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A Multilevel Inverter Fed High Speed Electric Drive Exhaust gas Energy Recovery Applications

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Abstract-. This paper deals with the solutions for developing the direct coupled electric drive to be used in combination with a radial turbo-expander for exhaust energy recovery in automotive applications. The descriptions of project realization of both the axial-flux permanent-magnet (PM) generator and the three-level boost-rectifier converter, which results as the preferred topology for the controlled rectifier, are given. The high rotational speed of the direct-driven PM generator results in high electric fundamental frequency also, which is challenging for the electric drive control issues.the proposed concept can be implemented for multilevel inverter fed high speed electric drive applications by using Matlab/Simulation software and the results are verified.

Keywords: Multilevel inverters, Power electronic converters, Axial flux permanent magnet (AFPM), Pulse width modulation

I.INTRODUCTION

Recent trend about the best ways of using the deployablesources of energy in to useful work in order to reduce the rateof consumption of fossil fuel as well as pollution. Out of allthe available sources, the internal combustion engines are themajor consumer of fossil fuel around the globe. Out of thetotal heat supplied to the engine in the form of fuel,approximately, 30 to 40% is converted into useful mechanicalwork. The remaining heat is expelled to the environmentthrough exhaust gases and engine cooling systems, resultingin to entropy rise and serious environmental pollution, so it isrequired to utilized waste heat into useful work. The recoveryand utilization of waste heat not only conserves fuel, usuallyfossil fuel but also reduces the amount of waste heat andgreenhouse gases damped to environment. It is imperativethat serious and concrete effort should be launched forconserving this energy through exhaust heat recoverytechniques. Such a waste heat recovery would ultimatelyreduce the overall energy requirement and also the impact onglobal warming. The Internal Combustion Engine has been aprimary power source for automobiles and automotives overthe past century. Presently, high fuel costs and concerns aboutforeign oil dependence have resulted in increasingly complexengine designs to decrease fuel consumption. For example,engine manufacturers have implemented techniques such asenhanced fuel-air mixing, turbo-charging, and variable valvetiming in order to increase thermal efficiency. However,around 60-70% of the fuel energy is still lost as waste heatthrough the coolant or the exhaust. Moreover, increasinglystringent emissions regulations are causing enginemanufacturers to limit combustion temperatures andpressures lowering potential efficiency gains [1]. As the mostwidely used source of primary power for machinery critical tothe transportation, construction and agricultural sectors,engine has consumed more than 60% of fossil oil. On theother hand, legislation of exhaust emission levels has focusedon carbon monoxide (CO), hydrocarbons (HC), nitrogenoxides (NOx), and particulate matter (PM). Energyconservation on engine is one of best ways to deal with theseproblems since it can improve the energy utilizationefficiency of engine and reduces emissions [2,]. Given theimportance of increasing energy conversion efficiency forreducing both the fuel consumption and emissions of engine,scientists and engineers have done lots of successful researchaimed to improve engine thermal efficiency, including supercharge, lean mixture combustion, etc. However, in allthe energy saving technologies studied. Engine exhaust heatrecovery is considered to be one of the most effective. Manyresearchers recognize that Waste Heat Recovery from engineexhaust has the potential to decrease fuel consumptionwithout increasing emissions, and recent technologicaladvancements have made these systems viable and costeffective [3].

This paper describes the technical solutionsadopted for the AFPM generator and for the controlled rectifier.As the high fundamental-frequency output of the direct-drivenAFPM generator is challenging for the electric drive control issues, therefore suitable arrangement is discussed for the controlarchitecture to be used in the generator-rectifier system.

Finallythis paper gives a comprehensive review of multilevel inverter fed high speed electric drives for exhaust gas energy recovery application.

II.HIGH-SPEED ELECTRIC GENERATING UNIT

In such an equivalent circuit, the PM generator is also represented with an idealized form (i.e., any power loss mechanism in the alternator is neglected), and the dc-link voltage V_{dc} is taken into account by means of an acvoltage source that provides—through an adjustable ratio autotransformer thus used for representing the effects of the inverter modulation index m_a—a phase rms voltage U_{ph} at the alternator terminals. Hence, at any given output fundamental frequency ω and phase

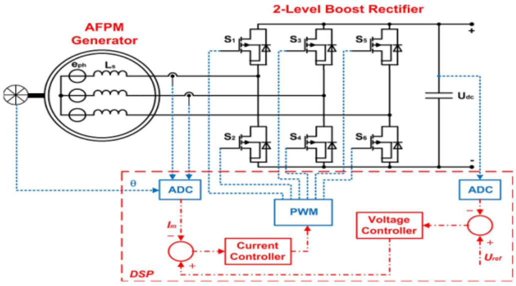


Fig.1. Power Generating Unit with Two-Level Boost-Rectifier Topology.

