Control of Multi-Level Converter Using By-Pass Switches

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Abstract— This paper describes a modification of the conventional bridge circuit under balanced conditions using two isolated-gate bipolar transistor (IGBT) by-pass valves connected to tapping points on the secondary windings of the transformer. This scheme permits a wide range of voltage control with a reduction in both the harmonic generation and reactive volt-ampere absorption. This scheme should improve the efficiency of voltage control; it possibly eliminates the need for an on-load tap-changer on the converter transformer.

The modified AC/DC converter is fully analyzed. A general mathematical model and the principle of operation for the modified converter have been determined. The characteristics for output DC voltage for the modified converter with two by-pass IGBT valves are obtained; and the mathematical equations have been derived for different modes of operation. The supply current harmonic contents, reactive volt-ampere absorption and power factor have been compared with a conventional bridge for different converter bridge arrangements, modified bridge using one IGBT by-pass valves and modified bridge with two IGBT by-pass valves. Simulation results are obtained using Matlab-Simulink for a model that has a three-phase bridge converter using conventional thyristors as main valves and two IGBT as by-pass valves employing a controllable digital firing angles with pulse generators maintained on a small firing angle of the main thyristors.

Keywords— Harmonics, Multi-level AC/DC converter, Reactive volt-ampere absorption (VAR), THD.

Nomenclature

V_d	dc voltage
V_{ph}	phase voltage
V_{rms}	rms value of phase voltage
$V_{a,rms}$	rms value of phase *a*
$V_{a_{1},rms}$	fundamental component of $V_{a,rms}$
V_A	instantaneous value of voltage for phase *a*
V_B	instantaneous value of voltage for phase *b*
V_C	instantaneous value of voltage for phase *c*
i_s	instantaneous value of current source
i_a	current of phase *a*
$I_{a,rms}$	rms value of phase *a* current
$I_{a1,rms}$	fundamental component of $I_{a,rms}$
a_o	fundamental component of Fourier series
a_m	magnitude of the m^{th} sinusoid harmonic
b_m	magnitude of the m^{th} cosinusoid harmonic
A_m	magnitude of the m^{th} harmonic
I_m	rms current magnitude of the m^{th} harmonic
$\emptyset_m$	phase of the m^{th} harmonic
$\emptyset_1$	phase shift angle between the fundamental supply current and voltage
$\emptyset$	phase shift angle between the voltage source and current source
a	turns ratio of the transformer
m	harmonic order

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F	supply frequency
ω	angular Frequency
n	transformer tap-section ratio modified with one IGBT valve
n_1	transformer tap-section ratio of the first tap-section in a modified converter with two IGBT valves
n_2	transformer tap-section ratio of the second tap-section in a modified converter with two IGBT valves
X_c	main valve commutation reactance
Q	reactive volt-ampere absorption
P	active power
S	apparent power
α	delay angle of main thyristor
α_0	delay angle due to unequal valve voltages
α_{b_1}	turn-on angle of the first by-pass IGBT valve
α_{b_2}	turn-on angle of the second by-pass IGBT valve
α_{c_1}	turn-off angle of the first by-pass IGBT valve
α_{c_2}	turn-off angle of the second by-pass IGBT valve
γ	commutation angle due to main valve
γ_{b_1}	commutation angle due to first IGBT by-pass valve through switch-on
γ_{b_2}	commutation angle due to second IGBT by-pass valve through switch-on
γ_{c_1}	commutation angle due to first IGBT by-pass valve through switch-off
γ_{c_2}	commutation angle due to second IGBT by-pass valve through switch-off

I. INTRODUCTION

Continuous and significant advancements in power electronics technologies especially AC to DC converters have been witnessed in many applications. The major problems associated with these loads are the harmonic current injection into power supply and volt-ampere absorption. Providing cheaper and more reliable controlled converters has become of a crucial importance [1] by improving power factor and absorbed volt-ampere (VAR). This is a very important issue in any AC system especially in high power applications like high voltage direct current applications (HVDC).

The control of conventional converters stations, which use three-phase controlled bridge for converting AC to DC is achieved by fast-acting control of the main valves firing angles. But this unfortunately reduces the power factor that should be near unity. This paper presents another algorithm to control the output voltage and improve the power factor. Tap-changers, which are fitted on the converter transformer, provide a near constant AC voltage input to the bridge to correct relatively slow changes of AC voltage. Over years several approaches were used to modify the conventional converter using filters [2], [3]. These solutions are based on the use of filters that can suppress higher order harmonics. The effect of PWM strategies on suppressing both AC harmonics and DC ripples is used [4], [5].

High pulse converters technique is used in [6]-[8]. High pulse converters 12, 24, 48 in the HVDC transmission system is used to reduce harmonics in the DC link. Increasing the number of pulses increases complexity. Thus, analyzing the higher number of components involved becomes tedious and complex.

A voltage control scheme for an HVDC convertor which uses by-pass thyristor valves connected to tapping points on the secondary windings of the transformer is suggested in 1990 in [9]. Fast and continuous control of the DC voltage is possible with good operational

characteristics and low values of reactive volt-ampere absorption. The on load tap-changer can be eliminated in this paper.
In [10] and [11], the authors suggested the use of a modified three-phase bridge converter which uses gate turn-off transistor (GTO) thyristors as by-pass valves are connected to tapping points on the secondary side of the converter input transformer. It resulted in a reduction in the VAR absorption. The harmonic content of the supply current is also generally reduced. Total harmonic distortion (THD) is reduced by 10% compared with the conventional full-wave fully-controlled converter. The power factor of the system was improved.
The technique of using a combination of two converters [12]-[14], and [15] was presented. In [12], the author proposed a combination of two three-phase thyristor bridges. In [13], the author used two modified series-connected bridges. In [14], the same algorithm as in the previous paper and a voltage control scheme which uses by-pass GTO thyristor valves connected to tapping points on the secondary windings of the transformer for one bridge with the other one operating as a conventional bridge are proposed. In [15], the GTO thyristor valve sections may be replaced by thyristors with forced-commutation circuitry. In all of the previous papers, the reactive volt-amperes and the AC current harmonics may be reduced.
In this paper, a modified converter with two IGBT by-pass valves connected to tapping points on the secondary windings of the transformer will be analyzed and compared with a conventional converter and a converter with one by-pass IGBT valve.

