SPECTRAL STUDY ON THE VOLTAGE WAVEFORM OF CLAW POLE AUTOMOTIVE ALTERNATOR

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KEYWORDS
Finite element, Claw Pole, K-factor, Harmonics

ABSTRACT

An increased number of vehicle functions necessitated by legislation and customer expectations have introduced many electronic control systems and electrically driven units in vehicles. The drastic increase in the non linear loads associated with the introduction of new technologies, produces distorted voltage and current waveforms which introduces harmonics. It is in this context of electrical distribution, that the K-factor was evolved for distribution transformers to compensate for the additional heating effects generated by the harmonic currents. This paper presents a spectral study of the voltage wave form of the claw pole automotive alternator under no load, balanced and unbalanced loads to estimate the variation of harmonic contents under these operating conditions. Theoretical study has been conducted using 3D finite element method and is supplemented by the experimental work on a 12 pole claw pole alternator. The K- factor has been computed and the design features needed in a highly nonlinear environment with K>4 are also suggested for the electrical, magnetic and dielectric circuits of the claw pole alternator.

INTRODUCTION

In recent years, the demand for electrical power in modern automobiles has constantly been increasing. For better fuel economy, many devices driven directly by the engine have to be driven electrically. Electrical equipments like electromechanical valve actuators and active suspensions etc. will triple the aggregate power demand. The efforts to meet this drastic increase in loads and introduction of several electronic control systems and electrically driven units for the customer satisfaction and safety measures have intensified the use of non linear loads such as solid state controls, electronic ballasts, high intensity lighting, switch mode power supplies and microprocessors etc. Greater challenges are expected in future. These non linear loads produce distorted voltage and current waveforms and are the sources of harmonics. The resultant harmonics produce increased losses, overheating of windings and cables, heating of neutral and nuisance operation.

Several studies have been carried out on automotive alternators (Zeisler and Brauer 1985; Roisse et al.1998; Henneberger et al. 1996). These studies were concerned with different modeling methodologies and the optimization of the alternator design for maximum output power. Bao et al. (2005) has reported a different modeling method and an approach to optimization of harmonics of output voltage of the alternator using this model. Investigations done in connection with further enhancement of the performance were reported (Ramesohl et al.1996,1999) by taking minimization of acoustic noise produced by the claw pole alternator as an added design constraint.

As the fraction of the non linear loads has increased, so has the anxiety over the effect of these loads. Derating the alternator is not a solution, since with increased losses it results in poor energy efficiency, defeating the very objective of derating. In this context of electrical distribution, the K-factor was evolved for distribution transformers. IEEE Standard $C_{57-110-1998}$ as well as Underwriter's Laboratory (UL) Standards $UL_{1561-1994}$ & $UL_{1562-1994}$ gives the K-factor as follows

$$\text{K-factor} = \sum_{n=1}^{\infty} n^2 I_n^2$$

Where I_n = rms value of the n^{th} harmonic in per unit. Hence a spectral study will give a K-factor for altering the design features of the claw pole alternator. An effort made in this direction of study was reported (Pillai K.P.P et al.2005).

In the present paper, NISA software is used for 3D modeling and the solver EMAG is used to calculate magnetic vector potential, allowing for the non-linearity of the B-H curve. The results are compared with the frequency spectra of generated voltage obtained from experiments on a 3 phase 12 pole claw pole alternator.

ALTERNATOR ON NO-LOAD

A 12 pole 36 slot claw pole alternator was analyzed for an excitation current of 1A and 428 DC field turns. The physical model was made using the preprocessing module NISA/DISPLAY III and the analysis is done

Proceedings 20th European Conference on Modelling and Simulation
Wolfgang Borutzky, Alessandra Orsoni, Richard Zobel © ECMS, 2006
ISBN 0-9553018-0-7 / ISBN 0-9553018-1-5 (CD)

using the solver NISA/EMAG. Due to geometry periodicity only 1/6th of the machine was studied. Meshing was manually done. About 59528 elements of NKTP 104 where to be used so as to keep skew, aspect ratio etc. within allowable limits. Contour plots of flux density distribution obtained on analysis, in the stator and rotor and in the air gap at stator surface are given in figure 1 to figure 3. The low flux density in figure 2 occurs across a stator slot opening. The induced voltage per phase on no load was calculated for a rotor speed of 2900 r/min from the flux density values. Its waveform is shown in figure 4.

