of Optimum Machines*

Meeting mechanical stress limits is an important consideration in the machine design. Based on finite element analyses, the salient wound-field alternator is the most robust stresswise among all four machines, followed by the non-salient wound-field alternator, the homopolar inductor alternator and the Lundell alternator. This rank order arises at least in part because we have considered stress only in the rotor iron. We are aware that it is common in wound-field machines for the maximum structural stress to occur not in the main rotor steel but rather in wedges or other structures which retain windings in their places. It is also possible that the most limiting effect of rotation and temperature does not occur in any part of the rotor structural material, but rather in the compressive load in the conductor itself. While the conductor is not in the load path, the yield stress of copper, especially at elevated temperature, is so low that this consideration may be more restrictive than the capability of the rotor structure. Although we acknowledge these effects, we do not expect them to render any of the machines analyzed here mechanically unsuitable for their intended duties, so we do not explore these matters further.

The Lundell alternator as expected has the highest stress due to the cantilevered pole structure protruding from the supporting disks. The stresses, though, are within the allowable limits set for steel.

The finite element models for each of the candidate machines are shown in Figures 5 through 8. The arrow in each figure points to the maximum stress location. In each case, symmetry is exploited to the maximum possible extent. In general we see one half of one pole, but in the case of the non-salient wound-field machine we see one half of one tooth. The models in these figures are not in any case the first model considered, but reflect adjustments made to reduce peak stress where needed.

It is frequently the case that the largest stress in the entire solution domain occurs at a geometric discontinuity. This occurs for two reasons. First, geometric discontinuities do introduce stress concentrations in true (physical) stress fields. Second, finite element methods give rise to mathematical, non-physical, large numbers due to approximation errors at geometric discontinuities. Fillets, and larger radii tend to improve the calculated stress by acting favorably on both effects, and finer grid geometries can be used to control approximation errors.

We have used both techniques, with special emphasis on fillets, to reduce the calculated stresses. We believe the geometries we have chosen represent reasonable approximations to practical solutions, and are not unduly compromised by insensitivity to good mechanical design. This last statement is probably least robust in the case of the Lundell alternator.

The only constraint which we placed on the mechanical stress was a requirement that the peak von Mises stress be less than $4 \times 10^8$ N/m$^2$ (a bit less than 60,000 psi). This may be conservative, relative to the strength obtainable in the parts under consideration. We found that with reasonable fillets we could get all the cost-optimum designs below this limit, so we were not motivated to investigate the credibility of some higher limit.