II. Converter Power Factor and Reactive Power

The first problem in the conventional three-phase bridge rectifier is the power factor, which is necessary to be near unity to reduce reactive power and obtain the maximum real active power to the load. Converter circuits, however, draw a non-sinusoidal current from the AC system. The effect of the delay angle (α) and commutation is to introduce a lagging power factor. This means that there is a reactive volt ampere absorbed by the rectifier. In the case of a non-sinusoidal current, the active power delivered per phase by the sinusoidal supply is given in (1) [16].

$$P = \frac{1}{T}\int_0^T v_{\mathrm{a}}(\mathrm{t})\mathrm{i}_{\mathrm{a}}(\mathrm{t})\ \mathrm{dt} = V_{a,rms}I_{a,rms}\cos\emptyset \quad (1)$$

Apparent power per phase is given by (2):

$$\mathrm{S} = \mathrm{P} + \mathrm{jQ} = \mathrm{V}_{\mathrm{a,rms}} \quad (2)$$

The relationship between the apparent power *S* and each of the active and reactive power is respectively shown in Fig. 1.

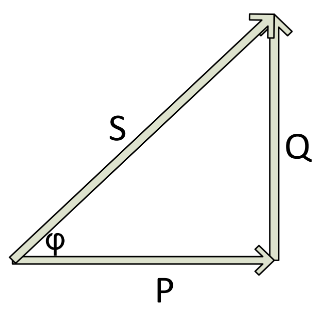


Fig. 1. Power phasor diagram

From Fig. 1, *pf* is given by (3) [16]:

$$pf = \frac{Active\ Powe\ (P)}{Apparent\ Power(S)} = \frac{V_{a,rms} I_{a_1,rms} cos\emptyset_1}{V_{a,rms} I_{a,rms}} \quad (3)$$

The Power Factor also can be given by (4) [16]:

$$pf = \frac{I_{a1,rms}}{I_{a,rms}} cos\emptyset_1 \quad (4)$$

Where

$$\frac{I_{a_1,rms}}{I_{a,rms}} = input\ distortion\ factor \quad (5)$$

and

$$cos\emptyset_1 = input\ displacement\ factor \quad (6)$$

The reactive component of power from the AC system to the converter is often expressed in terms of the active power under changing load conditions in (7).

$$Reactive\ power(Q) = P\ tan\emptyset \quad (7)$$

Where $\tan\emptyset$ is evaluated in (8) [11]:

$$tan\emptyset = \frac{sin\,(2\,\alpha+2\gamma) - sin(2\alpha) - 2\gamma}{cos(2\alpha) - cos(2\alpha+2\gamma)} \quad (8)$$

Equations (4) and (8) clearly show that due to the non-sinusoidal waveform of the currents, the power factor of the rectifier is negatively affected by both the firing angle α and the distortion of the input current. In effect, an increase in the distortion of the current produces an increase in the value of $I_{a,rms}$ which negatively influences the power factor.

III. Converter Harmonics

The conversion from AC to DC using static power switching devices generates harmonics. Harmonic voltages and current have undesirable effects, including communication interference, loss increase, heating, and voltage insulation stress due to resonance. The harmonics generated by converters in balanced and unbalanced three-phase systems, can be identified according to their origin as follows:

a) Characteristic harmonics.
b) Uncharacteristic harmonics.

Characteristic harmonics are caused in the current source by the conversion from AC to DC using switching devices under balanced conditions of the AC source of the three phases and without any errors in amplitude, frequency, or phase. Using switching non-linear devices is the main cause of this type of harmonics.

Any periodic waveform can be expressed by Fourier series as given in (9) to (12) [1].

$$F(\omega t) = a_0 + \sum_{n=1}^{\infty} (a_m\, cos(m\omega t) + b_m\, sin(m\omega t)) \quad (9)$$

$$a_0 = \frac{1}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} F(t)\ dt \quad (10)$$

$$a_m = \frac{2}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} F(t)\, cos\left(\frac{2m\pi t}{T}\right)\ dt \quad (11)$$

$$b_m = \frac{2}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} F(t)\, sin\left(\frac{2m\pi t}{T}\right)\, dt \quad (12)$$

THD which is defined as a measure of the waveform distortion is given in (13) [1]:

$$THD = \sqrt{\sum_{m=2}^{m=\infty}(\frac{A_m}{A_1})^2} \quad (13)$$

The currents of the line-commutated rectifiers are not sine waveform; the AC side current waveforms consist of the instantaneous differences between two rectangular secondary currents. The currents generated from the bridge rectifier with a star-connected transformer have the following harmonic content in (14) [1].

$$i_a = \frac{2\sqrt{3}}{\pi} I_D \left(cos\omega t - \frac{1}{5}cos5\omega t + \frac{1}{7}cos7\omega t - \frac{1}{11}cos11\omega t + \cdots \right) \quad (14)$$

Some of the characteristics of the current obtained from (14) include: i) the absence of triple harmonics; ii) the presence of harmonics of order 6m±1 for integer values of m; iii) those harmonics of orders 6m+1 are of positive sequence, and those of orders 6m-1 are of negative sequence; and iv) the rms magnitudes of the fundamental frequency and the mth harmonic are given in (15) and (16) [1] respectively:

$$I_1 = \frac{\sqrt{6}}{\pi} I_D \quad (15)$$

$$I_m = \frac{I_1}{m} \quad (16)$$

In practical systems perfect conditions for analysis of characteristic harmonics of a converter are never met. As a result, harmonics of uncharacteristic orders are produced. The magnitude of low order uncharacteristic harmonics is usually much smaller than that of characteristic harmonics generated by the same converter. In this paper the steady-state is studied, while the transient state is studied in [17]. Unbalanced operations are studied in [18] and [19].

