Practical Evaluation of Simple 12-Pulse Three-Phase-Bridge Diode Rectifier of Capacitor-Input-Type

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Abstract – A simple scheme to increase operating pulse-number and easily obtain high-quality input current waveform of three-phase diode rectifier without PWM is investigated in this paper. The topology and operation principle are described. Then, the performance is evaluated and compared with the ordinary 6-pulse rectifier by means of a 20kW setup. By referring to the experimental results, 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/Mains 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 for both the cases with and without an isolation transformer. Although this auxiliary circuit consists of only two diodes with very low rating (and an autotransformer with very low kVA for the case without isolation transformer), 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 5^{th} and 7^{th} 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 (into one-third in practice) 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 and feeds 3-phase voltages with almost no distortion) [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 involved in the voltages (υ_{XY} etc.) and the line currents (i_A etc.) on the ac input side. The remaining part is identical to the ordinary 6-pulse rectifier that consists of ac-inductors (L_A etc.), a dc-capacitor (one in the ordinary and two in the 12-pulse rectifier) and a dc-load R. This rectifier of capacitor input type produces greatly distorted input line currents if the series inductance on the utility side is provided by only such as leakage flux of transformers and is very low. In such a case, an independent inductor is connected between the Utility/Mains and the diode-bridge in each phase to mitigate the distortion. The inductors L_A, L_B and L_C in Fig.1 and 2 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 it's 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 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.

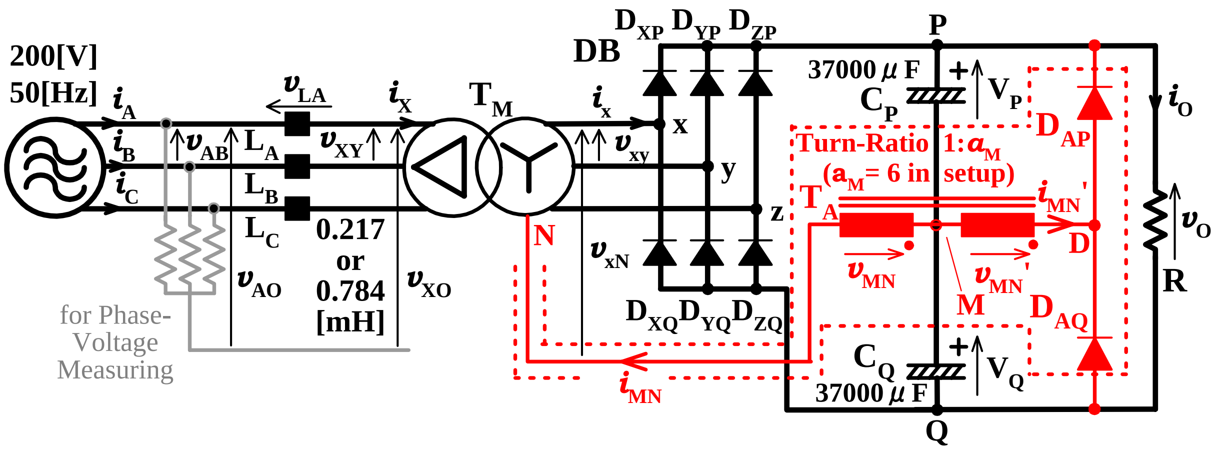


Fig. 1. Modified 12-Pulse Rectifier with Isolation Transformer.

