Development of Three-phase BLDC Motor Drive System for Diesel Engine Emission Reductions

Aswathy C J, Jebin Francis

***Abstract*— For the conventional vehicle, an efficient and effective heat source that provides autonomous exhaust temperature control is of interest, and one solution is a diesel burner which needs to adjust its air delivery based on transient operating conditions through a three-phase motor drive system powered by a 12 V lead-acid battery. The system proposed in this paper consists of dc-dc Push-Pull converter to step up the dc voltage and to match the impedance between the battery and motor load; and an IGBT inverter which provides the high-side phase currents to a 1 kW brushless DC motor. In order to enhance the steady-state performance, a torque ripple reduction technique is also implemented to the proposed design.**

The simulation results are also discussed and analyzed in order to verify the effectiveness of the proposed design.

***Index Terms*— Brushless dc (BLDC) motor, diesel engine, inverter, power electronics.**

I. Introduction

Improvements in diesel engine technology have resulted in their expanded usage in heavy-duty vehicles such as cargo-trucks and buses. But particulate matters (PM) that includes aerosols such as ash particulates, metallic abrasion particles, sulphates, and silicates; including soot in diesel exhaust gas have severe environmental problems. It is expected that emission of soot particles can penetrate into the lungs, causing human carcinogenic effects. The Diesel Particulate Filter (DPF) is a common component of the exhaust after-treatment system of Diesel engines that removes the harmful Particulate Matter (PM) in the exhaust gas.

The filters work by blocking passage of the diesel soot so that much less than 10% of the soot in the engines exhaust is released into the air. For the traditional diesel engine, when the exhaust goes through a DPF, soot particles accumulate, and unless managed over time, it results in high exhaust backpressure and eventual soot overload that damages the DPF. The process of removing the combustible portion of the collected soot is called “regeneration" which is the burning of of the soot by raising the temperature of the filter element so that combustion of the soot occurs.

For DPF regeneration process to take place, an air compressor and a fuel pump must be linked to a clean burner for increasing the exhaust temperature so as to control the DPF soot load. Typically, the air compressor system is powered mechanically through the engine crankshaft mounted within the front-end accessory drive (FEAD) system. However, this power source has its own disadvantages, i.e., the compressors speed cannot be easily controlled, and unless a clutch is integrated, its pulley cannot be disengaged, thus constantly applying engine power and consuming fuel.

As the only available dc electric power source in the conventional vehicle, a 12-V lead acid battery is preferred to power the air compressor, offering autonomous control across all conditions regardless of the engine speed. In this seminar, a motor drive system using an onboard 12-V battery as the source to drive a 1-kW brushless dc (BLDC) motor coupled with an air compressor is proposed which adjust the air delivery to the burner. Fig.1 shows the Thermal regeneration unit for the diesel exhaust system [1].

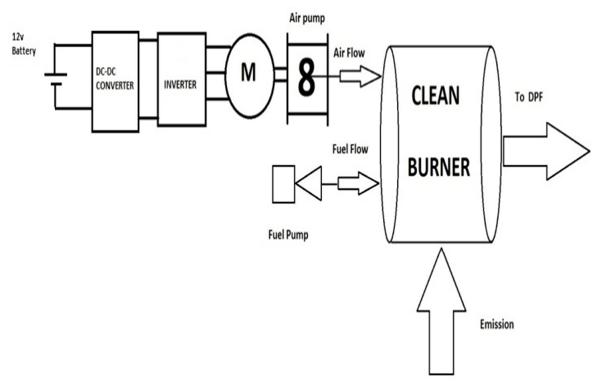

Fig.1: Thermal regeneration unit for the diesel exhaust system

To avoid large current demand of the motor, a more convenient method is applied, i.e., boosting 12 V to a high dc voltage and feeding it to a dc-ac voltage source inverter (VSI), driving a high-voltage motor, and reducing packaging demands and mass. The 12-V/1-kW motor drive system proposed in this paper consists of a dc-dc push-pull converter which provides high-efficiency power transfer and boosts the dc bus to 300 V, and an insulated-gate bipolar transistor inverter, which provides the high-side phase currents to a 1-kW/6000-r/min brushless dc motor (BLDC). Meanwhile, with the variable output voltage of this dc-dc converter, this design realizes a commutation torque-ripple reduction method, which will minimize the mechanical vibration.

