Paper

Mini-Scale Power Distribution Network Feeding Trapezoidal-Wave Voltages to Power Electronic Loads with Diode Rectifiers

Toshihiko Noguchi* Member
Masaru Imoto** Member
Yoshikazu Sato*** Member

This paper proposes a novel three-phase power distribution system feeding trapezoidal voltages to various power electronic loads with diode rectifier front-ends. The network distributes trapezoidal voltages generated by synchronous superposition of wave-shaping voltages onto sinusoidal voltages available from a utility power grid. The power distribution by the trapezoidal voltages allows reducing harmonics of the line currents without electronic switching devices because of a spontaneously widened conduction period of the current waveforms. The reduction of the harmonic currents also contributes to improve total power factor at the load input terminals and efficiency of the power transmission cables. Since the diodes of the rectifiers successively commutate the trapezoidal waves during periods of their flat parts, not only total harmonic distortion of the currents is improved, but also voltage ripple across the dc-buses of the rectifiers can effectively be reduced with less filter capacitors. In addition, the system offers an uninterruptible power supply function by immediately changing its outputs from the wave-shaping voltages to the trapezoidal voltages when interruption occurs in the power grid. In this paper, a prototype of the system is experimentally examined from various angles of operating characteristics and test results are presented to prove feasibility of the proposed system.

Keywords: trapezoidal voltage, power distribution, power electronic load, diode rectifier

1. Introduction

This paper describes a three-phase power distribution system feeding trapezoidal voltages to various power electronic loads with diode rectifier front-ends. The system is specifically designed for mini-scale power networks that may be employed on each floor of small buildings, factories, residential houses and so forth. In recent years, varieties of power electronic appliances based on inverters and choppers have extensively been used in those facilities and most of the appliances require ac-to-dc conversion circuits to obtain regulated dc voltages. From the viewpoint of practical implementation of such conversion circuits, use of diode rectifiers with electrolytic capacitors is the most effective solution because of their simplicity, reliability and inexpensiveness [1]. However, the diode rectifiers connected to sinusoidal utility power sources detrimentally cause current harmonics in the power grid, which should be regarded as a serious pollution. Also, low input-power-factor of the diode rectifiers makes utilization of the power transmission cables worse. In addition, product life and size of the power electronic appliances are considerably shortened and increased by the large electrolytic capacitors, although they are generally indispensable to suppress dc-bus voltage ripple of the diode rectifiers.

In order to solve the problems described above, a huge number of researchers have intensively explored sinusoidal PWM converters on the primitive assumption that sinusoidal voltages are fed from the utility power sources [2]~[7]. However, it is not always necessary to confine the discussion in the conventional fetters and approaches if all the appliances in specific facilities are replaced with inverters and choppers to improve total system functionality and efficiency of the whole facilities [8][9]. In other words, conventional sinusoidal-wave power distribution network is not always preferable to the power electronic loads with the diode rectifier front-ends. The three-phase trapezoidal-wave power distribution system discussed in this paper is a unique approach to solve the entangled problems and has a possibility of offering an alternative [10][11]. This system is applicable only to feed the power electronic appliances such as inverter-driven air-conditioners, fans, blowers, pumps, lightings, refrigerators and many sorts of variable-speed drives. Also, its power distribution is limited within small areas due to the voltage distortion. However, the system features the following advantages over the conventional sinusoidal-wave based systems:

1) The harmonics of the line currents are dramatically

* Nagaoka University of Technology
1603-1, Kamitomioka, Nagaoka, Niigata 940-2188, Japan
** Mitsubishi Electric Defense & Space Electronics Co.
271-2, Kamimachiya, Kamakura, Kanagawa 247-0065, Japan
*** Kawasaki Electric Co. R&D Center
19-5, Kanakame Yujiri, Kamiyama, Yamagata 999-3101, Japan