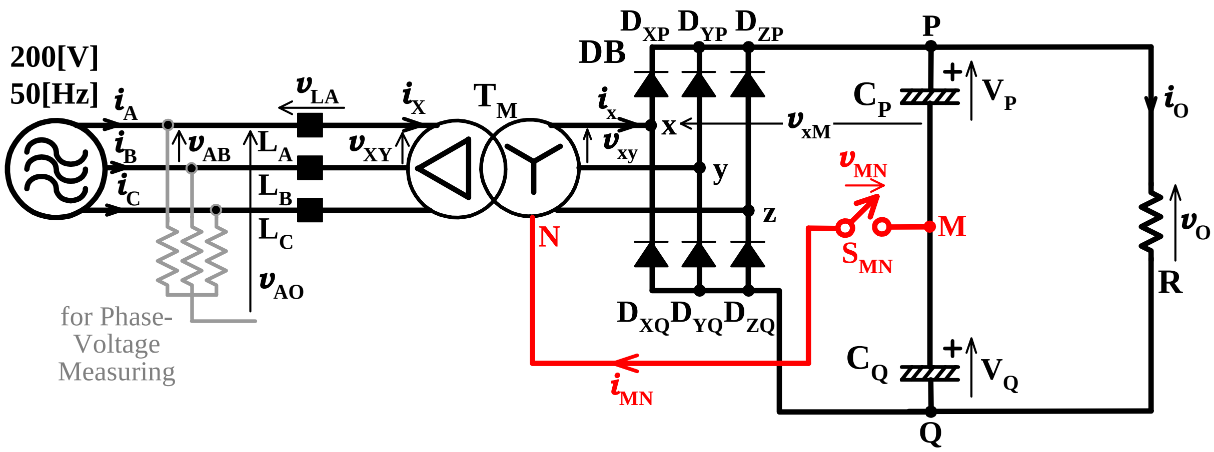


Fig. 2. Ordinary and Particular 6-Pulse Rectifiers Isolation Transformer.

III. OPERATION

The operation, especially its voltage waveform synthesis, of the modified 12-pulse rectifier is rather complicated. To understand the unique operation and the original idea in the invention of the 12-pulse rectifier, it's useful to consider that the 12-pulse nature is obtained by combining two 6-pulse rectifiers as similarly to the ordinary 12-pulse rectifier obtained by combining two 6-pulse rectifiers with a phase-shifting transformer. In this unique 12-pulse rectifier (without a phase-shifting transformer), one of the combined 6-pulse rectifiers is the ordinary one and the other is a particular one shown below.

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 an 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.

Although the detail is omitted in this paper, the operation of the unique 12-pulse rectifier can be understood as it obtained by combining the two rectifiers, i.e., the ordinary one and the particular one shown in Fig. 2. Thus, operating waveforms of the three rectifiers under ideal circuit condition (i.e., a continuous input line-current current condition) are shown in Fig. 3 where waveforms of the ordinary 6-pulse, the particular 6-pulse and the unique 12-pulse rectifiers are shown with dotted, solid and bold lines, respectively. The voltage and current symbols (e.g., i_x, bridge input line-current) of the three rectifiers are represented with the subscript of "$_{\text{-OPEN}}$" (e.g., $i_{X\text{-OPEN}}$), "$_{\text{-SHORT}}$" (e.g., $i_{X\text{-SHORT}}$) and "$_{\text{-OPTIM}}$" (e.g., $i_{X\text{- OPTIM}}$), respectively.

IV. EXPERIMENTAL RESULTS

Experimental setups of the 12-pulse and the 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 to 8 show operating waveforms of the 12-pulse and 6-pulse rectifiers with a low inductance ($L_{A,B,C}$=0.217mH) and a high ($L_{A,B,C}$=0.784mH) of the line-inductor. The output power is P_O=20kW. in all Fig. 4 to 8.

By comparing the input currents in Fig. 4 (a) and Fig. 5 (a) (for $L_{A,B,C}$ = 0.217mH) and Fig. 6 (a) and Fig. 7 (a) (for $L_{A,B,C}$ = 0.784mH), it is easily known that the 12-pulse rectifier offers a higher quality input

