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전동기 과전압 억제용 OUTPUT REACTOR의 최적 설계

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Cost-effective Design of an Inverter Output Reactor in ASD application

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Abstract

In this paper, the cost-effective design of output reactor which is used to suppress the over-voltage at the motor terminal in the Adjustable Speed Drives(ASD) application is proposed. In the elevator drive system, the power cable length is relatively shorter than other ASD applications and then the over-voltage at the motor terminal depends on the frequency characteristics of the output reactor at the over-voltage operating frequency. The over-voltage suppression mechanism of output reactor in ASD application is analyzed and the dominant parameters of output reactor for the over-voltage suppression are extracted. Using these parameters as the design values and considering the high frequency charateristics of iron core in the reactor, a new cost-effective structure of output reactor is proposed. Experimental results of the conventional reactor and the proposed reactor with a 15kW induction motor are given to verify the proposed scheme.

I. Introduction

Recent advancements in power electronic switching devices have enabled high frequency switching operation and have improved the performance of ASD. While the high switching speed improved the performance of the inverter-fed motors, the high rate of voltage-rise in inverter output arises the excessive over-voltage in the motor terminal, which has serious adverse effect on the motor insulation [1]-[3].

The over-voltage at the motor terminal is clearly analyzed with the voltage reflection theory for the cable end which explains that the voltage overshoot depends on the inverter output voltage rise-time, cable length, and the reflection coefficient of the cable end [4], [5].

Many papers propose various methods to solve this problem, and the output reactor at the inverter is the simplest method of conditioning the motor terminal voltage [6]-[8]. The output reactor reduces the dV/dt of inverter output voltage, which in turn reduces the dV/dt of the motor terminal voltage. In general, output reactor is designed at the fundamental frequency, having 3~5% Percent Impedance and the over-voltage suppression is almost proportional to the reactor impedance. But a higher value of impedance causes a rapid increase in cost. In the conventional reactor design, to extract the optimal parameter of the output reactor, the trial and error method is used, but this empirical way takes much time and high cost. Besides, a higher value of impedance at fundamental frequency causes a larger voltage drop across the reactor, which reduces the fundamental component of voltage at the motor terminals. In the elevator drive, the acceleration toque is larger than that of others and then a large voltage drop can result in the torque insufficiency. In this paper, we analyze the over-voltage suppression mechanism of output reactor and it is found that the over-voltage suppression performance of the output reactor depends on the certain parameters at over-voltage operating frequency. At several hundreds of kHz (over-voltage operating frequency), the magnetic penetration depth of reactor core is reduced and the flux distribution is different from that of the fundamental frequency. Using these characteristics, we proposes a cost-effective design of output reactor.

II. Over-voltage suppression mechanism of output Reactor

Fig.1 shows the motor driving system with output reactor. The output reactor is implemented at the inverter output. Fig.2 shows the voltage measured at the motor terminal. Fig.2(a) shows the voltage when the motor cable end(the neutral of Y-connection motor) is opened, and Fig.2(b) shows the voltage when the motor cable end is shorten.

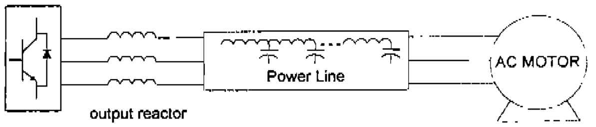


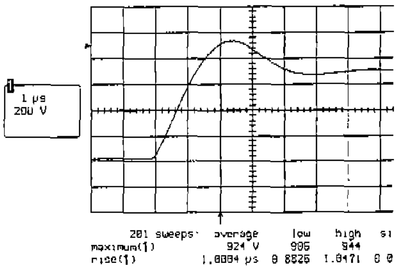
Fig. 1. Motor driving system

The results show that the over voltage charateristic is almost independent of the magnitude of the fundamental current.

Fig.3 shows the voltage and current measured at the motor terminal. The current waveform has the frequency characteristic which ranges several hundreds of kHz. This shows that the high frequency modelling of the system (motor, power cable, and output reactor) must precedes the the voltage suppression mode analysis.

