Energy Recovery from Exhaust Gases of Automobiles Using an Axial Flux Permanent Magnet Generator

Chetan N. C.[1] ***Ranjan N.A.***[2] ***Tejamoorthy M.E.***[3] ***Abhilash B.T.***[4]
(Jr. Lecture), (Associate Professor), (Associate Professor), (Asst. professor)
[1,2,3](Electrical and Electronics Dept., M.C.E. / Visvesvaraya Technological University, India)
[4](Electrical and Electronics Dept., R.I.T. / Visvesvaraya Technological University, India)
Email:- abhilash.b.thimmegowda@gmail.com

Abstract: The present work deals with the design solution adopted for an axial-flux permanent-magnet (AFPM) generator devoted to supplementing power in automotive 42 V electrical systems through a two level boost rectifier. The axial-flux permanent-magnet generator is suitably designed to be directly coupled with a radial turbo-expander which provides recovery of kinetic energy available from the exhaust gases of an internal-combustion engine. However, in the present work a prototype is developed with the axial flux permanent generator coupled to a DC motor in order to simulate the running conditions of an internal combustion engine. The boost rectifier is properly sized for systems having low voltages. The target output voltage of 42 volts was achieved at speed of 780 revolutions per minute.

Keywords: AFPM generator, Boost rectifier.

I. INTRODUCTION

As humans evolved their thirst for comfort, luxury made them to search for better technology. The best example to consider would be the automobile, which, when invented, was only meant to carry people from one destination to the other in an effortless way. In the present scenario, automobiles have changed from just being an equipment to transport people, to a piece of engineering, which signifies the economic status of the individual. Present day automobiles are not just an engine on four wheels but have evolved immensely to imbibe features such as air condition, multimedia system and safety features such as ABS (antilock braking system), Air bags, GPS etc. All these features need one thing in common i.e. the electric power.

The Lundell type alternator has been in use since a long time and is still in use to generate electricity. But the Lundell type alternator has become too inefficient whenever requested to deal with higher power output, as it draws the power required to drive the alternator from the mechanical shaft of the internal combustion engine (ICE) and thereby the increased electrical power demand inevitably results in increased fuel consumption. As a result of the increased electrical power requested on board, the power loss in a Lundell-type alternator is too high and the 14V voltage level being used in today’s cars results in higher current demand and thereby thicker wiring harnesses. As a consequence, the cost of the overall electrical system increases while the performance drops significantly. However, it is to be noted that the ICE exhaust gases still retain a significant amount of energy which is usually wasted. Substantial fuel saving can be achieved by using a radial turbo-expander to recover the kinetic energy available from the ICE exhaust gases to directly drive an electrical generator. This power can be adjusted suitably to supply the power-net architecture within the variable rotating speed region of the radial turbo-expander. Fig.1 shows the schematic of the scheme employed. Because of a few constraints, the automobile exhaust part is simulated in this work by a DC motor, to simulate all the conditions the generating unit might face when installed inside the hood of the vehicle, apart from the temperatures.