Electromotive force (EMF) rms value (i.e., E_0) set by the PM generator operation, the alternator phase rms current (i.e., I_{ph}) is suitably adjusted by regulating both the voltage U_{ph} and the load angle δ, and as usual, the maximum torque per ampere condition is accomplished by having the vector of the phase current aligned with the vector of the phase EMF. it is easily found that the component of the alternator output current being responsible for the transfer of electrical power to the dc link can be written as

$$I_{\mathrm{ph},P} = I_{\mathrm{ph}} \cos\delta = \frac{\pi P_g}{3\sqrt{2} m_a V_{\mathrm{dc}}} \qquad (1)$$

Where Pg is the mechanical power that the turbo-expander delivers at the generator shaft. On the other hand, the alternator current I_{ph} that the controlled rectifier is required to deal with is determined also by the current component $I_{ph,Q}$indicated which is in quadrature with the voltage U_{ph} and thereby is related to the exchange of reactive power between the alternator and the controlled rectifier. Simple math work yields

$$I_{\mathrm{ph},Q} = I_{\mathrm{ph}} \sin\delta = \frac{\sqrt{2} m_a V_{\mathrm{dc}}}{\pi E_0^2} \omega L_s I_{\mathrm{ph},P}^2. \qquad (2)$$

Hence, the rms value of the fundamental-frequency current that has to circulate in the power switches and diodes of the controlled rectifier can be written as

$$I_{\mathrm{ph}} = I_{\mathrm{ph},P} \sqrt{1 + \left(\frac{\omega L_s P_g}{3 E_0^2}\right)^2}. \qquad (3)$$

From (3), it clearly appears that, for any operating condition set by the alternator input torque and speed and for a given voltage of the dc link, the lower is the alternator synchronous inductance, the lower will be the rms value of the fundamental frequency current that circulates in the power switches and diodes of the controlled rectifier. Thereby, designing the PM generator with low value of the per-unit synchronous inductance is beneficial for the controlled rectifier in terms of reduced kilo volt ampere rating and power loss. However, a low value of the synchronous inductance negatively affects the waveform of the alternator phase current as, for a given value of the switching frequency used in the controlled rectifier, the lower is the alternator synchronous inductance, and the higher is the total harmonic distortion (THD) of the alternator current waveform. As a consequence, the rms value of the PM generator output current increases, and this may offset the advantages envisaged from the use of a low-inductance alternator. In other words, the use of an electrical generator having low synchronous inductance reduces the fundamental frequency component of the alternator output current while increasing the harmonic content in the same current. In order to retain the advantages resulting from a reduced value of the fundamental frequency component of the alternator output current, the power circuit arrangement used for the controlled rectifier should be appropriated.

Thereby, it is useful making a comparison among the various power electronic converter topologies that could be used as power conversion interface between a turbo-expander-driven PM generator and a 42-V rated voltage dc link. To this goal, the envisaged electric drive has been suitably modeled in order to investigate, through computer simulations, three alternative topologies for the controlled rectifier, namely, the conventional 2L-BR shown in Fig.1, the dc–dc boost converter in cascade with the diode rectifier (BOOST-DR), as depicted in Fig.2, and the three-level neutral point-clamped (NPC) boost rectifier (3L-BR) shown in Fig.3. Even though the Vienna topology is a well-known solution forrectification, the NPC configuration has beenconsidered in this project as three-level referencetopology because of its widely recognized standard rule for many applications in generating units. Several manufacturers have developed packaging modules for the NPC multilevel phase leg, with the perspective of future modules based on semiconductor devices technologies also different than insulated gate bipolar transistors (IGBTs) for many applications in the field of automotive and distributed power generation. The comparison between the NPC configuration and Vienna rectifier has been deeply discussed in the literature [5] with the conclusion of substantial equivalence in total power losses. However, the different distribution of power losses among the semiconductor devices can make the NPC multilevel converter preferable, even if it shows a more complicated topology, when MOSFET devices are used because of their lower conduction losses with respect to both diodes and IGBTs. The comparison among the three alternative topologies for the controlled rectifier is carried out by considering 30 kHz as switching frequency, with this value being still congruent with the use of switching devices having 150-A rated current for low-voltage applications.