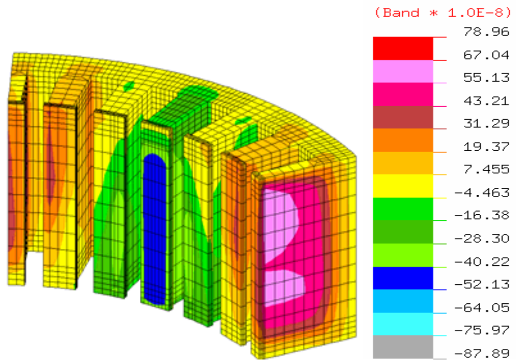


Figure 1: Flux Density Distribution in Stator

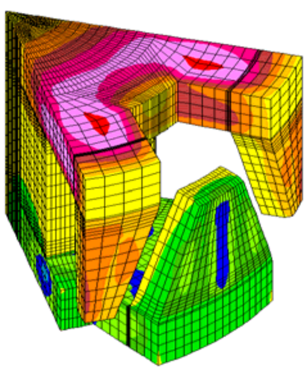


Figure 2: Flux Density Distribution in Rotor

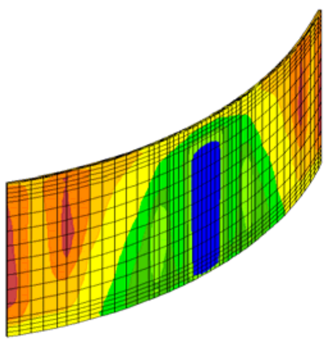


Figure 3: Flux Density Distribution in Air Gap

The machine was run at a speed of 2900 r/min by means of an induction motor coupled to it and the induced stator voltage recorded is given in figure4 along with the waveform obtained theoretically.

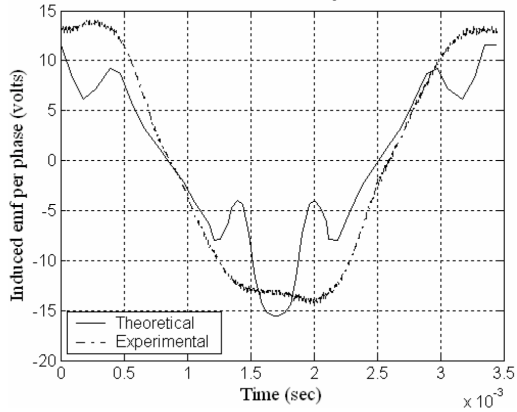


Figure 4: Induced Voltage in Stator Winding

ALTERNATOR ON SYMMETRIC LOAD

The same finite element model of the alternator, used in the no load analysis was used here also. Excitation of 1A dc was given to 428 field turns and a load current of 5A was maintained in all the three phases for analysis. The flux density distribution was obtained during post processing and the stator voltage waveform for a speed of 2900 r/min was computed and is given in figure 5.

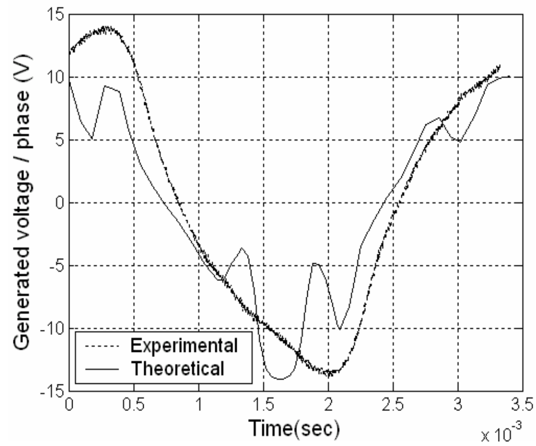


Figure 5: Stator Voltage Waveform
(Symmetric load)

Alternator was run at 2900 r/min and subjected to balanced loads ranging from 1A to 5A in steps of 1A, each time recording the voltage using a storage oscilloscope. The waveform obtained for a load of 5A is shown in figure 5 along with the theoretically obtained waveform.