IV. ANALYSIS OF THE BRIDGE CONVERTER

The bridge configuration has been established to be the most suitable for many applications for two reasons: lower transformer rating, and lower voltage rating of the valve. One of the most important converter circuits is the controlled three-phase bridge, which uses thyristor valves consisting of six thyristors separated into groups. The positive group consists of thyristors (1, 3, and 5); and the negative group (2, 4 and 6) has two thyristors used in every phase and at specific firing angles to achieve the desired voltage and current. The phase and valve numbers that are shown in Fig. 2 have two groups. The first group is, T_1 ,T_3, T_5. The upper side of the bridge forms the most positive commutating group. The second group is, T_2, T_4, T_6. The lower side of the bridge forms the most negative commutating.

Each group forms a closed cycle over 360° during which the valves successively fire every 120°. The bridge circuit is connected to the three-phases of AC system with one commutation inductance per phase.

During the commutation interval, two valves are conducting simultaneously; and a closed current circuit is formed. The commutation current flows as an increasing current through the valve which is turning-on. At the same time, the current is decreasing through the valve which is turning-off. This overlap reduces the mean DC voltage. The output voltage for the commutation case, the overlap angle γ, and the output DC current for the commutation case are given by (17), (18), and (19) respectively [20].

$$V_d = \frac{\sqrt{3}V_{ph}}{\frac{2\pi}{3}}\left[\int_{\left(\frac{\pi}{6}\right)+\alpha}^{\left(\frac{5\pi}{6}\right)+\alpha} \sin\theta \; d\theta + \int_{\alpha}^{\alpha+\gamma} \sin\frac{\pi}{6} \cos\emptyset \, d\emptyset\right] = \frac{3\sqrt{3}V_{ph}}{2\pi}[\cos\alpha + \cos(\alpha+\gamma)] \quad (17)$$

$$\gamma = \cos^{-1}\left[\cos\alpha - \frac{X_c I_d}{\sqrt{2}\,V_{ph}}\right] - \alpha \quad (18)$$

$$I_d = \frac{\sqrt{3}V_{ph}}{\sqrt{2}X_c}[\cos\alpha - \cos(\alpha+\gamma)] \quad (19)$$

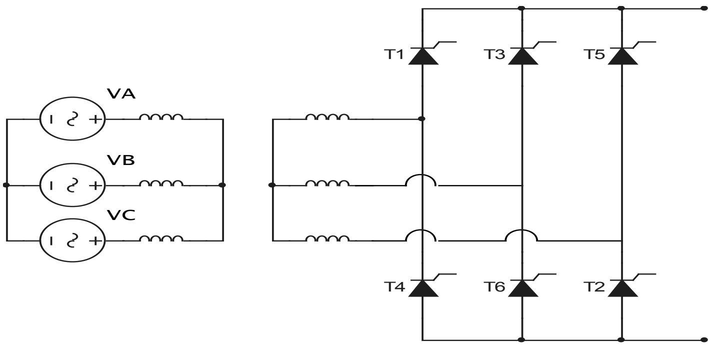


Fig. 2. Conventional three-phase fully-controlled rectifier

An inductive load consisting of a very large smoothing inductance (8H) in series with a resistance (100Ω) is used in this paper for three schemes: a conventional converter with one IGBT, and a converter with two IGBTs connected in series with the output line converter bridge to provide a well-smoothed DC current to a load connected at the converter output terminals, and to reduce the current transients during system operation. The supply voltage on the side of the transformer was three-phase AC source at 50Hz. It varies from zero to the maximum voltage, namely 520 volt line voltage in the three schemes.

V. Analysis of the Modified Converter with Two By-Pass IGBT Valves

The proposed scheme that will be analyzed in this paper depends on adding two by-pass IGBT valves on each phase. The block diagram of the proposed algorithm using two IGBTs by-pass valves is shown in Fig. 3.

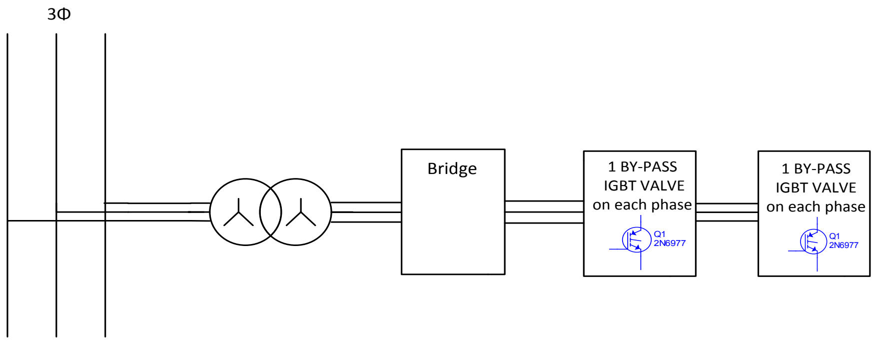


Fig. 3. Conventional bridge with two IGBTs by-pass valves block diagram

The schematic diagram and the equivalent circuit of the proposed algorithm using two IGBTs by-pass valves are shown in Fig. 4 and Fig. 5, respectively.

