

A Motor Surge Voltage Suppression Method With Surge Energy Regeneration

Toshihisa Shimizu, *Senior Member, IEEE*, Mikiya Saito, Masanori Nakamura, and Tomoo Miyazaki

Abstract—A novel motor surge voltage suppression method is proposed herein. The features of the proposed method are that: 1) there is no requirement for an LC filter for suppression of the motor surge voltage on the motor terminal; 2) the energy stored in the main power cable, which causes the motor surge voltage, is regenerated to the inverter dc-bus line; and 3) the motor surge voltage suppression effect is not influenced by the power cable length. Therefore, the proposed method offers advantages in terms of volume and efficiency compared with conventional surge suppression methods. The circuit configuration of the proposed system is presented and the operation principle is explained. The method used to design the circuit parameters is also presented. The effectiveness of the surge voltage suppression of the proposed method is confirmed experimentally.

Index Terms—AC motor drive, overvoltage protection, pulse width modulated inverter, power cables, surge protection.

I. INTRODUCTION

THE occurrence of a motor surge voltage on a motor terminal in a pulse width modulation (PWM) inverter drive system is a well-known problem [1], [2]. High Peak voltage causes dielectric breakdown of the stator winding insulation in the motor. Therefore, the surge voltage should be suppressed as much as possible. Overvoltage at the motor terminal has been analyzed using the voltage transmission and reflection theory for the cable end [3]–[7]. Pulse voltages generated at the inverter terminal are transmitted to the motor power cable, and a high voltage appears on the motor terminal at the time when the transmitted voltage wave is reflected at the motor terminal. The increase in amplitude of the surge voltage when the cable length is long and the voltage transient dv/dt is high can be explained by the transmission theory, which states that the maximum amplitude of the surge voltage becomes twice that of the inverter pulse voltage [8].

The insertion of a differential mode LC filter is a traditional method for suppressing the surge voltage [9], [10]. In this method, a large filter inductor along with an RC damping resistor is necessary in order to reduce the voltage transient dv/dt

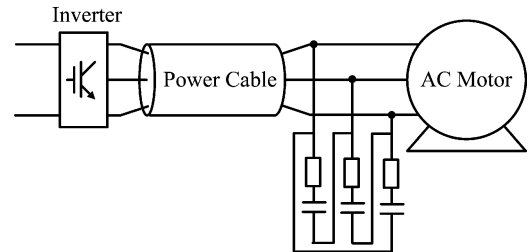


Fig. 1. Impedance matching method.

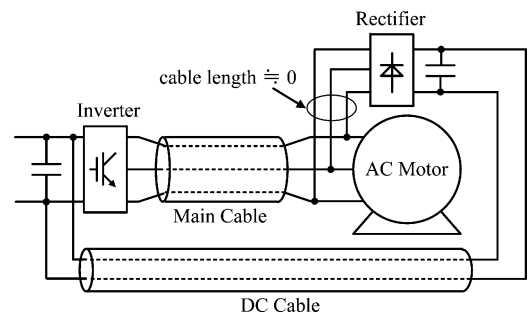


Fig. 2. Diode rectifier method.

and the peak amplitude of the motor terminal voltage. However, the disadvantages of this method include the requirement of using a heavy, bulky inductor and a large loss generated on the RC damping circuit. Efforts have been made to reduce the cost and volume of the inductor [11], but these problems have not yet been sufficiently addressed.

In order to solve the problems associated with the insertion of the LC filters, a number of alternative methods have been proposed. Fig. 1 shows a typical method in which the amplitude of the reflection voltage wave is reduced by connecting an impedance matching element in parallel to the motor terminal [12]. However, the loss on the impedance matching element cannot be avoided, and this loss increases with increase of the inverter voltage.

Fig. 2 shows another method in which a diode rectifier circuit is closely connected to the motor terminal [13], [14]. In this method, the amplitude of the surge voltage is clipped by the rectifier by setting the dc-bus voltage of the rectifier to the dc-bus voltage of the inverter. A distinctive feature of this method is that the surge energy is regenerated to the dc-bus line of the inverter, and hence the loss in the system can be reduced compared with that of the LC filter method. However, the ac terminal of the rectifier must be connected very close to the motor terminal. Therefore, this method is difficult to apply when there is no additional space around the motor terminal, as in the case

Manuscript received August 10, 2011; revised October 26, 2011; accepted November 29, 2011. Date of current version April 3, 2012. This paper was selected from the EPE-PEMC 2010 Conference. Recommended for publication by Associate Editor M. Ferdowsi.

T. Shimizu and M. Saito are with the Department of Electrical and Electronic Engineering, Tokyo Metropolitan University, Tokyo 92-0397, Japan (e-mail: shimizut@tmu.ac.jp; ito-mikiya@ed.tmu.ac.jp).

M. Nakamura and T. Miyazaki are with Oki Electric Cable Company, Kanagawa 211-8585, Japan (e-mail: nakamura767@oki.com; miyazaki991@oki.com).

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/TPEL.2011.2179319

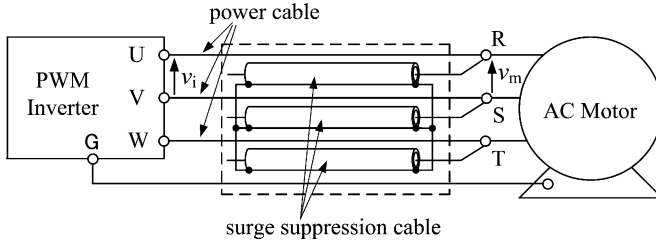


Fig. 3. Surge suppression cable method.

of electric/hybrid vehicles, industrial robots, and underwater drilling machines, for example. The operation principle of this method was described for an ideal step voltage of the inverter. However, the surge voltage when the actual pulse voltage of the inverter is used was not studied. Therefore, the effectiveness of the system was not clearly confirmed, even though some experimental results were presented.

Fig. 3 shows the third method, previously presented by the authors of the present study, in which a surge suppression cable is connected in parallel to the motor terminal [15]. The surge suppression cable is a specially made coaxial cable in which the high-frequency insertion loss of the cable is increased. In this method, the surge voltage apparent on the motor terminal is reduced by penetrating the surge energy into the surge suppression cable. The advantage of this method is that it is not necessary to insert filter elements into the power cable in series. However, the energy stored in the main power cable is still consumed in the surge suppression cable, which results in a temperature increase in the cable.

Taking these studies into consideration, the authors propose a novel motor surge voltage suppression method, in which the operational principles of the surge suppression cable and the voltage clamping circuit are combined. The features of the proposed method are: 1) the rectifier is located close to the inverter, and the ac terminal of the rectifier is connected to the motor terminal by a cable with a characteristic impedance that is the same as that of the main motor power cable, so that no additional space is required around the motor terminal; 2) a high surge suppression effect is realized, regardless of the inverter pulse voltage waveforms, by connecting an RC circuit in parallel to the rectifier terminal; and 3) the surge energy can be regenerated to the dc-bus line of the inverter through the rectifier, so that the surge voltage can be suppressed effectively without power loss.

In this paper, the concept of the proposed motor surge suppression method and a practical system configuration are first described. The operation principle of the proposed method is then explained for both ideal step voltage conditions and actual inverter pulse voltage conditions, which reflect the PWM inverter. Note that the RC circuit plays an important role in the suppression of the surge voltage during the rise time of the actual inverter pulse voltage. Experimental waveforms of the motor surge voltage and the rectifier voltage/current reveal the proper operation of the proposed method. Finally, the surge suppression effect and the surge energy regeneration factor for RC values are investigated, and an optimum RC value is suggested.

