A Simple Passive PFC Scheme for Three-Phase Diode Rectifier

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***Abstract* – A simple passive scheme for increasing operation pulse-number to obtain high-quality input current waveform of three-phase diode rectifier is investigated in this paper. The topology and operation principle are described. Then, the performance is evaluated by means of a 20kW setup. By referring to the evaluations result, the advantages in practical use of the rectifier are shown.**

I. INTRODUCTION

Several harmonic reducing schemes of diode rectifier (i.e., without PWM) have been proposed so far [1]-[3]. Some of these non-PWM schemes presented in recent years obtain fine input current waveforms, and they result in effective solutions to obtain uncontrolled dc power from the utility with low initial cost and high efficiency but without harmonic pollution. However, voltage source type inverters are commonly employed in inverter drive and UPS systems, and this type inverter needs a dc voltage source in the input. Since dc-voltage controllability is not always necessary in such applications, the 3-phase bridge diode rectifier of capacitor input type is the most suitable rectifier in those applications from the viewpoint of initial cost, size, operating efficiency, EMI noises and reliability. However, the rectifiers of this type without PWM technique have not been explored well in the past, especially from practical point of view.

With the above technical background, the authors proposed a 12-pulse diode rectifier using the conventional 3-phase bridge 6-pulse diode rectifier of capacitor input type and an auxiliary circuit. Although this auxiliary circuit consists of only two diodes with very low rating and an autotransformer with very low kVA, it plays the important role to increase the operating pulse number to double (e.g., 12 in single three-phase-bridge 6-pulse rectifier) under condition with and without an isolation transformer. Due to the pulse number increasing/doubling effect, dominant harmonics of 5th and 7th in the input line current of the conventional 6-pulse rectifier are eliminated in the 12-pulse one. As a result, total harmonic distortion factor of the input current of the conventional 6-pulse diode rectifier is significantly decreased in the 12-pulse rectifier. Thus, the ***Pulse-Doubler*** scheme offers an easy and cheap solution to mitigate harmonic pollution caused by diode rectifiers.

Since the purpose of the previous papers were to confirm the theory through a small scale setup with a large inductor on the ac-side (to obtain a continuous current condition and let the operating condition be as close to that of the theory as possible[4] or a larger scale (i.e., 12kW) setup but operated by an almost ideal 3-phase power source (i.e., a liner-amplifier without an internal impedance) [5]. Although practical evaluations have been done partially in the later study with 12kW setup, further practical studies, such as those with actual Utility/Mains with further larger power scale, are essential since the performance and the quality of the input current waveform are sensitive to the distortion of the 3-phase source voltages. This paper is focused on practical evaluations of the 12-pulse rectifier by means of 20kW setup operated under Utility/Mains.

The topology and the operating principle (waveform synthesis) are described and then, experimental results obtained from a 20kW setup are shown and the performance is evaluated. Referring to them, some points in practical use of the rectifier are drawn and a discussion regarding to the advantages vs. disadvantages is made.

II. CIRCUIT TOPOLOGY

Figure 1 shows the proposed simple 12-pulse diode rectifier. The part shown with red color and enclosed by dotted lines represents the auxiliary circuit to increase the operating pulse number from 6 to 12 and reduce harmonics of the voltages (v_{XY} etc.) on the ac input side and the utility line currents (i_A etc.). The remaining part is identical to the conventional 6-pulse rectifier that consists of ac-inductors (L_A etc.), dc-capacitors (C_P and C_Q) and a dc-load R. This rectifier of capacitor input type produces large harmonic currents if the series inductance on the utility side (provided by only such as leakage flux of transformers) is very low. In such case, an independent inductor is connected between the utility and the diode-bridge in each phase to limit the harmonics. The inductors L_A, L_B and L_C in Fig.1 are employed for this purpose. Further, two capacitors (C_P and C_Q) are connected in series between the dc-rails to obtain the mid-potential-point M on the dc-side although the dc-rail separation is not necessary in the conventional 6-pulse topology.

The auxiliary circuit consists of only two auxiliary diodes (D_{AP} and D_{AQ}) and an autotransformer T_A. The two diodes are connected in series between the dc-rails and a center-point D is obtained. The series connected smoothing capacitors C_P and C_Q present a center-point M. This point M is called "mid-potential-point" since its voltage potential is medium between those of the upper and lower dc-rails (i.e., the points P and Q in Fig. 1) under steady-state and normal condition. The autotransformer T_A is connected between the center-point M of the series connected auxiliary diodes (D_{AP} and D_{AQ}) and the neutral point N of the secondary windings of the

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isolation transformer T_M. The center-tap of the autotransformer T_A is connected to the mid-potential-point M. The turn-ratio a_M of the windings on the right and left side of the autotransformer T_A (i.e., "turn-number of right-side winding" / "turn-number of left-side winding") is set to a_M=6[4]-[5] in the setup as shown in Fig. 1.

III. OPERATION

To smoothly show the operation of the 12-pulse rectifier, the operation of the ordinary 6-pulse rectifier is reviewed first. Then, the topology and operation of a particular 6-pulse rectifier are discussed. At last, the operation of the 12-pulse rectifier is introduced as a combined one of the ordinary and the particular 6-pulse rectifiers.

