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A 12-pulse Diode Rectifier Using 3-Phase Bridge 6-Pulse Diode Rectifier with 2 Additional Diodes and An Auto-Transformer

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Abstract* – *This paper presents a 12-pulse diode rectifier of capacitor input type consisting of the conventional three-phase bridge 6-pulse diode rectifier with an auxiliary circuit. Although the auxiliary circuit consists of an auto-transformer with very low kVA and two auxiliary diodes with very low rating, it plays the roll to increase operation pulse number to 12. As a result, harmonics of the input line currents are greatly reduced and the THD is reduced to a quoter of the conventional 6-pulse rectifier. Since the new rectifier does not consist of a self-turn-off device nor a controller, the proposed scheme results in a compact, reliable and efficient solution to obtain uncontrolled dc-voltage from the utility without harmonic pollution.

In this paper, the unique arrangement and particular operation of the auxiliary circuit are introduced. Then, experimental results are shown to confirm the validity of the theory.

I. INTRODUCTION

Several harmonic reducing schemes of diode rectifier without PWM have been proposed so far [1]-[8]. 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 systems and UPS systems, and this type inverter needs a dc voltage source. Since dc-voltage controllability is not always necessary in these applications, the 3-phase bridge diode rectifier of capacitor input type is the most suitable from the viewpoint of initial-cost, operating efficiency and reliability. Though, harmonic reduction of this type rectifier without PWM technique has not been explored well in the past.

With the above technical background, the author proposes 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 auto-transformer with very low kVA, it plays the role to increase the operating pulse number to 12. Due to this effect, dominant harmonics of order of 5th and 7th in the input current of the conventional rectifier are eliminated. As a result, total harmonic distortion of the input current of the proposed rectifier is decreased to a quarter of the conventional 6-pulse diode rectifier.

In the following, theory of the pulse number doubling and harmonic reducing is introduced. Then, the validity of the theory is confirmed through experimental results.

II. CIRCUIT TOPOLOGY

Fig.1 shows the proposed 12-pulse diode rectifier with an isolation transformer. This isolation transformer is not always necessary, and the proposed rectifier circuit for that case is described later. The part enclosed by dotted lines represents the auxiliary circuit to increase the operating pulse number and reduce harmonics. The remaining part represents the conventional 6-pulse rectifier that consists of ac-inductors (L_A etc.), a 3-phase isolation transformer (main transformer Trf.M), a three-phase diode-bridge, dc-capacitors (C_P and C_Q) and a dc-load R_O. This rectifier of capacitor input type produces large harmonic currents if the series inductance of the utility (provided by such as leakage flux of transformers) is very low. In such case, an 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.

The auxiliary circuit consists of two diodes (D_P and D_Q) connected in series between the dc-rails and a single-phase auto-transformer T_M. The left-side winding of T_M is connected between the midpoint M and the neutral point N provided by the secondary windings of Trf.M. On the other hand, the right-side winding of T_M is connected between the midpoint M and midpoint D provided by the series connected diodes (D_P and D_Q).