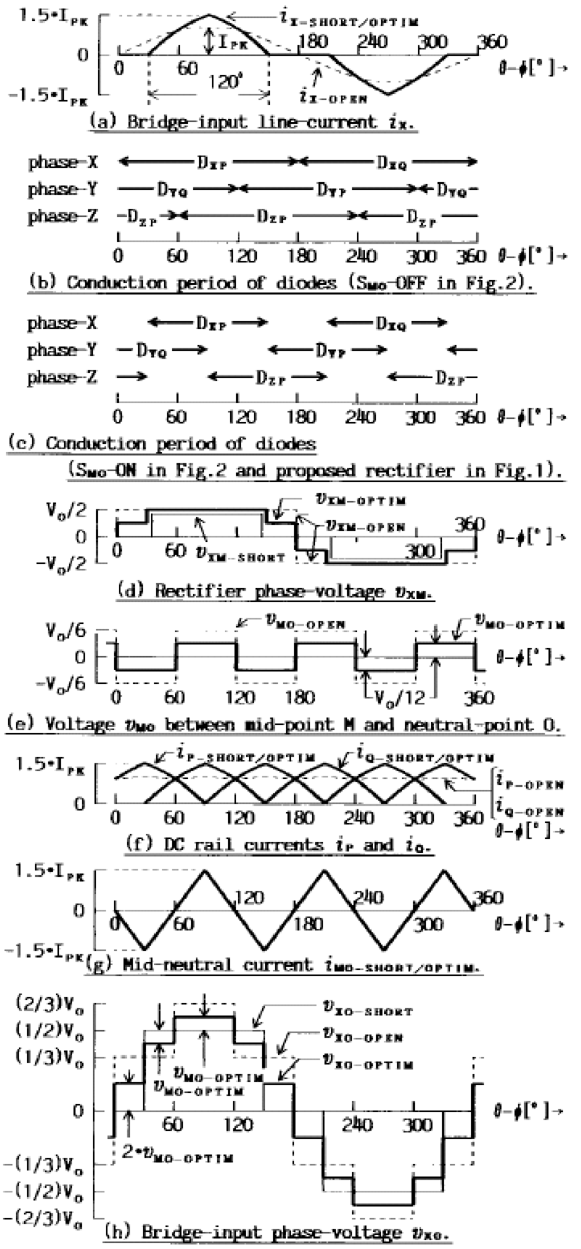


Fig. 3. Theoretical Operating Waveforms of Ordinary 6-Pulse, Particular 6-Pulse and Modified 12-pulse Rectifiers

current while that of the 6-pulse rectifier is distorted. The *THD*-i_S of the 12-pulse rectifier is 10.2 or 5.8% for the cases of the lower or the higher inductance, respectively, and those are almost one-third of that of the 6-pulse rectifier (29.0 and 18.7%, respectively). It is know by comparing the current waveforms in Fig. 4 (a) and Fig. 7 (a) that the 12-pulse rectifier offers a higher quality in the input current waveform even the inductance is decreased to one-third compared with the 6-pulse rectifier. Additionally, it is understood from the input current waveforms that the

TABLE-I. Measured Data in Experiments

	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 20kVA@200V_{RMS})**	**3.4**	**2.1**	**12.3**	**7.4**	**3.4**	**2.1**	**12.3**	**7.4**
Input Line-to-Line Voltage $V_{S, L-L}$ [V_{RMS}]	**198**	**198**	**198**	**199**	**199**	**199**	**199**	**198**
Input Voltage THD (*THD-v_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**

displacement angle of the 12-pulse rectifier is less 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) and Fig. 6 (b) are differ from those in theory shown in Fig. 3 (h) and (a), respectively. The dominant reason is that a continuous current condition is considered in the theory but the setup operates with a discontinuous current condition. Therefore, the waveforms in the case with higher line-inductance (i.e., with less current discontinuity) are more similar to those of the theory than the other.

The dc voltages in both the rectifiers are smooth since dc-capacitors of 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.

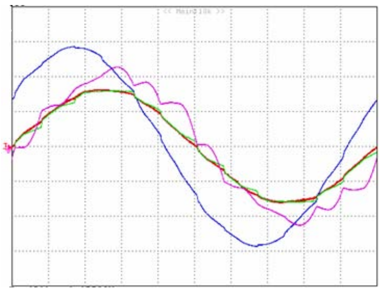
As seen in Fig. 8 (a) and (b), the primary and the secondary voltages of the auxiliary transformer T_A lose sharpness in the waveforms although those of the theory draw sharp rectangular waveforms with full width as shown in Fig. 3 (e). The distortion of the primary voltage is due to the discontinuity of the input current. Therefore, the primary voltage of the case with the lower line-inductance shown in Fig. 8 (a) is slightly more distorted compared with the other since the line-current discontinuity is greater in the case. The secondary voltage produces additional distortion especially on the top. This is caused by voltage drops on the windings due to leakage inductance and resistance of the windings. This phenomenon is understood by considering the triangular current (in theory) 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.

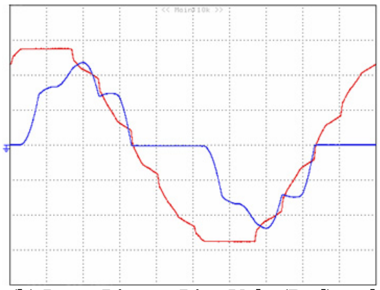
The efficiency η of the 12-pulse rectifier is decreased 1.0 to 1.5% compared with those of 6-pulse rectifier with the same line inductance since the auxiliary circuit dissipates some additional energy. This is a drawback in the modified rectifier. However, it is expected that the efficiency of the two rectifiers with the same *THD*-i_S (i.e., the 6-pulse rectifier with higher ***%IX*** and 12-pulse rectifier with lower ***%IX***) can be much closer or almost the same. In fact, the efficiency of the 12-pulse rectifier with less line-inductance and the 6-pulse one with higher line-inductance are close (97.2% vs. 98.3% in P_O=20kW) or the same (both 95.9% in P_O=12kW).