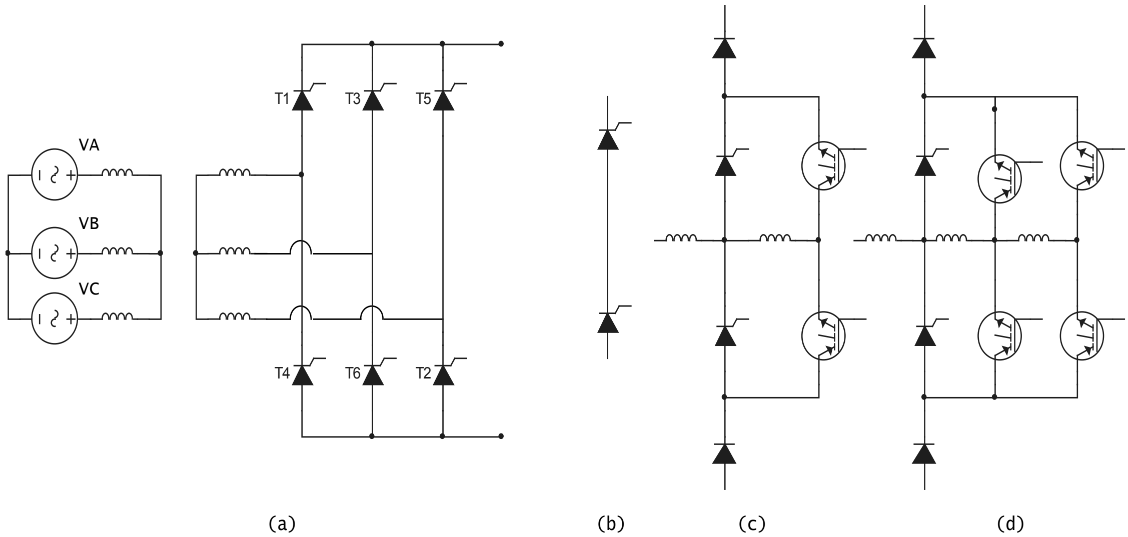


Fig. 4. Alternative schemes for conventional bridge converter: a) Conventional bridge rectifier, b) One phase of conventional scheme, c) One phase of alternative scheme using one by-pass IGBT valve and d) One phase of the proposed scheme using two IGBTs by-pass valves

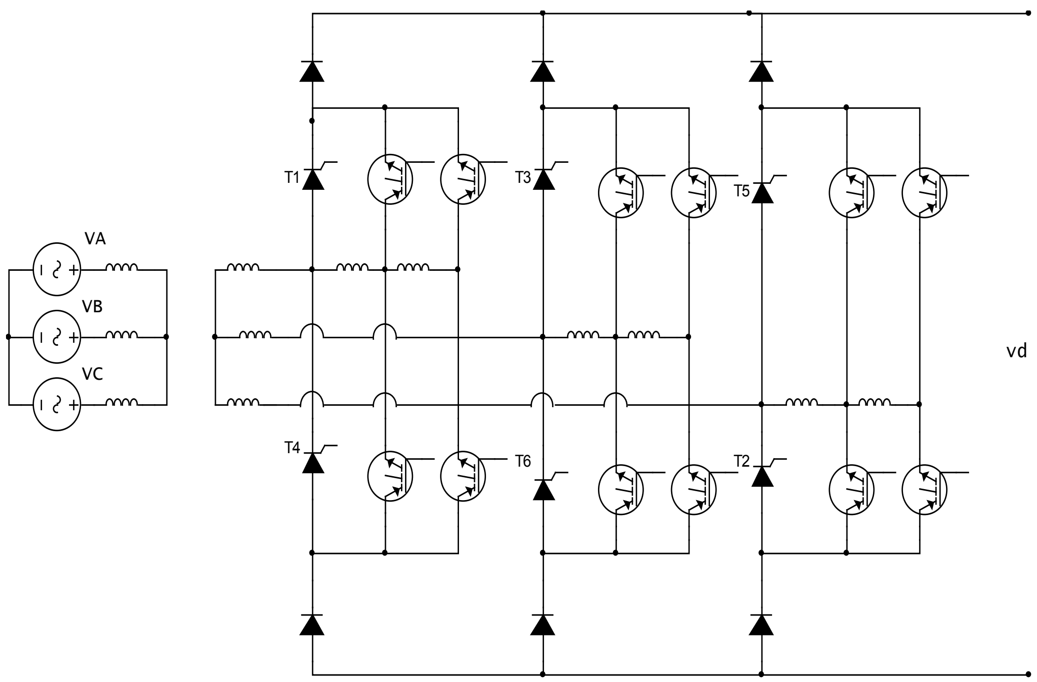


Fig. 5. Modified converter using two IGBTs by-pass valves

Tap-changers which are fitted on the converter transformer provide a near constant AC voltage input to the bridge to correct relatively slow changes of AC voltage. This approach is not efficient since it is manual and classic. By the modified three-phase AC/DC bridge converters, the control of the output voltage will be easily and achieved by control of by-pass IGBT valves and firing angles. For normal operation, the main valve thyristor firing angle α is kept near zero, say $(5° - 10°)$, to give minimum delay between input current and voltage source, i.e., minimum reactive volt-ampere absorption and higher power factor. DC voltage is controlled by a variation of the two by-pass IGBT valves turn-on and turn-off angles $(\alpha_{b_1}, \alpha_{c_1}, \alpha_{b_2},$ and $\alpha_{c_2})$.

A) Operation under Ideal Conditions (Negligible Overlap)

The average output voltage under ideal conditions of the modified converter, with zero firing angles of the main valves, is derived as given in (20):

$$V_d = \frac{3}{\pi}\sqrt{6}V_{ph}\left[1 + \frac{n_1}{2}\left(cos\,\alpha_{c_1} - cos\,\alpha_{b_1}\right) - \frac{n_1}{2\sqrt{3}}\left(sin\,\alpha_{c_1} - sin\,\alpha_{b_1}\right) - \frac{n_2}{2}\left(cos\,\alpha_{c_2} - cos\,\alpha_{b_2}\right) + \frac{n_2}{2\sqrt{3}}\left(sin\,\alpha_{c_2} + sin\,\alpha_{b_2}\right)\right] \quad (20)$$

B) Finite overlap

Under finite overlap by using two by-pass IGBT valves, five commutation processes are involved. Main valve commutation takes place when the transfer of current occurs from the main thyristor valve of one phase to another. Second commutation occurs when the current transfers from the main thyristor valve to the first by-pass IGBT valve in the same phase. Third commutation takes place when the current transfers from the first by-pass IGBT valve to the second by-pass IGBT valve in the same phase. Fourth commutation occurs when the current transfers from the second by-pass IGBT valve to the first by-pass IGBT valve in the same phase. Fifth commutation occurs when the current transfers from the first by-pass IGBT valve to the main thyristor valve in the same phase.