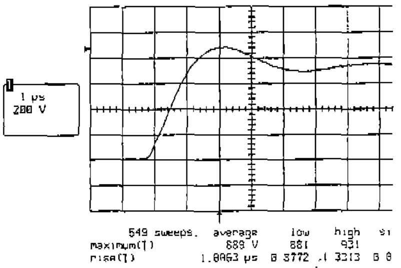
A. Motor model at high frequency

Many papers show various ways of the high frequency motor modelling. In this paper, the way of Takamasa Hori is used[9]. Fig.4 shows the Impedance vs frequency characteristic of the tested motor (7.5kW). The impedance charateristics of each phase coil of the motor is measured with Impedance Analyzer (HP4194A). Fig.5 shows the motor equivalent circuit for the single phase, and Table. I shows the calculated parameter of the given circuit.



(a) No fundmental current

(*when motor neutral is opened*)



(b) Rated current

(when motor neutral is shorted)

Fig. 2. The voltage measured at the motor terminal

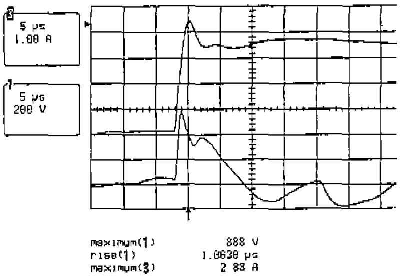
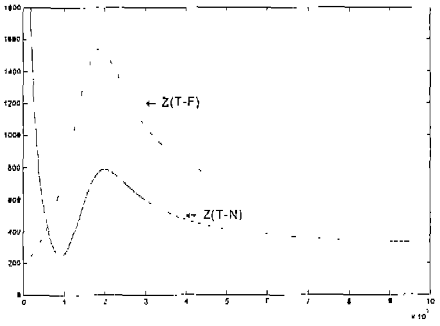


Fig. 3. *The voltage and the current measured at the motor terminal*

(Chl: voltage, Ch3: current, *when motor neutral is opened*)

B. Reactor model at high frequency

Fig.6 shows the output reactor circuit for the single phase, and Table. II shows the measured parameters of the given circuit. Impedance Analyzer (HP4194A) is used in measuring.



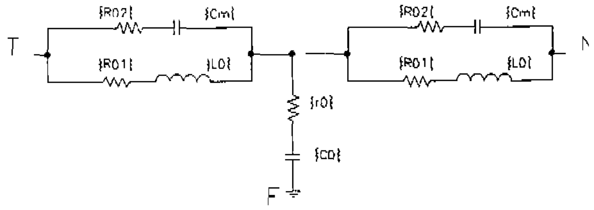


Fig. 5. The high frequency equivalent circuit of motor (single phase)

(T:motor input terminal, N:motor neutral, F: Frame ground)

Table I.

The caculated parameters

R01	80.3 ohm
R02	272 ohm
Lo	367 uH
Cm	2.1 nF
ro	27.7 ohm
Co	4.7 nF

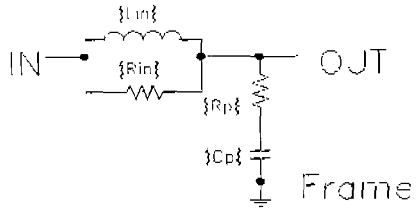


Fig. 6. The high frequency equivalent circuit of reactor (sigle phase)

Table II.

The measured parameters

Lin	76 uH
Rin	293 ohm
Rp	90 ohm
Cp	40 pF

C. The analysis of the over-voltage suppression mechanism.

In the elevator application, the power cable-length is less than 20[m]. If the output reactor increases the voltage rise-time, the effect of power cable can be ignored. Fig.7 shows the total system where the high frequency model of the previous chapter is used. Fig.8 shows the Pspice simulation results. The rise-time of input voltage (Vin) is 100nsec. The voltage overshoot at motor terminal depends on the current I(tot) into the motor terminal which is divided into two currents, I(L), I(C). Fig.8 shows that the current I(C) is dominant at the voltage transient, and then it is found that the Lo and R01 path in Fig.7 can be ignored in the voltage overshoot concern. Then, at the over-voltage operating frequency (ω_{typ}), the total system can be simplified into the circuit in Fig.9 . As a result, the design of output reactor for over-voltage suppression is simplified into the step response design of R-L-C series resonant circuit, that is, finding the R_s and L_s parameter for the desired voltage response.

