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HIGH SPEED ELECTRIC DRIVE WITH MULTILEVEL INVERTER FOR EXHAUST GAS ENERGY RECOVERY APPLICATIONS

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ABSTRACT

Electric drives offer an opportunity for efficient use of natural resources clean and (comparatively) quiet power conversion, improved process control, and very attractive life-cycle cost. High-speed electric drives utilize technology (including variable speed control) to meet the needs of a rapidly changing industrial world. 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

In recent years, there has been active research on exhaust gas waste heat energy recovery for hybrid electric vehicles (HEVs) [1]-[4]. Meanwhile, the use of solar energy is also proposed to promote on-board renewable energy and hence to improve their fuel economy [5]-[6]. These kinds of energy sources can be used to online feed various automotive electronics or charge the battery for storage, hence reducing the oil consumption and the carbon emission of the automobiles.

The Internal Combustion Engine has been a primary power source for automobiles and automotives over the past century. Presently, high fuel costs and concerns about foreign oil dependence have resulted in increasingly complex engine designs to decrease fuel consumption. For example, engine manufacturers have implemented techniques such as enhanced fuel-air mixing, turbo-charging, and variable valve timing in order to increase thermal efficiency. However, around 60-70% of the fuel energy is still lost as waste heat through the coolant or the exhaust. Moreover, increasingly stringent emissions regulations are causing engine manufacturers to limit combustion temperatures and pressures lowering potential efficiency gains [1]. As the most widely used source of primary power for machinery critical to the transportation, construction and agricultural sectors, engine has consumed more than 60% of fossil oil. On the other hand, legislation of exhaust emission levels has focused on carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and particulate matter (PM). Energy conservation on engine is one of best ways to deal with these problems since it can improve the energy utilization efficiency of engine and reduces emissions [2,]. Given the importance of increasing energy conversion efficiency for reducing both the fuel consumption and emissions of engine, scientists and engineers have done lots of successful research aimed to improve engine thermal efficiency, including supercharge, lean mixture combustion, etc. However, in all the energy saving technologies studied. Engine exhaust heat recovery is considered to be one of the most effective. Many researchers recognize that

Waste Heat Recovery from engine exhaust has the potential to decrease fuel consumption without increasing emissions, and recent technological advancements have made these systems viable and cost effective [3].

This paper deals with various configurations suitable for automotive generating systems devoted to recovering energy from exhausts. In particular, three alternative topologies for the controlled rectifier are investigated concerning the harmonic content of the generator output current which may be responsible for undesired effects such as noise and vibration on both mechanical coupling and turbo-expander blades. Idealized representation of the PM generator—controlled rectifier generating unit. Per-phase equivalent circuit diagram and Vector diagram shown in Fig.1

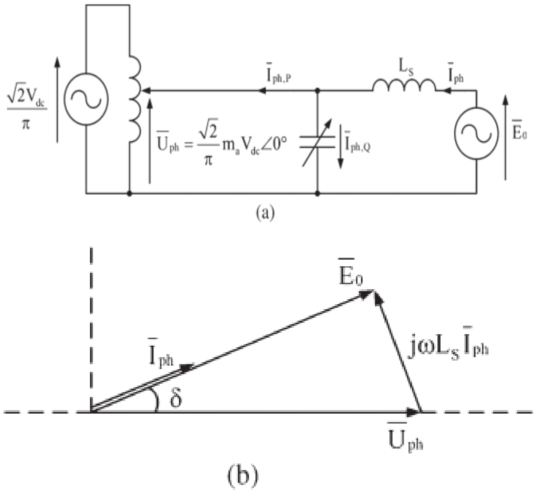

Fig.1. Idealized representation of the PM generator—controlled rectifier generating unit. (a) Per-phase equivalent circuit. (b) Vector diagram.

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

Finally this 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

The proposed high-speed electric generating unit is intended to operate within a 9000–18 000-r/min speed range with both rated power of 4 kW and overall efficiency of 90% at a 18 000-r/min rating speed. The minimum provided power output should be 500 W at 9000 r/min. At any rotational speed within the operating range, the generating unit is expected to supply a 42-V power-net architecture, with a maximum value of 48 V. According to that, a controlled rectifier with adjustable voltage gain is required to step up the PM generator three-phase output voltage against a 42-V rated voltage dc link [4]. In consideration of both the relatively low value of the alternator output voltage and the high fundamental frequency being considered in the envisaged application, it can be recognized that the synchronous inductance (i.e., L_s) of the PM generator plays a key role as discussed in the following.