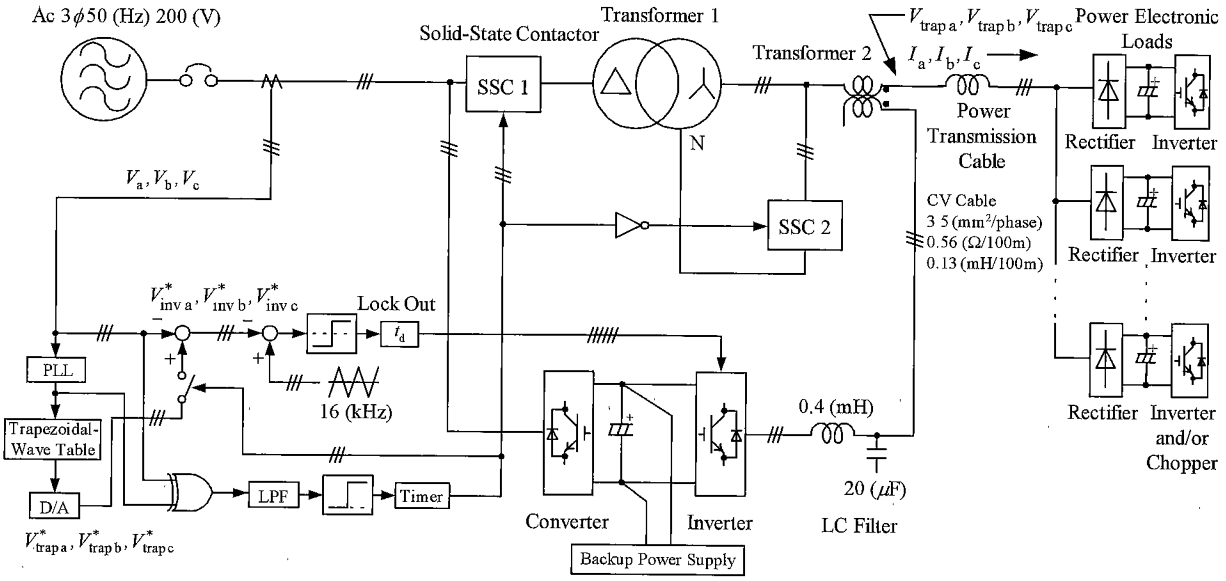


Fig. 1. Schematic diagram of three-phase trapezoidal-wave power distribution system.

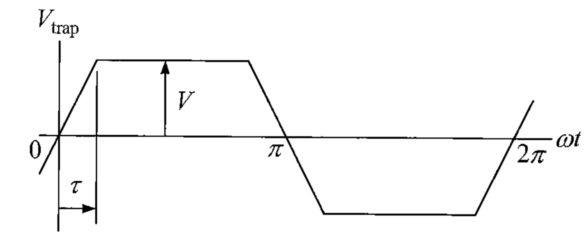
reduced without such complicated controllers as the sinusoidal PWM converters.

2) The total power factor at each load input and utilization of the power transmission cables are highly improved.
3) The dc-bus voltage ripple of each power electronic load can effectively be reduced with a small capacitor.
4) The system can deliver stable trapezoidal voltages regardless of voltage fluctuation in the power grid. Also, the system provides an uninterruptible power supply (UPS) function to cope with outage of the power grid.

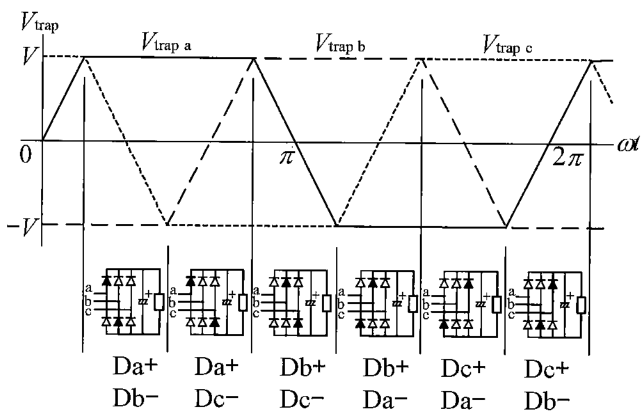
This paper describes a configuration and an operation of the trapezoidal-wave power distribution system, and presents various experimental results using a 4-kW prototype to prove feasibility of the proposed system.

2. System Configuration and Operation

Fig. 1 shows a schematic diagram of the proposed three-phase power distribution system feeding the trapezoidal voltages to the power electronic loads with the diode rectifier front-ends. A core of the system consists of a main inverter and a three-phase transformer, which generates wave-shaping voltages in phase with the 50 or 60-Hz utility sinusoidal voltages and superposes the wave-shaping voltages onto the sinusoidal voltages available from the utility power source. The wave-shaping voltage commands to the main inverter are calculated by simply subtracting the detected utility voltages from the trapezoidal voltage commands. Therefore, the voltage commands to the main inverter are errors between the detected utility sinusoidal voltages and the trapezoidal voltage commands in a normal operation, while they are trapezoidal during an interruption of the power grid as mathematically expressed by (1) and (2), respectively.



(a) Distributed voltage waveform.



(b) Commutation of diode rectifier front-end in power electronic load fed by three-phase trapezoidal voltage power source.