A. Review of Conventional 6-Pulse Rectifier Operation

Figure 2 shows a 6-pulse rectifier where the ordinary 6-pulse rectifier is modified as follows; the dc-side is sprit into upper and lower parts by series connected two smoothing capacitors C_P and C_Q and the mid-potential-point M is connected to the neutral point N of the star-connection secondary winding of the isolation transformer T_M through a switch S_{MN}. When the switch S_{MN} is opened the rectifier becomes the ordinary 6-pulse rectifier while the switch S_{MN} is closed it becomes a particular 6-pulse rectifier that is discussed in the following section ***B***.

Figure 3 shows operating waveforms of the ordinary 6-pulse, the particular 6-pulse and the new 12-pulse rectifiers. To discriminate voltages and currents of the three rectifiers, the subscript "$_{\text{-OPEN,}}$" "$_{\text{-SHORT}}$" or "$_{\text{OPTIM,}}$" is added to voltage/current symbols of the ordinary 6-pulse, the particular 6-pulse or the new 12-pulse rectifiers, respectively.

The capacitances of C_P and C_Q are the same and large enough so that the dc voltages V_P and V_Q are the same and entirely smoothed. Tnductances of L_A, L_B and L_C are the same and large enough so that the utility line currents i_A, i_B and i_C offers 3-phase symmetrical and continuous waveform.

Operating waveforms of this ordinary 6-pulse rectifier under continuous utility line-current condition are shown by dotted lines in Fig. 3, where the utility line-currents are assumed to be sinusoidal for drawing convenience although they distort and the distortion degree depends on inductance of the inductor L_A etc. The horizontal axis of Fig. 3 represents phase angel "ϕ-φ " [deg], where "φ " represents displacement angle of the utility line-current (i_A etc.) against the utility phase-to-neutral voltage (v_{AN}

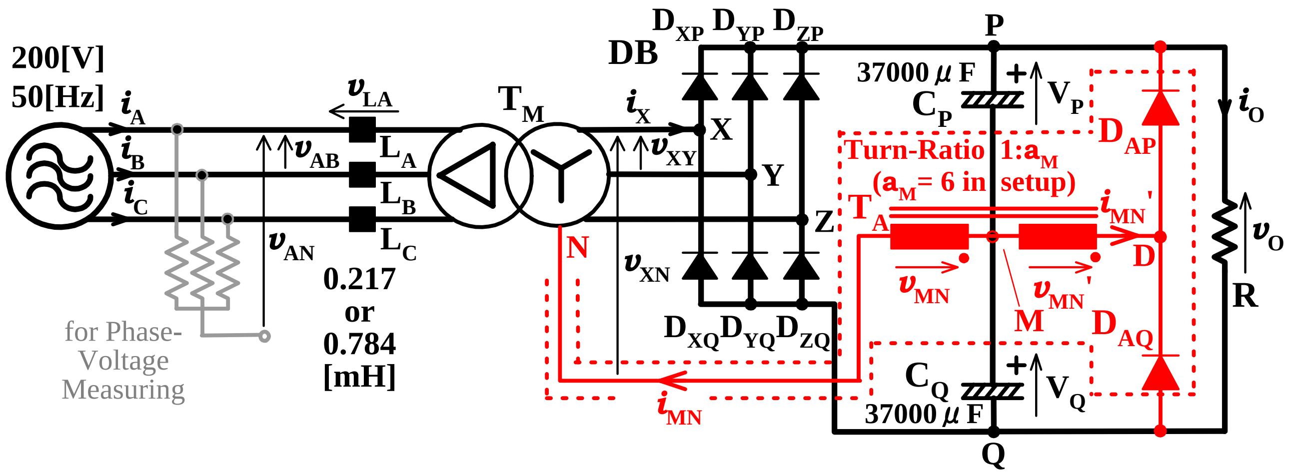


Fig. 1. Modified 12-Pulse Rectifier with Isolation Transformer.

