AUTOTRANSFORMER CONFIGURATIONS TO ENHANCE UTILITY POWER QUALITY OF HIGH POWER AC/DC RECTIFIER SYSTEMS

Sewan Choi *Prasad N. Enjeti*[*] *Ira J. Pitel*[**]

Power Electronics Laboratory[*]
Department of Electrical Engineering
Texas A&M University
College Station, Texas 77843-3128
Tel: (409) 845-7466
Fax: (409) 845-6259

Magna-Power Electronics[**]
85 Fulton st.
Boonton, NJ 07005
Tel: (201) 263-0017
Fax: (201) 263-1928

Abstract - In this paper new autotransformer arrangements with reduced kVA capacities are presented for harmonic current reduction and to improve AC power quality of high current DC power supplies. A twelve-pulse AC to DC rectifier is proposed employing only 0.18P_o (pu) transformer kVA. The 5th and 7th harmonics are absent in the utility line currents. Further it is shown that conventional 12-pulse operation can be increased to 24 pulse with the introduction of tabs on the interphase reactor. Analysis and Simulation of the proposed schemes confirm the cancellation of lower order harmonics. Several example implementations of the proposed schemes for high current DC power supplies are shown. All of the above schemes provide clean power utility interface and complies with IEEE 519 recommended practices.

I. INTRODUCTION

Large harmonics, poor power factor and high total harmonic distortion (THD) in the utility interface are common problems when nonlinear loads such as AC or DC power supplies are connected to the electric utility. Magnet power supplies are commonly used for high current particle accelerators. The conventional magnet supplies are conventional 6 pulse or 12 pulse rectifiers as shown in Fig. 1. As the research in high energy physics progresses and as the particle accelerators find many applications in industrial and medical areas, the magnet power supplies with high input power quality and better performance will increase in demand [1]. The recommended practice, IEEE 519, has evolved to maintain utility power quality at acceptable levels [2]. In response to these concerns, this paper proposes new autotransformer arrangements to reduce the kVA rating of the transformer. Fig. 2 shows a method to reduce kVA rating of 12-pulse diode rectifiers with hybrid connection of delta-wye transformer. The kVA rating of the hybrid delta-wye transformer is 0.78V_oI_o (pu). The kVA rating of 12-pulse rectifiers is further reduced by the proposed autotransformer arrangements shown in Fig. 3. In the proposed autotransformer arrangements, the windings are

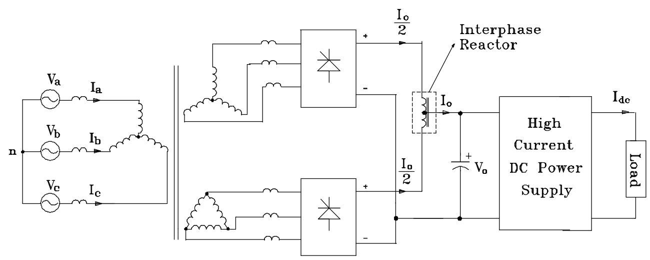


Fig. 1 Conventional 12-pulse diode rectifier for high current DC power supply (kVA rating of the transformer = 1.03V_oI_o)

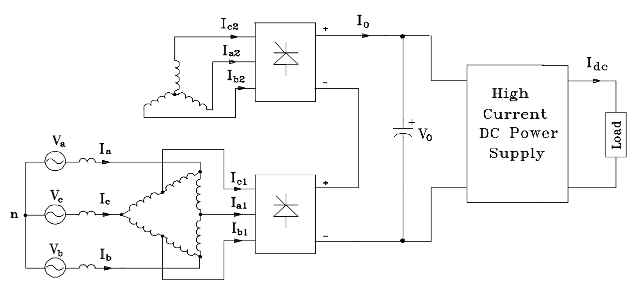


Fig. 2 Reduced kVA hybrid delta-wye 12-pulse diode rectifier (kVA rating = 0.78V_oI_o)

interconnected such that the kVA transmitted by the actual magnetic coupling is only a portion of the total kVA.The kVA rating of the autotransformer employed in 12-pulse rectifiers is 0.18V_oI_o (pu). The reduced kVA rating of the autotransformer makes it physically smaller, less costly, and of higher efficiency than isolation transformers. With the reduction of kVA rating of the transformer a new method to improve the quality of AC input currents by introducing taps on the interphase reactor of 12-pulse diode rectifiers is also proposed and discussed in the paper.