Thus, the focus in this case is which is practical; "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 the input, the modified 12-pulse rectifier is advantageous as understood from the data in the table.

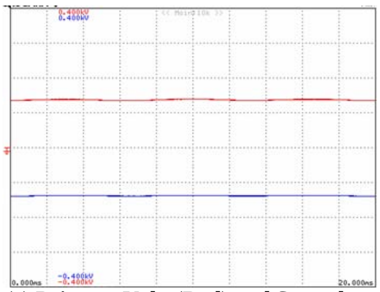
In such rectifiers operated with Utility/Mains, the voltages of the Utility/Mains distorts due to the distorted line-current and its internal impedance. It is easily expected that the distortion of the Utility/Mains voltage is lower in the case of the 12-pulse rectifier than that of the 6-pulse rectifier. In fact, the *THD*-v_S in the case of the 12-pulse rectifier is 1.0 to 1.7% 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



(a) Utility/Mains Line-to-Line Volt. (Blue), Utility/Mains Phase-Voltages (Red), Main-Trans. Prim. Phase-Volt. Green), Man-Trans. Input Line-Curr. (Pink). (100V/div. or 50A/div., 2ms/div.)

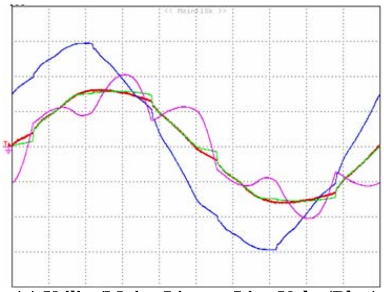


(b) Input Line-to-Line Volt. (Red) and Input Line-Curr. (Blue) of Diode-Bridge Input (100 V/div. or 50A/div., 2 ms/div.)

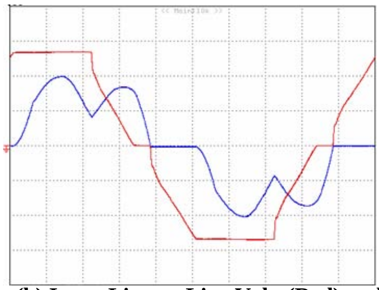


(c) Primary Volt. (Red) and Secondary Volt. (Blue) of Aux. Transformer. (50V/div. for Prim. or 10V/div. for Sec., 2ms/div.)

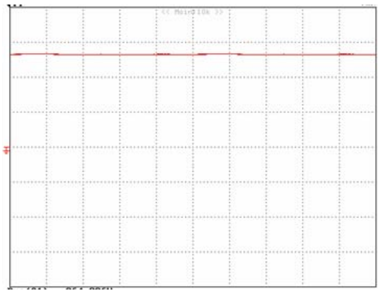
Fig. 4. Operating Waveforms of 12-Pulse Rectifeir with $L_{A,B,C}$=0.217mH



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

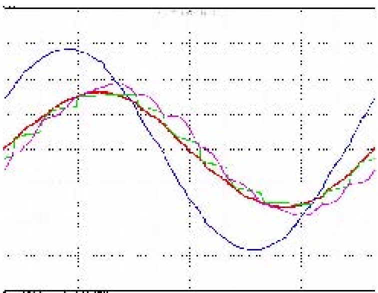


(b) Input Line-to-Line Volt. (Red) and Input Line-Curr. (Blue) of Diode-Bridge Input (100 V/div. or 50A/div., 2 ms/div.)

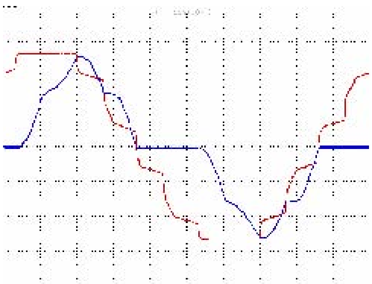


(c) DC Voltages. (100V/div., 2ms/div.)

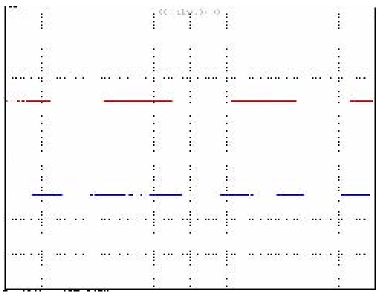
Fig. 5. Operating Waveforms of 6-Pulse Rectifeir with $L_{A,B,C}$=0.217mH



(a) Utility/Mains Line-to-Line Volt. (Blue), Utility/Mains Phase-Voltages (Red), Main-Trans. Prim. Phase-Volt. Green), Man-Trans. Input Line-Curr. (Pink). (100V/div. or 50A/div., 2ms/div.)