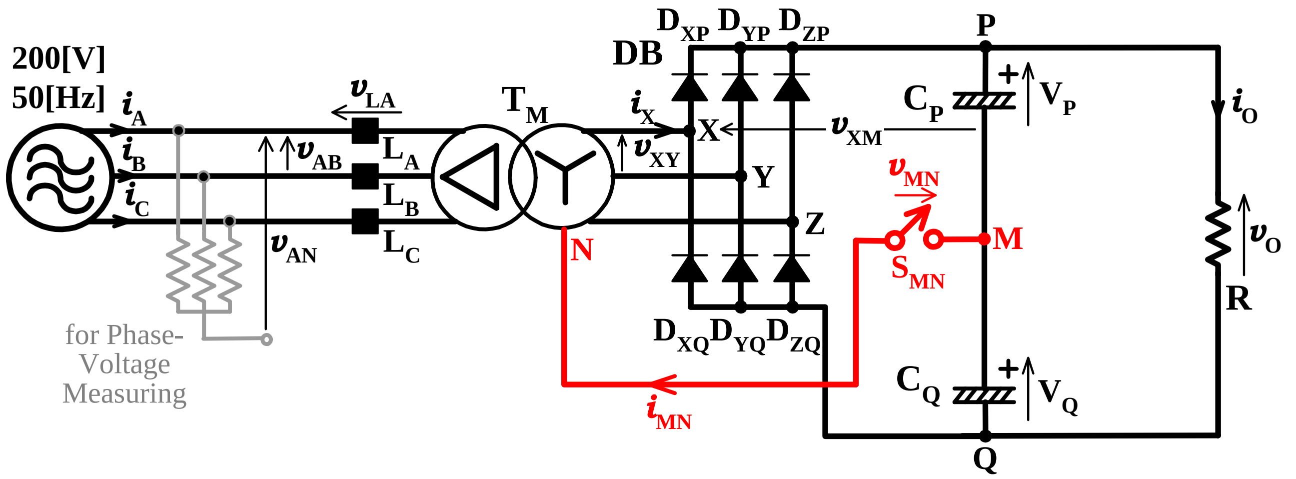


Fig. 2. Ordinary and Particular 6-Pulse Rectifiers Isolation Transformer.

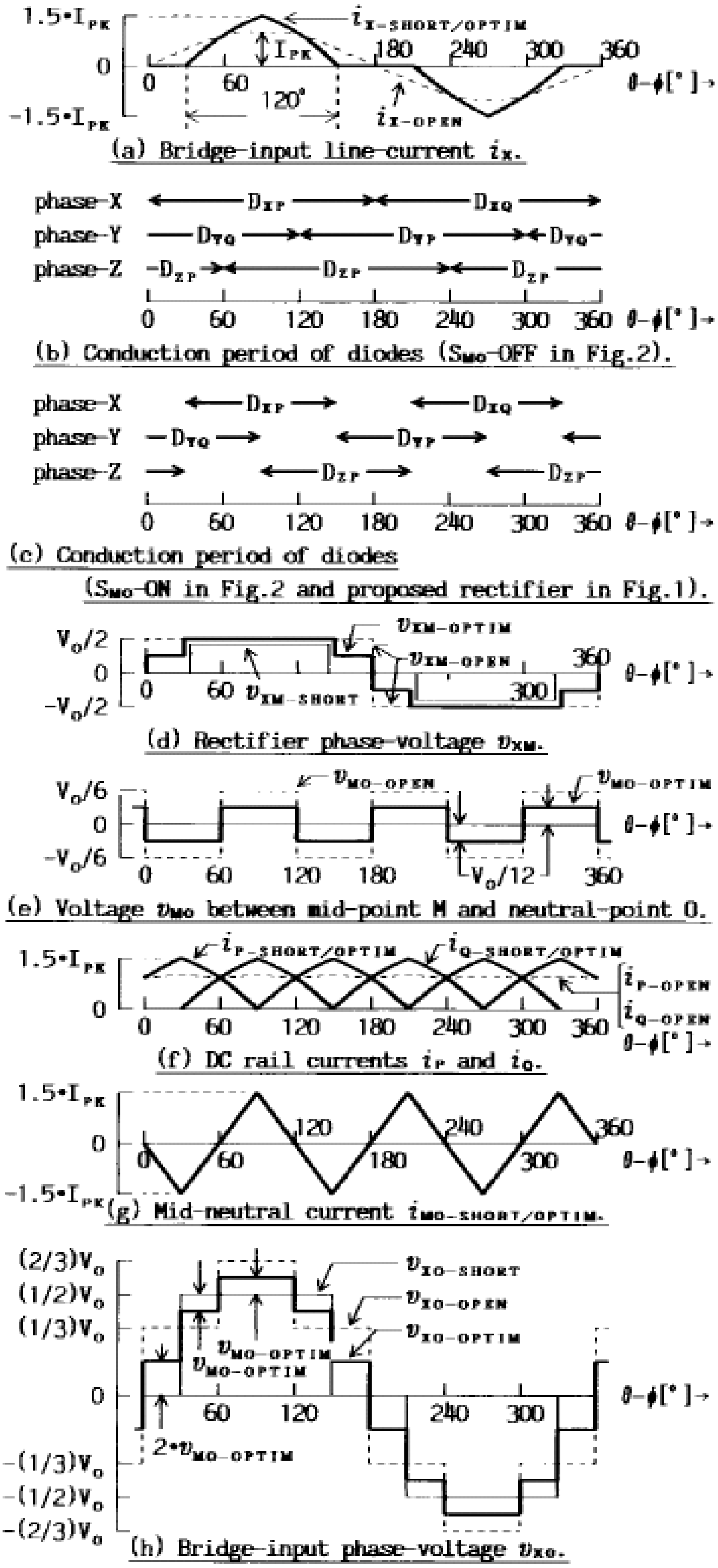


Fig. 3. Theoretical Operating Waveforms of Ordinary 6-Pulse, Particular 6-Pulse and Modified 12-pulse Rectifiers

etc.). Since the system has series inductors (L_A etc.) in the input, a lagging phase-displacement "φ" occurs between the voltages (υ_{AN} etc.) and the currents (i_A etc.).