ALTERNATOR ON UNBALANCED LOAD

An extension of the analysis done using NISA/EMAG on no load and balanced load is carried out to asses the performance under unbalanced load also. The unbalance factor ξ can be used as a measure of unbalance occurring, and is defined as the ratio of negative to positive sequence amplitudes. ξ can be varied from 0 to 1. In the present analysis, the extreme case of unbalance, i.e.ξ =1 has been chosen, which corresponds to single phase operation. The voltage waveform obtained theoretically is given in figure 6. The voltage waveforms were obtained experimentally for single phasing, for loads varying from 2A to 5A and the wave form for a load of 5A is given in figure 6.

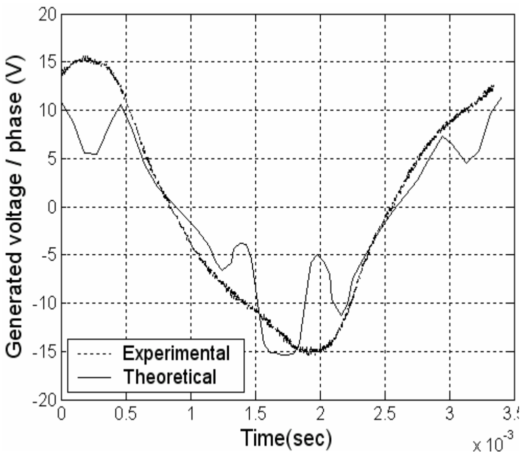


Fig 6: Stator Voltage Waveform (Unbalanced load)

DISCUSSION OF RESULTS AND CONCLUSION

The voltage waveforms were analyzed using Discrete Fourier transform to find the harmonic components and the magnitude of the harmonics as a percentage of the fundamental was calculated. Figures 7 and 8 show the frequency spectrum of the generated voltage obtained on no load by FEM and experimental measurement. A comparison of the theoretical and practical methods shows that the percentage of even harmonics is negligible in the two cases, while the odd harmonics are predominant. FEM gave consistently higher values for odd harmonics as a percentage of fundamental. As 3D mesh generation was not automatic in the FE software used, it was manually done and even when care was taken to keep the skew,

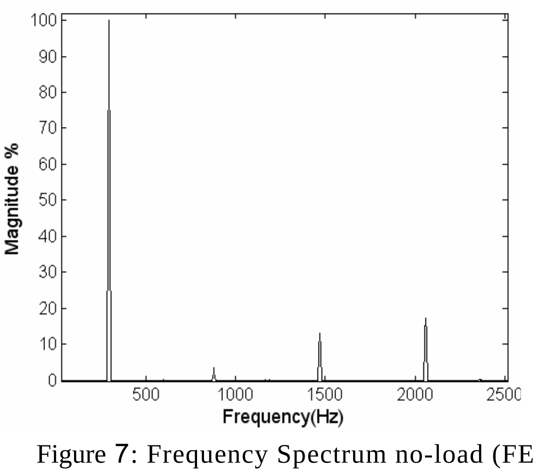


Figure 7: Frequency Spectrum no-load (FEM)