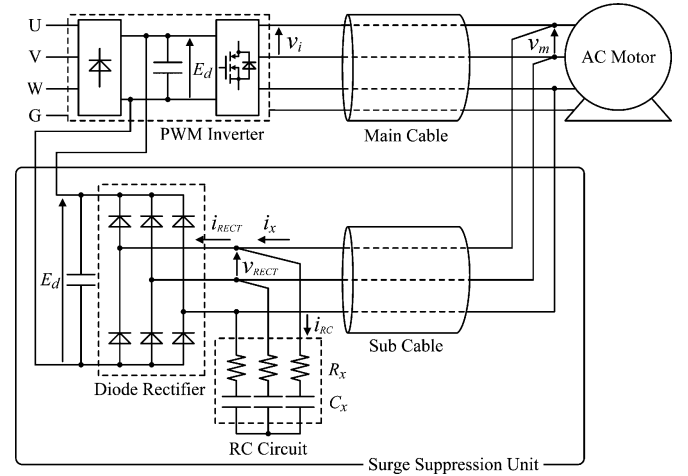


Fig. 4. Proposed method.

TABLE I
CIRCUIT PARAMETERS

Inverter output voltage	200 V, 50 Hz
DC bus voltage E_d	288 V
PWM carrier frequency f_s	10 kHz
AC motor (induction motor)	200 V, 750 W
Cable length of main-cable X_1	50 m
Cable length of sub-cable X_2	50 m
Characteristic impedance of main-cable Z_1	65 Ω (single-phase)
Characteristic impedance of sub-cable Z_2	65 Ω (single-phase)
Conductor sectional area of the cable	3.5 mm ²
Resistor R_x	47 Ω / 1 W
Capacitor C_x	50 – 14100 pF/ 630 V
Diode for rectifier	600 V / 6 A (SDP06S60;Infineon)

II. CIRCUIT CONFIGURATION

Fig. 4 shows the circuit configuration of the proposed method. The output terminal of the PWM inverter is connected directly to the induction motor terminals by a three-phase main cable. The surge suppression unit is composed of the three-phase sub-cable, a diode rectifier, and an RC circuit. One end of the sub-cable is connected to the motor terminal and the other end of the sub-cable is connected to the ac terminal of the rectifier. The dc terminal of the rectifier is connected to the dc-bus line of the inverter. The RC circuit is connected to the ac terminal of the rectifier. The circuit parameters of the experimental setup are given in Table I. The main cable and the sub-cable are both 50 m in length and the characteristic impedance of each of these cables is 65 Ω . The same types of cables are used as the main- and sub-cables, but it is not necessary to use the same cable in the practical system as long as the characteristic impedance is the same. Therefore, the thickness of the sub-cable can be small because only a small amount of current caused by the surge energy flows into the cable and it is less expensive. Moreover, the power ratings of the resistors, capacitors, and the diode are very small, i.e., $R = 47 \Omega/1 \text{ W}$, $C = 50\text{--}14100 \text{ pF}/630 \text{ V}$, and the diode is rated at 6 A/600 V. As such, the volume and cost of these components are generally low. In addition, the potential

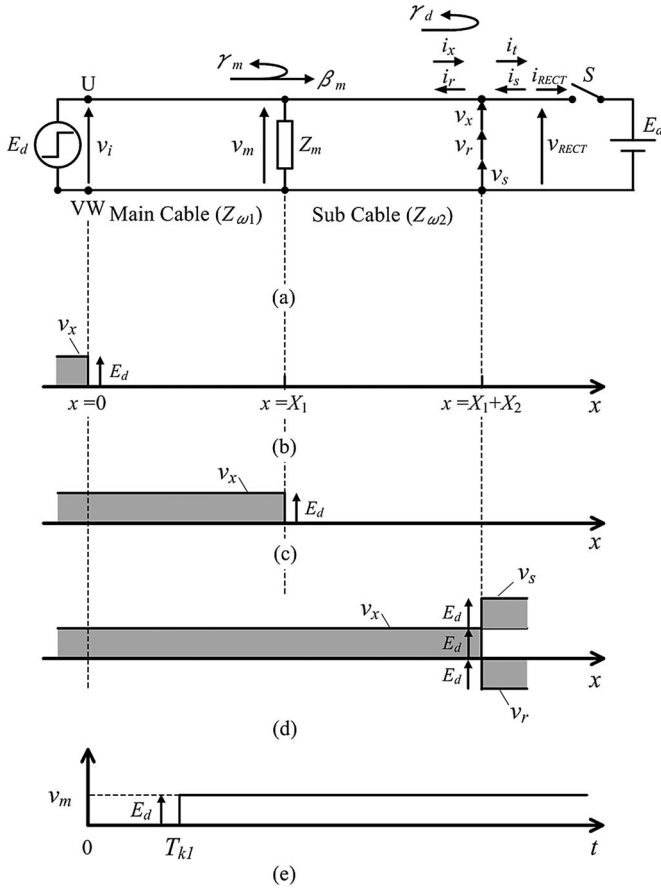


Fig. 5. Operation principle of the proposed method. (a) Single-phase equivalent circuit. (b) $t = 0$. (c) $t = T_{k1}$. (d) $t = T_{k1} + T_{k2}$. (e) Motor terminal voltage.

cost of the conventional method can be discussed as follows. The potential cost of the method shown in Fig. 3 may be higher because specially made cables must be used, which can greatly reduce the surge voltage. The method shown in Fig. 2 does not require an RC circuit and may be cheaper, but cannot reduce the surge voltage effectively. The method shown in Fig. 1 has the simplest circuit configuration. However, all of the surge energy is consumed by the RC circuit. Therefore, we need to create an RC circuit with high-power-rating components. As a result, the potential cost of the previous methods may higher than we expect.

III. OPERATION PRINCIPLE

Typically, only one phase switch of the PWM inverter changes its switching status during one switching transition. Therefore, the voltage potential on the corresponding output terminal of the PWM inverter is changed, while the voltage potentials on other terminals are not changed. By focusing on one switching transition and the resultant surge voltage on the motor terminal, the circuit configuration of the system can be simplified to a single-phase equivalent circuit, as shown in Fig. 5(a). The switching status of the U-phase switch is assumed to be changed, but the switching statuses of the V-phase and W-phase switches are not changed, so that the voltage source is assumed to be a step func-

tion. The power cables used in this system are assumed to be ideal transmission lines, and the characteristic impedances of the main- and subcables are defined as $Z_{\omega 1}$ and $Z_{\omega 2}$, respectively. In addition, both characteristic impedances have the same value, i.e., $Z_{\omega 1} = Z_{\omega 2}$. The impedance of the motor is denoted as Z_m .

A. Motor Surge Voltage When a Step Function Inverter Voltage is Assumed

The operation principle for surge suppression using the proposed system is first explained using an ideal step voltage. Fig. 5(b)–(d) show the ideal step voltage that propagates in the cables. Since the horizontal axis x indicates the distance from the inverter terminal, the step voltage propagation in the cables can be observed.

At $t = 0$, the inverter voltage v_i is changed from 0 to E_d , and an ideal step voltage of amplitude E_d appears on the sending terminal of the main cable [see Fig. 5(b)]. The voltage starts to propagate in the main cable toward the motor terminal as a forward-traveling voltage wave.