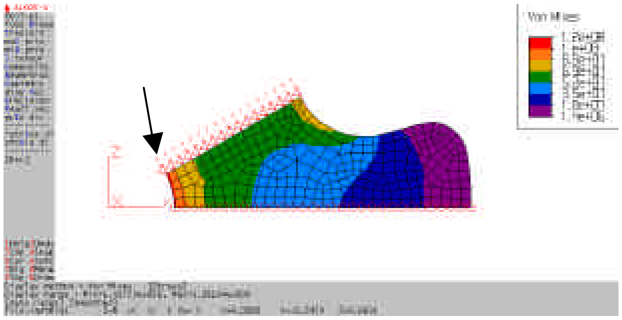

Fig. 5: Homopolar inductor alternator

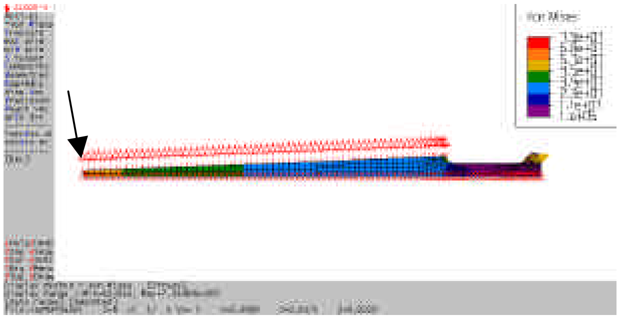

Fig. 6: Non-salient wound-field alternator

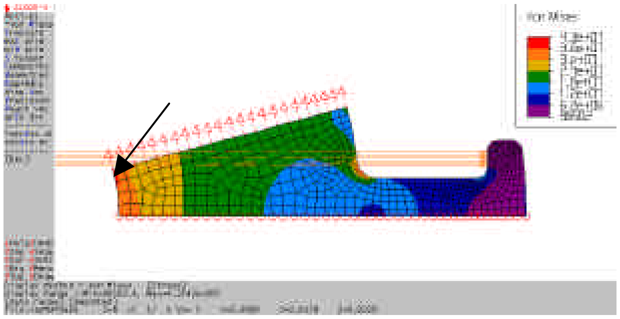

Fig. 7: Salient-pole wound-field alternator

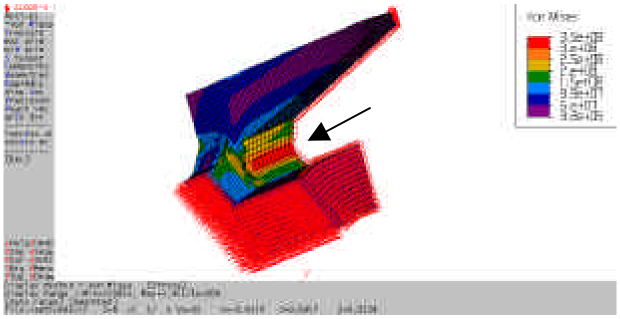

Fig. 8: Lundell alternator

Note that this study has left many possible investigations unexplored. In particular, in the optimization, we considered only one number of pole pairs and have constrained all machines to operate at the same speeds. This latter condition corresponds to considering only one possible drive ratio between engine and generator. Both limitations seem at least somewhat arbitrary.

There is a fairly strong justification for our choice not to vary pole count. In previous studies [1]-[2] involving similar modeling and the same load requirements and cost function, we included pole count as an optimization variable. There, we almost always observed a cost function which decreases monotonically but asymptotically as pole count increases. We find these results uninteresting. Common sense tells us that the true optimum is not at infinite pole count. Increased time in winding the machine, increased cost per unit for finer wire, the increased lamination expense and other system penalties of higher frequency operation, are real effects which put an upper bound on the practical pole count of a machine. We have chosen not to model these effects. Instead, we observe that at 6 pole pairs, we are still low enough so that the adverse effects of these neglected considerations are not large. But at the same time, the pole count is high enough so that the main effects of economy due to thinner back iron and shorter end turns have been realized.

As for the effect of generator speed on cost, there remains substantial room for further work. The principal reason for considering the homopolar inductor alternator is that its simple rotor structure should make it possible to use high rotor speeds.

The homopolar alternator results are a bit of a surprise, first that it comes out so expensive in this study, and second, that it is already a relatively high speed machine, as measured by surface speed and by rotor stress. Because it starts out so expensive, we need to anticipate great cost savings if higher speeds are considered. But there is only about a factor of 1.7 or so of allowable increase in surface speed, before the stress becomes comparable to that of the cost-leading Lundell alternator. This change in surface speed is unlikely to bring about a cost reduction of more than the factor of 3.4 needed to match the Lundell. Additionally, an increase in surface speed of this magnitude would put the air in the generator firmly in the realm of transonic, or compressible, flow. This means that temperature changes associated with fluid velocity changes are no longer negligible. The design challenges associated with producing a well cooled design in such a flow regime will be substantial. Additionally, flow noise will assume an increased importance, and the simple crude structure indicated by Figure 5 is unlikely to be acceptable without fairing and/or other treatments. In summary, given how far the homopolar inductor alternator has to go, it is not clear that this is a fruitful direction.