Fig. 2. Waveform and commutation of diode rectifier loads in trapezoidal-wave power distribution system.

$$\begin{cases} V^*_{\mathrm{inv\ a}} = V^*_{\mathrm{trap\ a}} - V_{\mathrm{a}} \\ V^*_{\mathrm{inv\ b}} = V^*_{\mathrm{trap\ b}} - V_{\mathrm{b}} \\ V^*_{\mathrm{inv\ c}} = V^*_{\mathrm{trap\ c}} - V_{\mathrm{c}} \end{cases} \quad \cdots\cdots\cdots (1)$$

$$\begin{cases} V^*_{\mathrm{inv\ a}} = V^*_{\mathrm{trap\ a}} \\ V^*_{\mathrm{inv\ b}} = V^*_{\mathrm{trap\ b}} \\ V^*_{\mathrm{inv\ c}} = V^*_{\mathrm{trap\ c}} \end{cases} \quad \cdots\cdots\cdots (2)$$

In case of the interruption, a phase-locked loop (PLL), which is used to synchronize the wave-shaping voltages with the utility sinusoidal voltages in the normal situation, freely runs to generate 50 or 60-Hz trapezoidal voltages consecutively. Once the electrical interruption occurs in the power grid, the main inverter immediately changes its own outputs from the wave-shaping voltages to the trapezoidal voltages and can continue to supply the demanded load power using backup power sources. To offer this UPS function, it is necessary to provide the system with such energy storage devices as batteries, flywheels and so forth. When the utility power system recovers from the interruption, the voltage commands to the main inverter are switched to the wave-shaping voltages again after a couple of seconds. This delay time is needed to let the PLL synchronize with the recovered utility sinusoidal voltages. Since the main inverter is redundantly placed in parallel with the utility power lines, the load power can be supplied from the utility power grid even in emergency case of an electrical and/or mechanical failure in the main inverter. Also, this configuration makes it possible to stabilize the distributed trapezoidal voltages because the superposed wave-shaping voltages can instantaneously compensate for voltage fluctuation of the utility power grid.

A trapezoidal voltage waveform of each phase (line-to-neutral) has been determined as illustrated in Fig. 2(a) [12][13]. A period of the flat parts in the waveform is chosen to be $2\pi/3$ (rad) so that the diode rectifiers can commutate successively from one phase to another and can output smooth dc-bus voltages without voltage notches as shown in Fig. 2(b). Therefore, rising or falling time of the waveform is determined to be $\tau = \pi/6$ (rad) and the trapezoidal voltage that satisfies this requirement can mathematically be expressed as (3).

$$V_{\mathrm{trap}} = \frac{24}{\pi^2} V \sum_{k=0}^{\infty} \frac{1}{(2k+1)^2} \sin(2k+1)\frac{\pi}{6} \sin(2k+1)\omega t \qquad \cdots\cdots (3)$$

This choice is also effective to reduce total harmonic distortion (THD) of the distributed voltages. On the other hand, amplitude of the waveform is determined to be $V = 140$ (V) because the dc-bus voltage in each diode rectifier front-end should be 280 (V), which is equal to the rectified dc-bus voltage available in the conventional 200-V (line-to-line) sinusoidal-wave power distribution system. Furthermore, the trapezoidal voltage expressed by (3) raises an rms value of the distributed voltage. Assuming that the peak voltage of the trapezoidal wave is equal to that of the sinusoidal wave, the rms voltage of the former is $\sqrt{14}/3$ times of the latter, which implies that more power can be transferred with same power transmission cables and that the transmission losses can accordingly be reduced by the trapezoidal-wave system.

Fig. 3 shows an example of the trapezoidal voltage and line current waveforms measured in a preliminary test. It can be seen that the utility sinusoidal voltage is properly converted to the trapezoidal voltage by synchronous superposition of the wave-shaping voltage. The diode rectifier load draws rectangular-shaped currents with $2\pi/3$-rad conduction periods. This current waveform is effective not only to reduce current harmonics and the dc-bus voltage ripple of each diode rectifier in the power electronic appliances, but also to improve efficiency and total power factor at each diode rectifier terminal.

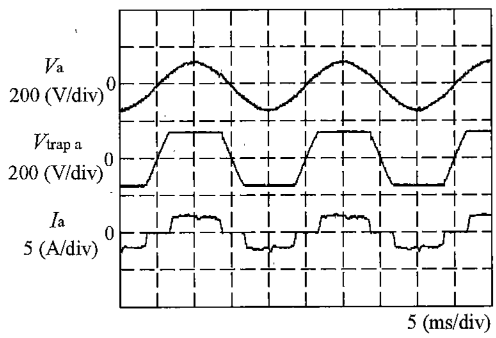
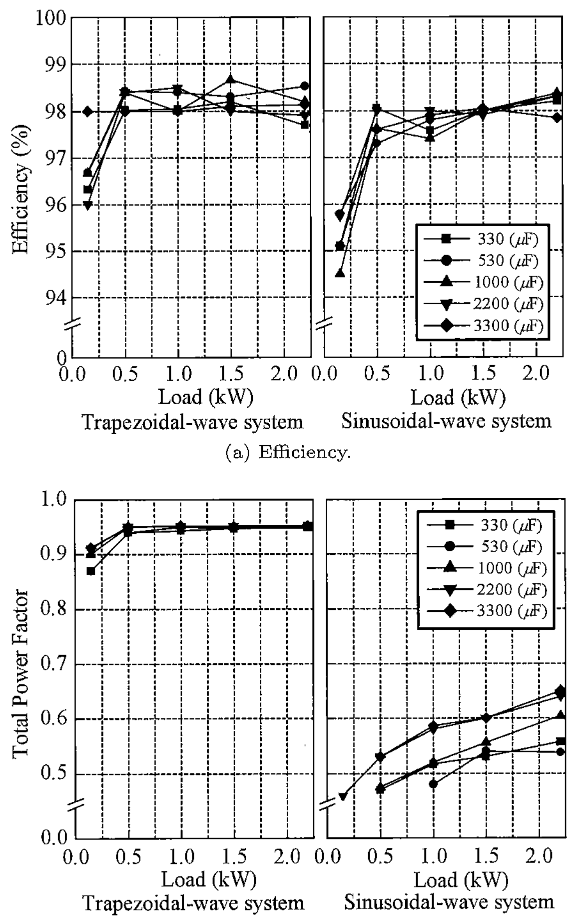