II. REDUCED kVA AUTOTRANSFORMER ARRANGEMENT FOR 12-PULSE RECTIFIERS

Fig. 3 shows the twelve-pulse configuration of the proposed approach to reduce kVA rating of the transformer. The interphase reactors are included to ensure the independent

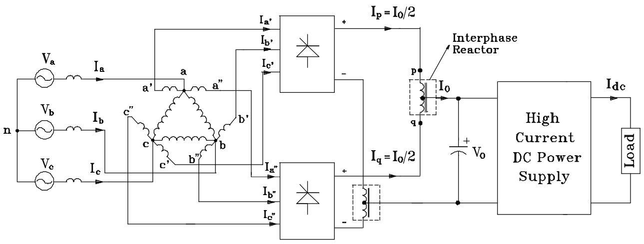
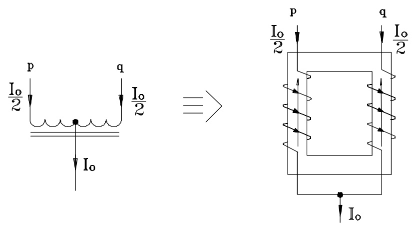
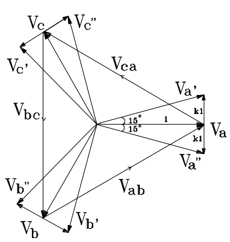
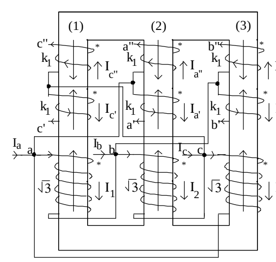


Fig. 3 Proposed reduced kVA twelve-pulse approach with autotransformer arrangements (kVA rating = $0.18V_oI_o$)



(a)





(b) (c)

Fig. 4 (a) Winding configuration of interphase reactor (b)Vector diagram (c) Winding configuration of the autotransformer of the proposed scheme (Fig. 3)

operation of the two three-phase diode bridge rectifiers supplying nonlinear loads. The practical winding configuration of an interphase reactor is shown in Fig. 4(a). The diodes in each diode bridge rectifier conduct for 120 degrees per cycle, and the rectifier input currents ($I_{a'}$, $I_{b'}$, $I_{c'}$ as well as $I_{a''}$, $I_{b''}$, and $I_{c''}$) consist of the six-pulse characteristic harmonics.

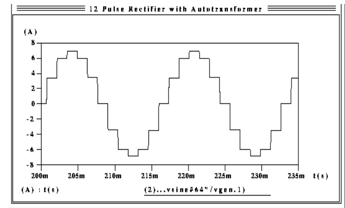
The vector diagram of the autotransformer connection and the winding representation on a three limb core are shown in Fig. 4 (b) and (c) respectively. The optimum phase shift angle between a'b'c' and a"b"c" is 30 degrees. Therefore, from Fig. 4 (b) the length k_1 becomes 0.26(pu).

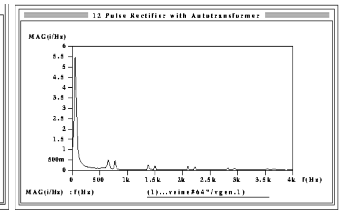
From the MMF balanced equations of the three limbs as shown in Fig. 4(c), the utility line current I_a is obtained by,

$$I_a = I_{a'} + I_{a''} + \frac{k_1}{\sqrt{3}}(I_{c''} - I_{b''} + I_{b'} - I_{c'}) \quad (1)$$

The proposed twelve-pulse approach is simulated on SABER for continuous operation. Fig. 5 (a) and (b) show the utility line currents and the frequency spectrum of the line current I_a. Note that the fifth and seventh harmonics are absent. It is also noted that the fundamental power factor is unity.

The autotransformer utilized in the proposed twelve-pulse system is designed such that the size (in kVA) of the transformer is minimized.





(a) (b)

Fig. 5 (a) Utility line current I_a (b) Frequency spectrum of I_a for a highly inductive load

Assume that dc output current I_o is highly inductive. Then the equivalent kVA of the autotransformer becomes,

$$kVA_{tot} = \frac{1}{2}\left(6|I_a^{'}||V_{aa}^{'}| + 3|I_1||V_{ab}|\right) \quad (2)$$
$$= 0.18\, I_o V_o$$

That is, the reduction of the size in kVA of the proposed 12-pulse scheme is 82% in comparison to the conventional 12-pulse diode rectifier.

The proposed approach can also be applied to twelve-pulse systems employing two three-phase diode bridge rectifiers feeding separate DC power supplies as shown in Fig. 6. The fifth and seventh harmonic current magnitude becomes,

$$|I_{a,5}| = 0.224|I_p - I_q| \quad (3)$$

and

$$|I_{a,7}| = 0.160|I_p - I_q| \quad (4)$$

Therefore if the two rectifier output dc current magnitudes I_p and I_q are identical, which is the case for Fig. 3 where $I_p = I_q = \frac{1}{2}I_o$, then the magnitude of the fifth and seventh harmonics of the input utility line currents go to zero, i.e. $|I_{a,5}| = |I_{a,7}| = 0$. When the output dc current amplitudes I_p and I_q are different, the fifth and seventh harmonics will be reduced to the magnitude of their difference as shown in eqns (3) and (4).

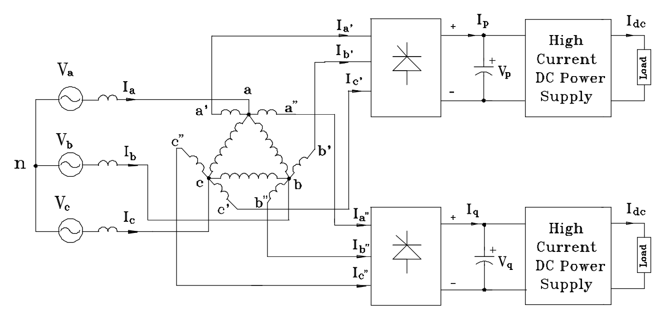


Fig. 6 Proposed twelve-pulse approach feeding two separate DC power supplies.