The sinusoidal shaping for the PM generator phase current is considered for the discussed application. Boost-rectifier topologies with either a switching rectifier or diode rectifier followed by a dc–dc converter allow the effective regulation of the input current; as a consequence, this project is focused on low-voltage machine solutions followed by boost-rectifier topologies. Assuming that the controlled rectifier is arranged by means of the three-phase pulse width-modulated (PWM) two-level voltage source inverter being operated in the regenerative mode (referred to as 2L-BR in the following) and that such a three phase boost rectifier behaves as an ideal sine wave converter to dc (i.e., the fundamental frequency ac power input is fully converted to dc power in the output), the fundamental frequency ac quantities in the alternator-rectifier system can be represented by means of the per-phase equivalent circuit shown in Fig.1(a) and the vector diagram shown in Fig.1(b).

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 ac voltage 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

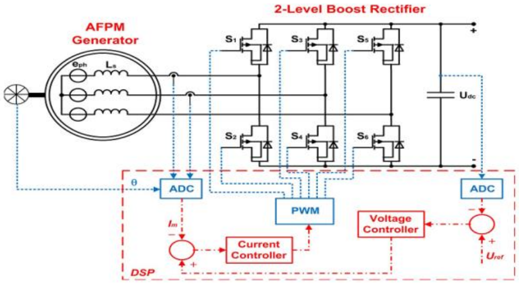

Fig.2. Power generating unit with two-level boost-rectifier topology

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. Based on the schematic representation depicted in Fig.1, 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

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

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 in Fig.1, 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

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

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

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

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.2, the dc–dc boost converter in cascade with the diode rectifier (BOOST-DR), as depicted in Fig.3, and the three-level neutral point-clamped (NPC) boost rectifier (3L-BR) shown in Fig.4. Even though the Vienna topology is a well-known solution for rectification, the NPC configuration has been considered in this project as three-level reference topology 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.

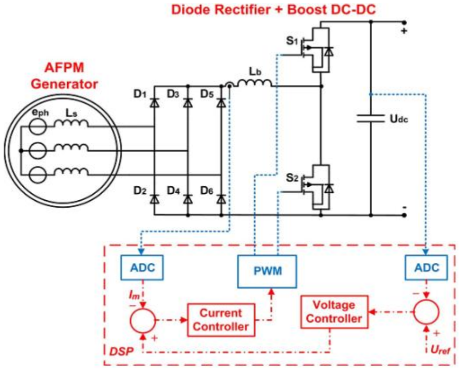

Fig.3. Power generating unit with dc–dc boost converter in cascade with diode rectifier topology

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.

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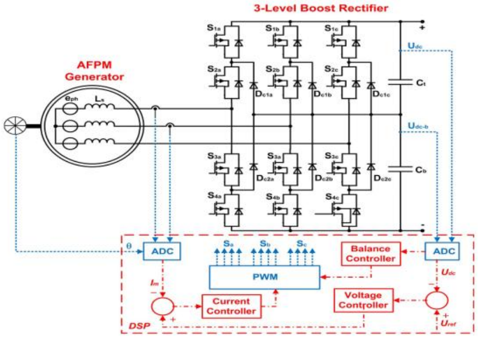

Fig.4. Power generating unit with three-level boost-rectifier topology

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 semiconductor switches to perform the power conversion in small voltage steps. There are several advantages to this approach when compared with the conventional power conversion approach. The smaller voltage steps lead to the production of higher power quality waveforms and also reduce voltage (dv/dt) stress on the load and the electromagnetic compatibility concerns [6]. Another important feature of multilevel converters is that the semiconductors are wired in a series-type connection, which allows operation at higher voltages. However, the series connection is typically made with clamping diodes, which eliminates overvoltage concerns. Furthermore, since the switches are not truly series connected, their switching can be staggered, which reduces the switching frequency and thus the switching losses. However, the most recently used inverter topologies, which are mainly addressed as applicable multilevel inverters, are cascade converter, neutral-point clamped (NPC) inverter, and flying capacitor inverter.

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 multilevel converters are particularly suitable is that of renewable photovoltaic energy that efficiency and power quality are of great concerns for the researchers [13].