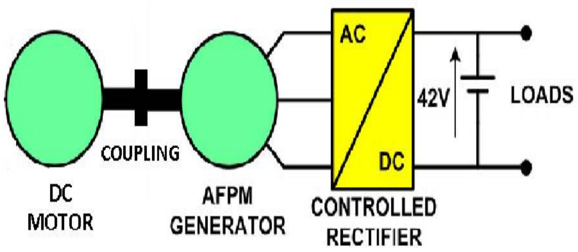


Fig.1: Schematic of the proposed work

II. LITERATURE REVIEW

The use of a Lundell alternator poses the requirements of higher investments on the infrastructure required for its manufacture and the power net architecture, especially when loads of 42V ratings are considered. Also an ICE driven generator should be accommodated on the ICE shaft and the ICE is usually arranged with its own shaft being perpendicular to the vehicle length. Hence a generator design resulting in high compactness, which results in the reduction of the overall power losses should be selected, also a generator casing incorporating a liquid coolant based cooling arrangement should be adopted to best serve the cooling needs of the electrical machine. In consideration of the tight design requirements as briefly outlined above, electrical machines with Nd-Fe-B (neodymium, iron and boron) permanent-magnet (PM) excitation are widely recognized to be the most suitable candidates for the hybrid electric vehicle (HEV) generator application. Within the broad category of PM machines found, slot less-winding axial-field PM machine (AFPM) topology was found to be of interest for such applications, as described by Augusto Di Napoli et al [1].

Antonio Di Gerlando et al [2] discusses some of the design and operation aspects of axial flux permanent magnet synchronous machines, wound with concentrated coils. Due to their high number of poles, compactness, and excellent waveform quality and efficiency, these machines are learned to show satisfactory operation at low speeds, both as direct drive generators and as motors. Fabio Crescimbini et al [3] proposes the design solution adopted for a high-speed axial-flux permanent-magnet generator devoted to supplementing power in automotive 42V electrical systems through a low-voltage multilevel neutral-point clamped converter. The axial-flux permanent-magnet generator is suitably designed to be directly coupled with a radial turbo-expander which provides recovery of kinetic energy available from the exhaust gases of an internal-combustion engine. The multilevel converter is properly sized for systems having low voltage and high first order harmonic frequency. It also describes the generating system and discusses various issues resulting from electromagnetic, thermal, and mechanical design of the high-speed axial-flux permanent-magnet generator. Nicola Bianchi et al [4] illustrate the potentials and limits of high–speed permanent– magnet (PM) motors. The influence of materials chosen for the PM, stator core, and retaining sleeve is highlighted in this work. Slotted and slot less topologies are considered and compared by computing the magnetic, electrical, mechanical, and thermal quantities by means of both analytical and finite-element approach. A criterion of optimization of the motor structure is described, with the diameter ratio and the iron flux density as main design variables.

III. METHODOLOGY

Despite best efforts to produce pure battery-powered vehicles (EVs), to date, the longstanding problem of battery range has remained insurmountable. With EVs destined for a niche role in the car industry, attention is now increasingly focused on fuel-cell and hybrid technologies as a way of producing breakthrough vehicles with alternative power plants. This work is designed to demonstrate how the kinetic energy present in the exhaust gases of automobiles can be utilized to extend the range of the batteries, thereby powering the HEVs and the electronics present in the vehicle efficiently by constructing a prototype which shall resemble the original unit intended to harness the kinetic energy of the exhaust gases in automobiles. The prototype uses an axial flux permanent magnet (AFPM) generator as the generating unit. The voltage achieved by the generator is boosted using a two level boost rectifier.

A). Modelling of the AFPM generator

The Axial Flux Permanent Magnet machine [AFPM], also called the disc-type machine, is an attractive alternative to the cylindrical Radial Flux Permanent Magnet machine due to its pancake shape, compact construction and high power density

Rotor: The rotor is composed of a thin MDF (Medium Density Fibre) sheet 4mm thick and 12 inches in diameter, with permanent magnets arranged in a radial pattern around it at a distance of 2.5 inches from centre. The disc is drilled with a hole of diameter 1.51 inches and magnets are placed inside the holes and fixed with an araldite gum as shown in Fig.2. The magnets chosen are Grade 52 neodymium-ferrite-boron rare earth magnets. There are twelve per rotor plate; twenty-four in total.

They are arranged at a radius of 5 cm's from the centre of plate to bottom edge of magnet. Magnets from K&J magnetic were chosen which have Nickel-Copper-Nickel (NiCuNi) plating and hence corrosion is eliminated. The dimensions of the magnets are 1.5" dia x 0.25" thk (in). The stator coils are wound accordingly to match the radius of the NdFeB magnets.