Fig. 3. Example of voltage and current waveforms.

3. Experimental Results and Evaluations

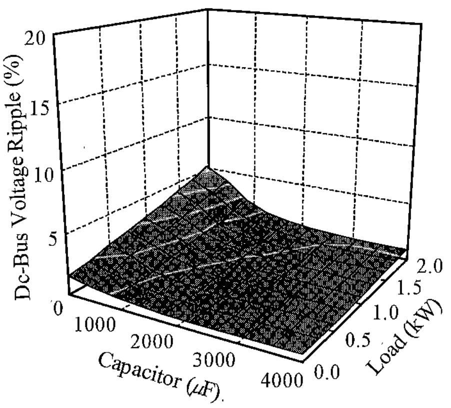
3.1 Efficiency, Power Factor and Dc-Bus Voltage Ripple Experiments were conducted to examine various characteristics of the trapezoidal-wave power distribution system compared with the conventional



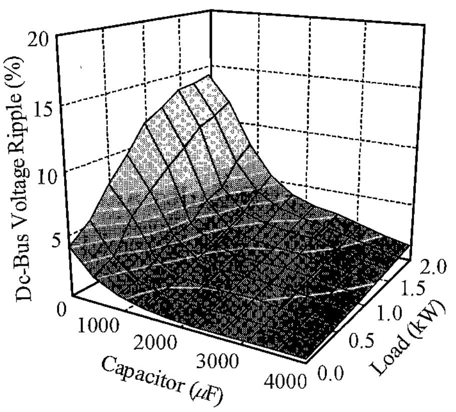
(a) Efficiency.

(b) Total power factor.

Fig. 4. Characteristics of efficiency and total power factor.



Trapezoidal-wave system



Sinusoidal-wave system

Fig. 5. Characteristics of dc-bus voltage ripple.

sinusoidal-wave based system. The first investigated points are basic characteristics with regard to the power transmission, i.e., the efficiency, the total power factor and the dc-bus voltage ripple of a diode rectifier front-end. All of the experiments were carried out with a 100-m power transmission cable listed in Fig. 1, changing the load power and the filter capacitance across the rectified dc-bus.

Figs. 4 (a) and (b) show the efficiency and the total power factor of the diode rectifier front-end. The efficiency in this figure represents an effective power ratio between power-transmitting terminals and the dc-bus of the diode rectifier; hence the transmission losses including conduction losses of the diode rectifier can be evaluated. As can be seen in Fig. 4 (a), the efficiency of the proposed system is more than 98%, which is slightly better than that of the sinusoidal-wave system, whereas a remarkable difference can be found in the total power factor characteristics. The trapezoidal-wave system naturally achieves 95-% total power factor over a whole load range because of its rectangular-shaped currents, while the sinusoidal-wave system reaches only 65% at most. The total power factor of the former is almost independent of the load power and the characteristic is hardly affected by the filter capacitance of the diode rectifier. On the other hand, the characteristic of the sinusoidal-wave system strongly depends on the capacitance. The pulse-shaped currents with high peak values

Table 1. Current harmonics at power grid terminals.

Harmonics	Guideline Class-A (A)	Trapezoidal wave (A)	Sinusoidal wave (A)
5th	1.14	0.975	2.04
7th	0.770	0.804	0.940
11th	0.330	0.238	0.430
13th	0.210	0.326	0.150
17th	0.132	0.130	0.190
19th	0.118	0.119	0.070
23rd	0.098	0.082	0.110
25th	0.090	0.011	0.030

of the sinusoidal-wave system detrimentally affect the total power factor and current harmonics at the diode rectifier input terminals.