The utility line currents are sinusoidal and continuous and thus, the bridge-input line currents ($i_{X\text{-OPEN}}$ etc.) are sinusoidal and continuous too, as shown by dotted line in Fig. 3(a). Thus, one of the upper diode or lower diode in each phase of the diode-bridge is always under conduction as shown in Fig. 3(b). When the upper diode (D_{XP} etc.) or the lower diode (D_{XQ} etc.) is in conduction state, the output voltage V_O is applied between the bridge-inputs (X, Y or Z) and the mid-potential-point M with the positive or negative direction, respectively. Thus, full-width rectangular voltages ($\upsilon_{XM\text{-OPEN}}$ etc.) with amplitude of $V_O/2$ appear between the input terminals (X etc.) and the mid-potential-point M, as shown by dotted line in Fig. 3(d).

Since the main transformer T_M is a three-phase transformer with three-limb structure, the sum of the three secondary winding voltages (i.e., $\upsilon_{XN\text{-OPEN}}+\upsilon_{YN\text{-OPEN}}+\upsilon_{ZN\text{-OPEN}}$) must be zero at any time. On the other hand, the sum of the voltages appearing between the bridge-inputs (X, Y and Z) and the mid-potential-point M (i.e., $\upsilon_{XM\text{-OPEN}}+\upsilon_{YM\text{-OPEN}}+\upsilon_{ZN\text{-OPEN}}$) is not zero since they obtain a full-width rectangular waveform. Thus, a full-width rectangular voltage $\upsilon_{MN\text{-OPEN}}$ with triple frequency and amplitude of $V_O/6$ appears between the mid-potential-point M and the neutral point N, as shown by dotted line in Fig. 3(e). Due to the effect of this rectangular voltage, the secondary winding voltages ($\upsilon_{XM\text{-OPEN}}$ etc.) are modified so that their sum becomes zero, as shown by dotted line in Fig. 3(h). These secondary voltages and the induced voltages (υ_{AB} etc.) on the primary winding offer 6-pulse waveform. This 6-pulse waveform involves high contents lower order harmonics such as 5^{th} and 7^{th}, while the utility voltage involves (almost) no harmonic.

The voltages applied on the ac-inductors (i.e., υ_{LA} etc.) are obtained by subtracting the utility phase-voltages (υ_{AN} etc.) and the primary phase-voltage (not shown in Fig. 2) of the transformer T_M. Since the amplitudes of the fundamental components of the utility phase-voltages and the primary phase-voltage are almost the same, the amplitude of fundamental component of inductor voltage υ_{LA} is very low (e.g., approximately 6% of the fundamental component in the 12kW prototype under full power condition). On the other hand, the amplitude of the dominant lower order harmonics involved in the inductor voltage υ_{LA} are the same to those of the primary phase-voltage (e.g., 20% and 14% of the fundamental component involved in the primary phase-voltage for the 5^{th} and the 7^{th}, respectively, under ideal condition). Thus, the contents factors of the dominant lower order harmonics are significant (e.g., more than 100% of the fundamental component of the inductor voltage). Although the inductor performs as a 1^{st} order filter for the relation between the applied voltage (i.e., υ_{LA} etc.) and the current (i.e., the line-currents i_A etc.), the line-current involves lower order harmonics with very high amplitudes since the harmonics in the voltage is extremely high in amplitude. Thus, a very high inductance is required to the inductors (L_A etc.) to reduce harmonics of the utility line-currents (i_A etc.) to an acceptable level. If the dominant 5^{th} and 7^{th} harmonics of υ_{XN} (and thus those of υ_{LA}) are significantly reduced or eliminated somehow, the inductance and thus the size, weight and cost of the inductors to reduce the utility line current harmonics can be greatly reduced. As described in part ***C***, this advantageous condition is obtained by adding the simple auxiliary circuit as shown in Fig. 1.

B. Particular 6-Pulse Rectifier and Its Operation.

If the switch S_{MN} is closed in the rectifier of Fig. 2, we obtain a 6-pulse rectifier. Although the circuit topology and the operation are particular, this rectifier offers a 6-pulse nature. Comparing with the ordinary 6-pulse rectifier, no advantage is obtained from this particular rectifier. However, its operation is discussed in the following because it's very interesting and useful to explain the operation of the proposed 12-pulse rectifier. Operating waveforms of this rectifier are shown in Fig. 2 by solid lines.

Because the secondary neutral point N and the mid-potential-point M are connected directly in this rectifier, subscript "$_{\text{-SHORT}}$" is added to symbols of the voltages and currents. It notes that waveforms of each current of this rectifier and the proposed 12-pulse rectifier are the same as described later and thus, they are overlapped in Fig. 3. Therefore, subscript "$_{\text{-SHORT/OPTIM}}$" is added to the current symbols in Fig. 3, and those waveforms are shown by bold lines in the figure.

1) Voltage Synthesis

Since the secondary neutral point N and the mid-potential-point M are connected directly, the two secondary phase-voltages ($\upsilon_{XN\text{-SHORT}}$ etc. and $\upsilon_{XM\text{-SHORT}}$ etc.) in each phase are the same each other, respectively. The secondary phase-voltages cannot involve any zero-sequence component (i.e., "$\upsilon_{XN\text{-SHORT}}+\upsilon_{YN\text{-SHORT}}+\upsilon_{ZN\text{-SHORT}}=0$") as described, and it does not depend on whether the secondary neutral-point N and the mid-potential-point are shortened or opened. To achieve this condition, waveform of the rectifier phase-voltages ($\upsilon_{XM\text{-SHORT}}$ etc., i.e., the bridge-input phase-voltage $\upsilon_{XO\text{-SHORT}}$ etc.) must be modified from those of the ordinary 6-pulse rectifier. To explain how the phase voltages are modified, let's consider a circuit condition where the secondary neutral-point N and the mid-potential-point M are connected through a variable resistor R_{MN} instead of the switch S_{MN} in Fig. 2.