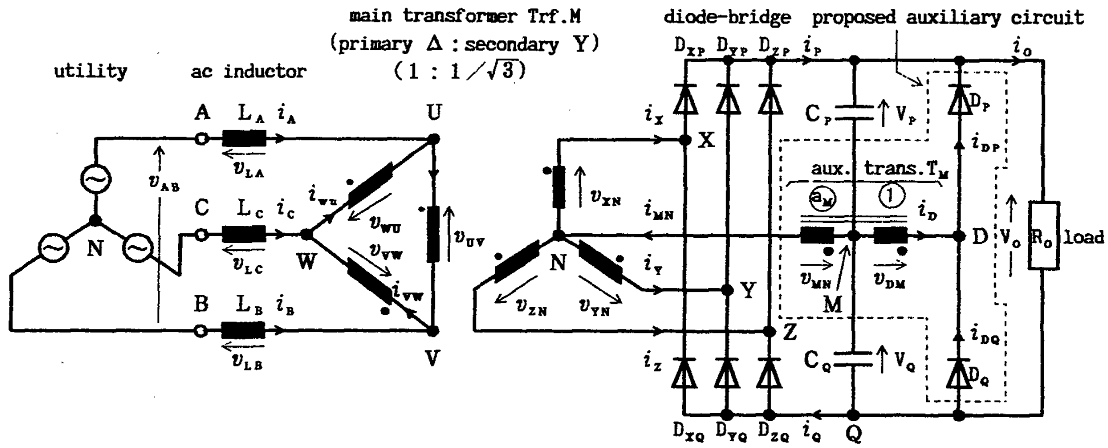


Fig.1. Proposed 12-Pulse Diode Rectifier (with Isolation Transformer).

III. OPERATION OF PROPOSED RECTIFIER

A. Review of Conventional 6-Pulse Rectifier Operation

Operation of the conventional 6-pulse rectifier shown in Fig.2 is reviewed in this part "*A* ". Because the midpoint M is necessary to compare the operation of the conventional and proposed rectifiers, two capacitors (C_P and C_Q) are employed in Fig.2 too. Additionally, the midpoint M and the neutral point N are connected through the dotted line and the switch S_{MN} in Fig.2, since it's necessary to short these points in the succeeding discussion in part "*B* ". When the switch S_{MN} is held open, the circuit of Fig.2 becomes the conventional 6-pulse rectifier. Therefore, subscript "$_{\text{-OPEN}}$" is added to symbols of voltages and currents of the conventional 6-pulse rectifier.

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. Inductances of L_A etc. are the same and large enough so that the utility line currents (i_A etc.) draw 3-phase symmetrical and continuous waveforms. Operating waveforms of this 6-pulse rectifier under continuous utility line current are shown by dotted lines in Fig.3, where the input line currents are assumed to be sinusoidal for drawing convenience. Horizontal axis of Fig.3 represents phase angel "θ−φ", where "φ" represents displacement angle of the utility line current against the utility phase-to-neutral voltage.

The utility line currents are continuous, and thus the bridge-input line currents ($i_{X\text{-OPEN}}$ etc.) are continuous too, as shown by dotted line in Fig.3(a). Thus, one of the upper diode (D_{XP} etc.) or lower diode (D_{XQ} etc.) in each phase of

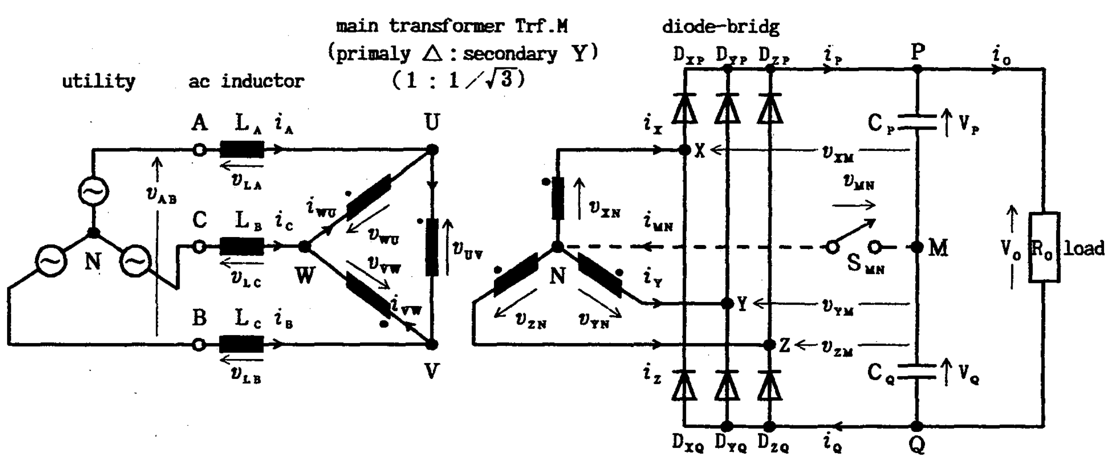


Fig.2. Convenrtional 3-Phase Bridge 6-Pulse Diode Rectifier (with Isolation Transformer).