Turn-on angle α_{b_1} can be varied from $-\alpha_0$to turn-off α_{c_1}; and the turn-on angle α_{b_2} can be varied from $-\alpha_0$ to turn-off of the second IGBT valve α_{c_2}. Also, turn-off angles α_{c_1} & α_{c_2} can be varied from $\alpha_0 + \gamma$ to $\frac{2\pi}{3}$.

This means there are several modes of operation for different ranges of $\alpha_{b_1}$and α_{b_2}. Two of these profiles are shown in Fig. 6:

a) For$\left(\alpha + \gamma < \alpha_{b_1} < \alpha_{c_1} - \gamma_{b_1}\text{and } \alpha_{b_1} + \gamma_{b_1} < \alpha_{b_2} < \alpha_{c_2} - \gamma_{b_2}\right)$, this case is the normal case; and in this case the main thyristor valve will conduct from $(\alpha + \gamma)$ to turn-on firing angle of the first by-pass IGBT valve $(\alpha_{b_1} + \gamma_{b_1})$. The first by-pass IGBT valve will conduct from its turn-on firing angle plus the commutation angle $(\alpha_{b_1} + \gamma_{b_1})$ to the turn-on of the second by-pass IGBT valve α_{b_2}. Then the second IGBT by-pass valve is conducting from α_{b_2} to its turn-off firing angle α_{c_2}. The first by-pass IGBT valve will conduct again from $\alpha_{c_2}$to its turn-off α_{c_1}. Finally the main thyristor valve will conduct one more time from α_{c_1} to $(\frac{5\pi}{6} + \alpha)$. Output DC voltage for this case is given in (21). The commutation angles γ, γ_{b_1} and γ_{b_2} are given in (22), (23) and (24) respectively.

$$V_d = \frac{3}{\pi}\sqrt{6}V_{ph}\left[\frac{1}{2}cos(\alpha+\gamma) + \frac{1}{2}cos\,\alpha + \frac{1}{2}n_1\,cos\left(\alpha_{b_1} + \gamma_{b_1}\right) - \frac{1}{2\sqrt{3}}n_1\,sin(\alpha_{b_1} + \gamma_{b_1}) + \frac{1}{2}n_2\,cos\left(\alpha_{b_2} + \gamma_{b_2}\right) - \frac{1}{2\sqrt{3}}n_2\,sin\left(\alpha_{b_2} + \gamma_{b_2}\right) - \frac{1}{2}n_2\,cos\,\alpha_{c_2} - \frac{1}{2}n_1\,cos\,\alpha_{c_1} + \frac{1}{2\sqrt{3}}n_1\,sin\,\alpha_{c_1}\right] \quad (21)$$

Now

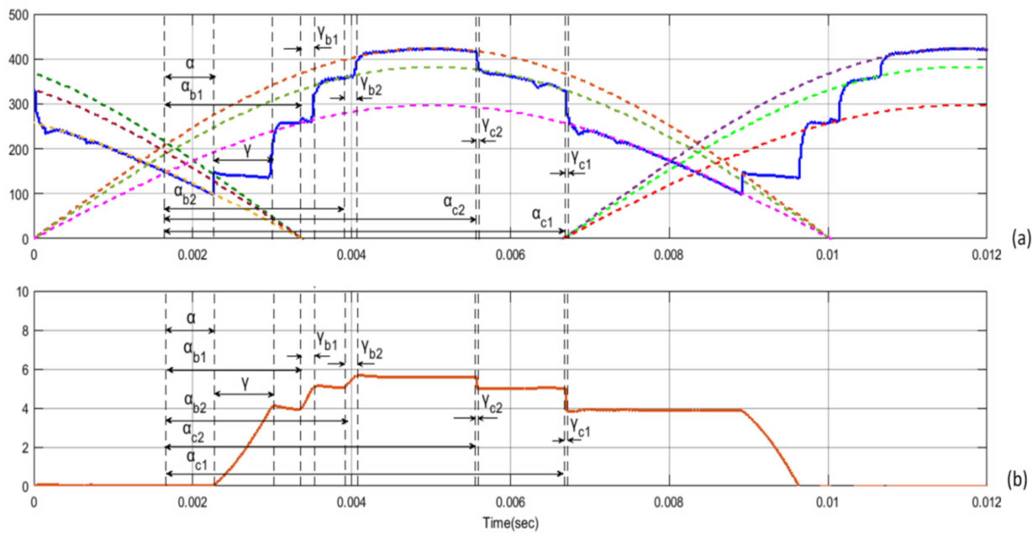
$$\gamma = cos^{-1}\left[cos\,\alpha - \frac{X_C I_d}{\sqrt{6}V_{ph}}\right] - \alpha \quad (22)$$

$$\gamma_{b_1} = cos^{-1}\left[cos(\frac{\pi}{6}+\alpha_{b_1}) - \frac{X_{b_1} I_d}{\sqrt{2} n_1 V_{ph}}\right] - (\frac{\pi}{6}+\alpha_{b_1}) \quad (23)$$