At $t = T_{k1}$, the forward-traveling voltage v_x arrives at the motor terminal [see Fig. 5(c)]. Here, T_{k1} is given by

$$T_{k1} = \frac{X_1}{v} \quad (1)$$

where X_1 is the length of the main cable and v is the propagation velocity of the traveling voltage wave. The reflection voltage v_r at the motor terminal for the forward-traveling voltage v_x and the motor voltage v_m are given as follows [15], [16]:

$$v_r = \gamma_m v_x \quad (2)$$

$$v_m = v_x + v_r = (1 + \gamma_m) v_x \quad (3)$$

where the reflection coefficient γ_m and the transmission coefficient β_m at the motor terminal are given as follows:

$$\begin{aligned} \gamma_m &= \frac{(Z_m Z_{\omega 2} / Z_m + Z_{\omega 2}) - Z_{\omega 1}}{(Z_m Z_{\omega 2} / Z_m + Z_{\omega 2}) + Z_{\omega 1}} \\ &= \frac{Z_{\omega 2} - Z_{\omega 1} + (Z_{\omega 1} Z_{\omega 2} / Z_m)}{Z_{\omega 2} + Z_{\omega 1} + (Z_{\omega 1} Z_{\omega 2} / Z_m)} \end{aligned} \quad (4)$$

$$\beta_m = 1 - \gamma_m. \quad (5)$$

Since the characteristic impedances of the main cable and the sub cable are the same, i.e., $Z_{\omega 1} = Z_{\omega 2}$, and the motor impedance Z_m is much larger than $Z_{\omega 1}$ and $Z_{\omega 2}$, the reflection coefficient is $\gamma_m = 0$ and the transmission coefficient is $\beta_m = 1$. Hence, no reflection voltage appears at the motor terminal, and the transmitting voltage v_t of the amplitude of E_d , which is the same as the forward-traveling voltage v_x , transmits to the sub cable.

At $t = T_{k1} + T_{k2}$, the transmitting forward-traveling voltage v_x arrives at the ac terminal of the rectifier [see Fig. 5(d)], where T_{k2} is given by

$$T_{k2} = \frac{X_2}{v}. \quad (6)$$

Since the amplitude of the forward-traveling voltage is the same as that of the dc-bus voltage of the rectifier, the diode switch

S of the rectifier is turned ON. The reflection coefficient γ_d at the rectifier terminal for the forward-traveling voltage wave is given by

$$\gamma_d = \frac{0 - Z_{\omega 2}}{0 + Z_{\omega 2}} = -1 \quad (7)$$

because the impedance of the voltage source E_d is assumed to be zero.

The forward-traveling voltage v_x , the reflection voltage v_r , the transmission voltage v_t , and the related currents at the rectifier terminal are given as follows:

$$v_x = E_d \quad (8)$$

$$v_r = \gamma_d v_x = -E_d \quad (9)$$

$$v_t = v_x + v_r = (1 + \gamma_d)E_d = 0 \quad (10)$$

$$i_x = \frac{E_d}{Z_{\omega 2}} \quad (11)$$

$$i_r = \gamma_d i_x = -\frac{E_d}{Z_{\omega 2}} \quad (12)$$

$$i_t = i_x - i_r = \frac{2E_d}{Z_{\omega 2}}. \quad (13)$$

In addition, another transient phenomenon arises by the turn-on action of the diode switch S, and the new traveling voltage and current, v_s and i_s , which are given as follows:

$$v_s = E_d \quad (14)$$

$$i_s = \frac{E_d}{Z_{\omega 2}} \quad (15)$$

propagate to the subcable. Then, the overall backward-traveling voltage and current, v_p and i_p , which propagate to the subcable, and the input voltage and current, v_{RECT} and i_{RECT} , at the rectifier terminal are given as follows:

$$v_p = v_r + v_s \quad (16)$$

$$i_p = i_r + i_s \quad (17)$$

$$v_{\text{RECT}} = v_x + v_r + v_s \quad (18)$$

$$i_{\text{RECT}} = i_t - i_s. \quad (19)$$

Substituting (8), (9), (13), (14), and (15) into (16), (18), and (19), we can obtain $v_p = 0$, $v_{\text{RECT}} = E_d$, and $i_{\text{RECT}} = E_d/Z_{\omega 2}$. This means that the voltage and current that reflect back to the subcable are diminished. Hence, only the step voltage shown in Fig. 5(e) appeared on the motor terminal. The current i_{RECT} , which has the same amplitude of the traveling current i_x , flows into the rectifier, and hence the power transmitted through the subcable is regenerated to the dc-bus line of the PWM inverter. Note that the arrived traveling voltage and current are regenerated to the dc-bus line of the inverter, and hence undesirable power losses, such as the losses on the damping resistor and the filter inductor, which are unavoidable when decreasing the surge voltage in the conventional method, can be prevented [10].

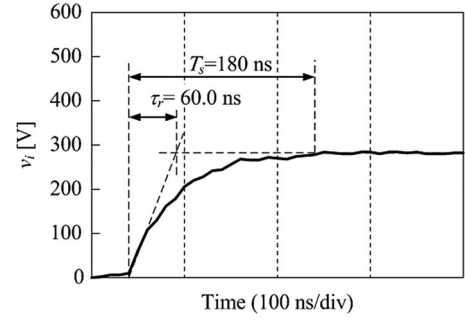


Fig. 6. Actual waveform of inverter pulse voltage.

B. Motor Surge Voltage for the Actual Inverter Output Pulse Voltage Without the RC Circuit Connected

The actual voltage waveform of the inverter output pulse voltage v_i is not usually a pure step waveform but instead is as shown in Fig. 6, and the actual voltage waveform can be expressed as an exponential function having voltage rise time τ_r and settling time T_s

$$v_i(t) = E_d(1 - e^{-t/\tau_r}). \quad (20)$$

However, in this case, an unexpected reflection voltage occurs at the ac terminal of the rectifier. The mechanism of the reflection phenomenon is explained hereinafter.

Fig. 7 shows the voltage and current, as well as the waveforms at the ac terminal of the rectifier. When the forward-traveling voltage v_x arrives at the ac terminal of the rectifier, the voltage v_{RECT} at the ac terminal of the rectifier starts to increase. However, while $v_{\text{RECT}} < E_d$, the reflection coefficient at the end of the subcable is $\gamma_d = 1$ because all diodes on the rectifier keep it in turn-off state. Hence, all of the traveling current i_x reflects back to the subcable as the reflecting current $i_r = v_x/Z_{\omega 2}$, and no transmitted current i_t flows into the rectifier. Furthermore, since the amplitude of the reflection voltage v_r is the same as that of forward-traveling voltage v_x , the amplitude of $v_{\text{RECT}} = v_x + v_t$ is twice the voltage of v_x , and the settling time of v_{RECT} is reduced to $T_s/2$. Note that the reflected voltage v_r propagates to the motor terminal and causes the surge voltage.

When the rectifier terminal voltage v_{RECT} increases to the dc-bus voltage, i.e., $v_{\text{RECT}} = E_d$, the diodes on the rectifier are turned ON (switch S in Fig. 7(a) turns ON), and the reflection coefficient changes to $\gamma_d = -1$. Along with this change of state, the polarities of the reflection voltage v_r and the reflection current i_r are reversed, as shown in Fig. 7(b). In addition, as a result of the turn ON action of the diodes, a new transition voltage $v_s = E_d$ and current $i_s = E_d/Z_{\omega 2}$ appear and propagate to the subcable. Until $t < T_s$, the backward-traveling voltage v_p and current i_p , which are given by (16) and (17), and $v_p > 0$ and $i_p > 0$ because $|v_r| < E_d$, propagate to the subcable, and hence the surge voltage at the motor terminal still exists. When the forward-traveling voltage v_x increases to E_d , the backward-traveling voltage v_p and current i_p become $v_p = 0$ and $i_p = 0$, and the surge voltage on the motor terminal is diminished.