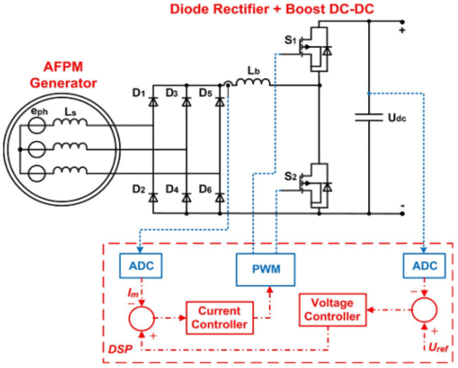


Fig.2. Power Generating Unit with DC–DC Boost Converter in Cascade with Diode Rectifier Topology.

For simulation purposes, a total amount of 2.7 mF is supposed as dc-link capacitance in order to assure the dc-link voltage ripple within 0.25% of the rated value for the conventional 2L-BR topology. A three-phase AFPM machine having a 4-kW rated power at a 18 000-r/min rated speed is considered with design characteristics such as the 17-V rms value of the phase EMF at a nominal output frequency of 1200 Hz and a 4-μH synchronous inductance. As usual in generating unit applications, a two-loop control architecture is envisaged by considering an outer voltage loop—which is in charge for regulating the dc-link voltage and, thereby, the 42-V battery charging/discharging operation and an inner current loop devoted to controlling the three-phase output currents of the PM generator.

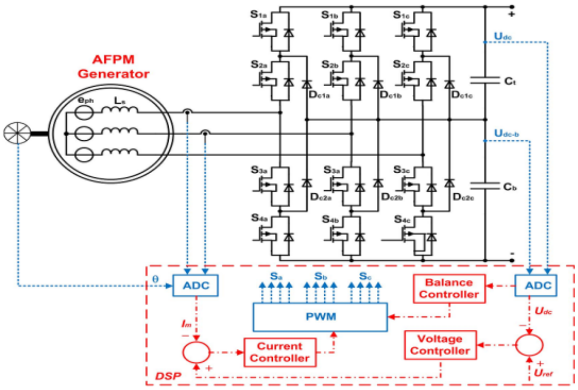


Fig.3. Power Generating Unit with Three-Level Boost-Rectifier Topology.

The 2L-BR with sinusoidal PWM is the state-of-the-art solution in most electric drive systems. However, it is not naturally the best choice as it leads to quite high value of the phase current ripple and the power switches are operated in discontinuous conduction mode for a large fraction of the sinusoidal current period, with consequent increasing of both the rms value for the phase current and the switching stress of semiconductor devices. As a result, supplementary power loss in both the electrical generator and the controlled rectifier should be expected, unless a much higher switching frequency is utilized, thereby accepting higher power loss in the controlled rectifier due to switching.

Despite the simple control structure, the BOOST-DR requires the additional boost inductor L_b to limit the current ripple. For the simulation purposes, a value of 12μH has been considered for the boost inductor in order to reduce the peak to-peak current ripple within 15–20 A. As an additional disadvantage compared to the other two topologies being considered, the BOOST-DR does not allow vector control of the alternator phase current, so the maximum torque per ampere cannot be exploited. The use of a diode rectifier causes significant distortion of the generator current waveforms with respect to the sinusoidal shape, and as a consequence, the generator torque contains a pulsating component having relatively high amplitude. This is a remarkable disadvantage as the presence of such a pulsating torque can significantly influence the durability and reliability of the turbo-expander/generator unit. Furthermore, the conduction power loss in the BOOST-DR is mainly related to the rectifier diodes, which show worse conduction performance with respect to low-voltage power switches as MOSFETs. The 3L-BR shows a more complex hardware and control structure, mainly due to both the number of switches and the third harmonic injection for the balancing of the dc-link capacitor middle point. However, the implementation of the control algorithm is still congruent with conventional industrial-grade digital signal processors (DSPs); moreover, future trends of the power electronics market could limit higher costs related to semiconductor devices and driving circuits. On the other hand, the use of a multilevel configuration for the controlled rectifier leads to effectively reducing the current ripple to an acceptable value, thereby allowing low values for the THD, which is an essential requirement for the desired high efficiency and to lower both mechanical vibrations and acoustic noise.