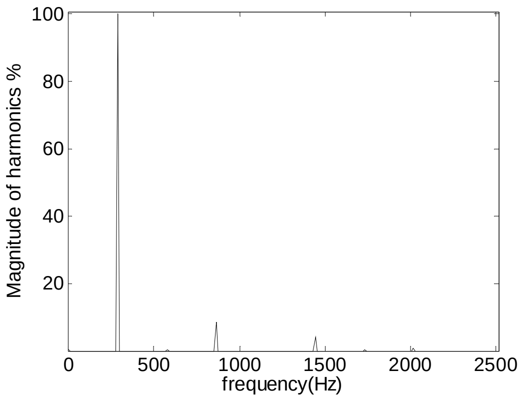


Figure8: Frequency Spectrum no-load (Experimental)

aspect ratio etc. within limits, the interfacing errors between hybrid elements were usually present. Secondly, the flow of circumferential flux on the outer boundary of stator necessitates a difference in magnetic potential and hence the circumferential component of curl A has a finite value on the outer boundary, unless the yoke thickness is taken as semi infinite. However the software could not handle such sophistication, hence the odd harmonic content of generated voltage waveform obtained through FEM was seen consistently higher than experimental value.

Kudla and Sikora (2004) have used Mawell 3D to analyze the no load characteristics of a 12 pole claw pole alternator with various contrasts in the modeling. The details of the grid patterns used are not mentioned in the paper. The results presented by the authors show predominant 7^{th}, 5^{th} and 3^{rd} harmonic components, corroborating the present investigation results.

The harmonic spectrum of the generated voltage waveform obtained theoretically using FEM for a symmetric load of 5A and that obtained experimentally for various loads is shown in figures 9 and 10. The corresponding harmonic spectrums for the unbalanced load condition are portrayed in figures 11 and 12.

Figures. 13 to 16 show the variation of the fundamental component, 3^{rd}, 5^{th} and 7^{th} harmonic of the generated voltage respectively for both 3-phase symmetrical loading and the unsymmetrical loading, the load current varying from 2 to 5 A in steps of 1A in each case. This variation is independent of load current as along as the type of load remains the same. The variation of the harmonic components at a given load was also studied and due to limitation in space, the curves are not included.

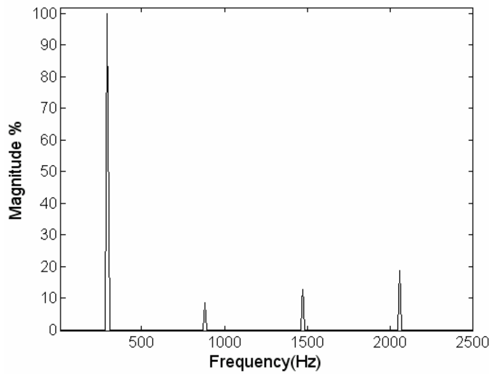
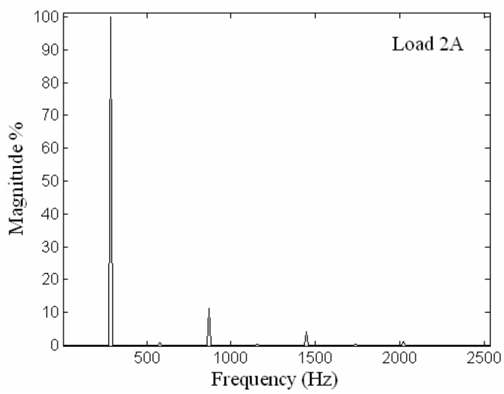
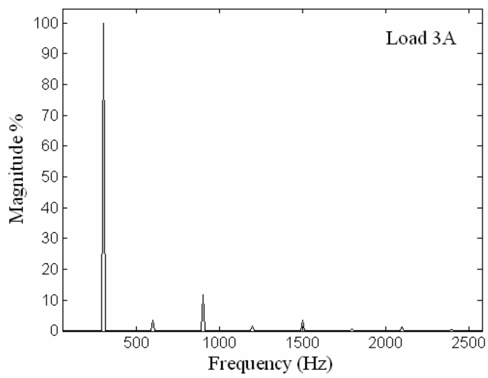
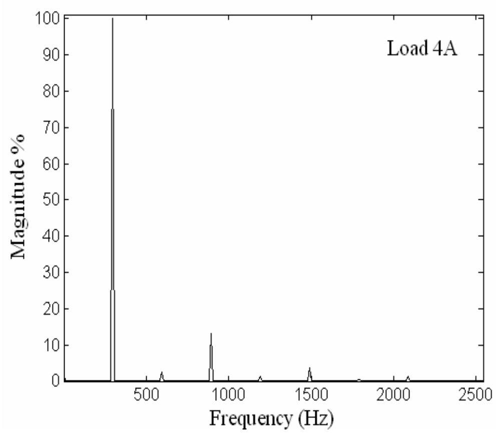