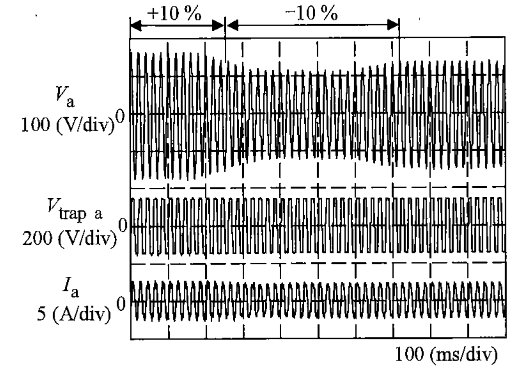
Fig. 5 shows characteristics of the dc-bus voltage ripple of the diode rectifier front-end, in which ripple amplitude is normalized by 280-V dc-bus voltage. From this figure, it can be seen that the dc-bus voltage ripple can be reduced by the trapezoidal-wave system to approximately 5% even though the filter capacitance of the diode rectifier is less than 1,000 (μF). The capacitance reduction makes it possible to introduce film capacitors to the load appliances instead of electrolytic capacitors to smooth the dc-bus voltages, which extends product life, improves reliability and reduces physical volume of the power electronic appliances.

Table 1 shows current harmonics at the power grid terminals (primary terminals of transformer 1 in Fig. 1) measured at load power of 2 (kW). As can be seen in this table, the trapezoidal-wave system is capable to reduce low-order harmonic currents, especially 5th and 11th.

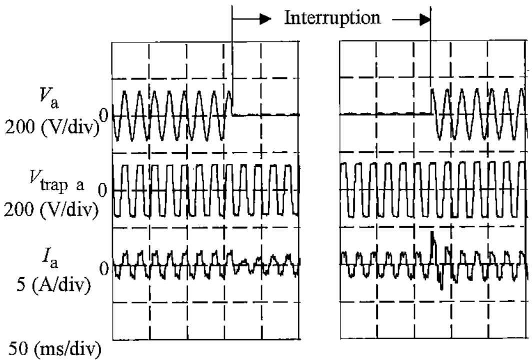
3.2 Uninterruptible Power Supply Operation

Figs. 6(a) and (b) show test results of an uninterruptible power supply operation. Even in such a severe condition shown in Fig. 6(a) where the power source voltage fluctuates by $\pm 10\%$, the trapezoidal-wave system stably regulates its distributed voltages. Since the wave-shaping voltages from the main inverter dynamically compensate for instantaneous variations of the power grid voltages, the system can provide the power electric loads with high-quality electric power. This function is also capable to compensate for non-repetitive disturbances such as flickers.

Fig. 6(b) shows responses to a sudden interruption of the utility power grid. As can be seen in this figure, the proposed system keeps delivering the trapezoidal voltages to the loads with neither voltage sags nor notches. At the very moment when the interruption is detected, the main inverter immediately changes its outputs from the wave-shaping voltages to the trapezoidal voltages. Depending on duration of the interruption to be compensated for, one or more sorts of backup power sources, i.e., batteries, flywheels, engine generators, fuel cells and so forth, must appropriately be chosen to supply the load power stably. Also, the other result recovering from the interruption is shown in the same figure and it can be seen that the trapezoidal voltage waveform is consecutively delivered before and after the interruption. Before one solid-state contactor SSC1 turns on and the

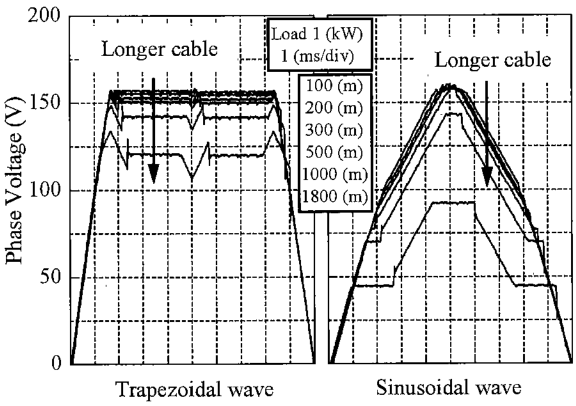


(a) Response to power grid voltage fluctuation.

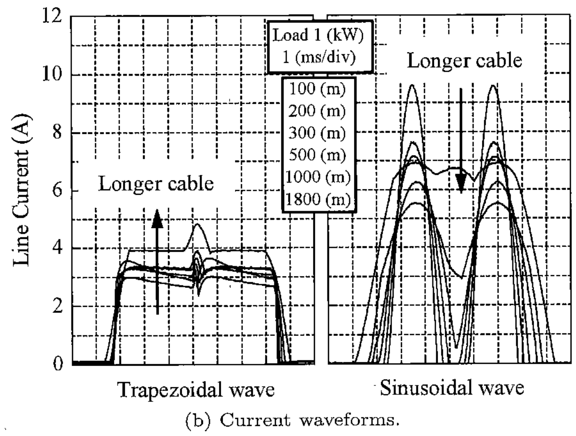


(b) Response to power grid outage.

Fig. 6. Uninterruptible power supply operation.



(a) Phase voltage waveforms.



(b) Current waveforms.

Fig. 7. Waveforms of distributed voltages and currents.