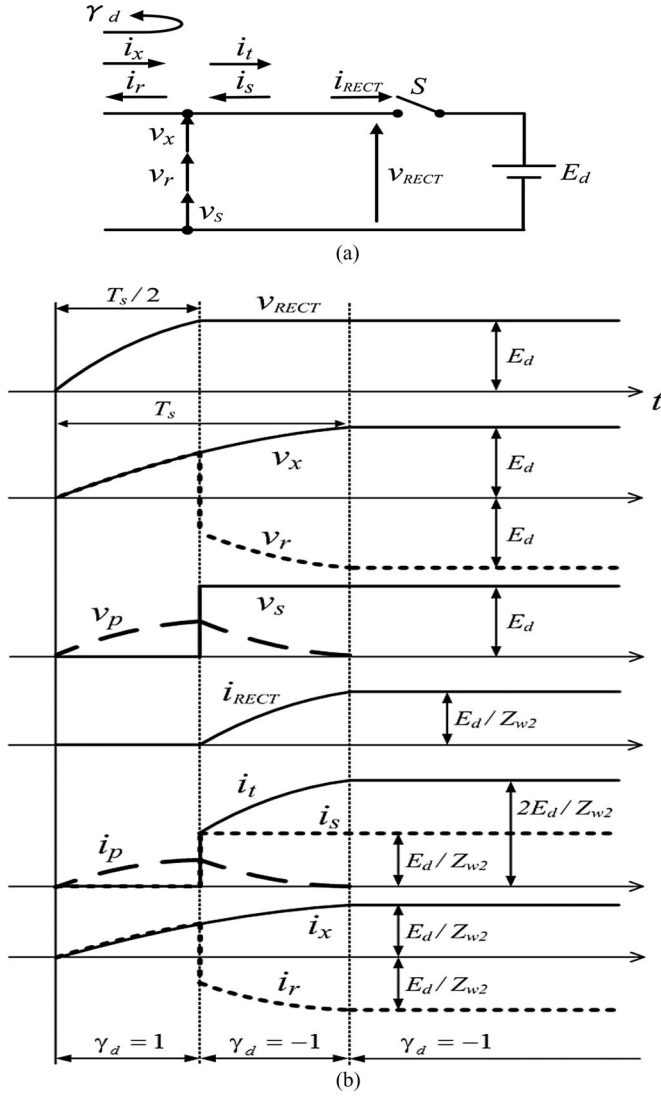


Fig. 7. Voltage and current waveforms on the rectifier terminal when the RC circuit is not connected. (a) Equivalent circuit. (b) Operation waveforms.

Hereinafter, the rectifier voltage and current are $v_{RECT} = E_d$ and $i_{RECT} = E_d/Z_{w2}$, and flow into the rectifier.

Based on the aforementioned analysis, the backward-traveling voltage and current, v_p and i_p , which propagates toward the subcable, remain during the settling time T_s , and hence a surge voltage with a narrow pulse width occurs at the motor terminal.

C. Motor Surge Voltage for the Actual Inverter Output Pulse Voltage With the RC Circuit Connected

In order to remove the narrow surge voltage, a transient matching method, in which the RC circuit is connected in parallel to the ac terminal of the rectifier, is proposed.

Fig. 8 shows the voltage and current as well as the corresponding waveforms at the ac terminal of the rectifier of the proposed method. The RC current i_{RC} , which flows into the RC circuit, plays an important role. During the settling time T_s , the arrived traveling current i_x flows into the RC circuit, but does

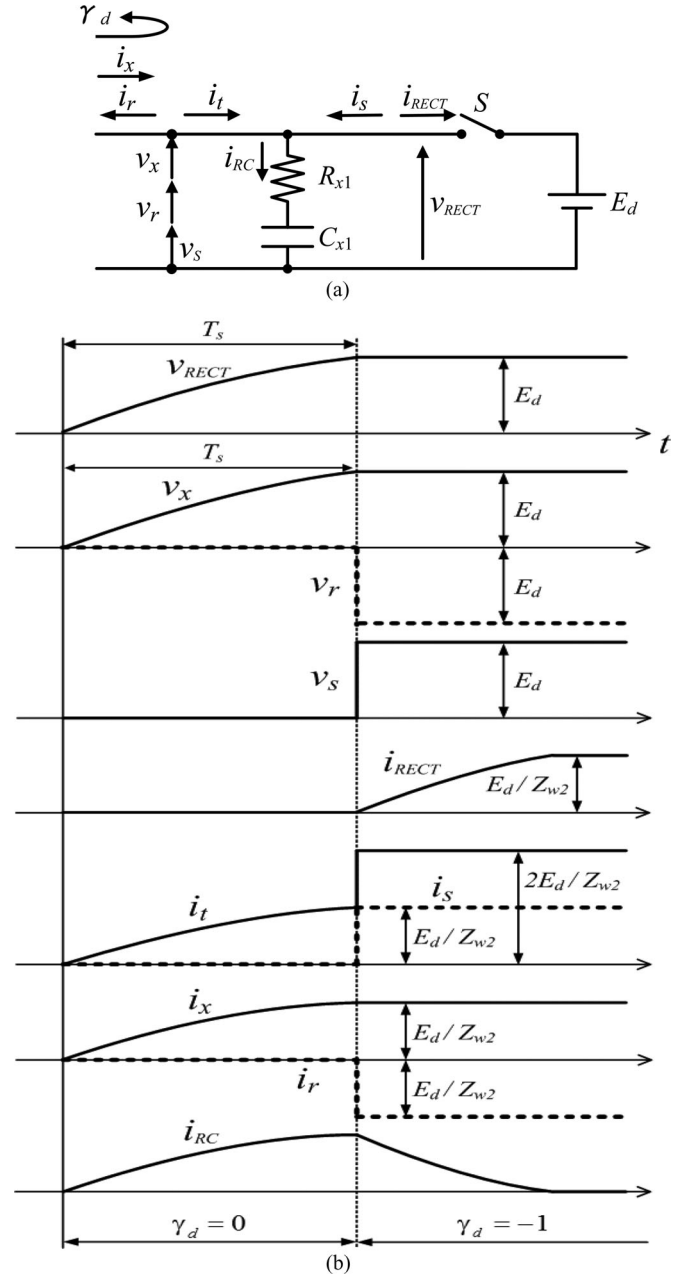


Fig. 8. Voltage and current waveforms on the rectifier terminal when the RC circuit is connected. (a) Equivalent circuit. (b) Operation waveforms.

not flow into the ac terminal of the rectifier. The magnitude of i_{RC} in the RC circuit is approximated as follows:

$$i_{RC} \approx \frac{v_x}{R_{x1}} \quad (21)$$

when a sufficiently large capacitance C_{x1} is selected. Here, the value of R_{x1} is set to be equal to the characteristic impedance Z_{w2} of the subcable. Therefore, all of the current i_x flows into the RC circuit, and the reflection coefficient γ_d is equal to zero

$$\gamma_d = \frac{R_{x1} - Z_{w2}}{R_{x1} + Z_{w2}} = 0. \quad (22)$$

Therefore, the reflection voltage is $v_r = 0$ and hence no backward-traveling voltage v_p appears. Since the ac terminal voltage v_{RECT} is equal to the forward-traveling voltage v_x during the settling time T_s , the settling time of v_{RECT} becomes equal to T_s .