The circuit in Fig. 2 with a resistor R_{MN} of finite resistance represents the conventional rectifier with disconnection between the secondary neutral-point N and the mid-potential-point M.

As the resistance R_{MN} decreases to a finite value, the current i_{MN} begins to flow. However, if R_{MN} is still high and i_{MN} is very low, conduction periods of diodes are the same to those of the ordinary rectifier. Thus, the voltage

υ_{MN} in this condition with R_{MN} of high resistance equals $\upsilon_{MN\text{-}OPEN}$. Due to the polarity of υ_{MN} (=$\upsilon_{MN\text{-}OPEN}$ shown in Fig. 3(e)), i_{MN} flows with the direction so that the amplitude (or absolute value) of the bridge-input line-current (i_X etc.) with maximum amplitude is increased while amplitudes of the remaining two line currents are decreased. For example, i_X is increased while i_Y and i_Z are decreased for "θ-ϕ" = 60 to 120 and 240 to 300 [deg] (refer to waveform in Fig. 3(a)). If the resistance R_{MN} is further decreased, the current i_{MN} is further increased and finally, the bridge-input line-current with the minimum amplitude is eliminated. This condition is held until R_{MN} is decreased to zero. Since the condition of R_{MN}=0 equals the condition of the particular rectifier, one of the secondary line currents (i_X etc.), that is of the minimum amplitude in the ordinary 6-pulse rectifier, does not flow in this condition as same as the particular rectifier. As a result, the bridge-input line-currents ($i_{X\text{-}SHORT}$ etc.) flow discontinuously and offer a quasi- triangular waveform as shown by bold line in Fig. 3(a). Due to this effect, conduction period of the diodes in the bridge is shortened to 120 [deg] as shown in Fig. 3(c).

When upper or lower diode (e.g., D_{XP} or D_{XQ} in phase-A/X) is conducting, the bridge-input phase-voltage (e.g., υ_{XM}) equals a half of the output voltage V_O with positive or negative polarity, respectively. The phase voltage in the remaining period does not determined by the bridge operation, but it must be zero as follows.

When both of upper and lower diodes in a same phase (for example phase-A/X) are not conducting (it occurs "θ-ϕ" = -30 to 30, 150 to 210 [deg] in Fig. 3), upper diode in one of the remaining phase (i.e., phase-Z for "θ-ϕ" = -30 to 30 [deg] or phase-Y for "θ-ϕ" = 150 to 210 [deg]) and lower diode in other remaining phase (i.e., phase-Y for "θ-ϕ" = -30 to30 [deg] or phase-Z for "θ-ϕ" = 150 to 210 [deg]) are conducting as understood from Fig. 3(c). Thus, phase-voltage in the phase with a conducting upper diode (i.e., phase-Z or phase-Y for "θ-ϕ" = -30 - 30 or 150 to 210 [deg], respectively) or in the phase with a conducting lower diode (i.e., phase-Y or phase-Z for "θ-ϕ" = -30 to 30 or 150 to 210 [deg], respectively) equals positive or negative half of the output voltage V_O, respectively. Thus, the phase-voltage in a phase without conducting diode must be zero since the sum of the three phase-voltages must be zero. Referring to the above discussion, it is known that the phase-voltages (υ_{XM} etc. or υ_{XN} etc.) offer a discontinuous rectangular waveform with width of 120 [deg] and amplitude of $V_O/2$, as shown by solid lines in Fig. 3(d) and (h). This phase-voltage waveform is a 6-pulse one, and its harmonic contents are the same to those of the ordinary 6-pulse rectifier.

2) Current Synthesis

Since the bridge-input phase-voltages of the particular and the ordinary 6-pulse rectifiers offer different waveforms each other, those of the bridge-input line-currents are different. Although the detail is omitted in this paper, the secondary line currents ($i_{X\text{-}SHORT}$ etc.) offers the waveform shown in Fig. 3(a). As a result, the upper and lower dc-rails current ($i_{P\text{-}SHORT}$ and $i_{Q\text{-}SHORT}$) obtains the waveform (i.e., quasi-triangular one) shown in Fig. 3(f). Since the neutral current i_{MN} is obtained as difference between the upper and lower dc-rail currents, it draws a quasi-triangular waveform with three times frequency of the utility voltage as shown in Fig. 3(g).