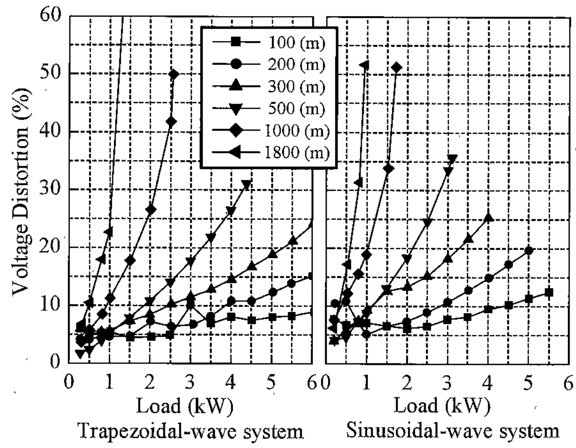
other SSC2 turns off, the system has already completed to synchronize the PLL with the utility sinusoidal voltages and the outputs of the main inverter have been in phase with the utility sinusoidal voltages. Therefore, smooth switching operation without fluctuation of the trapezoidal voltage can be achieved as shown in the figure.

3.3 Limitation of Transmission Cable Length

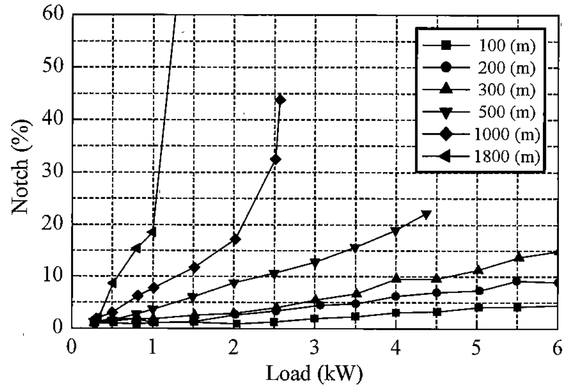
The most unique feature of the trapezoidal-wave power distribution system is its distributed voltage waveforms. Being rather different from the conventional sinusoidal-wave based system, the distributed waveform itself contains a large quantity of harmonics; hence the waveform distortion due to impedance of the transmission lines is a serious problem, which strongly affects the system performance. In other words, the problem can be discussed in terms of limitation of the transmission length because the proposed system inherently aims at mini-scale power distribution networks as mentioned earlier.

Figs. 7(a) and (b) show waveforms during a half-cycle of the distributed voltages and currents with respect to the transmission cable length. All of the waveforms are measured under the same conditions, i.e., peak voltages of both systems are equalized at the transmitting terminals. The experiments were carried out by using a transmission cable model that covers distances from 100 to 1,800 (m). The model consists of several 100-m units and 500-m units and each unit is composed by inductance and resistance without capacitance. The parameters of the 100-m unit are identical to those listed in Fig. 1. As can be seen in Fig. 7, distributed voltage waveforms are apparently distorted worse as the transmission cable is longer. It should be noted that the sinusoidal-wave system could no longer maintain its sinusoidal waveform due to non-linearity of the diode rectifiers. Also, voltage drops due to the line impedance are observed in both cases.

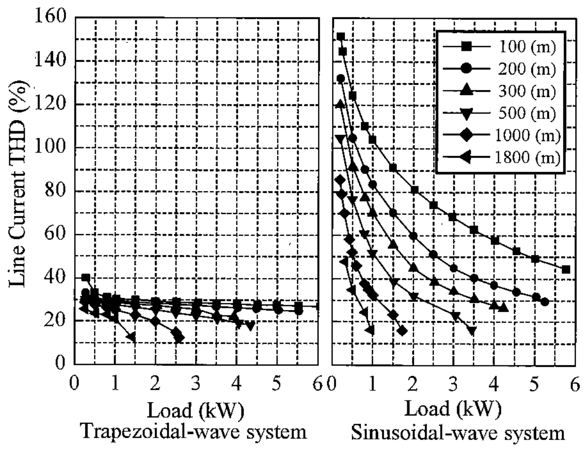
Fig. 8(a) shows the voltage distortion, which is defined as a root mean square error between the voltage waveforms at the transmitting terminals and the load input terminals. Also, Fig. 8(b) shows a characteristic of the voltage notches observed in the middle of flat parts of the trapezoidal waveforms. From these results, it is confirmed that the overall voltage distortion of the trapezoidal-wave system is almost half of that of the sinusoidal-wave system, e.g., the former is 12% but the latter is 20% at 5 (kW) and 200 (m). Also, it can be seen that the voltage notch characteristic restricts the cable length within 200–300 (m). The limitation of the transmission cable length is severer as the load power increases. On the other hand, Fig. 8(c) shows THD of the line currents and it can be found that the THD of the trapezoidal-wave system is hardly affected by the cable length as well as the load power. The trapezoidal-wave system demonstrates superior characteristics to the conventional sinusoidal-wave system in the THD. The THD of the sinusoidal-wave system widely changes according to the cable length and the load power, and can be improved by employing a longer cable because of larger inductance.