The very low stress levels computed for the wound field machines suggest that consideration of these machines at higher speeds may be productive. There are two general concerns about this direction. First, as discussed above, the real rotational speed limit in these machines may not be in the rotor steel, but in parts that have yet to be considered. A detailed mechanical design can give guidance about the possible existence and detailed nature of these limits, but the result will be harder still to include in a cost-optimizing grid search. Second, the compressible flow and flow noise concerns discussed in connection with the inductor alternator remain considerations for wound field machines.

While there may be benefits to considering different machines operating at different speeds, the results are definitely beyond the scope of this study.

In terms of inertia, the salient-pole wound field machine has the least inertia followed by the Lundell machine, the non-salient pole wound-field machine and the homopolar inductor alternator. In general, the smaller the rotor structure, the lower the inertia. Since the salient-pole wound-field and Lundell alternators optimized to the smallest rotor sizes due their effectiveness in generating flux and being relatively less limited by the performance constraints, their inertias are the lowest.

### C. *Optimization results using diode rectifier*

In order to assess the effect of the switched-mode rectifier on the cost of the optimized alternators, a separate set of runs were performed on all four machines while run with simply a diode rectifier where the effective voltage seen at the output can only be 42V. The set of cheapest machines for the optimization with (previous results) and without the switched-mode rectifier are compared in Table II below.

The results show that the switched-mode rectifier results in a decrease in cost of the least expensive machines by more than 10% from those obtained without using a switched-mode rectifier. At least part of the cost of implementing the switched-mode rectifier is offset by the savings that it enables.

From Table II, notice that the switched-mode rectifier is used only at the idle point. It is at the idle point where the field-ampere turns required are highest. It is also at the idle point where the air gap flux densities are highest. Therefore, it is at the idle point where back-iron thicknesses are determined which in turn affect cost. If the output voltage is lowered, the result is that the equivalent switched-mode rectifier resistance decreases and the internal power angle increases, the net result of which is a decrease in the flux density in the airgap. In order to meet the output power, the armature current increases and so does the back-emf through the field ampere turns. Despite these increases in currents, the net effect on the flux density is still a decrease. Given the decrease in flux density, there is now more room for cost optimization. The air gap radius can then be decreased which results in an increase in the flux density but a decrease in cost. Thus, the optimal machine used with the switched-mode rectifier is likely to have a smaller radius.

TABLE II
COMPARISON OF LEAST EXPENSIVE MACHINES OBTAINED WITH AND WITHOUT THE SWITCHED-MODE RECTIFIER

| | Diode rectification | Switched-mode recitification | Percent decrease in cost |
|---|---|---|---|
| Non-salient WFSM | 18.46 | 16.19 | 12.3% |
| Salient WFSM | 14.20 | 11.98 | 15.6% |
| Lundell | 13.53 | 11.45 | 15.4% |
| Homopolar | 44.86 | 40.30 | 10.2% |

## III. CONCLUSION

In part I, the lumped parameter models for the four alternators are tied together with the circuit model for the switched-mode rectifier in order to derive analytical expressions for machine performance at the load matched condition. To validate the performance of the four machines and make more accurate comparisons, Part II presents the results of an exhaustive grid search optimization done to determine which machine is most cost effective while meeting the more demanding requirements of next generation automobiles.

Looking at the optimization results while taking note of the predictions made using the analytical expressions, it is understandable that the Lundell alternator is the most cost effective alternator. What is surprising is that it has mechanical stresses below allowable limits while meeting these challenging power and efficiency requirements. The salient-pole wound-field alternator does perform well and comes in as a close second. To the accuracy of this study, the two machines are virtual equivalents from a cost viewpoint.

We expect that for this application, the industry will continue to select the Lundell alternator because of the vastly larger experience base with such machines. But the results here suggest that for another specification, even one only slightly more challenging to the Lundell machine, a different machine might be preferred.

The optimization runs done on the Lundell alternator using only a diode rectifier show that the switched mode rectifier results in a 15% decrease in the cost of the optimal machine. A switched-mode rectifier is also useful for transient voltage suppression and jump starting thus sparing us the cost of additional components used for these functions.

## ACKNOWLEDGEMENT

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