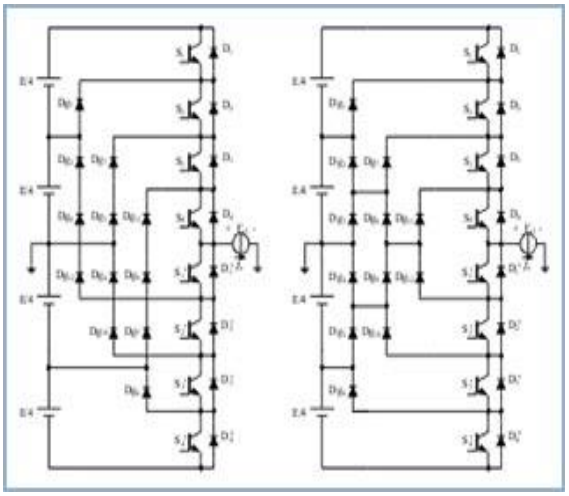

Fig.5.single leg of five level NPC inverter

IV. MATLAB/SIMULINK RESULTS

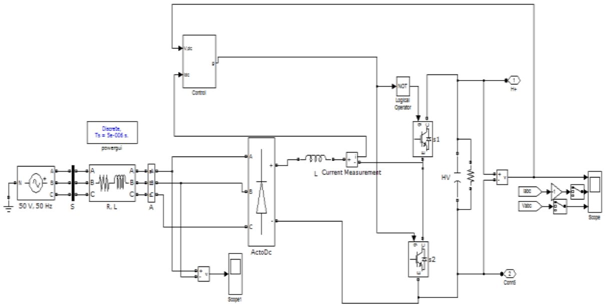

Fig.6.Simulink circuit for rectifier + boost converter

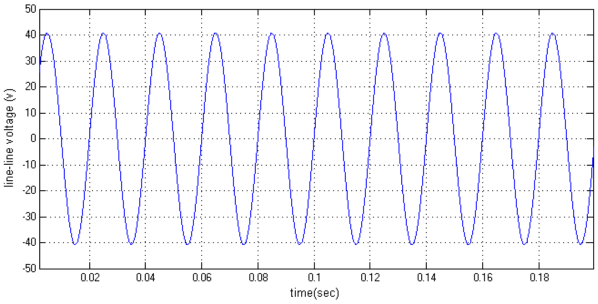

Fig.7.Simulation result for input line to line voltage

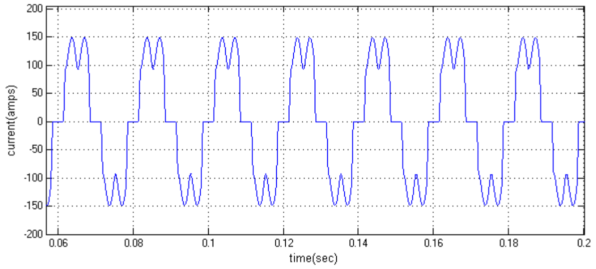

Fig.8.Simulation result for source current

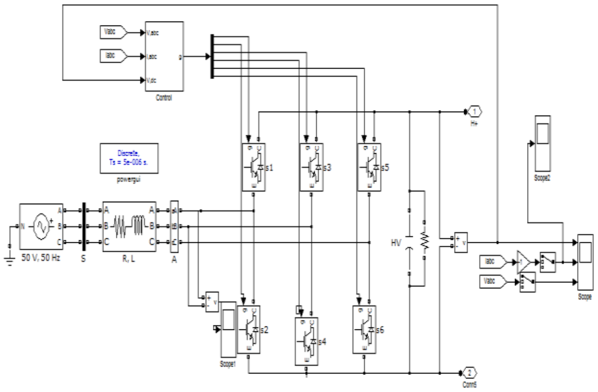

Fig.9. Simulink circuit for Two Level boost rectifier

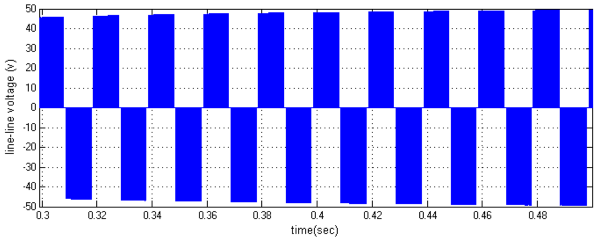

Fig.10.Simulation result for line to line voltage

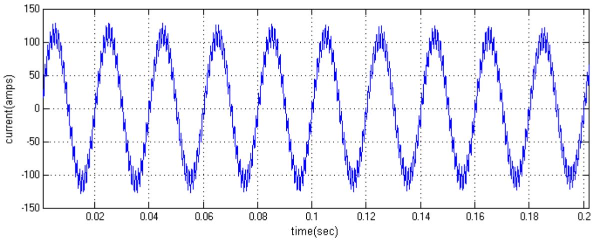

Fig.11.Simulation result for current

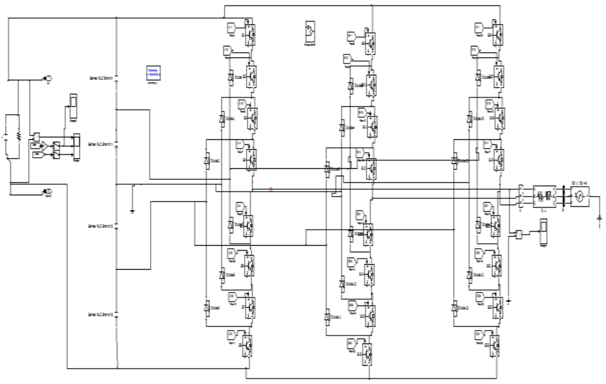

Fig.12.Simulink circuit for Three Level Converter

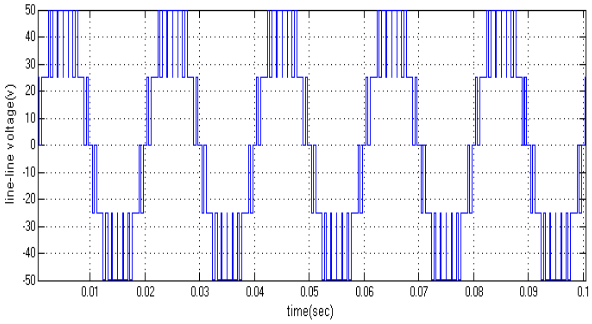

Fig.13.Simulation result for Three Level output voltage

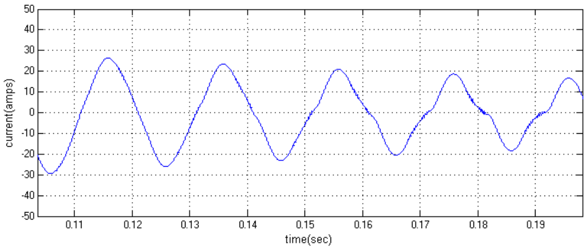

Fig.14.Simulation result for voltages and current.