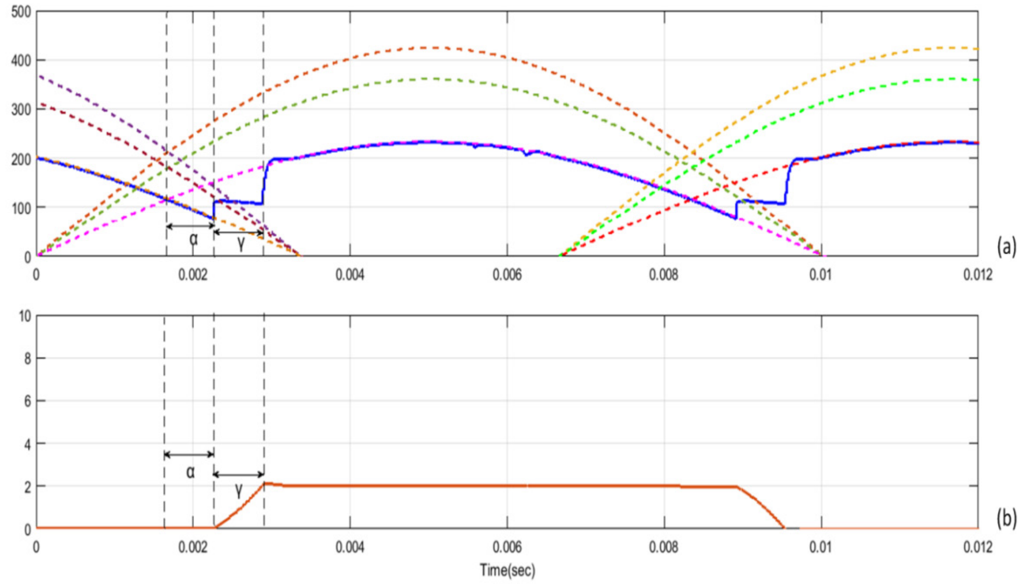
$$\gamma_{b_2} = cos^{-1}\left[cos(\frac{\pi}{6}+\alpha_{b_2}) - \frac{X_{b_2} I_d}{\sqrt{2} n_2 V_{ph}}\right] - (\frac{\pi}{6}+\alpha_{b_2}) \quad (24)$$

b) For($\alpha_{c_1} < \alpha_{b_1} < \alpha_{b_2}$)and ($\alpha_{c_2} < \alpha_{b_2}$), both of the by-pass valves will not conduct. The main valve will conduct from ($\frac{\pi}{6}+\alpha+\gamma$) to ($\frac{5\pi}{6}+\alpha$). The output voltage is given in (25) while the overlap angle γ is given in (22).

$$V_d = \frac{3}{\pi}\sqrt{2}V_{ph}\left[\frac{3\sqrt{3}}{4}cos\,\alpha + \frac{1}{4}sin\,\alpha + \frac{\sqrt{3}}{2}cos(\alpha+\gamma)\right] \quad (25)$$



(A)



(B)

Fig. 6. Voltage and current waveforms of rectifier with two by-pass IGBT valves at $X_c = 3\Omega$, $n_1 = 0.3$, $n_2 = 0.15$: A) $(\alpha+\gamma < \alpha_{b_1} < \alpha_{c_1} - \gamma_{b_1}$ and $(\alpha_{b_1}+\gamma_{b_1} < \alpha_{b_2} < \alpha_{c_2} - \gamma_{b_2})$, ($\alpha = 10°$, $\alpha_{b_1} = 30°$, $\alpha_{b_2} = 40°$, $\alpha_{c_2} = 70°$, $\alpha_{c_1} = 90°$): a) Positive and negative direct voltage and b) AC line current of phase *a*, B) ($\alpha_{c_1} < \alpha_{b_1} < \alpha_{b_2}$)and ($\alpha_{c_2} < \alpha_{b_2}$), ($\alpha = 10°$, $\alpha_{b_1} = 30°$, $\alpha_{b_2} = 40°$, $\alpha_{c_2} = 20°$, $\alpha_{c_1} = 25°$)

VI. INPUT CURRENT HARMONICS

A comparison between the three schemes, i.e. the conventional converter, the modified converter with one IGBT by-pass valve and the modified converter with two by-pass valves is listed in Table 1.

It can be seen that in all cases of the same conditions the modified converter with two by-pass IGBT valve has minimum THD of the input current source.

It is clear that the harmonics is decreased as the commutation reactance X_c increases. This results in increasing commutation angle γ. The input AC current becomes approximately sine waveform at high values of commutation angle.

Fig 7 compares the harmonic contents for the three algorithms. It can be seen that the modified rectifier with two by-pass IGBT valve has minimum value of harmonic contents. It can be seen that harmonics generation is reduced for the modified rectifier with two by-pass IGBT valves, compared with the modified rectifier with one by-pass IGBT valve, and the conventional rectifier.