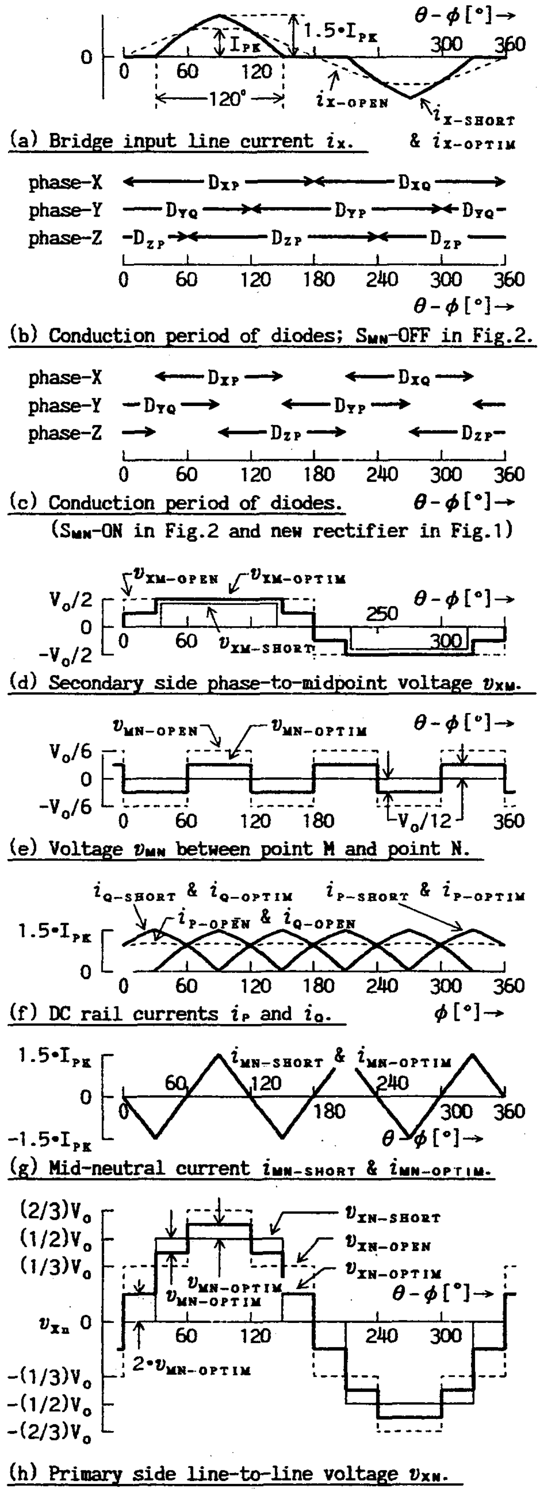


Fig.3. Operating waveforms of diode rectifiers.

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 midpoint M in the positive or negative direction, respectively. Thus, rectangular voltages (v_{XM} etc.) with amplitude of $V_O/2$ appear between the input terminals (X etc.) and the midpoint M, as shown by dotted line in Fig.3(d).

Since the main transformer Trf.M is a three-phase transformer, sum of the voltages of the secondary windings (i.e., $v_{XN\text{-}OPEN}+v_{YN\text{-}OPEN}+v_{ZN\text{-}OPEN}$) must be zero. On the other hand, sum of the voltages appearing between the bridge-inputs (X, Y and Z) and the midpoint M (i.e., $v_{XM\text{-}OPEN}+v_{YM\text{-}OPEN}+v_{ZM\text{-}OPEN}$) is not zero. Thus, a rectangular voltage $v_{MN\text{-}OPEN}$ with triple frequency and amplitude of $V_O/6$ appears between the midpoint 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 ($v_{XN\text{-}OPEN}$ 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 (v_{UV} etc.) on the primary winding draw 6-pulse waveform. This 6-pulse waveform involves high content lower order harmonics such as 5th and 7th, while the utility voltage involves almost no harmonic.