Therefore, the whole system contains dc-dc and dc-ac portions, with an overall topology, as shown in Fig.2. Here, a three-phase two-level integrated power module (IPM) is employed to form the inverter. Section II is focused on the analysis of the dc-dc converter using push-pull topology. Section III based on the control theory of the BLDC drive proposes a torque-ripple-reduction method interacting the dc-ac inverter with the dc-dc converter. Sections IV and V

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deals with the simulation results of the proposed design and conclusion.

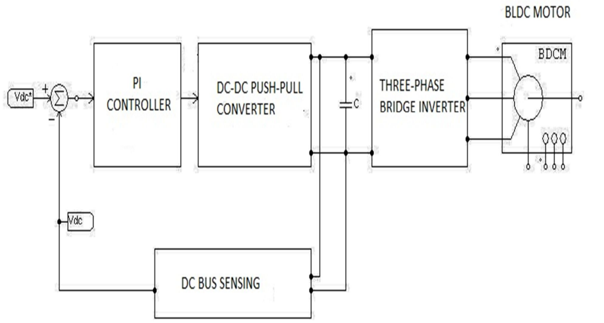

Fig. 2: Block Diagram of proposed motor drive system

II. OPERATIONAL ANALYSIS OF DC-DC PUSH-PULL CONVERTER

Switch mode DC-DC converters efficiently convert an un-regulated DC input voltage into regulated DC output voltages. Compared to linear power supplies, switching power supply offers much more efficiency and power density. Switching power supply includes solid-state devices such as transistors and diodes to operate as a switch: either completely turn-on or completely turn-off. The basic push-pull converters consist of inductors, capacitors, diodes, transistors and transformer to step-up or step-down a voltage input [2]. The Fig. 3 shows the push-pull converter circuit. When designing a push-pull converter, it is convenient to select the transformer turns ratio n such that duty cycle D does not vary in wide range. At the same time, high values for n should be avoided to ensure that the IGBT voltage inverter operates with low modulation index. The push-pull converter's input voltage is the 12-V battery voltage. The push pull transformer is usually the preferred choice in high power switching transformer applications exceeding one kilowatt[3]. Power ratings for push pull transformer can vary from a fraction of a Watt to Kilowatt. The push-pull output voltage (E) depends on the input voltage (V), the duty cycle (D), and the high frequency transformer turns ratio (n),

$$E = \frac{n}{1-D} \tag{1}$$

$$D = \frac{t_{on}}{T} \tag{2}$$

where, D defines the duty cycle and ton corresponds to the total time interval when both switches conduct. Thus, the proposed design of DC-DC Push Pull Converter should successfully step-up battery voltage of 12 V dc output voltage into 312 V dc voltage. The Fig.3 shows the push-pull converter circuit.

There are two important considerations with the push pull converter:

a) Both switches must not conduct together, as this would effectively short circuit the supply, which means that the conduction time of each MOSFET switch must not exceed half of the total period for one complete cycle, otherwise conduction will overlap.
b) The magnetic behavior of the circuit must be uniform, otherwise the transformer may saturate, and this would cause destruction of S1 and S2. This requires that the individual conduction times of S1 and S2 be exactly equal and the two halves of the centre-tapped transformer primary be magnetically identical.

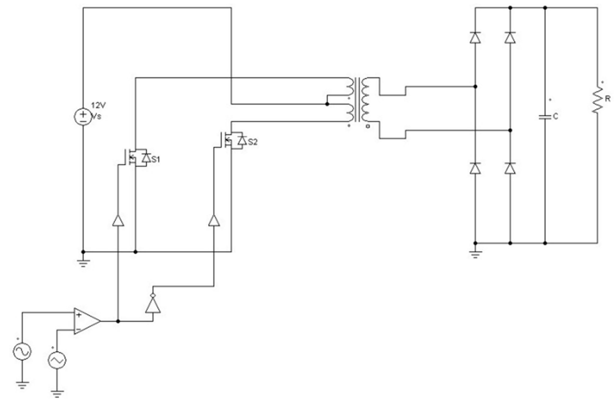

Fig.3: Push-pull Converter circuit

In the proposed motor drive system, actual DC bus voltage (Vdc) is sensed and it is compared with a reference value given by Vdc*. The error in voltage is processed through a PI (Proportional Integral) controller. PI controller is used to get good steady-state accuracy and to attenuate noise. The PI controller is tuned accordingly to give the correct duty cycles for MOSFET switches. Thus, by controlling the converter's duty cycle, the inverters dc input voltage can be varied, allowing more flexible inverter operation at different power levels. The stepped by DC voltage from the dc-dc Push-Pull Converter is fed to the three-phase two-level IGBT Inverter and BLDC motor (340 V/1 kW/6000rpm) combination. Thus the whole system contains DC-DC and DC-AC portions, with an overall topology, as shown in Fig.4.