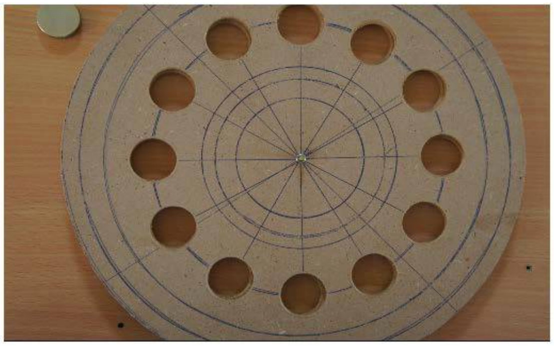


Fig.2: Drilled MDF board

Fig.3: Neodymium-Ferrite-Boron Magnets

When designing the generator, it is important to realize the relation between the number of coils and the number of magnets for alternating three-phase power, table 1 indicates the number of coils required for a given set of coils. The magnets must alternate poles as they go around the plate. This means that they must alternate N, S, N, etc. as they go around. This also means that there must be an even number of magnets so that the alternation comes out properly. The magnets are arranged onto the rotor plate built from a piece of wood and then gently tapped into position. A Curing time of 16 hours is needed before use.

I. Table indicating the preferred coil & magnet arrangement

No. of Coils	No. of Magnets/Rotor Plate
6	8
9	12
12	16

The rotor plates must be created opposite of one another with respect to the magnetic arrangement i.e. a starting position from which we lay out the magnets has to be picked. Mark that point on the plate. Lay out the first rotor with alternating poles all the way around. Then when starting the second rotor, start from the same point on the new plate as did on the first. Now the second rotor is laid out starting with the opposite pole as started on first plate. Then the poles are alternated, the rest of the way around as normal. When the generator is assembled, this ensures that opposite poles all face one another, enhancing the magnetic flux.

Stator: The stator is constructed on a wooden plate 8.2 inches in diameter with nine coils arranged inside. The coils are arranged after the araldite gum is applied onto the wooden plate. Any number of coils can be used but they must be a multiple of three (since three phase power is produced). Note table 1 for the coil & the magnet arrangement. Fig.4 shows the finished stator. Each coil used has around 300 turns. It can be built simply from scrap material. Each coil is wound in order to make them tight and evenly wrapped. Three - phase alternators can be wired in two configurations: Y configuration or delta. The Delta Configuration for the stator windings has been adopted in the present work. Each coil used in the stator has the diameter as that of the NdFeB magnets i.e. 1.5” (inches).

Fig.4: Stator Assembly

Air gap: The air gap is the space between the face of the rotor and the face of the stator on each side. By carefully casting each, this gap can be adjusted to be very small. Magnetic potential falls off quickly across air so any small change in the air gap can make an impact on generator performance. Care has to be taken to ensure that the stator & the rotor are not rubbing each other at any point of contact. The air gap in the present work has been maintained at 4 mm.

IV. BLOCK DIAGRAM

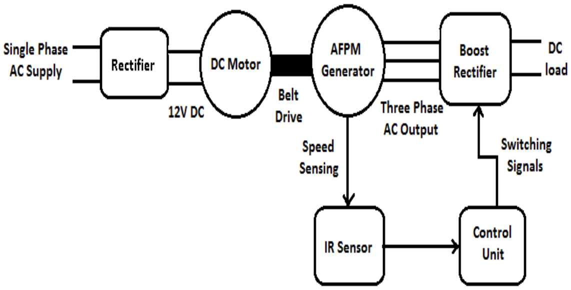


Fig.5: Block diagram of the proposed work

In this work a 12V DC motor is used to simulate the driving conditions of an automobile. The single phase ac supply, obtained using an autotransformer is rectified and is fed to the 12V DC motor as shown in Fig.6. An arrangement is employed to simulate the accelerating and decelerating conditions of an automobile. Also through this arrangement the speed of the axial flux permanent magnet generator is controlled. The full bridge rectifier IC is used to rectify the varying single phase ac voltage. The dc motor chosen is a 12V, 0-0.20 hp machine with a rated speed of 1500 revolutions per minute. The dc motor is coupled to the AFPM generator through a belt drive.