The voltages (v_{LA} etc.) applied on the ac-inductors are obtained by subtracting the utility voltages and the primary winding voltages, and amplitudes of the fundamental components of the utility and primary winding voltages are almost the same. Thus, amplitude of fundamental component of v_{LA} is very low while those of the lower order harmonics are very high. Therefore, amplitudes of the lower order harmonics involved in v_{LA} and v_{UV} are the same but contents (or percentage against the fundamental) of them in v_{LA} are much higher than those in v_{UV}. Thus, a high inductance is required to the inductors (L_A etc.) to reduce harmonics of the utility line currents. If the dominant 5th and 7th harmonics of v_{XN} (and thus those of v_{UV} and v_{LA}) are eliminated, the ac-inductors to reduce utility line current harmonics can be greatly reduced in size, weight and cost. As described in part "*C* ", this advantageous condition is obtained by adding the proposed auxiliary circuit.

B. Unexplored 6-Pulse Rectifier and its Operation.

If the switch S_{MN} is closed in Fig.2, we obtain a rectifier circuit. Although the circuit topology and the operation have not been discussed in the past, this circuit obtains a 6-pulse rectifier operation as explain below. Comparing with the conventional 6-pulse rectifier, no advantage in harmonic reduction is obtained from this unexplored rectifier. Though, its operation is discussed in the following because it's very interesting and useful to explain the operation of the proposed 12-pulse rectifier.

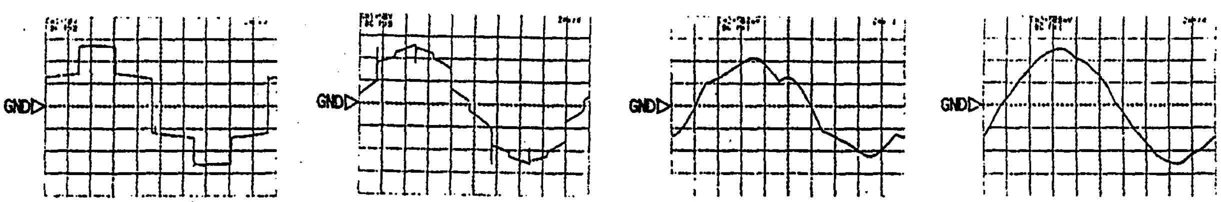
Operating waveforms of this rectifier are shown in Fig.3 by solid lines or bold lines when overlapped with those of that the polarity of $i_{MN\text{-}OPTIM}$ shown in Fig.3(g) equals that of the voltage $v_{MN\text{-}OPTIM}$ shown in Fig.3(e) for whole period. When $i_{MN\text{-}OPTIM}$ flows through the left-side winding of T_M with the positive direction ($i_P > i_Q$ in this condition), a counter current i_D flows through the right-side winding with the positive direction to cancel the ampere-turn produced by the left-side winding and $i_{MN\text{-}OPTIM}$. Since this counter current i_D can flow through only the auxiliary diode D_P, this diode turns-on and the voltage V_P ($=V_O/2$) is applied on the right-side winding of T_M with the positive direction (i.e., $v_{DM}=V_O/2$). Therefore, a voltage $a_M V_O/2$ is induced on the left-side winding with positive direction (i.e., $v_{MN}=a_M V_O/2>0$, $a_M>0$ and $V_O>0$), where a_M represents the turn-ratio of T_M as shown in Fig.1. On the other hand, when the mid-neutral current $i_{MN\text{-}OPTIM}$ flows with the negative direction ($i_P < i_Q$ in this condition), the voltage $v_{MN\text{-}OPTIM}$ turns the direction to negative but the amplitude (or the absolute value) is not changed and equal to $a_M V_O/2$ (i.e., $v_{MN\text{-}OPTIM}= -a_M V_O/2<0$). Since the mid-neutral current $i_{MN\text{-}OPTIM}$ alternates the flowing direction with triple frequency as shown by bold line in Fig.3(g), $v_{MN\text{-}OPTIM}$ alternates its direction with triple frequency too, as shown by bold line in Fig.3(e). As a result, the polarity of the induced voltage $v_{MN\text{-}OPTIM}$ on the left-side winding of T_M becomes to be the same to that of the mid-neutral current $i_{MN\text{-}OPTIM}$.