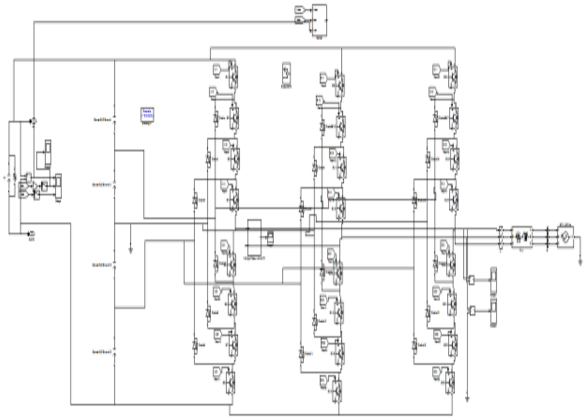

Fig.15.Simulink circuit for Five Level Converter

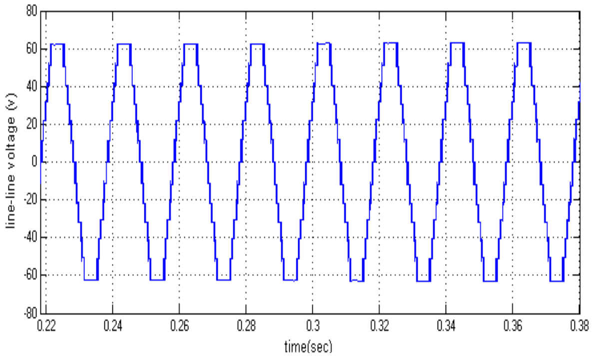

Fig.16.Simulation result for five level output voltage

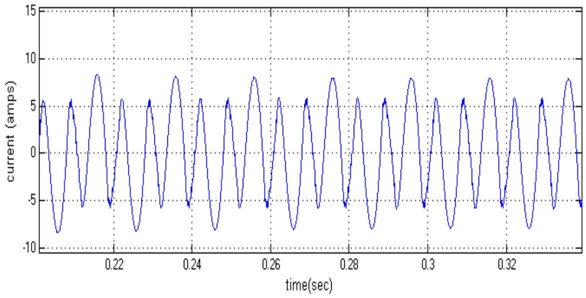

Fig.17. Simulation results for current.

V. CONCLUSION

With reference to 42-V onboard generating systems for automotive applications, this paper has described the technical solution used for a generating unit which uses a radial turbo-expander to recover energy from exhaust gases through the direct coupling with a PM generator. For the investigated application, the AFPM machine topology and the three level boost-rectifier configurations have been selected for the high-speed electric drive. For the rated torque operation with 1200-Hz electric 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 is shown that the three-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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