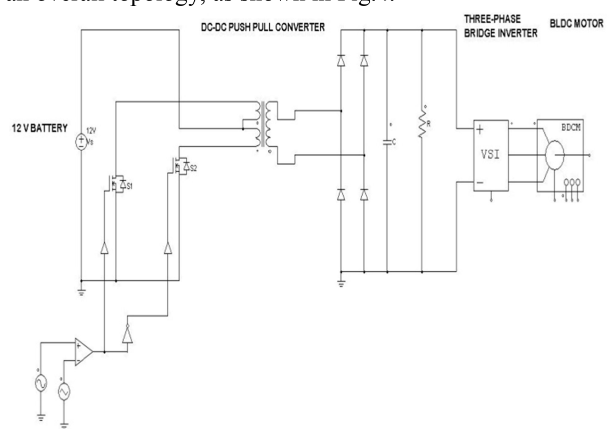

Fig. 4: Topology for the 12-V/1-kW motor drive system

III. TORQUE-RIPPLE REDUCTION FOR BLDC MOTOR

At the inverter side, a three-phase two-level topology is the most widely used, which could drive either permanent-magnet synchronous motors (PMSM) or BLDC motors, but BLDC (340 V/1 kW) motors are chosen to simplify its control strategy. Hall effect sensors are used to achieve closed-loop speed control of the motor through sampling the shaft position.

Due to their noticeable advantages such as: high power density, high torque to current ratio, good dynamics, low maintenance cost and simple control and because of the recent growth in the area of permanent magnets and power electronic switches; BLDC motors with trapezoidal back-EMF waveform are widely used in many applications such as aerospace, electric vehicles and household products.

Brushless DC motors (BLDC) are electronically commutated inverter fed synchronous permanent magnet motors with speed torque characteristics similar to a dc motor. Electronic commutation in these motors is achieved by sensing the rotor position and switching the inverter switches accordingly so that the flux rotates in the required direction [4].

One of the most significant drawback of BLDC motors which restricts their application is commutation torque ripple which results in acoustic noise and vibrations. In BLDC motors with low moment of inertia commutation torque ripple also causes speed fluctuations. The commutation torque ripple is present at every instant of commutation. It develops because the sum of currents in the outgoing and incoming phases is never constant during commutation intervals. Commutation torque ripple appears as current "spike" or "dip" depending upon the rotor speed and source voltage. In the Fig.5, ia, ib, ic will be called as outgoing current, incoming current, and non-commutating current respectively.

The Fig.6 shows a Typical BLDC drive with VSI. The stator of the motor is composed of concentrated non-overlapping three phase winding and the rotor structure is made up of surface mounted permanent magnets. Back EMF is of trapezoidal shape and that of phase currents rectangular. The motor is driven by three pole inverter structure as shown in the Fig.6. The switches (S1-S6) are switched so that two out of three phases are excited at a time and, the resultant flux rotates either in the forward or backward direction. The switching instants are determined from the rotor position feedback through hall sensors, placed 120° apart on the stator structure. Node M stands for the neutral point of the inverter, and node N stands for the neutral point of the motor windings in the Y-connection [5].