3) Comparing voltage waveforms of ordinary and particular rectifiers

The bridge-input phase-voltages (υ_{XN} etc.) of the two 6-pulse rectifiers offer different waveforms as shown by dotted lines and solid lines, respectively, in Fig. 3(h). Though, harmonics involved in the two voltages are the same in the orders and the amplitudes. Thus, the particular rectifier can be recognized as a 6-pulse one, although it has not been explored well in the past. It must be noted that the harmonics of order of "6m+l" and "6m-1" (m = even numbers = 2,4,6, ...; i.e., 11-th, 13-th, 23-th, 25th, etc.) involved in the voltages of the two rectifiers are the same in phase angle, while harmonics of order of "6m+ 1" and "6m- 1 " (m = odd numbers =1, 3, 5, ...; i.e., Sth, 7-th, 17-th, 19-th, etc.) are opposite in phase angle. Thus, the average (or the sum) of the bridge-input phase-voltages of the two rectifiers (i.e., [$\upsilon_{XN\text{-}OPEN}$+$\upsilon_{XN\text{-}SHORT}$]/2 etc.) offers a 12-pulse waveform, in which the dominant harmonics (i.e., 5th and 7-th) involved in the 6-pulse waveform are eliminated. If such a 12-pulse voltage is obtained, harmonics of the utility line-currents are greatly reduced by a very small ac-inductor as mentioned. In the proposed rectifier, the average voltage consisting of 12-pulse waveform is obtained by means of a unique technique using the auxiliary circuit as described in the following part ***C***.

C. Proposed 12-Pulse Rectifier Operation

This proposed rectifier circuit, shown in Fig.1, is arranged so that the bridge-input phase-voltages ($\upsilon_{XN\text{-}OPTIM}$ etc.) obtain a 12-pulse waveform that is optimum from the viewpoint of harmonic reduction of the utility line-currents. Thus, subscript "$_{\text{-OPTIM}}$" is added to symbols of the voltages and currents of this rectifier. The operating waveforms of this rectifier are shown by bold lines in Fig. 3.

As mentioned above, the target 12-pulse phase-voltage can be achieved when the phase-voltage equals the average of those of the ordinary and the particular rectifiers (i.e., $\upsilon_{XN\text{-}OPTIM}$=($\upsilon_{XN\text{-}OPEN}$+$\upsilon_{XN\text{-}SHORT}$)/2 etc.). It can be predicted from the fact that if the 12-pulse phase-voltage is realized the mid-neutral voltage υ_{MN} should realize the average condition too (i.e., $\upsilon_{MN\text{-}OPTIM}$=($\upsilon_{MN\text{-}OPEN}$+$\upsilon_{MN\text{-}SHORT}$)/2). Since the amplitude of $\upsilon_{MN\text{-}OPEN}$ equals $V_O/6$ while the amplitude of the $\upsilon_{MN\text{-}SHORT}$ equals zero, the amplitude of the mid-neutral voltage $\upsilon_{XN\text{-}OPTIM}$ to obtain the 12-pulse phase-voltage equals $V_O/12$. To obtain this voltage, the auxiliary transformer T_A and two diodes (D_{A1} and D_{A2}) are employed as shown in Fig. 1 [4]-[5]. To obtain this appropriate rectangular voltage, the neutral current i_{MN} can be utilized by means of the auxiliary circuit shown in Fig. 1. The operating mechanism is as follows.

The polarity of the secondary current i_{MN}' (=i_{MN}/a_A; a_A is the turn-ratio of T_A) of the auxiliary transformer T_A is identical to that of the primary current i_{MN} at any time. Thus, the secondary current i_{MN}' flows through the upper diode D_{AP} or the lower diode D_{AQ} in the period when the primary current i_{MN} is in positive or negative polarity, respectively. When the upper diode D_{AP} or the lower diode D_{AQ} turns on, the voltage V_P of the upper capacitor C_P or the voltage V_Q of the lower capacitor C_Q, respectively, is applied on the secondary winding of the auxiliary transformer T_A. The voltages (V_P and V_Q) of the two smoothing capacitor are both a half of the output voltage V_O under steady state and normal operating condition. Therefore, we obtain a rectangular voltage with an appropriate waveform on the primary winding under the condition. The amplitude of the primary voltage $\upsilon_{MN\text{-}OPTIM}$ is organized as to be appropriate by adjusting the turn-ration a_A. Fig. 3(e) shows the appropriate neutral voltage $\upsilon_{MN\text{-}OPTIM}$ obtained by means of the auxiliary circuit where the turn-ration a_A is set to 6 that is very close to the optimum under ideal condition.

IV. EXPERIMENTAL RESULTS

Experimental setups of the modified 12-pulse and the ordinary 6-pulse rectifiers with nominal output rating of 20kW have been build and tested. The dominant circuit parameters and measured data are shown in Fig. 1 and TABLE-I, respectively. Fig. 4 and 5 show operating waveforms of the 12-pulse and 6-pulse rectifiers under condition with output power P_O = 20kW.

By comparing the input currents in Fig. 4 (a) and Fig. 5 (a) it is easily known that the 12-pulse rectifier offers a higher quality input current while that of the 6-pulse rectifier is distorted. The *THD*-i_S of the 12-pulse (10.2%) is one-third of that of the 6-pulse rectifier (29.0%). Additionally, it is understood from the input current waveforms that the displacement-angle of the 12-pulse rectifier is lower than that of the 6-pulse rectifier. Considering the lower *THD*-i_S and displacement-angle in 12-pulse rectifier, it is expected that the TPF of the rectifier is higher than that of the 6-pulse one.

The waveforms of the line-to-line voltage and line current of the rectifier shown in Fig. 4 (b) are slightly differ from those in theory shown in Fig. 3 (h) and (a), respectively. The reason is that a continuous current condition is considered in the theory but the setup operates with a discontinuous current condition.