When the rectifier terminal voltage v_{RECT} increases to the dc-bus voltage, i.e., $v_{\text{RECT}} = E_d$, the diodes on the rectifier are turned ON (switch S in Fig. 8(a) turns ON), and the reflection coefficient changes to $\gamma_d = -1$. Along with this change of state, the reflection voltage $v_r = -v_x = -E_d$ and the reflection current $i_r = -E_d/Z_{\omega 2}$ appear as shown in Fig. 8(b). In addition, by the turn-on action of the diodes, a new transition voltage $v_s = E_d$ and current $i_s = E_d/Z_{\omega 2}$ appear and propagate to the subcable. Hence, the backward-traveling voltage and current are obtained as $v_p = v_r + v_s = 0$ and $i_p = i_r + i_s = 0$, and $i_x = E_d/Z_{\omega 2}$ flows into the ac terminal of the rectifier.

Consequently, since no backward-traveling voltage or current appear during entire periods, the motor surge voltage can be suppressed even when the inverter pulse voltage waveform takes an exponential function.

Note that the energy stored in the capacitor C_{x1} is charged and discharged through the resistor R_{x1} , which results in energy loss on R . In general, settling time T_s is much shorter than the switching interval. The time constant of the RC circuit can be selected as a small value, because the RC circuit must operate only during the settling time T_s . Hence, the required capacitance of the capacitor C_{x1} can be reduced, and the resultant loss on the RC circuit is minimized. In addition, note that most of the arrived energy due to the arrived voltage and current is regenerated to the dc-bus line through the rectifier. As a result, surge voltage suppression can be realized through surge energy regeneration.

IV. DETERMINATION OF RC CIRCUIT PARAMETERS

The optimum values of the RC circuit parameters are discussed in this section. As shown in Section III, in order to prevent the reflection voltage at the rectifier terminal during the settling time T_s , the value of R_{x1} should be chosen to be equal to the characteristic impedance $Z_{\omega 2}$ of the subcable, and the capacitance of C_{x1} should be selected so that the time constant of $R_{x1}C_{x1}$ is equal to or greater than the time constant, τ_r , of the inverter pulse voltage. Under this condition, the RC current i_{RC} , which flows into the RC circuit, is almost the same as the arrived traveling current i_x during the settling time T_s .

The RC parameters being discussed on the single-phase equivalent circuit should be converted to the practical RC parameters on the three-phase system. Since RC circuits on the three-phase system have a Y-connection, the resistor R_x on the three-phase system is $R_x = (2/3)R_{x1}$. In addition, the measured result of the characteristic impedance, which is measured between the U and VW phase terminals, is $Z_{\omega 2} = 65 \Omega$. The value of R_x can be obtained as follows:

$$R_x = \frac{2}{3}Z_2 = 43.3 \Omega. \quad (23)$$

Capacitance C_{x1} is determined by the time constant τ_r of the inverter output voltage v_i . The rise time of the voltage waveform, as shown in Fig. 5, is $\tau_r = 58.0 \text{ ns}$. Then, the capacitance of the

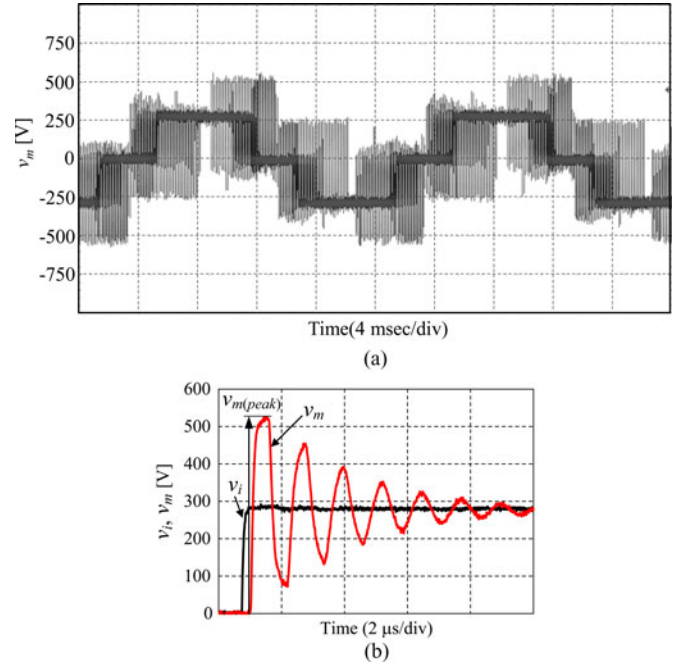


Fig. 9. Motor surge voltage when no surge suppression unit is connected. (a) Overall voltage waveforms. (b) Motor surge voltage.

single-phase equivalent circuit and of the three-phase system, C_{x1} and C_x , are obtained as follows:

$$C_{x1} = \frac{\tau_r}{R_x} \quad (24)$$

and

$$C_x = \frac{3}{2}C_{x1} = 1500 \text{ pF}. \quad (25)$$

In the experimental setup, $R_x = 47 \Omega$ and $C_x = 1470 \text{ pF}$. These values are hereinafter referred to as standard values.

V. EXPERIMENTAL RESULTS

A. Evaluation of Motor Surge Voltage

Table I shows the circuit parameters of the experimental setup. The output power ratings, the carrier frequency, and the dc-bus voltage of the PWM inverter are 1 kW, 10 kHz, and 288 V, respectively. The cable length and the characteristic impedance of both the main cable and the subcable are 50 m and 65Ω , respectively. A three-phase induction motor with a power rating of 750 W is used. Voltage/current waveforms are measured on the PWM modulated waveform condition. The inverter voltage v_i , the motor voltage v_m , and the rectifier terminal voltage v_{RECT} are measured between the U-phase terminal and the V-phase (or W-phase) terminal by triggering when the U-phase switch is changed from low level to high level (whereas the voltages on the V-phase and W-phase terminals remain at the low level at the moment).

Fig. 9 shows the experimental results of the inverter output voltage v_i and the motor terminal voltage v_m for the case in which no surge suppression unit is connected. Fig. 9(a) shows the overall waveforms and Fig. 9(b) shows the motor surge

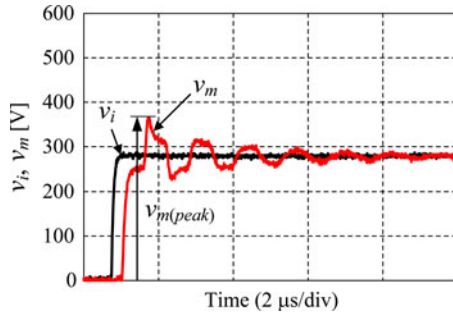


Fig. 10. Motor surge voltage on the proposed system when no RC circuit is connected.

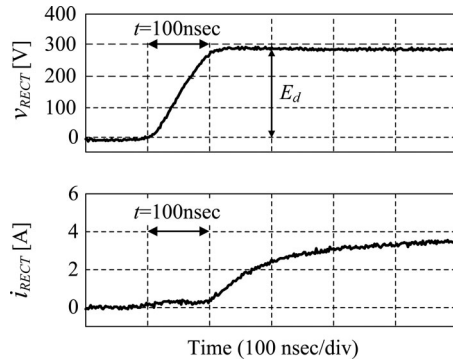


Fig. 11. Voltage and current waveforms on the rectifier terminal.

voltage waveform when the U-phase switch is changed. The inverter output voltage v_i has a quasistep waveform with an amplitude of 288 V, and the motor terminal voltage v_m contains an oscillatory waveform with a peak amplitude of $v_{m(\text{peak})} = 524$ V. This high surge voltage has a risk of a dielectric breakdown of the stator windings of the motor.