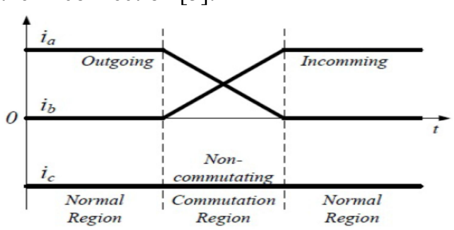

Fig.5: Current waveform in normal and commutation region

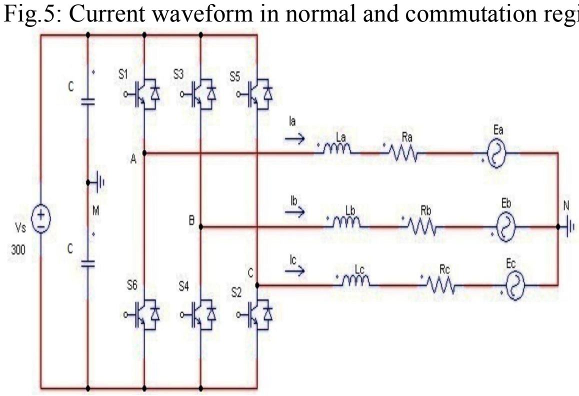

Fig.6: Typical BLDC drive with VSI

The work presented here is based on the assumptions as follows. The motor is unsaturated, and cogging torque is not considered. The stator windings are arranged symmetrically, and resistance, self and mutual inductance of the stator windings are constant. In the work, torque ripple caused by the commutation is focused mainly. The Thevenin's equivalent circuit regarding each phase, respectively, is shown in Fig.7. Ignoring the winding resistance voltage drop, the circuit voltage loop for each phase can be then determined as follows according to Kirchhoff's voltage law:

$$\frac{3}{2}L\frac{dI_a}{dt} = V_{am} - \frac{V_{bm} + V_{cm}}{2} + \frac{E_b + E_C}{2} - E_a \qquad (3)$$

$$\frac{3}{2}L\frac{dI_b}{dt} = V_{bm} - \frac{V_{am} + V_{cm}}{2} + \frac{E_a + E_C}{2} - E_b \qquad (4)$$

$$\frac{3}{2}L\frac{dI_c}{dt} = V_{cm} - \frac{V_{am} + V_{bm}}{2} + \frac{E_a + E_b}{2} - E_c \qquad (5)$$

where Ea, Eb, and Ec denote the back EMF of each phase. Vam, Vbm and Vcm are the inverter midpoint voltage with respect to the dc source midpoint voltage. They all depend on the state of the switches S1 and S6, S3 and S4, and S5 and S2, respectively [6].

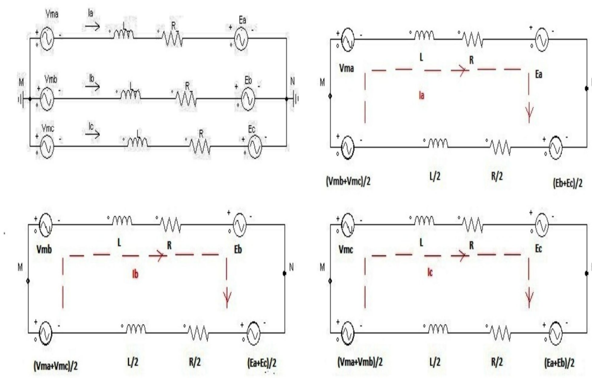

Fig.7 Equivalent circuits for three-phase motor drive during commutation

Take Vam for example. Vam = Vdc/2 when S1 is on and S6 is off, otherwise Vam = −Vdc/2. Fig. 8 shows the commutation process: phase A is non-commutating with a positive current defined in Fig.5, phase B current is approaching zero, and phase C is building up a negative current. To commute the current from Phase B to Phase C, S3 and S4 (Phase B) are turned off, whereas Phase A leg switches (S1 and S6) and phase C leg switches (S5 and S2) are switching. In this commutation process, the following could be derived assuming the commutation process is short and that the back EMF is constant:

$$E_a = E \qquad (6)$$

$$E_b = -E \qquad (7)$$

$$E_c = -E \qquad (8)$$

where E is the peak back EMF value at a specific speed.

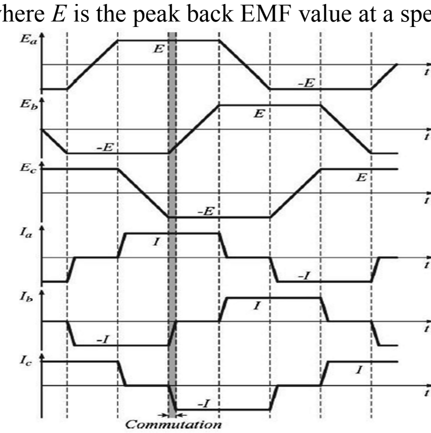

Fig.7: BLDC commutation process

To commute the current from Phase B to Phase C, S3 and S4 (Phase B) are turned off, whereas Phase A leg switches (S1 and S6) and phase C leg switches (S5 and S2) are switching. The PWM switching method, motor terminal voltage and line-line voltage is shown in Fig.8.