The dc voltages in both the rectifiers are smooth since dc-capacitors of a large capacitances are employed in the setup. The necessity of two dc-capacitors to obtain the mid-potential point M is a drawback in the 12-pulse rectifier.

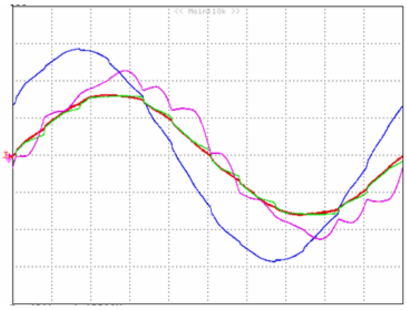
As seen in Fig. 4 (d), the primary and the secondary voltages of the auxiliary transformer T_A lose sharpness in the waveforms although those of the theory draw sharp rectangular waveforms with full width as shown in Fig. 3 (e). Although the distortion of the primary voltage is due to the discontinuity of the input current, the secondary voltage produces additional distortion on the top. This is caused by voltage drops on the windings due to leakage inductance and resistance of them. This phenomenon is understood by considering the triangular current shown in Fig. 3 (g).

It is understood from the data in TABLE-I that the 12-pulse rectifier offers a high quality input current (e.g., *THD*-i_S=10.2 and 5.8% for lower and higher ***%IX*** condition) while the 6-pulse rectifier produces a distorted one (e.g., 29.0 and 18.7% for lower and higher ***%IX*** condition), all at P_O=20kW. The data describes that the *THD*-i_S is reduced to one-third of that of the ordinary 6-pulse rectifier (in all the cases in TABLE-I) by applying the modified rectifier. Since the *THD*-i_S is reduced significantly, the input Total-Power-Factor TPF is improved in the 12-pulse rectifier by 5% or more compared with the 6-pulse rectifier.

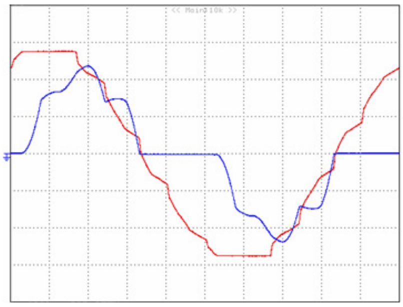
The efficiency η of the 12-pulse rectifier is decreased 1.0 to 1.5% compared with those of 6-pulse rectifier since the auxiliary circuit dissipates some additional energy. This is a drawback in the modified rectifier. However, it is expected that the efficiency of the two rectifiers with the same *THD*-i_S (i.e., the 6-pulse rectifier with larger ***%IX*** and 12-pulse rectifier with lower ***%IX***) can be much closer or almost the same. Thus, the focus in this case is which is practical whether "a slightly complicated rectifier with a smaller line-inductor" or "a simple rectifier with a bulky line-inductor." From the viewpoint of the dc voltage variation (caused mainly by voltage drops on the line inductor) and the Total-Power-Factor of,

TABLE-I. Experimental Data

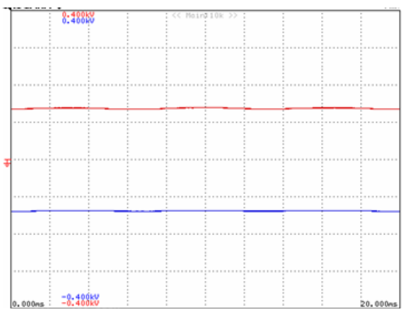
Type of Rectifier	12-Pulse				6-Pulse			
Line-Inductor $L_{A,B,C}$ [mH]	0.217		0.784		0.217		0.784	
%IX of $L_{A,B,C}$ [%](for 20 or 12kVA@200V_{RMS})	3.4	2.1	12.3	7.4	3.4	2.1	12.3	7.4
Input Line-to-Line Voltage $V_{S,L\text{-}L}$ [V_{RMS}]	198	198	198	199	199	199	199	198
Input Voltage THD (*THD*-υ_S) [%]	1.7	1.2	1.6	1.0	4.3	3.3	2.9	2.9
Input Line Current I_S [A_{RMS}]	62.6	35.4	62.1	36.6	63.2	38.3	65.1	38.4
Input Current THD *THD*-i_S [%]	10.2	11.4	5.8	7.3	29.0	38.3	18.7	23.9
Input Total-Power-Factor TPF [%]	97.7	97.6	96.7	96.8	92.7	90.2	91.7	91.6
DC-Output Voltage V_O [V]	271	277	261	270	262	(268)	246	258
DC-Output Power P_O [kW]	20.2	12.0	20.0	12.0	19.9	12.1	20.2	12.0
Efficiency η [%]	97.2	95.9	97.3	95.2	98.7	97.2	98.3	95.9



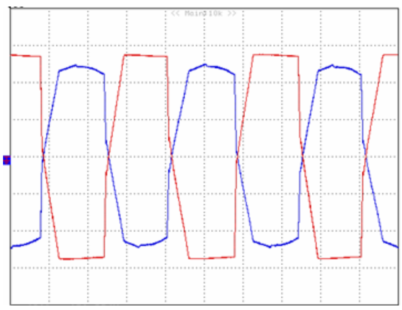
(a) Utility/Mains Line-to-Line Volt. (Blue), Utility/Mains Phase Voltages (Red), Main-Trans. Primary phase Volt. (Green) and Man-Trans. Input Line Curr. (Pink).
(Vertical - 100 [V/div] or 50 [A/div] ; Time - 2 [ms/div])