III. MULTILEVEL INVERTERS

Multilevel power conversion was first introduced more than two decades ago. The general concept involves utilizing a higher number of active semiconductorswitches to perform the power conversion in small voltagesteps. There are several advantages to this approach whencompared with the conventional power conversion approach.The smaller voltage steps lead to the production of higher powerquality waveforms and also reduce voltage (dv/dt) stress onthe load and the electromagnetic compatibility concerns [6].Another important feature of multilevel converters is that thesemiconductors are wired in a series-type connection, whichallows operation at higher voltages. However, the series connection is typically made with clamping diodes, which eliminatesovervoltage concerns. Furthermore, since the switches are nottruly series connected, their switching can be staggered, whichreduces the switching frequency and thus the switching losses.However, the most recently usedinverter topologies, which are mainly addressed as applicable multilevel inverters, are cascade converter, neutral-pointclamped (NPC) inverter, and flying capacitor inverter.

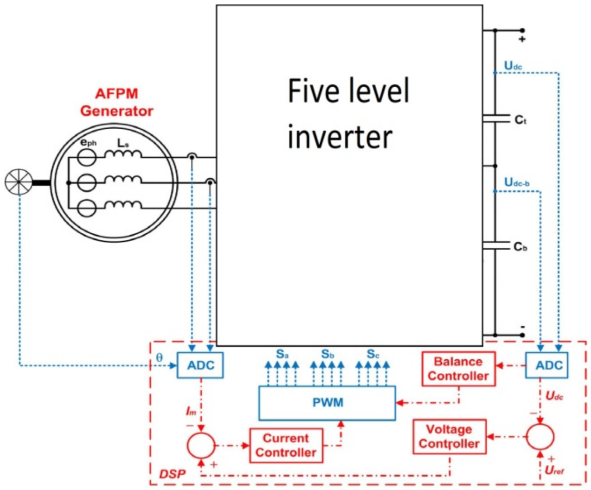
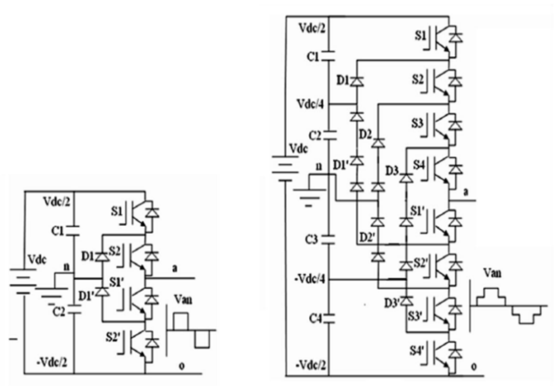


Fig.4. Five-Level Boost-Rectifier Topology.

Some applications for these new converters include industrial drives [7], flexible ac transmission systems (FACTS) [8]–[10],and vehicle propulsion [11], [12]. One area where multilevelconverters are particularly suitable is that of renewable photovoltaic energy that efficiency and power quality are of great concerns for the researchers [13].



(a) (b)

Fig.5. Topology of the diode-clamped inverter (a) three-level inverter, (b) five -level inverter

IV. MATLAB/SIMULINK RESULTS

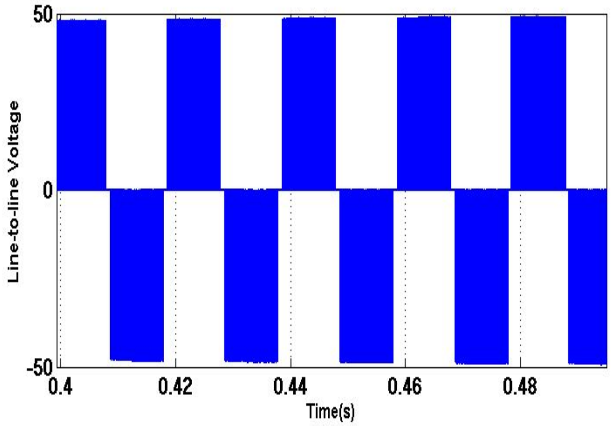


Fig.6.Simulation Result of Line to Line Voltage for 2- level Boost Rectifier

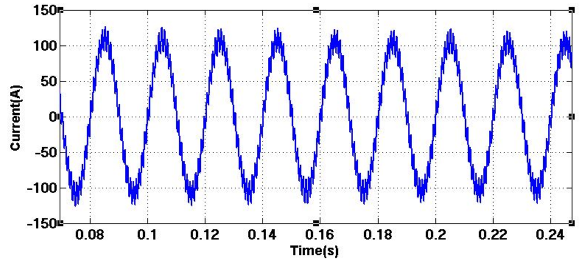


Fig.7.Simulation Result of phase Currentfor 2- level Boost Rectifier.

