Investigation of High Frequency Induction Heating Power Supply for Reduction of Particulate Matter

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In this paper, we propose a new circuit topology for soft switching in high frequency applications for reduction of particulate matter exhausted from diesel engines. The principle of a zero current switching as a soft switching which utilizes an overlapping commutation phenomenon is elucidated with switching mode transition. Particulate reduction system applied by the high frequency inverters is developed.

1. Introduction

Recently, in the midst of discussions of the environmental problems on the global scale, the measures for the exhaust gas from ships are examined together with the discussions at IM0 (International Maritime Organization).

Atmospheric pollutant contained in the exhaust gas includes NOx, SOx, unburnt hydrocarbon, particulate matters (PM), etc. The authors made a report1) on the generation of the emulsified fuel oil using the ultrasonic homogenizer and remarkable reduction of NOx by applying the fuel to the marine diesel engines.

In the paper, focus is made on the particulate matter which has been noticed as one of the causes for lung cancer and allergy, and a novel method using the high frequency induction heating is developed as the measures to reduce the particulate matter, and made a report on the principle of operation, the characteristic, etc.

2. System to Reduce Particulate Matter

Fig. 1 shows the scheme of principle of the PM reduction system in the exhaust gas from the marine diesel engine proposed in this paper.

Methods to reduce the PM in ships are in the dark, and none has been established yet. In the diesel engines of trucks and buses, the method2) that PM is trapped by the ceramics filter, and burnt by the Nichrome wire is examined, but there are many problems to be examined, e.g., the combustion control method of PM and

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The high temperature of 550-600oC is necessary in order to efficiently burn the PM. The combustion environment conditions of higher temperature are required according to the conditions such as the combustion speed. When such a combustion condition is considered, the heating method by the heat generated by the metallic filter itself based on the high frequency induction heating is considered to be the method of combustion of excellent efficiency in comparison with the heating method by other heating method using the Nichrome wire heater.

Fig. 2 shows the induction heating unit on the trial basis. The induction heating unit in Fig. 2 consists of a ceramics cylinder of about 10 cm in diameter, a number of tubes made of magnetic stainless steel incorporated therein, and the litz wire for high frequency coiled over the insulation material as the working coil. In the high frequency induction heating, when the high frequency AC is energized in the working coil, the magnetic flux Q to be generated by the current is changed at high speed while piercing the metallic filter, and the induced electromotive force is generated in the metallic filter, and as a result, the eddy current flow therein. The metallic filter itself is heated by this eddy current.

Fig. 1 System for reduction of PM
The magnetic material capable of withstanding the high temperature corrosion is needed for the material of the metallic filter. The structure easy for the eddy current to be generated by the high frequency alternating magnetic flux to flow is preferable, and the resonance frequency of the high frequency inverter as the high frequency power supply is changed according to the material and the structure. The structure of the metallic filter includes various types such as the lattice type, layer type, honeycomb type, and particle type in addition to the tubular type in Fig. 2. Generally speaking, in the high frequency induction heating, the small the shape of the work to be heated, the higher the resonance frequency, and the design of the high frequency power supply is greatly affected. The structure and the material of various metallic filters are under examination now.

3. High Frequency Induction Heating Power Supply

In the combustion of the PM by the high frequency induction heating, the design of the high frequency inverter becomes important as the metallic filter in addition to as the high frequency inverter. Applications of the high frequency inverter as the induction heating power supply include many kinds of experiences such as the melting and hardening of metals, together with the electro-magnetic cooker for domestic use. In the applications of the high frequency inverter, the higher frequency, miniaturization, and the higher efficiency are promoted in association with the higher power and higher speed of the self turn-off type high speed switching device. On the contrary, however, the following factors are noticed as the problems accompanied by the higher frequency.

(1) Increase of the switching loss
(2) Generation of surge voltage and current
(3) Generation of switching noise

As the measures to cope with these factors, various circuit methods of the zero current switching (ZCS) as the soft switching technology to achieve the switching at the zero cross point of the switching current or switching voltage making use of the resonance of the circuit or the zero voltage switching (ZVS) are examined. However, these soft switching circuits generally include problems that additional switching circuits are provided to make the circuit constitution complicate, or the operating duty of the operation of the switching element becomes severer.

Authors have examined the soft switching circuit of the ZCS operation making use of the overlapping commutation phenomenon by the connection of overlapping commutating reactor.

Fig. 4 shows the principle of operation. In the switching resonance arm in Fig. 4 (a), when S2 is turned on in conducting Dp1, the current flowing in Dp1 can...
not be zero rapidly due to the effect of the reactor L1, and decreased with some gradient. At the same time, the turn-on current of S2 is increased with some gradient from zero because of the suppression of di/dt due to the effect of L2, and both lead to ZCS operation.