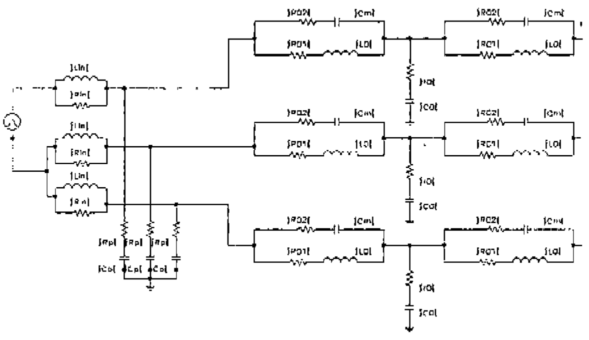


Fig. 7. The system model at the high frequency

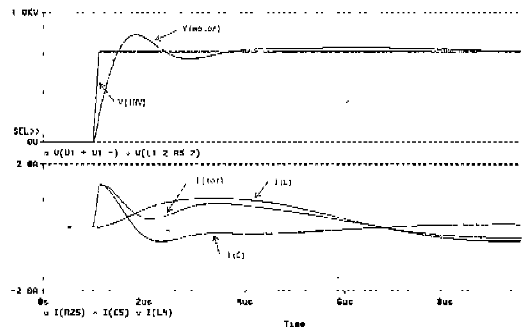


Fig. 8. The Pspice simulation result

I(tot): total current, I(C): current in Cm, I(L):current in Lo

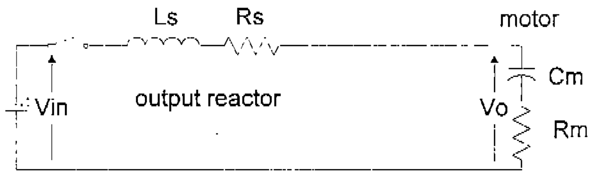


Fig. 9. The simplified system

In Fig.9,

$$R_s = \frac{(w_{typ} L_{in})^2 R_{in}}{R_{in}^2 + (w_{typ} L_{in})^2} \quad (1)$$

$$L_s = \frac{L_{in} R_{in}^2}{R_{in}^2 + (w_{typ} L_{in})^2} \quad (2)$$

The tranfer function of the simplified system is

$$\frac{V_o}{V_{in}} = \frac{R_m C_m s + 1}{L_s C_m s^2 + (R_s + R_m) C_m s + 1} \quad (3)$$

Then, the characteristic equation of the system is

$$\Delta = s^2 + \frac{R_s + R_m}{L_s} s + \frac{1}{L_s C_m} = 0 \quad (4)$$

In the general second order system,

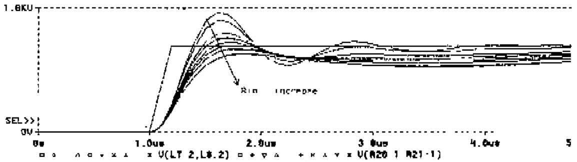
$$\Delta = s^2 + 2\xi w_n s + w_n^2 = 0 \quad (5)$$

Then,

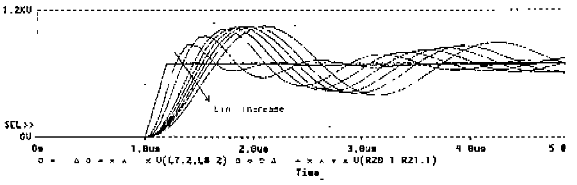
$$\xi = \frac{R_s + R_m}{\sqrt{4L_s / C_m}}, \quad w_n = \frac{1}{\sqrt{L_s C_m}} \quad (6)$$

In Eq.(6), ξ is the damping ratios and ω_n is the natural frequency. From Eq.(6), we can find that the increase of R_s makes the increase of damping ratio and that the increase of L_s makes the decrease of the damping ratio, and the natural frequency.