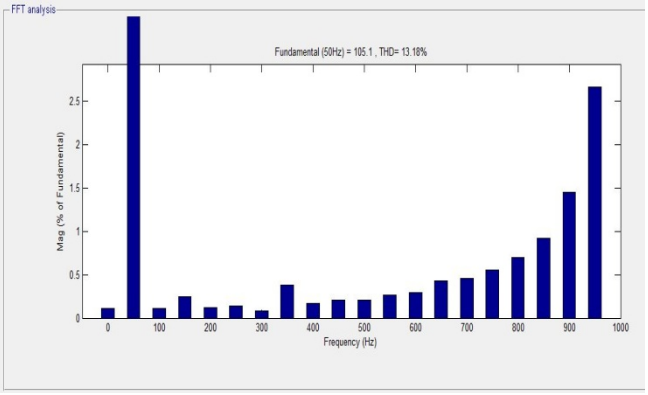


Fig.8.THD for Two level boost rectifier.

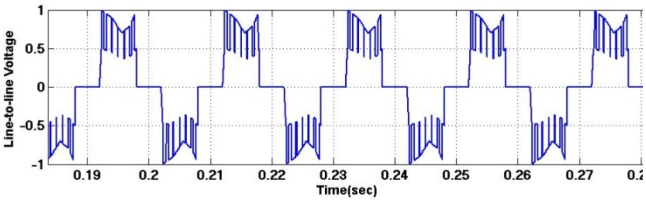


Fig.9.Simulation Result of Input Line To Line Voltagefor Rectifier+Boost Converter.

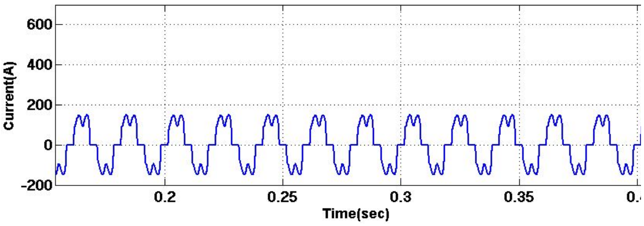


Fig.10.Simulation Result for Output Voltage, Source Current and Voltage.

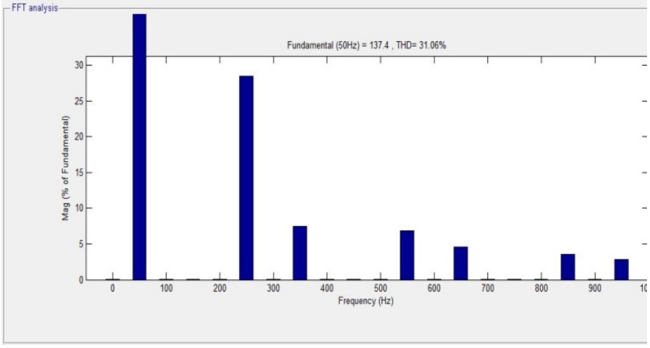


Fig.11.THD for Rectifier + Boost Converter.

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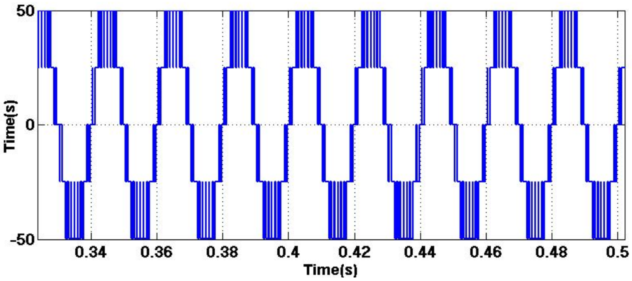

Fig.12.Simulation Result for Three Level Output Voltages.