The amplitude of $v_{MN\text{-}OPTIM}$ is controllable by the turn-ratio a_M. Thus, the turn-ratio a_M is set to 1/6 to obtain the optimal amplitude (i.e., $|v_{MN\text{-}OPTIM}|=|a_M v_{DM}|=a_M V_O/2=V_O/12$) as shown by bold lines in Fig.3(e). As mentioned above, the voltage v_{MN} can be set to the optimum value ($v_{MN\text{-}OPTIM}$) by means of the auxiliary circuit, and thus significant harmonic reduction of the utility line currents is obtained by a small ac-inductors in the new rectifier shown in Fig.1.

IV. EXPERIMENTAL RESULTS

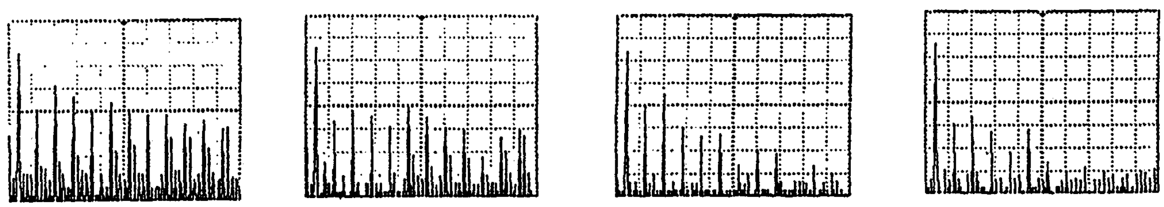
Experimental waveforms and their harmonic analysis are shown in Fig.4 and 5, respectively. The parameters and measured data are listed in Table 1. The line-to-line voltage $v_{UV\text{-}OPEN}$ of the conventional rectifier draws almost ideal 6-pulse waveform as shown in Fig.4(a), while that of the proposed rectifier ($v_{UV\text{-}OPTIM}$) draws quasi 12-pulse waveform as shown in Fig.4(b). Although waveform of $v_{UV\text{-}OPTIM}$ is slight differ from that of theory due to influence of leakage inductance of transformers, great reduction of dominant harmonics of order of 5th and 7th is confirmed by comparing harmonic analysis shown in Fig.5(a) and (b).

Due to the effect of harmonic voltage reduction, waveform of the utility line current is greatly improved as shown in Fig.4(c) and Fig.4(d). From harmonic analysis shown in



(a) $v_{UV\text{-}OPEN}$ (conventional rectifier) (b) $v_{UV\text{-}OPTIM}$ (proposed rectifier) (c) $i_{A\text{-}OPEN}$ (conventional rectifier) (d) $i_{A\text{-}OPEN}$ (conventional rectifier)

Fig.4. Waveforms of primary line-to-line voltage v_{UV} and utility line current i_A (experiment).
(Vertical - 50 [V/div.] or 5 [A/div.]; Horizontal - 2.5 [ms]/[div.])