The experimental results obtained using the proposed method are shown in Figs. 10–13. Here, SiC diode rectifiers [6]00 V/6 A: SDP06S60 (Infineon)] are used in the rectifier circuit in order to prevent the reverse-recovery current of the diode. Fig. 10 shows the experimental results for the inverter output voltage v_i and the motor terminal voltage v_m on the proposed surge suppression unit without the RC circuit. The peak amplitude of the motor surge voltage $v_{m(\text{peak})}$ is suppressed to 364 V, although a surge voltage with a small amplitude remains. The remaining surge voltage is caused by the reflected voltage at the rectifier terminal. Fig. 11 shows the experimental results for the voltage v_{RECT} and current i_{RECT} when the transmitted forward-traveling voltage wave v_x arrives at the ac terminal of the rectifier. The input current i_{RECT} does not flow into the rectifier until the voltage v_{RECT} reaches the dc-bus voltage E_d . This means that all of the traveling voltage and all of the current, v_x and i_x , are reflected to the subcable, and the reflection coefficient $\gamma_d = 1$. The reflected voltage and current generate the surge voltage on the motor terminal, as shown in Fig. 10. Since twice the amplitude of v_x occurs on v_{RECT} , the settling time t is reduced to 100 ns, which is approximately equal to $T_s/2 = 90$ ns. When the voltage v_{RECT} reaches the dc-bus voltage E_d ,

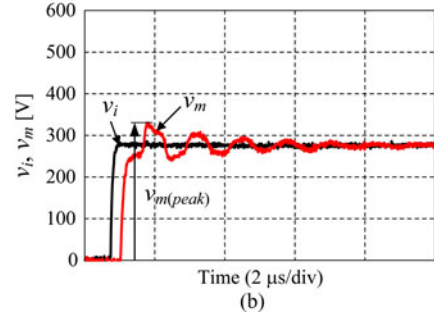
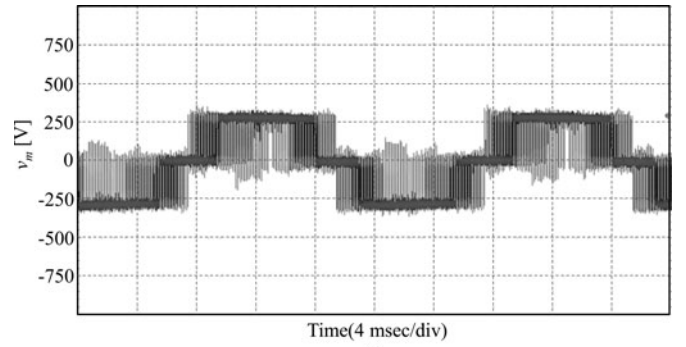


Fig. 12. Motor surge voltage on the proposed system when RC circuit is connected. (a) Overall voltage waveforms. (b) Motor surge voltage.

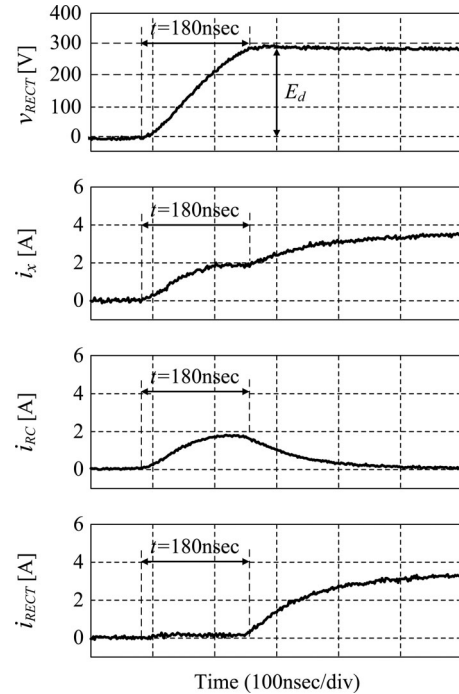


Fig. 13. Voltage and current waveforms on the rectifier terminal.

the forward-traveling current i_x flows into the rectifier as the input current i_{RECT} , but the motor surge voltage still appears.

Fig. 12 shows the experimental results of the inverter voltage v_i and motor terminal voltage v_m when the proposed surge suppression unit with the RC circuit is used. Fig. 12(a) shows the overall waveforms and Fig. 12(b) shows the motor surge voltage waveform when the U-phase switch is changed. The peak

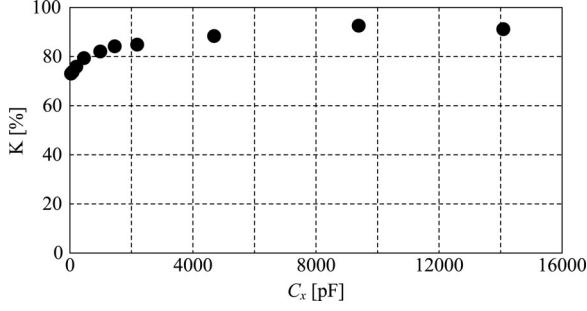


Fig. 14 Surge suppression ratio.

amplitude of the motor surge voltage is reduced to $v_{m(\text{peak})} = 334$ V. Fig. 13 shows the experimental results of the voltage and current waveforms when the transmitted forward-traveling voltage wave v_x arrives at the ac terminal of the rectifier. The forward-traveling current i_x flows into the RC circuit as the RC current i_{RC} during the settling time T_s . Since reflection coefficient γ_d is close to 0, no reflection voltage or current arises. Then, the ac terminal voltage v_{RECT} is approximately the same as the forward-traveling voltage v_x , and the settling time t of v_{RECT} is 180 ns, which is close to the settling time T_s . When the amplitude of the forward-traveling voltage v_x reaches the dc-bus voltage E_d , the RC current i_{RC} commutates to the input current i_{RECT} . This means that all of the forward-traveling current i_x flows into the rectifier, and the energy stored in the inductance component of the power cable is regenerated to the dc-bus line of the inverter.

We have also tested the use of a small cable having the same characteristic impedance $Z_{w2} = 65 \Omega$, and obtained the same surge suppression effect.

Fig. 14 shows the surge suppression ratio of K when the capacitance C_x is changed. Here, K is defined as follows: where $C_x = 0$ means that no RC circuit is connected

$$K = \frac{2E_d - v_{m(\text{peak})}}{E_d} \times 100[\%]. \quad (26)$$

The surge suppression ratio increases as the capacitance C_x is increased but is limited at approximately 90%, even if a large capacitor is connected. The aforementioned observations indicate that the power loss on the resistor increases as the capacitance increases. Considering the power loss, the use of a standard value of $C_x = 1470$ pF appears to be sufficient and using a large value is not recommended, as will be discussed in the next section.

B. Ratio of Energy Regeneration

In this method, the energy accompanying the traveling wave can be regenerated to the dc-bus line of the inverter. However, the power loss on the RC circuit will increase if a larger value of C_x is selected, which results in low-energy regeneration. Therefore, the optimum capacitance C_x of the RC circuit requires further investigation.