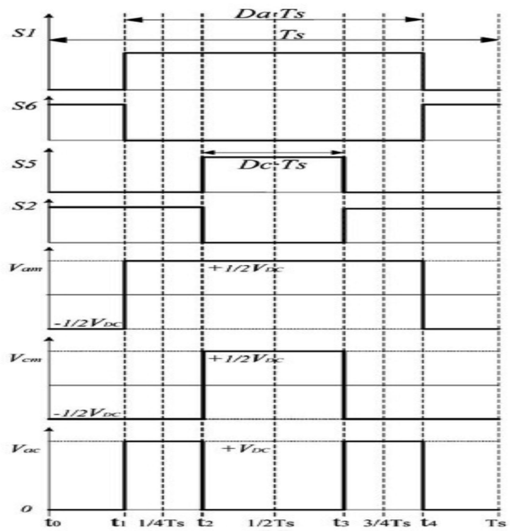

Fig.8: PWM switching method, motor terminal voltage, and line-line voltage

The average voltage of the motor terminal voltage referenced to the inverter neutral point M is derived as follows:

$$V_{am} = \frac{V_{dc}}{2}(2D_a - 1) \quad (9)$$

$$V_{bm} = \frac{V_{dc}}{2} \quad (10)$$

$$V_{cm} = \frac{V_{dc}}{2}(2D_c - 1) \quad (11)$$

where Da, b, c are the duty cycles of the top switches. Assume the current slope of phase B and C are Kb and Kc. The slopes of Ib and Ic during commutation are derived as follows:

$$K_c = \frac{dI_c}{dt} = \frac{2}{3L}\left[\frac{V_{dc}}{2}(2D_c - 1 - D_a) + E\right] \quad (12)$$

$$K_b = \frac{dI_b}{dt} = \frac{2}{3L}\left[\frac{V_{dc}}{2}(2 - D_c - D_a) + E\right] \quad (13)$$

The shutting-off phase current Ib will immediately start falling by free-wheeling through the S3 body diode after S3 and S4 are turned off. However, Ic is built up by switching S5 and S2. Once the rising slope of Ic is different from the falling slope of Ib, i.e., |Kb| ≠|Kc|, Ia will have the fluctuation causing the current dip in Phase A, and further, the torque ripple as torque could be expressed as follows:

$$T_e = \frac{E_a I_a + E_b I_b + E_c I_c}{\omega_m} \quad (14)$$

where ωm is the angular speed of motor. The proposed torque-ripple reduction method targets at making |Kb| = |Kc|. In the commutation process, S1 and S2 are held on right after Phase B shuts down, which makes Da = 1 and Dc = 0. From (13), the time needed for Ib to freewheel from Iref to zero is:

$$t_{b,fall} = \frac{3I_{ref}\,L}{2(\frac{V_{dc}}{2} + E)} \quad (15)$$

The time needed for Ic to build up, as determined by equation (12), is

$$t_{c,rise} = \frac{3I_{ref}\,L}{2(V_{dc} - E)} \quad (16)$$

To make tb,fall = tc,rise :

$$V_{dc} = 4E \quad (17)$$

which also makes dIa/dt = 0. Therefore, equation (17) is the precondition to neutralize the torque ripple. In most of the motor drive system, Vdc is a constant value. But the motor speed, thereby the back EMF, is forever changing, which make it impossible to realize equation (17) at all times [1]. However, in the proposed system, dc-bus voltage is controlled by the DC-DC converter, which can always adjust the dc-bus voltage by changing the duty cycle of the dc-dc push-pull converter.

IV. RESULTS AND DISCUSSION

The proposed design is verified by computer simulation using Powersim (PSIM) software package. The low-voltage push-pull dc-dc converter is supplied by a 12-V 140-Ah onboard lead-acid battery bank which successfully steps-up 12-V DC upto 300-V DC. The system parameters of dc-dc push-pull converter and the motor parameters are listed in Table I and II respectively.