As a result, the switching loss or reduction of noise is realized, but in a case where the current of S1 or S2 is forced turn-off in the transient operation such as when the power supply is started and when the load is suddenly changed, the spike voltage could be generated between the terminals of L1 or L2. Because the current flows in L1 or L2, the conduction loss is increased in this case.

In the circuit in Fig 4 (b) as the improved type, the problem of the conduction loss of L1 and L2 in the case of the conduction in S1 and S2 is solved while the Dp1.S2 and Dp2.S1 overlapping commutating operation is realized by devising the connecting position of the reactors L1, L2. In addition, the circuit of asymmetrical type in Fig. 4 (c) to be reported this time, the reactor L2 is omitted with the ZCS operation in mind making use of the Dp1.S2 overlapping commutation and the natural commutating operation mode in S2 turn-off, and the conduction loss is further reduced.

In the conventional high frequency inverter of the circuit constitution to use the diode to be antiparallel connected to the main switch, focus has been placed to reduce the stray inductance component Ls to be connected in series to the main switch and the diode as much as possible, and the modularization has been examined.

This is mainly because generation of the spike voltage due to Ls.(di/dt) is suppressed as much as possible when (di/dt) in the turn-off of the main switch or the antiparallel diode is large, and the snubber circuit is also necessary.

However, in the circuit constitution proposed this time, the small reactor is connected in series to the antiparallel diode, employing the completely opposite idea to the conventional circuit constitution.

That is the utilization of the overlapping commutation phenomenon in the switching operation due to the connection of small reactors L1, L2. By making use of this overlapping commutation phenomenon, (di/dt) is suppressed low, generation of the spike voltage is suppressed, and the ZCS as the soft switching is realized, which are largely different from those in the conventional topology.

The switching operation including the overlapping commutation phenomenon of the high frequency inverter of this method will be described in detail in the next chapter.

4. Asymmetrical Full-Bridge ZCS High Frequency Inverter

4.1 Circuit Constitution and Principle of Operation

Fig. 5 shows the asymmetrical full-bridge ZCS high frequency induction heating power supply. The characteristic of this circuit lies in the asymmetrical constitution between the small commutating reactors L1, L2 to be connected in series to the anti-parallel diodes Dp1, Dp2 of S1, S2, and the switch arms S3, S4 of reverse current blocking type. Fig. 6 shows the switching operation mode, and Fig. 7 shows the pattern of the switching operation principle respectively. The switching operation mode is further classified into the following ones.

Mode (a): S1.S2 conducting single-current mode
Mode (b): Dp1.Dp2 conducting single-current mode
Mode (d): S3.S4 conducting single-current mode
Mode (e): Al1 switch-off, off mode

In Fig. 7, when S1.S2 is triggered and turned on at the time t = 0, the switch current i1,i2, b become the sinusoidal current with the initial value of zero leading to the mode (a). When the current becomes negative due to the series resonance, Dp1.Dp2 conducting mode (b) is realized. Triggering S3.S4 at the time when Dp1.Dp2 are conducting lead to the mode (c), and the current of Dp1, Dp2 is not rapidly changed due to the effect of the reactors L1, L2 and reduced with some gradient. At the same time, the currents b, h of S3.S4 are not rapidly changed similarly from the condition of continuity of i1, b and i0 and rise with the initial value zero with the following condition.

\[ i_3 = i_2 - i_0, \quad i_4 = i_1 - i_0 \]  \hspace{1cm} (1)

The S3.S4 single-current mode of the mode (d) where the current of Dp1, Dp2 becomes zero is realized, and the currents b, h become zero, the off mode (e) of all switch-off is realized by the reverse blocking diodes Ds3, Ds4.
Thus, in this inverter, all switches realize the ZCS operation to achieve the soft switching without any R-C snubber or additional commutating circuit like the conventional circuit.

4.2 Characteristic Analysis

The characteristic analysis of the circuit was made by introducing the normalized parameters indicated in Table 1 for the purpose of the versatility of the analytical solution. In the numerical analysis, the 4th order Lunge-Kutta method was used to achieve the numerical calculation from the starting condition to the steady-state condition. The steady-state characteristic quantities and the waveforms are printed out with the steady-state condition where the fluctuation of the initial value of $\omega_0*$ of each cycle is within 0.5%.

The equations of motion in each mode are as follows.