The AFPM generator speed is the same as that of dc motor because of the coupling. The speed of the AFPM generator is sensed by means of Infrared sensors. Infrared sensors are used in the present work to measure the speed of the generator and are designed to give an output of 30 pulses per revolution. The sensor tells at any point of time whether it sees black or white. Then, if there are 30 divisions in the wheel, you can look at the pattern of black/white reading to see how fast the wheel is turning around. Because 360 degrees divided by 30 divisions is 12 degrees/division, the sensors can sense the speed whenever the rotor turns 12 degrees. The rotor is fitted with 30 pieces of black/white strips, each measuring 13mm*4mm. A 5mm gap is provided for sensing the distance between metal piece and the sensor. The control unit comprising the Atmega32 microcontroller monitors the output of the sensor and displays the speed on the LCD display.

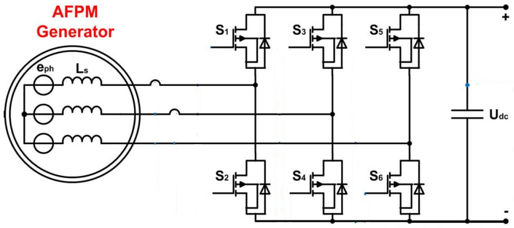


Fig.6: Adopted rectification schem.

The switching scheme for the boost rectifier is derived from the control unit. The microcontroller uses the speed of the AFPM generator to derive the switching signals for the boost rectifier. It has to be noted that the three phase ac output has a frequency which is dependent on the speed of the machine. Hence the control unit derives the switching signals for the MOSFET's based on the speed sensed by the IR sensors. This implementation was able to develop the target of 42V dc at a speed of 780 rpm.

V. EXPERIMENTAL SETUP AND RESULTS

Implementation of the proposed work is shown in Fig.7. The control circuitry consisting of the infrared sensor to achieve the switching signals for the two level boost rectifier. A USART circuit was designed and interfaced to microcontroller for transmitting the measured speed at every one second.

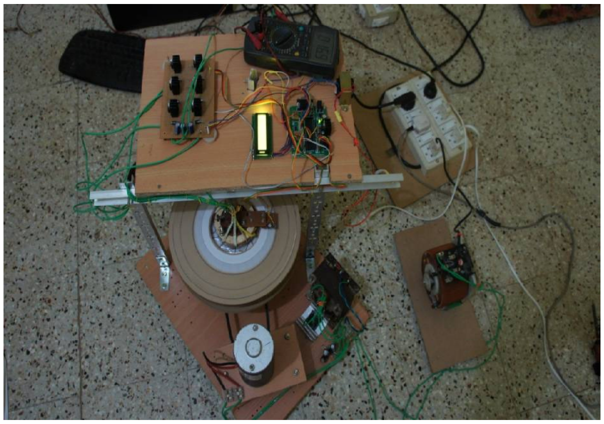


Fig.7: Experimental setup

The cubic inches of displacement *(CID)*, revolutions per minute for the turbine *(RPM)* and the engine volumetric efficiency *(VE)* must be known. *CID* and *VE* are engine specifications. RPM depends on the vehicle and the driving scenario in which turbine might be used. To calculate the airflow rate in cubic feet per minute *(CFM)*, the following equation was used

$$Airflow = \frac{CID*RPM*VE}{3456} \tag{1}$$

where 3,456 is a conversion factor from cubic inches to cubic feet and include a ½ parameter needed for four-stroke engines which only exhausts every other revolution. This airflow rate is based upon atmospheric pressure; it does not consider the boost pressure i.e. the pressure and air is raised by the compressor. It is to be noted that the compressor in the turbocharger, compresses the high velocity, low pressure air stream to a low velocity, high pressure (boost pressure) air stream. Since the boost pressure is not known we limit our calculations of airflow rate to atmospherically pressure. Although, if the boost pressure (*Pb*) is known, the airflow rate can be calculated by using the pressure ratio (PR),