Fig.10 shows the characteristics of the voltage overshoot with the variance of R_s and L_s. Fig.10(a) shows that the voltage overshoot decreases when R_s increases, and Fig.10(b) shows that the natural frequency decreases when L_s increases.



(a) When R_s increases



(b) When L_s increases

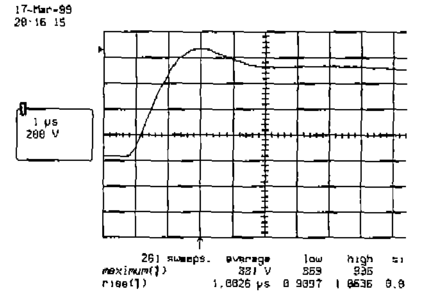
Fig. 10. The voltage overshoots with the variances of Ls and Rs

III. Design of Output Reactor

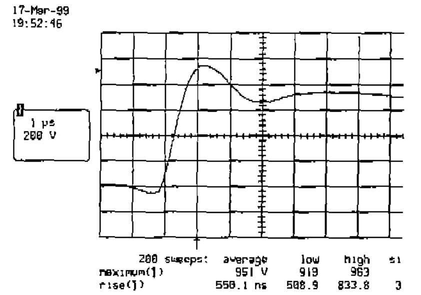
From the previous chapter, it is expected that the over-voltage suppression charateristics of output reactor depends on L_s and R_s parameters at the over-voltage operating frequency(ω_{typ}). Then the over-voltage suppression design becomes the design of cutput reactor having the required L_s and R_s parameters at over-voltage operating frequency (ω_{typ}). L_s and R_s depend on the flux linkage and the core loss inside the reactor whichare related to the flux distribution inside the reactor core. The reactor design considerations for the over-voltage suppression are as following.

A. The effect of core Saturation

If the saturation arises inside the reactor, L_s and R_s values of the reactor are changed. Then, the over voltage suppression charateristics of output reactor is also changed. Fig.11. shows the voltage overshoot at the motor terminal when the current is (a) 40Arms and (b) 80Arms. The inductance of the used reactor is 0.35mH when 40Arms flows but decrease to 0.27mH when 80Arms because of core saturation. In Fig.11(b), it is found that the voltage overshoot becomes higher and the voltage rise time decreases, which shows the effect of the core saturation. From this result, it is found that the iron core of output reactor must not be saturated even when the maximum current flows. This causes the increase of the cost and the size of the output reactor.

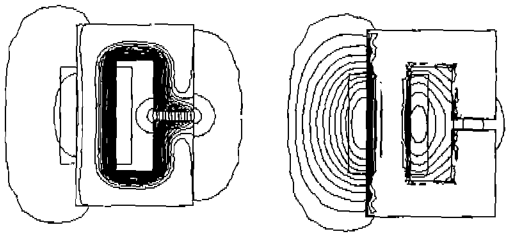


(a) 40Arms (0.35mH)



(b) 80 Arms (0.27mH, saturated)

Fig. 11. The motor terminal voltages at different currents



(a) 60Hz (b) 200kHz

Fig. 12. The flux distribution at the different frequency

B. The Flux distribution in high frequency

When the current produces a magnetic field(Ho) and a flux density(Bo) in the core walls, the flux penetration into the iron core laminations is given by one dimension diffusion equation [10].

$$\frac{d^2B}{dx^2} - \frac{j}{p^2} = 0 \qquad (7)$$

where

p =Penetration depth
ρ =Iron resistivity
μ =Iron permeability
ω =Angular frequency
x =Distance

The solution for Eq.(7) is given

$$B(x,\omega) = B_o \exp\left(-\frac{x}{p}\right) \qquad (8)$$

According to Eq.(8), the flux penetration depth in reactor core decreases rapidly, when the source frequency increases. Fig.12 shows the flux distribution in the core, when the current frequency is (a)60Hz, and (b)200kHz. F.E.M (finite element method) is used for the analysis of the flux distribution. The single phase reactor structure is adopted, and the lamination effect is neglected for the convenience of the analysis. Although there can be some deviations because of this simplification, the approximate trends can be found. The flux leakage at high frequency (Fig.12(b)) is more apparent than that at low frequency (Fig.12(a)).