Mode (a)

$$\frac{di_o*}{dz} = \frac{2\pi}{\mu} (1 - \omega_0* - \lambda i_o*)$$

$$\frac{di_1*}{dz} = \frac{2\pi}{\mu} (1 - \omega_0* - \lambda i_o*)$$

$$\frac{di_2*}{dz} = \frac{2\pi}{\mu} (1 - \omega_0* - \lambda i_o*)$$

$$\frac{di_3*}{dz} = 0$$

$$\frac{di_4*}{dz} = 0$$

$$\frac{dt_\omega*}{dz} = \frac{2\pi}{\mu} i_o*$$

(2)

Mode (b)

$$\frac{di_6*}{dz} = \frac{2\pi}{\mu (1 + 2\alpha)} (1 - \omega_0* - \lambda i_o*)$$

$$\frac{di_7*}{dz} = \frac{2\pi}{\mu (1 + 2\alpha)} (1 - \omega_0* - \lambda i_o*)$$

$$\frac{di_8*}{dz} = \frac{2\pi}{\mu (1 + 2\alpha)} (1 - \omega_0* - \lambda i_o*)$$

$$\frac{di_9*}{dz} = 0$$

$$\frac{di_{10}*}{dz} = 0$$

$$\frac{dt_{\omega}*}{dz} = \frac{2\pi}{\mu} i_o*$$

(3)

Mode (c)

$$\frac{di_{11}*}{dz} = \frac{2\pi}{\mu} (1 + \omega_0* + \lambda i_o*)$$

$$\frac{di_{12}*}{dz} = \frac{2\pi}{\mu \alpha}$$

$$\frac{di_{13}*}{dz} = \frac{2\pi}{\mu \alpha}$$

$$\frac{di_{14}*}{dz} = \frac{2\pi}{\mu \alpha}$$

(33)
5. Evaluation of ZCS Characteristic

5.1 Switching Characteristics

In the switching operation of the high frequency inverter, the ratio of the turn-on time and the turn-off time in the switching period is increased. As a result, the switching loss in the turn-on or turn-off period can not be neglected. At the same time, the switch current of di/dt, or switch voltage of dv/dt is also increased, causing the spike voltage or the surge current.

In this type of inverter, the switching loss and the spike voltage are suppressed by suppressing di/dt in the turn-off and turn-on of all switches by the ZCS operation.

Suppression of di/dt is largely affected by the reactor ratio \( u = L_1/L \) (\( L_1 = L_2 \)). Figs. 8 and 9 show the switching waveforms indicating the S3 turn-on characteristic and the Dp1 turn-off characteristic respectively when the value of \( \alpha \) is changed as \( \alpha = 0, 0.1, 0.3 \). In this type of inverter, the switching characteristics of the voltage \( v_{sl} \) and the current \( i_{il} \) in the S1 turn-on show the identical ZCS characteristic irrespective of \( u \) because S1 is triggered and turned on in the off mode. Similarly, the natural commutating operation irrespective of the commutating reactor is realized in the S3 turn-off, and not affected by the value of \( c \).

Regarding the S3 turn-on and the Dp1 turn-off the ZCS operation making use of the overlapping commutation mode by the commutating reactors L1, L2 is realized, and the switching characteristics are largely affected by the value of \( \alpha \). That means, the switching loss as \( \int v_{s3} \cdot dt \) is increased due to the steep rise of the current \( i_3 \) during the period of about 1 LLs where the switch voltage \( v_{s3} \) is transferred from the voltage in OFF condition to that in ON condition at \( u = 0 \) in Fig.8 (a).

On the contrary, in the case of \( \alpha = 0.1 \) in Fig. 8 (b), the rise of the current \( b \) is suppressed due to the effect of the reactors \( L_1, L_2, di/dt \) is reduced, and as a result, the switching loss is also reduced. The effect is further remarkable with \( \alpha = 0.3 \) in Fig. 8 (c).

Comparing the turn-off characteristic of Dp1 in Figs. 9 (a)-(c) in terms of the switching waveform of the voltage and the current, the severe oscillation phenomenon attributable to the recovery current is generated, because the gradient of the current in the Dp1 turn-offs large at \( u = 0 \) in Fig 9 (a), and the over voltage close to 2.5 times the power-supply voltage is generated when Dp1 is off.

On the other hand, di/dt is suppressed in the Dp1 turn-off at \( L = 0.1 \) in Fig. 9 (b), and the vibration of the recovery current is slightly reduced, and the over voltage is also suppressed to around 1.9 times the power.
supply voltage. The vibration and the over voltage are further suppressed at $\alpha = 0.3$ in Fig. 9 (c).

It is thus proved that the larger $u$ becomes, the more effective the suppression of the switching loss and the oscillating voltage by the diode recovery is regarding the switching characteristic.

Fig. 10 shows the comparison of the waveform of the steady-state operation of the $S_1$ voltage and current at $\alpha = 0, 0.1, 0.3$. At $\alpha = 0$ in Fig. 10 (a), the generation of the oscillating over voltage is recognized similar to Fig. 8 (a). When the value of $u$ is increased, the voltage due to the effect of the conduction of the reactors $L_1, L_2$ becomes effective to $S_1$ in the form of the reverse bias and the forward bias as indicated in the voltage wave-form at $u = 0.3$ in Fig. 10 (c). Thus, the withstand voltage of the main switch and the reverse blocking inseries diode is necessary.