(a) Characteristics of voltage distortion.



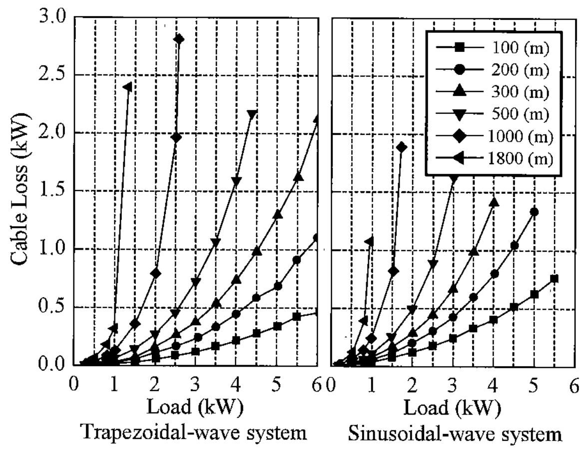
(b) Characteristic of voltage notch in trapezoidal voltages.



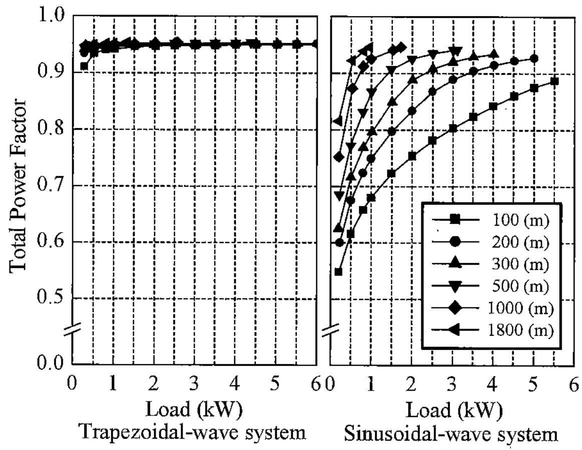
(c) Characteristics of line current THD.

Fig. 8. Characteristics of distributed voltages and currents with respect to cable length.

Figs. 9(a) and (b) show characteristics of the power transmission cable losses and the total power factor at load input terminals, respectively. As can be seen in Fig. 9(a), the cable losses increase as a longer cable is used in both cases but the cable losses of the trapezoidal-wave system is half of the sinusoidal-wave system because the rms values of the distributed voltages are different. Fig. 9(b) represents that the total power factor of the trapezoidal-wave system is always 95% independently of the cable length and the load power. Consequently, it is inferred that practical limitation of the cable length is 200–300 (m), judging from every aspect of the experimental results obtained above.



(a) Characteristics of cable losses.



(b) Characteristics of total power factor.

Fig. 9. Characteristics of cable losses and total power factor with respect to cable length.

4. Conclusion

This paper has described a novel three-phase trapezoidal-wave power distribution system specialized for power electronic appliances with diode rectifier front-ends. The system is inherently suitable for mini-scale power distribution networks in which all of the loads are inverters and/or choppers. With merely using simple diode rectifiers with filter capacitors instead of complicated sinusoidal PWM converters in the load appliances, unique features and various advantages over the conventional sinusoidal-wave system are gained owing to the trapezoidal voltage waveforms as follows:

1) It is not necessary to employ the sinusoidal PWM converter in each rectifier front-end to improve total power factor and total harmonic distortion of the line currents at the input terminals, which is effective to enhance an economical aspect and reliability of the load appliances. Also, it is possible to miniaturize the load appliances because much smaller capacitance can be used to suppress the dc-bus voltage ripple sufficiently.
2) Without electronically controlled switching, the total power factor at load input terminals can easily be improved to 95 % and the line current harmonics can

effectively be reduced because of the rectangular-shaped currents with spontaneously widened conduction periods. Furthermore, reduction of the line current harmonics is effective to suppress the current harmonics at the power grid terminals, especially low-order harmonic components.

3) It has been confirmed through experiments that the proposed system can compensate for voltage fluctuation of the utility power grid and properly functions as an uninterruptible power supply in sudden outage of the power grid.

4) Influences of a transmission cable length on the distributed waveforms have been investigated and practical limitation of the cable length has experimentally been clarified. It is inferred from the experimental results that the limitation of the cable length is 200-300 (m).

In the future study, direct superposition of the wave-shaping voltages without transformers is to be investigated, which is indispensable to reduce system losses.