C. Cost-effective design of output reactor

In the large inertia system like the elevator, the current for acceleration is more than two times of the rated current. If the closed yoke type reactor is adopted in this application, it causes a great increase in the cost to avoid the over-current saturation problem. Fig.13 shows the design concept of the proposed output reactor structure. Fig.13(a) shows the low frequency flux distribution in conventional closed yoke type where the flux is equally distributed in the whole core.

Fig.13(b) shows the flux distribution at the high frequency where the flux leakage is dominant. Fig.13(c) shows the proposed open yoke type structure which also has the similar flux distribution with that of conventional type in Fig.13(b). It is expected that the over-voltage suppression charateristics will be similar because their flux distributions are similar at the over-voltage operating frequency. Having the same over-voltage suppression charateristics, the open yoke type has some merit beyond the closed yoke type. In low frequency, the open yoke type reactor has lower flux density than the closed type, which can reduce the size and the cost of reactor without the saturation problem. Fig.14 shows the proto-type of the proposed structure (single lag). Fig.15 shows the two different types of 3 phase reactors which are designed for the similar over-voltage suppression characteristics. Table.Ⅲ shows the design results of two different type reactors in Fig.15. At 60Hz, the inductance of the proposed reactor is smaller than that of conventional type, and then the voltage drop across the inductor becomes smaller. This will increase the available torque range. Fig.16 shows the measured Ls and Rs values of two reactors. It is found that two reactors have similar characteristics in the over-voltage operating frequency (200kHz ~ 500kHz).

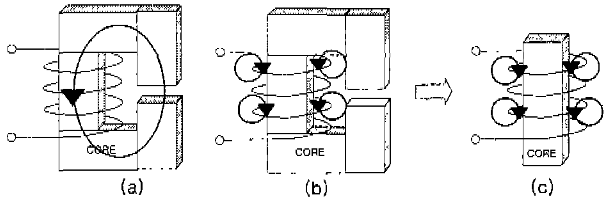


Fig. 13. The flux distribution in output reactor

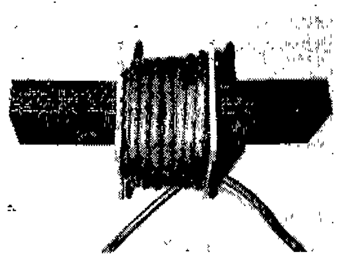


Fig. 14. Proto-type of the proposed output Reactor (single Leg)

Fig. 15. The conventional type and the proposed type

Fig.17 shows the voltage at the motor terminal when the reactor at inverter output is (a) the conventional type and (b) the proposed type. For the accuracy, the statistical analysis using more than 200 samplings is accomplished. Table.Ⅳ shows these results. Although the overall voltage characteristics are similar, there are small differences in values. We can guess that the differences are due to the parameter difference of two reactors. Smaller L_s value and larger R_s value of the conventional type cause the increase of the damping ratio and the decrease of the natural frequency.

Table. Ⅲ.