$$PR = \frac{P_b + 14.7}{14.7} \tag{2}$$

to calculate the new flow rate at the given back pressure the flow rate is calculated using the pressure ratio,

$$Corrected\ CFM = Old\ CFM * PR \tag{3}$$

the air flow rate for a 1200 Cubic Centimeters (CC) engine, which translates as 73.23 cubic inches of displacement (CID), operating in the 2000-3000RPM range is calculated and is given in table 2. For a clear understanding, the air intake measured in cubic foot per minute is converted to litres per minute *(ltr/min)* and is presented in the table 2. The engine volumetric efficiency is taken to be 80%, which is provided by the engine manufacturer. With the above data, if the turbine, in turn the AFPM alternator employed in the present work is to be rotated at 3000 rpm (assuming no losses to occur due to the coupling) a torque of $37.6556*10^{-3}$ Nm/sec is required. It is seen that the torque required for the alternator to rotate is a meager amount proving that the technology is worthy. It should also be noted that the data in table 2 have been arrived at, by assuming standard ambient temperature and pressure values. Let us, for instance, assume the boost pressure to be around 4psi (pounds per square inch), and the temperature is maintained at 150°C at an engine speed of 3000 rpm. The torque is then calculated to be 7.218*10-3Nm/sec, which is in support of the present work.

II. Measure of the air intake

Engine Speed *(RPM)*	**Cubic Foot/Minute** *(ft^3/min)*	**Litres/minute** *(ltr/min)*
2000	34	960
2100	35.7	1011
2200	37.4	1059
2300	39	1104
2400	40.68	1152
2500	42.4	1206
2600	44	1246
2700	45.76	1296
2800	47.46	1344
2900	49.16	1392
3000	50.85	1444

Also since the AFPM generator employs a coreless stator, the starting torque is not a matter of importance and this fact is proved in the results. The above calculations and data were to show the validity of the proposed work. However the actual prototype differs and it does not extract energy from the turbocharger. The results are depicted by tabulating the DC voltage and the DC current against the speed of the AFPM generator.

In the design of the prototype, a different approach was used since it would be difficult to utilize the energy of the wind through conventional construction techniques. Hence, the prototype developed in this work uses a 12V DC motor, with a rated speed of 1500 RPM to drive the axial flux permanent magnet (AFPM) generator. The coupling between the DC motor and the AFPM generator is achieved using a belt drive. The alternator speed range of 0-1000 RPM, the 12V DC motor has been selected keeping in mind the power requirements to run the motor and the mechanical fixtures that would be used to hold the motor in place. Any motor with a higher power and speed rating would be inconvenient because of the matters associated with size and the mechanism to hold the motor in place. The parameters of interest in this work would be the rectified outputs from the boost rectifier;