That means, the increase of $c_L$ is effective to the improvement of the switching characteristic due to the suppression of the switching loss or the surge voltage, while the excessive value of $c_L$ leads to the severe operating duty of the switching element operation as the maximum value of the voltage. Even in the range of $\alpha = 0.1-0.3$, the effect of suppression of the switching loss and the surge voltage is large, and the reverse voltage on the main switch during the commutating reactor conduction is small in the range, and the value of $\alpha = 0.1-0.3$ is considered appropriate in the circuit design.
5.2 ZCS Operating Region and Output Power Distribution

In this type of inverter, the ZCS is realized by making use of the overlapping commutation phenomenon due to the commutating reactor connection. It is thus necessary to clarify the load condition of ZCS or non-ZCS, and the boundary regions in the change in the operating frequency.

Fig. 11 shows the ZCS operating region at \( \alpha = 0.1 \) on the normalized \( p - \mu \) plane. Fig. 12 shows the waveform (numerical calculation) in the ZCS and non-ZCS regions in Fig. 11 for comparison.

Fig. 12 (a) shows the critical region of the ZCS at the conduction of anti-parallel diodes \( D_p 1, D_p 2 \), and in the region (d) with FL being further smaller than that in this region, \( S_1, S_2 \) are conducted again in the region of the forced commutation. The surge is also likely to be generated similar to the case (b). Thus, in this type of inverter, the parameters FL, X are selected to realize the circuit operation in the ZCS operating region such as (e) to be surrounded by the critical regions (a), (c).

Fig. 13 shows distribution of the output power \( P_0^* \) in the ZCS operating region at \( \alpha = 0.1 \). The distribution of \( P_0^* \) is indicated by the equi-power line connecting the equal values which are obtained through the numerical calculations of the \( P_0^* \) at each point of the ZCS operating region which are divided into fine meshes. It is proved from the figure that \( P_0^* \) is not changed much even when \( \lambda \) is changed in the region of FL < 0.6. This means that \( P_0^* \) is stable against the load variation but the input voltage must be high to obtain the prescribed output power because \( P_0^* \) is small in this region. However, this non-preferably leads to the high with-stand voltage accompanied by the voltage build-up applied to the switching element.

In the region of \( / < 0.2, p > 0.8 \), \( P_0^* \) is changed much against the load variation, and it is safe to avoid this region in the circuit design.
6. Burning Experiment on PM Induction Heating

On the assumption that the PM of the exhaust gas from the diesel engine is burnt, the high frequency induction heating power supply is designed referring to the ZCS characteristic in the pre-stage, and the burning experiment of the soot-like particles sampled from the exhaust tube of the diesel engine was carried out.

Table 2 shows the design specifications of the high frequency induction heating power supply.

The burning experiment was carried out by spraying the soot-like particles from the top in the condition where the high frequency AC of 20.57 kHz in the output frequency, and of 1.1 kW in the output power was energized, and the metallic filter was heated close to 700°C (measured by the temperature sensor) as shown in Fig. 14. Fig. 14 is the photo of the instant of the combustion of the soot-like particles. The soot-like particles were instantaneously burnt in the metallic filter, confirming the effectiveness of the PM combustion.

Fig. 15 shows the waveforms of the operation of each part of the high frequency inverter, where the stable operation is realized while suppressing the surge voltage due to the effect of the ZCS operation. The waveform from the experiment agrees well with the waveform from the numerical analysis, resulting in the support of the theory.

7. Postscript

In this paper, the system for reduction of particulate matter is proposed, and the asymmetrical full-bridge ZCS high frequency inverter was developed as the high frequency induction heating power supply to clarify the ZCS characteristic. The versatility as the system for reduction of the PM from the diesel engine is recognized by the basic experiment of the combustion of soot-like particles.

Concerning the combustion of PM in the actual system, it is necessary to examine the shape, structure...
Discussions:

Questioner: Mr. Kazuhiro Mizushima, Research Institute of Hitachi Zosen

[Question] On the heating system for reduction of particulate matter, the thermal efficiency as the total system becomes important in considering the practical use. How much power is required for heating?

[Answer] On the thermal efficiency of the total system, the highly efficient operation may be possible by absorbing the thermal energy of the exhaust gas at the outlet of the high frequency induction heating unit through the exhaust gas economizer.

In the actual system, the thermal efficiency is different according to the specifications of the diesel engine, the burning condition of the PM, the structure and material of the metallic filter, etc. In the present situation, the induction heating experiment of various metallic filters is carried out in the open condition without being connected to the exhaust tube of the diesel engine, and further examination will be made in the condition where the system is connected to the exhaust tube regarding the concretely required power.

References