Table I: Parameters of DC-DC Push-Pull Converter

Components Parameter	Value
Low Side Voltage	12v
High Side Voltage	Up to 350v
Switching Frequency (fs)	20kHz
Turns Ratio (n)	1:28
Output Filter Capacitance (C)	540µF

Table II: Motor Parameters

Components Parameter	Value
Motor Winding Inductance	750µH
Motor Line-Line RMS back-EMF	39.4V/krpm

The Fig.9 shows the simulated output voltage of DC-DC Push-pull converter of the closed-loop BLDC drive system. The DC bus voltage output obtained at a speed of 6000rpm is about 300V.

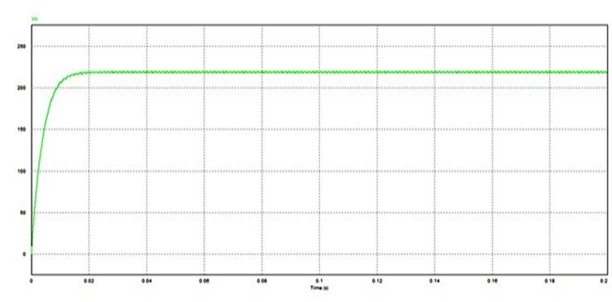

Fig.9 DC bus voltage output (Vo=300V)

The Fig.10 shows a typical toque ripple and commutation current ripple waveform without the proposed torque-ripple reduction method. The Total Harmonic Distortion (THD) measured for the torque ripple in open-loop BLDC Drive System is about 31.12%.

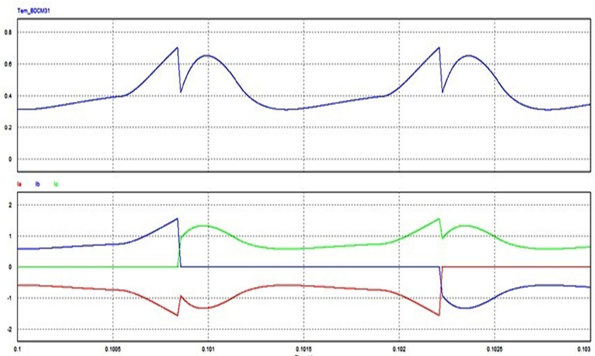

Fig.10 a) Torque ripple caused by phase current ripple (THD= 31.12%) b) Typical three-phase currents during commutation at 6000 rpm

The Fig.11 shows the toque ripple and commutation phase current ripple waveform with the proposed torque-ripple reduction method. The Total Harmonic Distortion (THD) measured for the torque ripple is reduced to about 5.99%. Simulation can be done at different speeds with the VSI dc-bus voltage changing.

Fig.11 a) Torque ripple caused by phase current ripple(THD= 5.99%) b)Typical three-phase currents during commutation at 6000 rpm

On comparing Fig.11 with Fig.10, it can be inferred that current ripple of phase A and the torque ripple during commutation interval reduces significantly; i.e, THD has decreased from 31.12% to 5.99% at a speed of 6000 rpm. It can be seen that commutation current ripple is reduced significantly by using variable Vdc=4E and controlled PWM.

CONCLUSION

After simulation of the proposed design in Powersim(PSIM), it is proven that a 1kW BLDC motor can be driven using an on-board 12-V,140Ah lead-acid battery. The system was observed to be feasible and efficient in the simulation.

Different from other approaches that directly use 12-V motors, the proposed design first uses a push-pull topology to boost the 12-V on-board battery voltage to a higher value and then applies this high voltage to an IGBT-based VSI. The dc-dc push-pull topology provides high-efficiency energy transfer. The IGBT inverter provides the high-side phase currents to drive the 1kW brushless DC motor.

To summarize, such an approach has the following advantages:

1) *Enhanced system performance*: A torque-ripple reduction method is also proposed to enhance steady-state performance. By varying the dc-bus voltage of the inverter by the dc-dc converter, the proposed method could compensate the torque ripple in most of the speed range.

2) *Low motor cost*: This is realized by boosting the dc bus to high voltage to about (~ 300 V).

Therefore such a type of 12-V motor drive system using an onboard battery can be employed in highway vehicle applications to rotate an air pump to adjust its air delivery to the burner, thereby providing autonomous exhaust temperature control for the conventional diesel engine vehicles. It secures high efficiency, low motor cost, low volume and minimizes mechanical vibrations.

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