1. DC Voltage
2. DC Current
3. Speed of the generator.

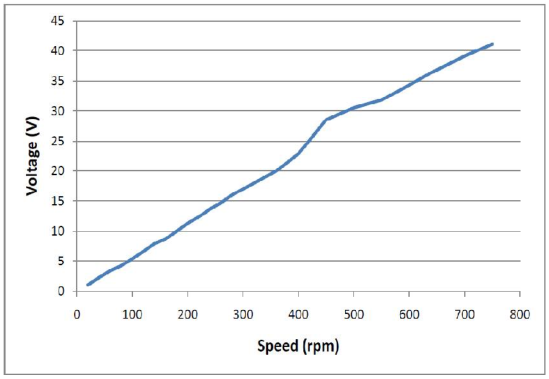


Fig.8: DC voltage versus AFPM Speed

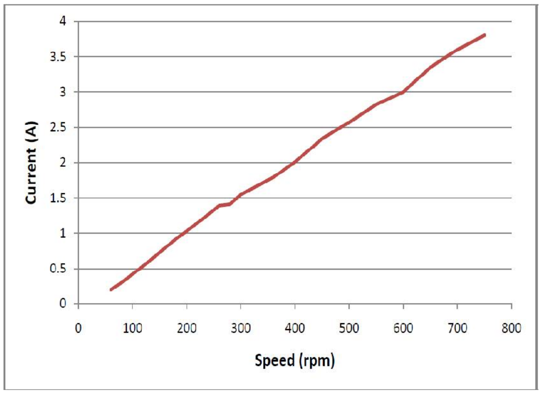
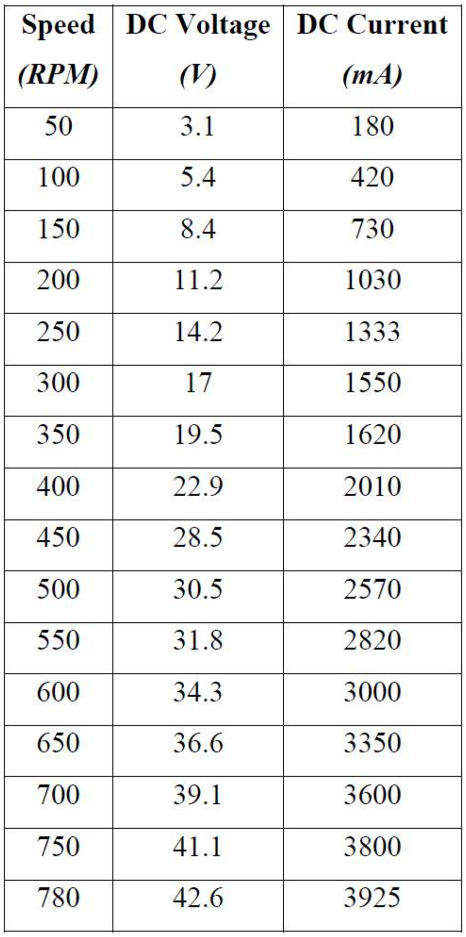


Fig.9: DC current versus AFPM speed

Table 3 shows the experimental data of the present work. Fig.8 shows the trend of the DC voltage generated against the generator speed & Fig.9 shows the trend of the DC current generated against the generator speed. With the above results, the intention of the proposed work is justified, by the fact that the target of 42V DC has been reached at lower generator speed i.e. 780 RPM.

III. Experimental data obtained from the prototype



Speed (RPM)	DC Voltage (V)	DC Current (mA)
50	3.1	180
100	5.4	420
150	8.4	730
200	11.2	1030
250	14.2	1333
300	17	1550
350	19.5	1620
400	22.9	2010
450	28.5	2340
500	30.5	2570
550	31.8	2820
600	34.3	3000
650	36.6	3350
700	39.1	3600
750	41.1	3800
780	42.6	3925

VI. CONCLUSION

The prototype employed in this work, designed to supply a power net architecture of 42V, is in view of the wide array of automobiles that are plying on the roads of our country, including the hybrid electric vehicles that are entering the roads of our nation. Assuming the vehicle to be driven at highway driving conditions in an average speed of 40kmph, the engine speed is bound to reach 2000 RPM. Even with losses due to mechanical fixtures standing at 50%, the proposed work will be able to supply the power net architecture of the automobile. By using the experimental data, if we were to approximate the results for higher rpm's the prototype is capable of generating 52V at 1000 rpm which is well over the required limits. In the case of a hybrid electric vehicle, the batteries will be able to get charged while it is commuting on highways and switch over to the batteries once it reaches the driving conditions of a crowded city. If, on the other hand, the proposed unit was installed in a normal automobile the life of the battery can be extended as the electric load on the battery is reduced.

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