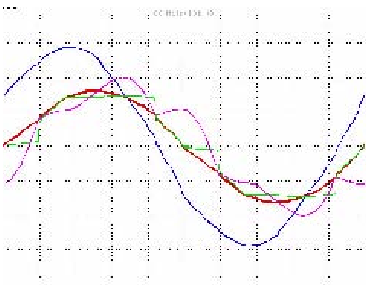


(b) Input Line-to-Line Volt. (Red) and Input Line-Curr. (Blue) of Diode-Bridge Input (100 V/div. or 50/div., 2 ms/div.)

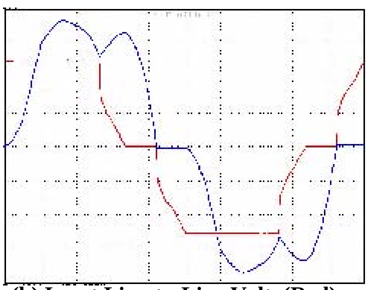


(c) DC Voltages. (100V/div., 2ms/div.)

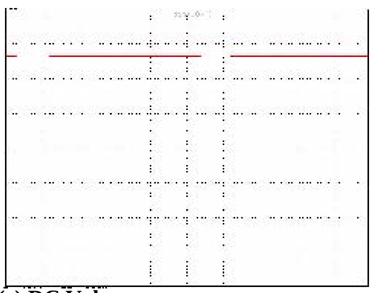
Fig. 6. Operating Waveforms of 12-Pulse Rectifeir with $L_{A,B,C}$=0.784mH



(a) Utility/Mains Line-to-Line Volt. (Blue), Utility/Mains Phase-Voltages (Red), Main-Trans. Prim. Phase-Volt. Green), Man-Trans. Input Line-Curr. (Pink). (100V/div. or 50A/div., 2ms/div.)

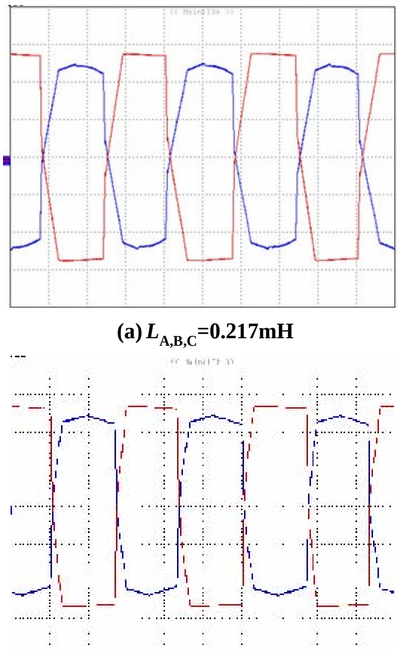


(b) Input Line-to-Line Volt. (Red) and Input Line-Curr. (Blue) of Diode-Bridge Input (100 V/div. or 50/div., 2 ms/div.)



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

Fig. 7. Operating Waveforms of 6-Pulse Rectifeir with $L_{A,B,C}$=0.784mH



(a) $L_{A,B,C}$**=0.217mH**

(b) $L_{A,B,C}$**=0.784mH**

Fig. 8. Primary Voltage (Red) (50V/div.) and Secondary Voltage (Blue) (10V/div.) of Auxiliary Transformer. (Time-Scale: 2ms/div.)

the input line current since the voltage synthesis (and the resulted current synthesis) is sensitive to the distortion of Utility/Mains voltage waveform and the performance may easily obstructed by the distorted. Thus, the difference of $THD\text{-}i_S$ of the 6-pulse and the 12-pulse rectifiers in practice (i.e., with Utility/Mains having a certain impedance) may be greater than that in theory (and Utility/Mains with lower impedance or higher capacity). Although the exploration of this phenomenon is essential to evaluate the performance and usefulness of the 12-pulse rectifier especially in a weak Utility/Mains condition, it is omitted in this paper.

Although an exact analysis has not completed, a significant harmonic reduction by increasing the line inductance is disadvantageous since the effect saturates in medium to low $THD\text{-}i_S$ range. Thus, the scheme with increasing the operating pulse number is advantageous to mitigate the distortion into middle to low level.

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, necessary inductance of the line inductor, dc-voltage variation, reliability and simplicity of the rectifier topology.

Although detail analysis of ratings of the auxiliary components has not been described 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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