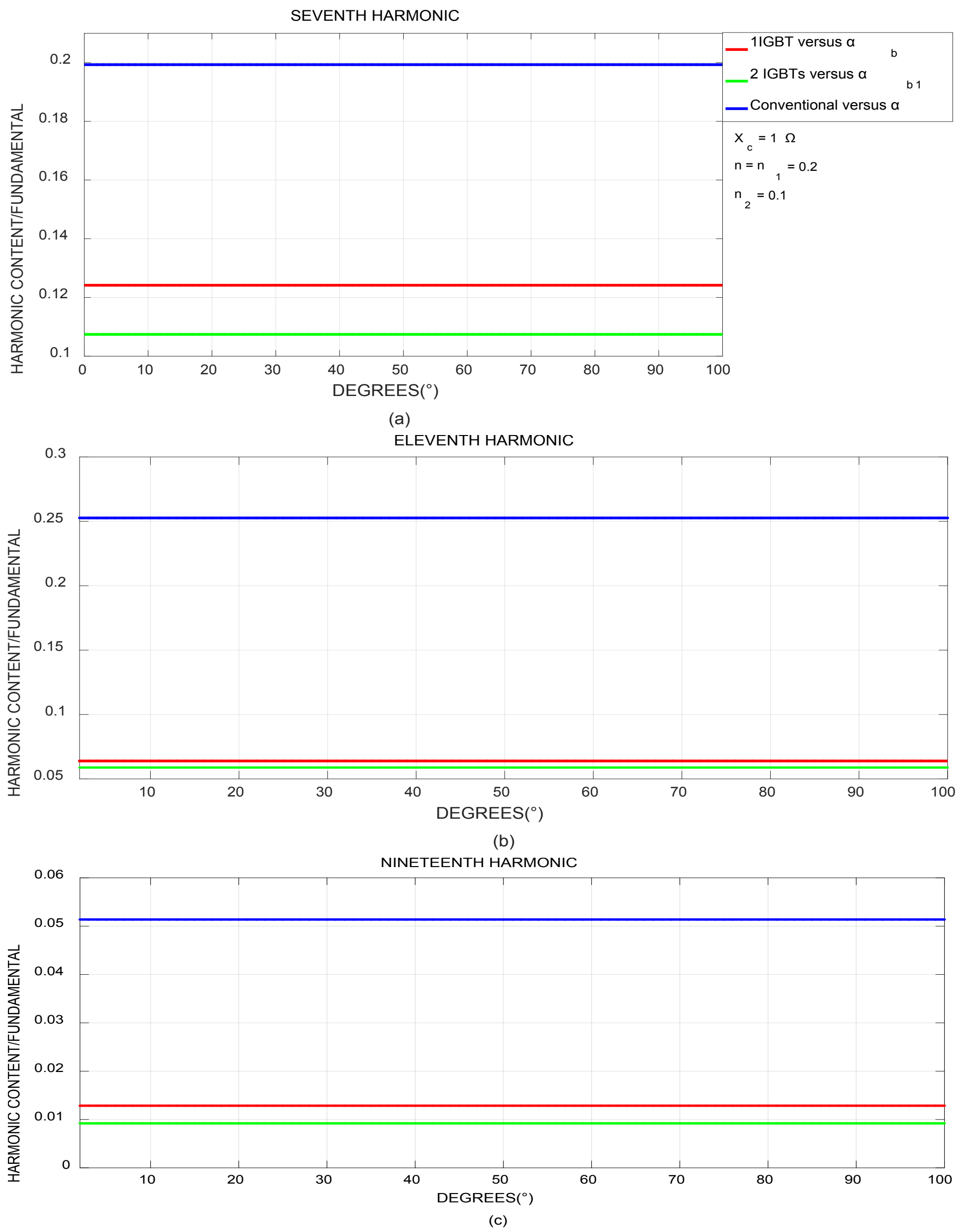


Fig. 7. Harmonic contents for three algorithms: a) 7th harmonic, b) 11th harmonic and c) 19th harmonic

TABLE 1
AC INPUT CURRENT THD FOR THE THREE ALGORITHMS

Different commutation reactance $\boldsymbol{X_c}(\Omega)$ at $\boldsymbol{\alpha = 5°}$	AC current THD, %		
	Conventional Converter	Modified converter with one by-pass IGBT valve	Modified converter with two by-pass IGBT valve
0	30.7	27.68	25.86
1	27.97	26.7	24.56
3	27.37	25.59	23.92
5	26.1	24.67	23.35
Different firing angle of the main thyristor $\boldsymbol{\alpha}$ at $\boldsymbol{X_c = 1\ \Omega}$	Conventional Converter	Modified converter with one by-pass IGBT valve	Modified converter with two by-pass IGBT valve
0°	26.93	25.59	22.82
5°	27.97	26.7	24.56
10°	28.93	28.51	26
30°	32	31.44	26.72

VII. REACTIVE VOLT-AMPERE AND POWER FACTOR

Fig. 8 shows the reactive volt-ampere absorption of the three cases against the turn-on firing angles at different values of the commutation reactance X_c at tap-section ratio $n = n_1 = 0.2$, and tap-section ratio $n_2 = 0.1$. It can be seen that the reactive volt-ampere absorption is minimum in the modified converter with two by-pass IGBT valves.