Fig. 15 shows the experimental results of the voltage and current waveforms of the rectifier circuit, and the RC circuit

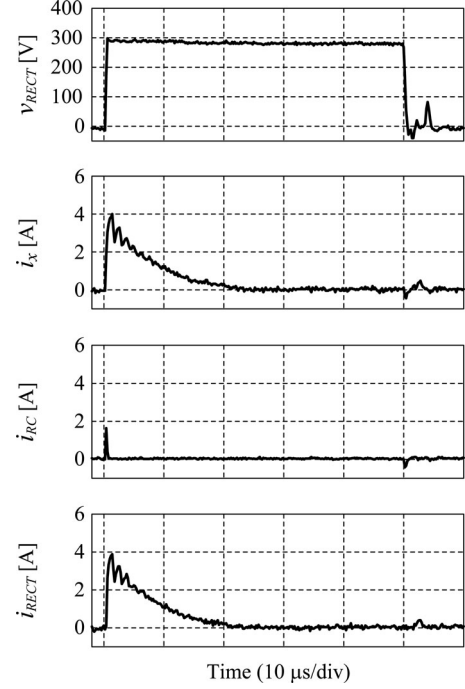


Fig. 15. Voltage and current waveforms on the rectifier terminal during one switching interval.

during one switching interval of the inverter. The input current i_{RECT} flows into the rectifier, except during the starting transient of the rectifier voltage v_{RECT} .

The arrived power from the subcable P_x , the regenerative power to the inverter P_{RECT} , and the power loss on the RC circuit P_{RC} are calculated as follows:

$$P_x = \int_0^{T_{\text{sw}}} v_{\text{RECT}} i_x dt \quad (27)$$

$$P_{\text{RECT}} = \int_0^{T_{\text{sw}}} v_{\text{RECT}} i_{\text{RECT}} dt \quad (28)$$

and

$$P_{RC} = \int_0^{T_{\text{sw}}} v_{\text{RECT}} i_R dt \quad (29)$$

where T_{sw} is the switching period of the inverter. In (27), the rectifier terminal voltage v_{RECT} is used instead of the forward-traveling voltage v_x because, although the sum of the arrived voltage v_x and the reflecting voltage v_r appears on the rectifier terminal, the individual values cannot be measured. However, for the case in which the RC circuit is connected to the rectifier terminal, the reflecting voltage is very small and the traveling voltage can be assumed to be $v_x = v_{\text{RECT}}$.

The peak amplitude of the current flowing in the subcable is decided by (11) and its waveform is shown in Fig. 15. The switching frequency is 10 kHz. Taking the earlier condition into account, we can calculate the rms value of the current i_x flowing through the subcable. In this case, the rms value of the current i_x is approximately 0.3 A. This result reveals that a cable having a small cross section can be used for the subcable.

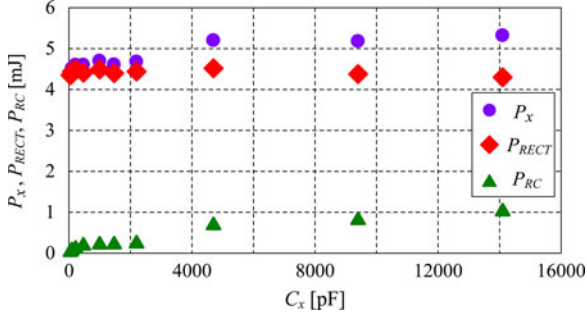


Fig. 16. Measured power at the rectifier terminal.

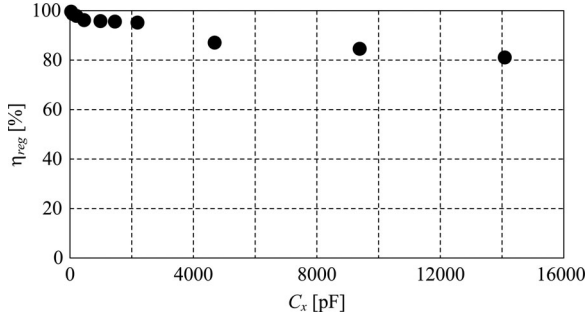


Fig. 17. Power regeneration ratio.

Fig. 16 shows the measured results for the arrived power P_x , the regenerative power P_{RECT} , and the power loss P_{RC} for various values of capacitance C_x . Note that the power loss on the RC circuit is sufficiently small. However, the amount of regenerative power is reduced if a large capacitance C_x is used.

The regenerative power ratio is defined as follows:

$$\eta = \frac{P_{RECT}}{P_x} \quad (30)$$

and the experimental results for the regenerative power ratio η for various capacitances C_x are shown in Fig. 17. Regenerative power ratios η of 99.4%, 95.4%, and 80.9% are realized for $C_x = 50$, 1470, and 14 100 pF, respectively. As shown in Fig. 14, a higher surge suppression ratio of K cannot be realized, even though a large capacitance is used. Therefore, the use of a capacitance C_x given by (10) is sufficient to achieve a high regenerative power ratio and sufficient motor surge suppression.

From Fig. 17, the power loss P_{RC} is approximately 0.3 W when C_x is less than 2000 pF. The power loss of the RC method (see Fig. 1) is shown in [14], and P_{RC} is 208 W for a cable length of 200 m and a switching frequency of 15 kHz. By adjusting the cable length and the switching frequency, we obtain a P_{RC} of 34 W. Based on the aforementioned results, the proposed method can reduce the power loss to 1/100.

The experimental results indicate that the motor surge voltage cannot be suppressed completely even when the RC circuit is used. The reason for this is explained by the skin effect of the cables. Rudenburg has shown that the wave-head voltage of the pulse voltage transmitted in the transmission line is expressed

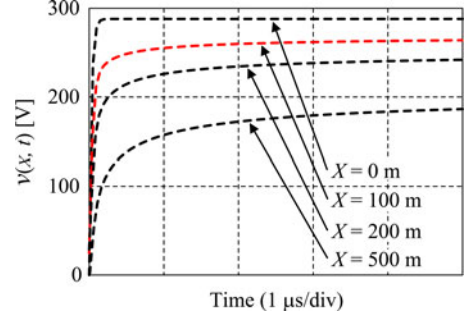


Fig. 18. Skin-effect on the wave-head voltage of the forward-travelling voltage.

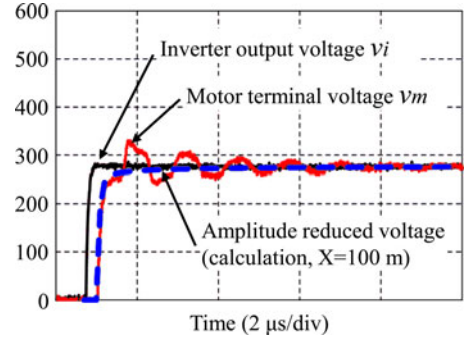


Fig. 19. Wave-head voltage and motor terminal voltage.

as follows [15], [17]:

$$v_z(x, t) = e^{-\alpha x} v_i(t - T) \quad (31)$$

$$\alpha = \frac{R_w}{2Z_w} \sqrt{\frac{\sigma - t - T}{t - T}} \quad (32)$$

where v_z is the voltage at the cable end, v_i is the pulse voltage, T is the transmission time on the cable, R_w is the dc resistance of the cable, Z_w is the characteristic impedance of the cable, and σ is the skin effect coefficient. Fig. 18 shows the calculated results for the wave-head voltage of the forward-traveling voltage v_x , when the cable length X is changed. The amplitude of wave-head voltage decreases as the cable length increases and is smaller than the dc-bus voltage. In this experiment, the cable length $X = 100$ m, and the wave-head voltage is approximately 260 V, whereas the dc-bus voltage is 288 V. In addition, some tens of microseconds is required in order to reach 288 V. During this time, the reflection coefficient γ_d is not zero, although it is close to zero. Then, a small reflection wave exists, and the reflected voltage appears at the motor terminal as the surge voltage. Fig. 19 shows the calculated waveforms of the wave-head voltage v_z , the measured waveforms of the motor terminal voltage v_m , and the step voltage on the inverter output v_i . The step voltage component in the motor terminal voltage coincides well with the wave-head voltage, which means that the decrease in amplitude of the wave-head voltage is the cause of the slight motor surge voltage that remains. However, since the amplitude of the remaining surge voltage is small, the proposed method is still effective.