Figure9: Frequency Spectrum of Generated Voltage on Symmetric 5 A Load (FEM)







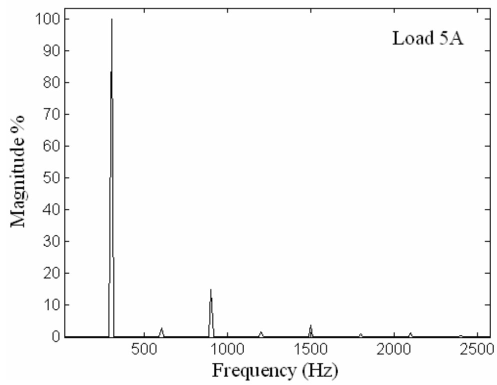


Figure 10: Frequency Spectrum for Symmetrical Loading (Experimental Method)

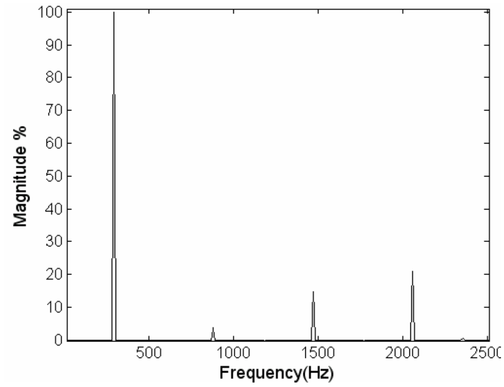
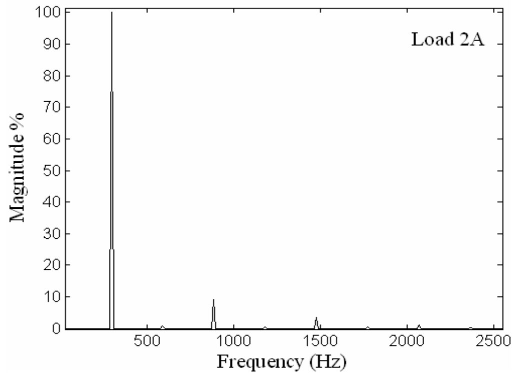
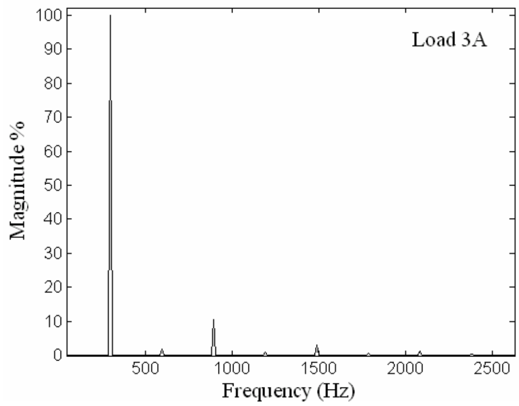


Figure 11: Frequency Spectrum for unbalanced Loading (FEM)