The specification of two reactors in Fig .15

(Inducdance are measured at 60Hz)

Item	conventional	proposed
Rated current	55 Arms	55 Arms
Rated inductance [mH] (at rated current)	0.25	0.185
Overload Inductance [P.U.] (at 200% current)	89.8% of rated value	89.3% of rated value
Core size(W*H*D[mm])	220*160*40	160*110*40
Total weight [Kg]	10.5	4.5

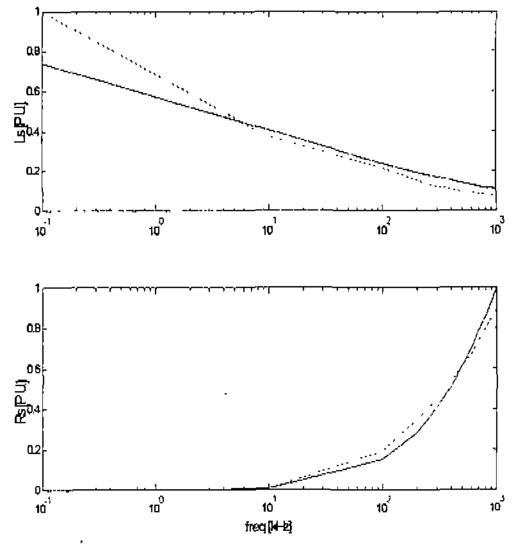


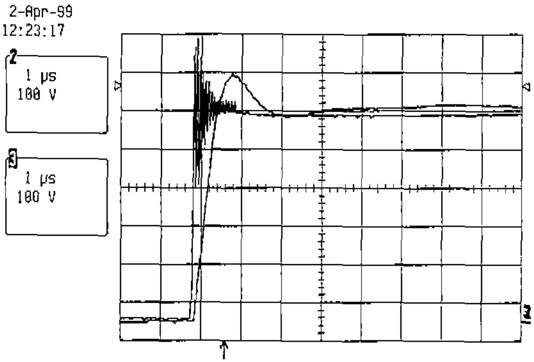
Fig. 16. The Ls and Rs values vs. the frequency [P.U.]

(Dashed line: conventional, Continuous line : proposed)

Table Ⅳ.

The voltage overshoot measured at the motor terminal (when DC Link voltage is 540Vdc)

Item	Conventional		Proposed	
	Average	variance	Average	variance
the max. voltage[V]	636	10	667	15
rise time [nsec]	451	7	490	35



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      213 sweeps:  average    low    high   sigma
maximum(2)           723 V    681    747      26
rise(2)              40 ns     31     48       7
maximum(3)           636 V    622    647      10
rise(3)             451 ns    436    459       7
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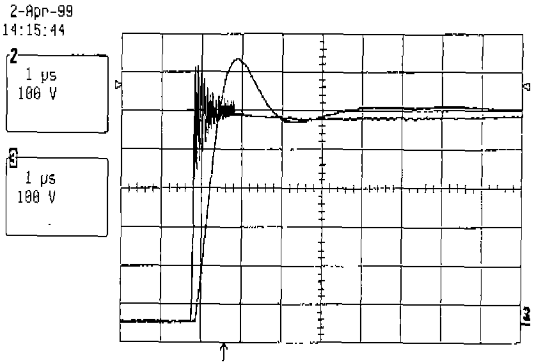
(a) conventional



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      205 sweeps:  average    low    high   sigma
maximum(2)           644 V    612    683      22
rise(2)              33 ns     31     35       1
maximum(3)           667 V    644    684      15
rise(3)             490 ns    450    533      35
```

(b) proposed

Fig. 17. The voltage-overshoot at the motor terminal (Ch2: the voltage at reactor input, Ch3: the voltage at motor terminal)

V. Conclusions

In this paper, the cost-effective design of output reactor which is used to suppress the over-voltage at the motor terminal in ASD application has been proposed.

From the analysis of over-voltage suppression mechanism, it was found that the over-voltage suppression performance of the output reactor depends on certain parameters at the over-voltage operating frequency and that the flux leakage is dominant at that frequency. The L_s and R_s parameters which are dominant in over-voltage suppression was adopted as the design values of the reactor. And the open yoke sturucture which needs smaller core size than the conventional closed yoke type has been proposed.

Experiments of the conventional reactor and the proposed reactor with a 15kW induction motor showed the similar results, which verifies the proposed scheme. In elevator application(15kW), the size and the weight in the proposed design can be reduced to about a half of those in the conventional.

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