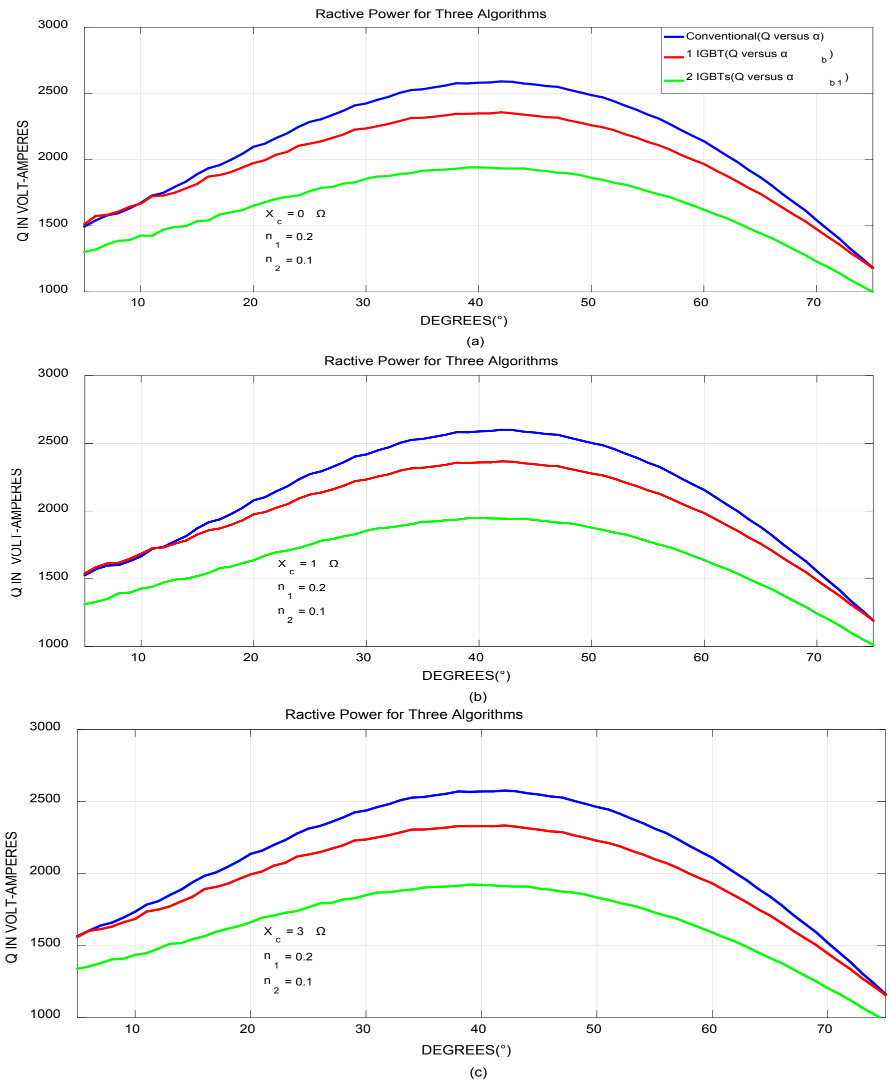
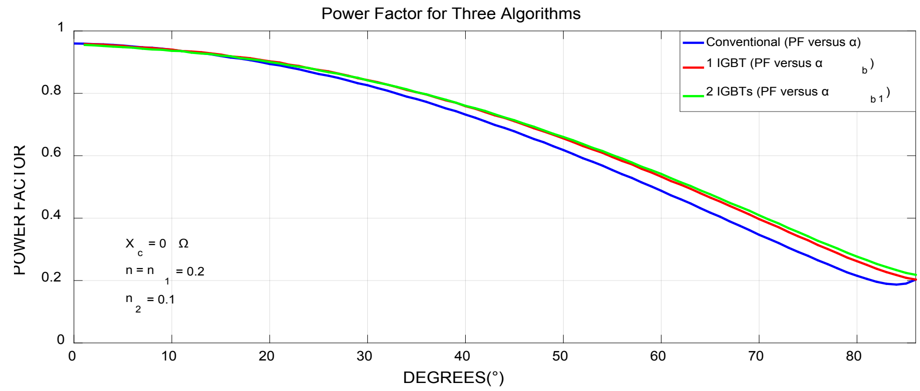
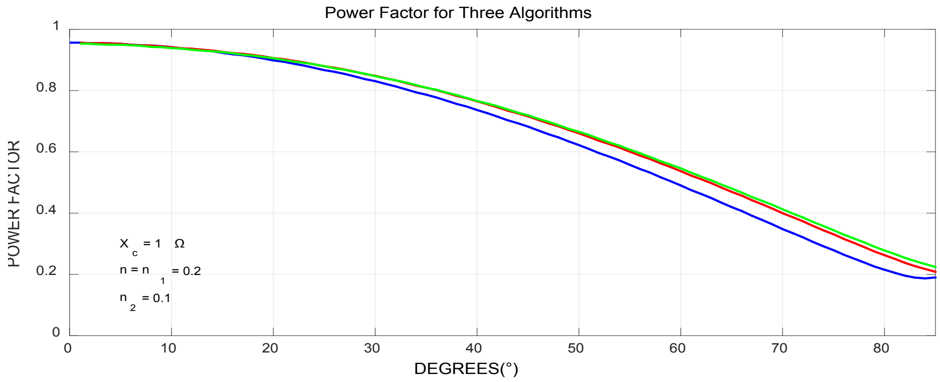


Fig. 8. Reactive volt-ampere for the three algorithms at different X_c, a) $X_c = 0$, b) $X_c = 1\Omega$ and c) $X_c = 3\Omega$

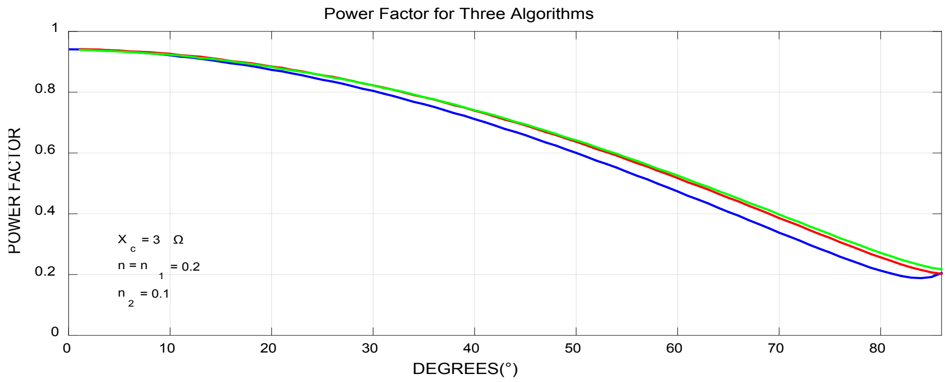
Fig. 9 shows the power factor of the conventional converter, the modified converter with one by-pass valve and the modified converter with two by-pass IGBT valves versus the turn-on firing angles at different values of the commutation reactance X_c, at tap-section ratios $n = n_1 = 0.2$ and $n_2 = 0.1$.



(a)



(b)



(c)

Fig. 9. Power factor for the three algorithms versus the turn-on firing angles at different X_c, a) $X_c = 0$, b) $X_c = 1\Omega$ and c) $X_c = 3\Omega$

VIII. CONCLUSIONS

The characteristics of the DC voltage of the modified converter with two by-pass IGBT valves are obtained for several modes of operation. Supply current harmonics, input power factor and reactive volt-ampere absorption for a conventional one IGBT by-pass valve and two IGBT by-pass valves converters have been discussed and compared.

Fast and continuous control of the DC voltage is obtained with minimum values of the firing angles of the main thyristors. The DC output voltage can be controlled by the turn-on and turn-off angles of the two IGBT by-pass valves. In this paper, the analysis is made at different values of these angles. The DC voltage may be varied over a range of 29% to eliminate the need for the on-load tap-changer. The main advantage is that the VAR absorption is generally reduced. More reduction takes place in the VARs when a turn-off facility (i.e. IGBT) is included. The power factor using the modified converter with two by pass IGBT valves is improved.

The self-turn-off capability and high $\frac{di}{dt}$ rating of the IGBT provide advantages over conventional force commutated thyristors. Performance improves with the use of IGBTs instead of GTOs. IGBT has superior on-state characteristics, good switching speed and excellent safe operating area; IGBTs are replacing GTOs in high voltage applications with lower conduction losses.

The overall cost of the equipment has increased as the number of devices increases. The complexity of the system increases; and the control process of the firing angles of all the switches become more complicated. The triple harmonics may exist in the star connection transformer.

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