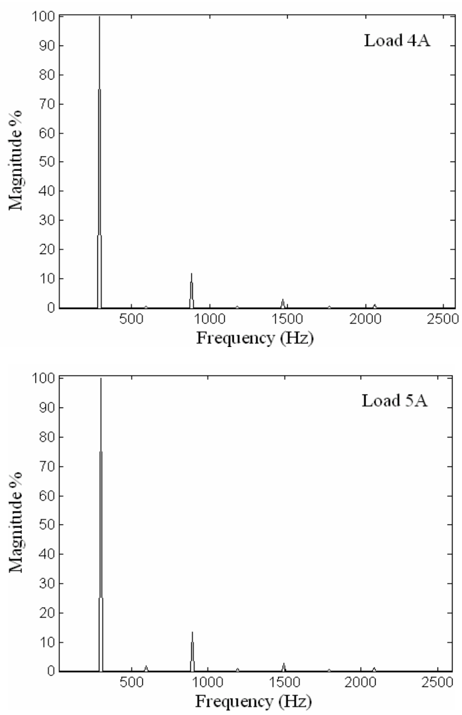


Fig 12: Frequency spectrum for 1-phasing (Experimental method).

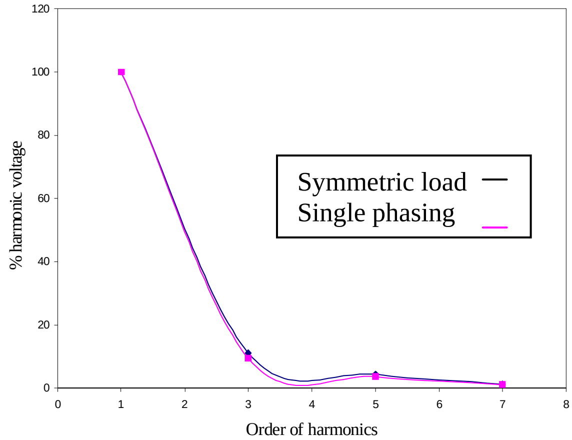


Figure 13: Harmonic voltage as % of fundamental at 2 A loads

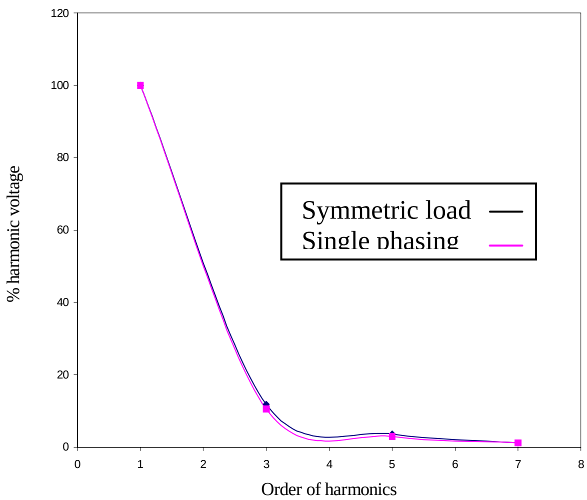


Figure 14: Harmonic voltage as % of fundamental at 3 A load

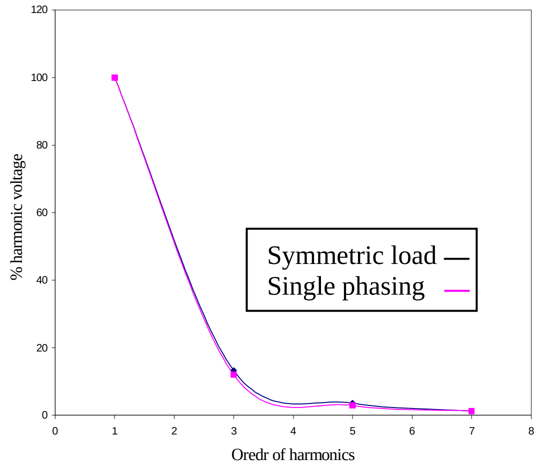


Figure 15: Harmonic voltage as % of fundamental at 4 A load

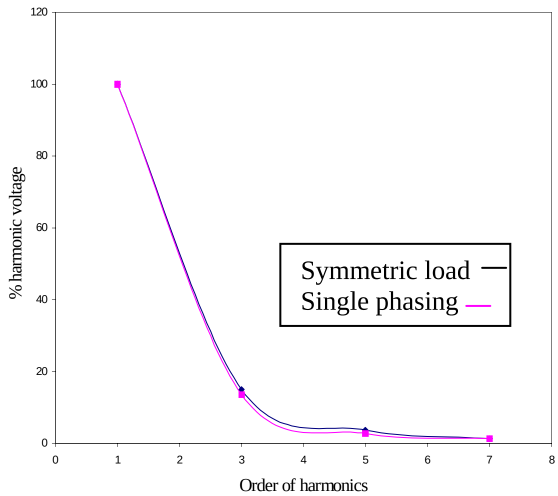


Figure 16: Harmonic voltage as % of fundamental at 5 A load

Figure 17 gives the result of a typical NISA analysis at 5A load for both symmetrical 3-phase and 1-phase loading. The harmonic component of voltage as percentage of fundamental is plotted in the figure.

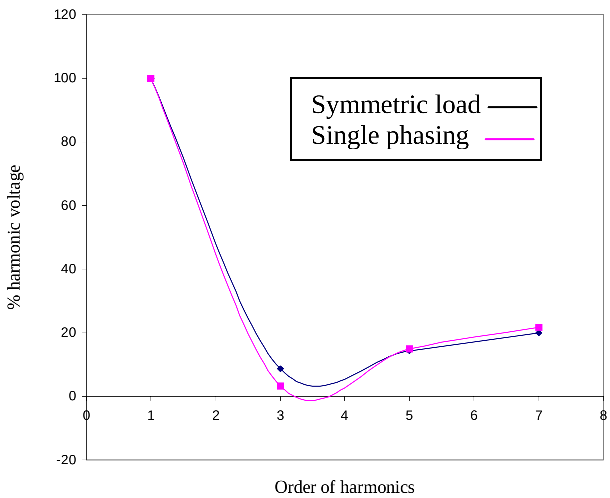


Figure 17: Percentage of harmonic voltage vs. order of harmonic at 5 A load (NISA analysis).

Power electronics in modern automobiles has to deal with widely varying system voltages and destructive high voltage transients and spikes and hence a study of the harmonic spectrum of the alternator voltage is useful in developing protective circuits and altering design features. The K-factor can be worked out for a typical case of NISA analysis (vide figure 17) for single phasing as follows

Fundamental		(1^2)	$\times 1^2$ =	1.00
3rd harmonic	4%	$(0.04)^2$	$\times 3^2$ =	0.014
5th harmonic	15.7 %	$(0.157)^2$	$\times 5^2$ =	0.616
7th harmonic	22 %	$(0.22)^2$	$\times 7^2$ =	2.372

$$\text{K-factor} = \sum n^2 I_n^2 = 4.002$$

The nearest standard K-factor is K-4. However, this is obtained with a purely resistive load. In modern automobiles with severe non-linear loads the K-factor requirement can rise to much higher values and accordingly the design requirements should be altered.

The design features at K-factors above 4 should cover electrical, magnetic and dielectric circuits. In the electrical circuit, as triplen harmonics add up in the neutral, the neutral conductor and neutral terminals have to be double the size of phase conductor and phase terminal respectively, as is being done in distribution transformers with K>4. The large skin effect at higher harmonics will necessitate segmented conductors in the armature. In the magnetic circuit, stray loss has to be reduced by studying the leakage flux path using FEM. Non-magnetic material has to be used for core clamping. In general, the flux density in the claw pole should also be slightly reduced. In the dielectric circuit, higher harmonics and spikes can cause overheating, especially at hot spots. Hence class H insulation would be necessary to withstand local overheating.

A comparative work can be taken up using Maxwell 3D software with automatic mesh generation for the entire twelve pole geometry as well as static and dynamic excitation capabilities. A direct linking of FE software to Simulink would enable development of a control strategy directly in Simulink with the FE model described in Maxwell. During the computation, Maxwell and Simulink can be run in transient co-simulation. Studies like this are extremely useful to facilitate the use of claw pole alternator with its inherent manufacturing advantages and infrastructure investment, to meet the automotive power requirements of the future.

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