VI. CONCLUSION

A novel motor surge voltage suppression method with surge energy regeneration was proposed. The operation principle was explained based on the signal transmission theory. The motor surge voltage under both an ideal step voltage and actual exponential voltage conditions is explained. The surge suppression effect during the rise time of the output pulse voltage of the PWM inverter can also be realized by inserting an RC circuit into the diode rectifier. The experimental results revealed that the relation of the RC circuit parameters to the arrived power, the regenerative power, the RC power loss, the regenerative power ratio, and the motor surge voltage. Although a small surge voltage caused by the skin effect remains, the effectiveness of suppression of the motor surge voltage is not impaired.

REFERENCES

- [1] E. Persson, "Transient effects in application of PWM inverters to induction motors," *IEEE Trans. Ind. Appl.*, vol. 28, no. 5, pp. 1095–1101, Sep./Oct. 1992.
- [2] V. Jouanne, P. Enjeti, and P. Gray, "The effect of long motor leads on PWM inverter fed AC motor drive systems," in *Proc. 10th Annu. Applied Power Electron. Conf. and Exposition (APEC)*, 1995, pp. 592–597.
- [3] E. Zhong, T. A. Lipo, and S. Rossiter, "Transient modeling and analysis of motor terminal voltage on PWM inverter-fed AC motor drives," in *Proc. IEEE 33rd IAS Annu. Meeting Ind. Appl. Conf.*, 1998, vol. 1, pp. 773–780.
- [4] G. Skibinski, D. Leggate, and R. Kerkman, "Cable characteristics and their influence on motor over-voltages," in *Proc. 12th Appl. Power Electron. Conf. and Exposition (APEC)*, 1997, pp. 114–121.
- [5] S. Amarir and K. Al-Haddad, "A modeling technique to analyze the impact of inverter supply voltage and cable length on industrial motor-drives," *IEEE Trans. Power Electron.*, vol. 23, no. 2, pp. 753–762, Mar. 2008.
- [6] L. Wang, C. Ho, F. Canales, and J. Jatskevich, "High-frequency modeling of the long-cable-fed induction motor drive system using TLM approach for predicting overvoltage transients," *IEEE Trans. Power Electron.*, vol. 25, no. 10, pp. 2653–2664, Oct. 2010.
- [7] S. Moriyasu and Y. Okuyama, "Surge propagation of PWM-inverter and surge voltage on the motor," *Trans. IEE Jpn*, vol. 119-D, no. 4, pp. 508–514, 1999.
- [8] R. J. Kerman, D. Leggate, D. Schlegel, and G. Skibinski, "PWM inverters and their influence on motor over-voltage," in *Proc. Appl. Power Electron. Conf. and Exposition (APEC)*, 1997, pp. 103–113.
- [9] A. Jouanne, H. Zhang, and A. K. Wallace, "An evaluation of mitigation techniques for bearing currents, EMI and overvoltages in ASD applications," *IEEE Trans. Ind. Appl.*, vol. 34, no. 5, pp. 1113–1122, Sep./Oct. 1998.
- [10] N. Aoki, K. Satoh, and A. Nabae, "Damping circuit to suppress motor terminal overvoltage and ringing in PWM inverter-fed AC motor drive systems with long motor leads," *IEEE Trans. Ind. Appl.*, vol. 35, no. 5, pp. 1014–1020, Sep./Oct. 1999.
- [11] H. Kim, G. Lee, C. Jang, and J. Lee, "Cost-effective design of an inverter output reactor in ASD applications," *Trans. Ind. Electron.*, vol. 48, no. 6, pp. 1128–1134, 2001.
- [12] G. Skibinski, "Design methodology of a cable terminator to reduce reflected voltage on AC motors," in *Proc. Conf. Record IAS*, 1996, pp. 153–161.
- [13] C. Chen and X. Xu, "Loss-less and cost-effective cable terminator topologies with no voltage overshoot," in *Proc. 13th Appl. Power Electron. Conf. and Exposition (APEC)*, 1998, pp. 1030–1034.
- [14] M. Tsai, J. Liu, and T. Cheng, "A novel method for suppression of high voltage gradient transient effects in voltage-fed PWM inverter," in *Proc. IEEE 33rd Annu. Power Electron. Specialists Conf. (PESC)*, 2002, pp. 1557–1542.
- [15] T. Shimizu, M. Saito, and M. Nakamura, "Calculation of motor surge voltage under the use of a surge suppression cable," in *Proc. 13th Eur. Conf. Power Electron. and Appl. (EPE)*, 2009, pp. 1–10.
- [16] C. R. Paul, *Analysis of Multiconductor Transmission Lines*. New York: Wiley, 1994.
- [17] R. Rüdenberg, *Elektrische Wanderwellen*. Berlin, Germany: Springer-Verlag, S. 41, 1962.



Toshihisa Shimizu (M'93–SM'02) was born in Tokyo, Japan, in 1955. He received the B.E., M.E., and Dr.Eng. degrees in electrical engineering from Tokyo Metropolitan University, Tokyo, Japan in 1978, 1980, and 1991, respectively.

In 1998, he was a visiting professor at Virginia Polytechnic Institute and State University, Virginia. He joined Fuji Electric Corporate Research and Development, Ltd., in 1980. Since 1993, he has been in the Department of Electrical Engineering, Tokyo Metropolitan University, where he is currently a Full

Professor. He has written more than 70 journal papers and 120 international conference proceedings, and six technical books. He also holds ten patents and more than ten patents pending. His research interests include power converters, high-frequency inverters, photovoltaic power generations, UPSs, EMI problems, high power density converter design, and inductor loss analysis.

Dr. Shimizu received Transactions Paper Awards from the Institute of Electrical Engineers of Japan in 1999 and 2010. He also received two Best Paper Awards at the IPEC2010-ECCE Asia, and the Best Paper Award at the EPE-PEMC2010. He is an Associate Editor of the IEEE TRANSACTIONS ON POWER ELECTRONICS. He is a senior member of the Institute of Electrical Engineers of Japan (IEEJ).



Mikiya Saito was born in 1985. He received the M.S. degree in electrical engineering from Tokyo Metropolitan University, Tokyo, Japan, in 2006.

His research interests include power converters and motor surge voltage issues.

Mr. Saito is a member of the Institute of Electrical Engineers of Japan (IEEJ).



Masanori Nakamura was born in 1949. He received the B.S. degree in electronics and telecommunication engineering from the Musashi Institute of Technology, Setagaya, Tokyo, in 1971.

He is currently a Deputy General Manager of Electric Cable Department at Oki Electric Cable Company, Kawasaki-shi, Japan. He has been involved in the development of various kinds of electric wires including power cables suitable for power electronics equipment.

Mr. Nakamura is a member of the Institute of Electrical Engineers of Japan (IEEJ).



Tomoo Miyazaki was born in 1973. He received B.S. degree in electrical engineering from Tokyo Denki University, Tokyo, Japan, in 1997.

He has been with Oki Electric Cable Company since 1997. He has been involved in the development of various kinds of electric wires including power cables suitable for power electronics equipment.

Mr. Miyazaki is a member of the Institute of Electrical Engineers of Japan (IEEJ).