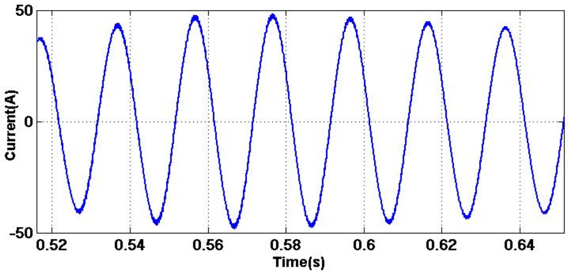

Fig.13.Simulation Result forThree Level Output Current.

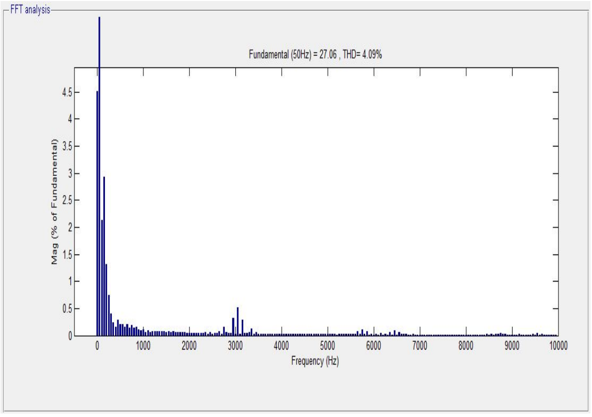

Fig.14.THD for Three Level Converter.

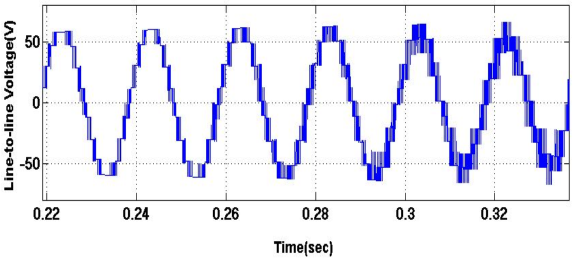

Fig.15.Simulation Result for Five Level Output Voltage.

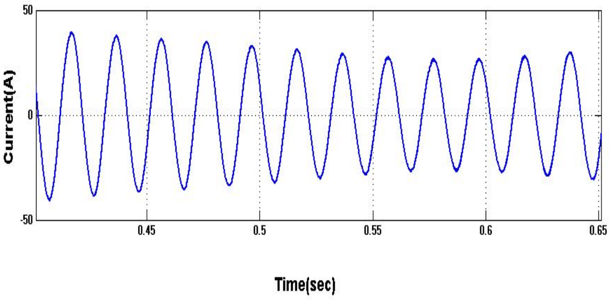

Fig.16. Simulation Result for Five Level Output Current

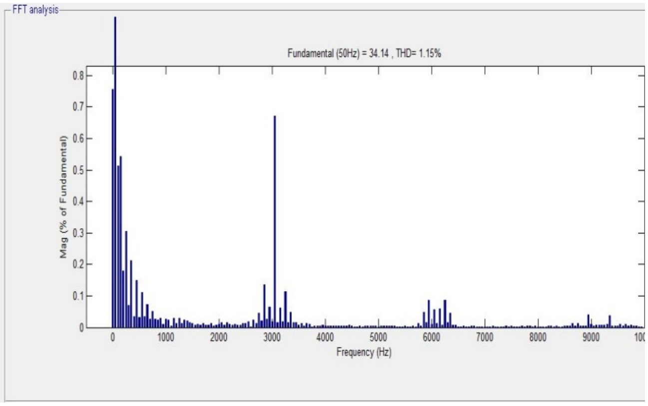

Fig.17.THD for Five Level Converter.

THD Comparison

2- level Boost Rectifier	Rectifier +Boost Converter	3- level Boost Rectifier	5- level Boost Rectifier
13.18%	31.06%	4.09%	1.15%

V.CONCLUSION

For the investigated application, the AFPM machine topology and also the3level and 5 level boost-rectifier configurations arechosen for the high-speed electrical drive. For the rated Torque operation with 1200-Hz electrical frequency, an eight-pole generator assembly with litz-wire conductors for the Stator winding and low-loss thin non oriented electrical steel for the stator core is proposed. it's shown that the three-level and 5 level boost rectifier configuration is able to effectively limit the electric generator current ripple to an acceptable value, even though the PM alternator has a relatively low synchronous inductance. A low value of the THD is achieved for the alternator output current waveform, which, in fact, is an essential requirement for low mechanical vibrations and acoustic noise, as well as for high efficiency. The proposed generating unit arrangement proves to be a viable solution for improving the fuel saving on board road vehicles.

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