(Manuscript received July 15, 2002,
revised Dec. 9, 2002)

References

(1) M. Sakui and H. Fujita: "A Harmonic Analysis of Three-Phase Rectifier with a Dc Filter Capacitor", *IEE-Japan Trans. Ind. Appl.*, Vol.114-D, No.2, pp.144–149 (1994-2) (in Japanese)

(2) J.W. Dixon and B.T. Ooi: "Indirect Current Control of a Unity Power Factor Sinusoidal Current Boost Type Three-Phase Rectifier", *IEEE Trans. Ind. Elec.*, Vol.35, No.4, pp.508–515 (1988-4)

(3) R. Wu, S.B. Dewan, and G.R. Slemon: "Analysis of an Ac-to-dc Voltage Source Converter Using PWM with Phase and Amplitude Control", *IEEE Trans. Ind. Appl.*, Vol.27, No.2, pp.355–364 (1991-2)

(4) T. Noguchi, H. Tomiki, S. Kondo, and I. Takahashi: "Direct Power Control of PWM Converter without Power-Source Voltage Sensors", *IEEE Trans. Ind. Appl.*, Vol.34, No.3, pp.473–479 (1998-3)

(5) Y. Jang and M.M. Jovanovic: "A Comparative Study of Single-Switch Three-Phase High-Power-Factor Rectifier", *IEEE Trans. Ind. Appl.*, Vol.34, No.6, pp.1327–1334 (1998-6)

(6) L. Malesani, P. Mattavelli, and S. Buso: "Robust Dead-Beat Current Control for PWM Rectifiers and Active Filters", *IEEE Trans. Ind. Appl.*, Vol.35, No.3, pp.613–620 (1999-3)

(7) D.-C. Lee, G.-M. Lee, and K.-D. Lee: "Dc-Bus Voltage Control of Three-Phase Ac/dc PWM Converters Using Feedback Linearization", *IEEE Trans. Ind. Appl.*, Vol.36, No.3, pp.826–833 (2000-3)

(8) S. Kondo and H. Meguro: "Feasibility Study on Square-Wave Voltage Power Distribution System", *IEE-Japan Trans. Ind. Appl.*, Vol.116-D, No.5, pp.556–562 (1996-5) (in Japanese)

(9) P.K. Jain, J.R. Espinoza, and H. Jin: "Performance of a Single-Stage UPS System for Single-Phase Trapezoidal-Shaped AC-Voltage Supplies", *IEEE Trans. Pow. Elec.*, Vol.13, No.5, pp.912—923 (1998-5)

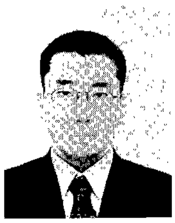
(10) S. Yoshikazu and T. Noguchi: "Trapezoidal-Wave-Voltage Power Distribution System with UPS Function", *IEE-Japan Proc. Annual Conf. Ind. Appl. Soc.*, Vol.1, pp.219–222 (1999) (in Japanese)

(11) T. Noguchi and S. Yoshikazu: "Trapezoidal-Wave Power Distribution System with Uninterruptible Power Supply Function", *Proc. Int. Pow. Elec. Conf. IPEC-Tokyo*, Vol.3, pp.1513–1518 (2000)

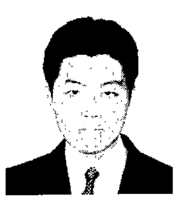
(12) K. Taniguchi and H. Irie: "Trapezoidal Modulating Signal for Three-Phase PWM Inverter", *IEEE Trans. Ind. Elec.*, Vol.IE-33, No.2, pp.193–200 (1986)

(13) M. Nakaoka, W. Sun, and Y. Ogino: "Output Performance Evaluations of Three-Phase Voltage-Fed PWM Inverter for Induction Motor Drives Using Optimum Trapezoidal-Wave Signal", *IEE-Japan Trans. Ind. Appl.*, Vol.110-D, No.7, pp.831–840 (1990) (in Japanese)

Toshihiko Noguchi (Member) was born in Kuwana, Japan, in 1959. He received the B. Eng. degree in electrical engineering from Nagoya Institute of Technology, Nagoya, Japan, and the M. Eng. and Ph.D. degrees in electrical and electronics systems engineering from Nagaoka University of Technology, Nagaoka, Japan, in 1982, 1986, 1996, respectively. In 1982, he joined Toshiba Corporation, Tokyo, Japan. He was a Lecturer at Gifu National College of Technology, Gifu, Japan, from 1991 to 1993 and a Research Associate in electrical and electronics systems engineering at Nagaoka University of Technology from 1994 to 1995. Since 1996, he has been an Associate Professor at Nagaoka University of Technology. His research interests are static power converters and motor drives. Dr. Noguchi is a Senior Member of the Institute of Electrical and Electronics Engineers (IEEE).



Masaru Imoto (Member) was born in Tokushima, Japan, in 1977. He received the B. Eng. and M. Eng. degrees in electronic engineering and in electrical and electronics systems engineering from Nagaoka University of Technology, Nagaoka, Japan, in 2000 and 2002, respectively. Since 2002, he has been with Mitsubishi Electric Defense & Space Electronics Co.



Yoshikazu Sato (Member) was born in Yamagata, Japan, in 1973. He joined Kawasaki Electric Co. in 1992 and has been with Kawasaki Electric Co. R&D Center as a Chief Engineer.