(b) Input Line-to-Line Volt. (Red) and Diode Bridge Input Line Curr. (Blue)
(Vertical - 100 [V/div] or 50 [A/div] ; Time - 2 [ms/div])

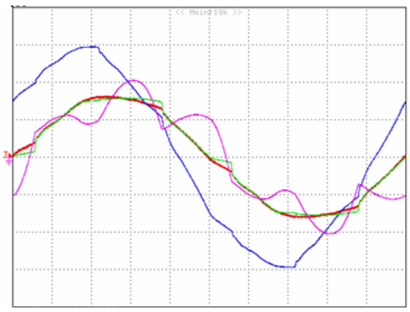


(c) DC Voltages; Upper Side (Upper Trace, Red) and Lower Side (Lower Trace with Reverse Polarity, Blue).
(Vertical - 100 [V/div] ; Time - 2 [ms/div])

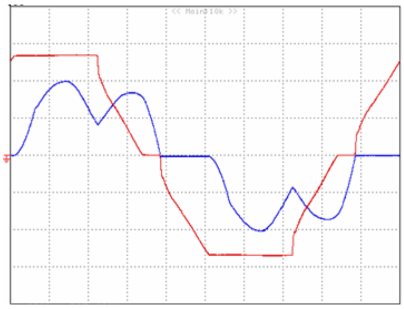


(d) Primary Volt. (Red) and Secondary Volt. (Blue) of Auxiliary Transformer
(Vertical - 50 [V/div] for Prim. or 10 [V/div] for Sec. Voltages ; Time - 2 [ms/div])

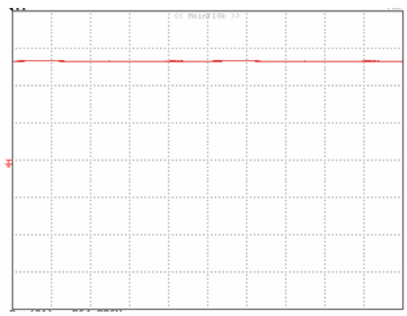
Fig. 4. Operating Waveforms (Experiments) of Modified 12-Pulse Rectifiers. (P_O = 20 kW)



(a) Utility/Mains Line-to-Line Volt. (Blue), Utility/Mains Phase Voltages (Red), Main-Trans. Primary phase Volt. (Green) and Man-Trans. Input Line Curr. (Pink).
(Vertical - 100 [V/div] or 50 [A/div] ; Time - 2 [ms/div])



(b) Input Line-to-Line Volt. (Red) and Diode Bridge Input Line Curr. (Blue)
(Vertical - 100 [V/div] or 50 [A/div] ; Time - 2 [ms/div])



(c) DC Voltages.
(Vertical - 100 [V/div] ; Time - 2 [ms/div])

Fig. 5. Operating Waveforms (Experiments) of 6-Pulse Rectifiers (P_O = 20 kW).

of the input, the modified 12-pulse rectifier is advantageous as understood from the data in the table.

In such rectifiers operated with Utility/Mains, the voltages of the Utility/Mains distorts due to the distorted current and its internal impedance. It is easily expected that the distortion of the Utility/Mains voltage is lower in the case of the 12-pulse rectifier than that of the 6-pulse rectifier. In fact, the $THD\text{-}v_S$ in the case of the 12-pulse rectifier is 1.0 to 2.0% while that in the case of 6-pulse rectifier is 2.9 to 4.3%. It must be noted that a higher distortion of the Utility/Mains voltage may cause a higher distortion of the input line current. Thus, the difference of $THD\text{-}i_S$ of the 6-pulse and the 12-pulse rectifiers in practice (i.e., with Utility/Mains) may be greater than that in theory. Although the exploration of this phenomenon is essential to evaluate the usefulness of the 12-pulse rectifier, it is omitted in this paper.

V. CONCLUSIONS

A simple and passive harmonic reducing scheme for 3-phase bridge diode rectifier of capacitor-input type has been evaluated under practical condition. It has been shown that the modified 12-pulse rectifier is advantageous for the ordinary 6-pulse rectifier when considering whole the performance including THD of the input current and Utility/Mains voltage, TPF of the input, efficiency, required inductance of the line inductor, dc-voltage variation and reliability and simplicity of the rectifier topology.

Although detail analysis of ratings of the auxiliary components has not been given in this paper, these are very low according to experimental results. Thus, the desirable features of the modified diode rectifier, such as compact, economical, efficient and reliable, are not obstructed while the new feature of low harmonic pollution and high-power-factor is obtained in the 12-pulse rectifier.

By replacing the auxiliary diodes to PWM switches, the rectifier becomes a hybrid PFC rectifier and the waveforms of the input line-current is greatly improved (i.e., to almost sinusoidal). Passive and Hybrid PFCs are now under investigating and the results, especially those from the practical viewpoints, will be presented future.

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