III. REDUCED KVA 24-PULSE DIODE RECTIFIER

Fig 7 shows the proposed 24-pulse system which is identical to the conventional 12-pulse system with the exception of the two diodes connected to the interphase reactor.

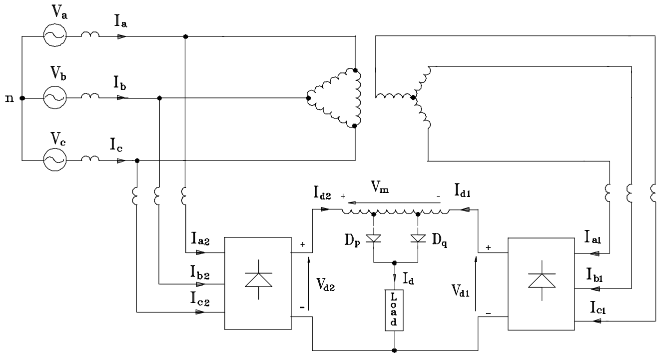


Fig. 7 Reduced kVA 24-pulse system
(kVA rating = $0.52V_oI_o$)

Fig. 8 shows the operation of the two diodes connected to the interphase reactor and the practical winding configuration of the interphase reactor according to two modes: P-mode(Fig. 8(a)) and Q-mode(Fig. 8(b)). Whenever the voltage across the interphase reactor goes positive ($V_m > 0$), diode D_p is turned on and D_q is turned off (P-mode) and therefore diode D_p carries load current I_d. From the MMF relationship of the interphase reactor for the P-mode, the output currents of the two diode bridge rectifiers is given by,

$$I_{d1} = (0.5 - k) I_d \quad (5)$$

$$I_{d2} = (0.5 + k) I_d \quad (6)$$

where $k = N_o/N_t$ and N_o is the total number of turns of the interphase reactor and N_t is the number of turns between the midpoint and the tapped points of the interphase reactor.

Whenever $V_m < 0$, diode D_q is turned on, and D_p is turned off and therefore diode D_q carries load current I_d (Q-mode). Similarly, for Q-mode the output currents of the two diode bridge rectifiers can be obtained by,

$$I_{d1} = (0.5 + k) I_d \quad (7)$$

$$I_{d2} = (0.5 - k) I_d \quad (8)$$

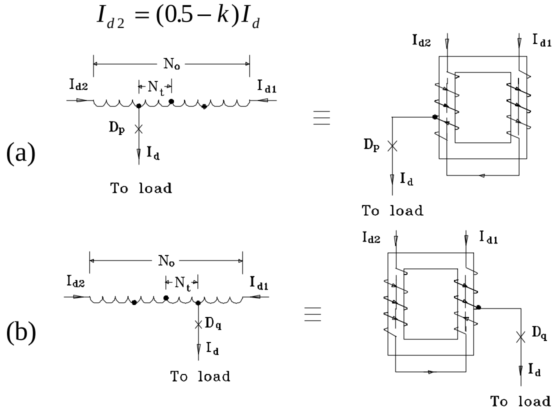


Fig. 8 Operation of the interphase reactor with two tapped-diodes (a) P-mode (b) Q-mode

The value k which minimize THD of the input current I_a is obtained by,

$$k = \frac{N_t}{N_o} = 0.2457 \quad (9)$$

The kVA rating of the delta-wye transformer of the proposed 24-pulse system is $0.5238V_oI_o$. Fig 5 shows input line current I_a which has a typical 24-pulse waveform. Note that all the harmonics are absent up to n = 22 and the significant harmonics are n = 23,25,47,49,etc..

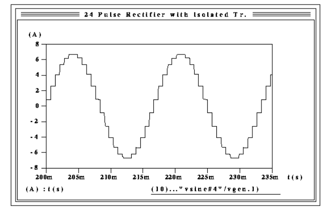


Fig. 5 Input line current I_a of the 24-pulse approach

IV. CONCLUSION

In this paper several autotransformer arrangements to enhance the utility power quality of high current DC power supplies have been proposed. The size (in kVA) of the twelve-pulse rectifier with the proposed autotransformer arrangement is reduced to 18% of the conventional 12-pulse rectifier. The proposed 24-pulse rectifier draws near sinusoidal currents in the AC input utility. They are summarized in the table below.

	kVA rating of transformer	Harmonics eliminated	# of interphase reactor
Conventional 12-pulse	$1.0306V_oI_o$	5,7th	1
Hybrid delta-wye	$0.7834V_oI_o$	5,7th	0
Autotrans. 12-pulse	$0.1834V_oI_o$	5,7th	2
reduced kVA 24-pulse	$0.5238V_oI_o$	5,7,11,13,17, 19th	1

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