(a) $v_{UV\text{-}OPEN}$ (conventional rectifier) (b) $v_{UV\text{-}OPTIM}$ (proposed rectifier) (c) $i_{A\text{-}OPEN}$ (conventional rectifier) (d) $i_{A\text{-}OPEN}$ (conventional rectifier)

Fig.5. Harmonic analysis of primary line-to-line voltage v_{UV} and utility line current i_A in Fig.5.
(Vertical - amplitude in [dB]; Horizontal - frequency in Linear, 1.25 [kHz]/full-scale or 125 [Hz]/[div.])

Table 1. Parameters and measured data in Experiment.

PARAMETERS			
AC Inductors : L_A etc.			9.2 [mH]
DC Capacitors : C_P & C_Q			13,600 [μF]
MEASURED DATE			
Items		Conventional Rectifier	Proposed Rectofoer
Utility Side			
Line-to-line voltage :	V_{AB} [V_{RMS}]	100	100
Total-Harmonic-Distortion of line-to-line voltage v_{AB} :	THD_V [%]	2.7	1.9
Line current :	I_A [A_{RMS}]	8.7	7.2
Total Harmonic Distortion of line current i_A :	THD_i [%]	**13.0**	**3.4**
Utility apparent power [kVA]		1.33	1.55
Total-Power-Factor [%]		84.0	86.6
Active Power [kW]		1.12	1.34
DC Output Side			
Output voltage :	V_O [V]	102	109
Output current :	I_O [A]	9.8	10.6
Output power :	P_O [kW]	1.00	1.15
Efficiency :	η [%]	89.8	86.0

Fig.5(c) and Fig.5(d), it is known that dominant harmonics, such as order of 5th and 7th, of the utility line current i_A in conventional rectifier are greatly reduced in the proposed rectifier. As shown in Table 1., Total Harmonic Distortion (THD_i) of the utility line current i_A of the conventional 6-pulse rectifier is 13.0[%], while that of the proposed rectifier is decreased to 3.4[%]. Thus, the THD_i is reduced to almost a quarter by means of the proposed scheme.

From the experimental results, it is confirmed that the proposed rectifier operates as a 12-pulse rectifier and harmonics of the voltages and especially of the utility line currents are greatly reduced as compared with the conventional 6-pulse rectifier.

Although it is not mentioned in this digest due to space limitation, parallel operation of the two 6-pulse rectifiers discussed in part "*A*" and "*B*" in chaper III obtains 12-pulse operation as same as the rectifier proposed in this paper. Its detail will be discussed in near future.

VI. CONCLUSIONS

A new harmonic reducing scheme for 3-phase bridge diode rectifier of capacitor-input type with non-PWM scheme has been proposed in this paper. Since the proposed scheme requires only passive components such as low rating diodes and a low kVA auto-transformers, it gives an economical, reliable and efficient solution to mitigate the harmonic pollution produced by rectifiers.

The ratings of the components in the auxiliary circuit have not been analyzed in this paper, these are very small and kVA of the auxiliary auto-transformer T_M and product of RMS current and maximum applied voltage of the auxiliary diodes (D_P and D_Q) are around 10 [%] of the output power. This fact is easily understood by considering that the voltage applied on the auxiliary auto-transformer T_M and the current flowing through the auxiliary diodes are both very low comparing the dc-output voltage V_O and current I_O

For applications without isolation between the utility and dc output, a three-phase zigzag transformer is applicable to obtain the neutral point of the proposed rectifier. The kVA of this zigzag transformer is less than a quarter of kVA of the isolation transformer Trf.M in Fig.1 and 2. Large ac-inductors are employed in the experiments to confirm the theoretical operation. If the inductance is decreased, harmonics with higher contents are involved in the utility line currents of the proposed rectifier. Though, utility line currents of the conventional 6-pulse rectifier involve higher contents harmonics too in the same condition. Thus, harmonic reducing effect of the proposed scheme (or ratio of THD_i of proposed and conventional rectifiers) does not depend on the inductance.

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