Fast and Continuous Control of a Modified HVDC Converter

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Abstract- Control strategy for the modulation of the DC power for Modified HVDC Systems is proposed. A microprocessor- based firing scheme is presented which control the firing angles for modified HVDC converter with by-pass valves. Fast and continuous control of the DC voltage is possible with good operational characteristics. Using table-look-up algorithm to speed up the response, it gives a full range control of the firing angle for both rectifier and inverter modes. The algorithm is experimentally verified and is found to give a very-fast, precise and equidistant control of the thyristor triggering. Harmonic generations into the AC system and the converter reactive volt-ampere absorption have been reduced. The operations of modified bridge, the control algorithm and the microprocessor implementation are described. Experimental results on a laboratory model compare well with the predicted values.

Keywords: HVDC Converter, Harmonics, Continuous Control, By-Pass-Valve, Microprocessor,

1 Introduction

Phase-Commutated static power converters have been used in power conversion application for more than four decades in various manufacturing processing, transportation industries and HVDC transmission [1-4]. This trends is now creating serious problems of harmonics distortion and low input-power factor.

In the field of system voltage control, several arrangements have been reported [2-5] which use thyristors to switch or assist in switching and various schemes to control the firing angle of thyristor converters have been described. The application described in this paper however is differ from the other schemes, since the new control feature is essentially a modification of the bridge circuit itself and uses techniques that are well established in conventional bridge operation.

The conventional bridge is modified [6-14] in such a way that it has additional thyristors which form by-pass thyristors on each phase. In this configuration, fast and continuous control of the DC voltages is possible, and the need for an on-load tap-changer may be removed. The direct voltage can be controlled by controlling the firing angles of the by-pass thyristors. Harmonic generation into the AC system and the converter reactive volt-ampere absorption may be reduced, but more switching devices and therefore control circuit are required compared with the conventional converter requirements.

The digitized AC power signal together with software algorithm are used to find the correct firing output signals, which result in reduced parts count, improved dynamic performance, and increased control capability.

2 Modified Converter

The conventional bridge is modified by additional valves which form by-pass valves on each phase. In this configuration, fast and continuous control of the DC voltage is possible, and hence an on-load tap-changer no longer used. The direct voltage can be controlled by controlling the firing angles of the by-pass valves. Harmonic generation into the AC system and the converter reactive volt ampere absorption may be reduced.

2.1 Converter analysis

Figure (1) shows the circuit schematics for a conventional bridge and a modified scheme in which by-pass valves are used to control the output voltage and input current harmonics.

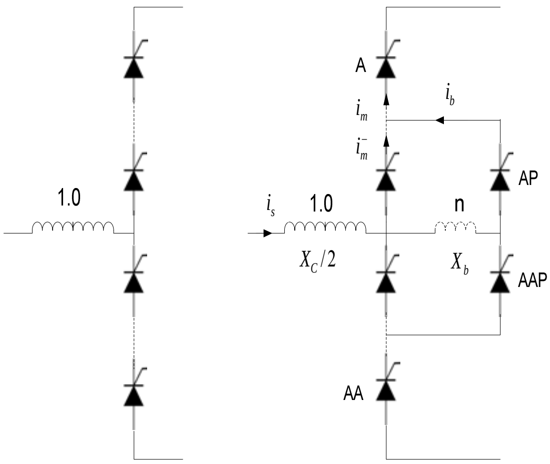


Figure.1: Converter schematics

Two modes of operation are possible with the modified bridge.

a-Normal operation in which the main valve firing angle α is kept near zero in the rectifier mod, and DC voltage is controlled by variation of the by-pass valve firing angle (α_b) as shown in Figure (2). When the bridge is operating as an inverter Figure (3), the by-pass valves are fired before the main valve because commutation occurs from higher (more negative) voltage to lower (less negative) voltage, The DC voltage can be controlled by varying the angle of advance (β_b) which provide a safe extinction angle. The angle at which natural commutation occurs is delayed by an α_0, owing to the difference between the main and by-pass valve voltages. The value of α_0 may be calculated from the following formula [6].

$$\alpha_0 = \tan^{-1}\left[(n.\tan 30)/(2+n)\right] \qquad (1)$$

Table.1. shows a range of values of α_0 against the transformer ratio of the tap section (n).

Table.1 : α_0 against the transformer ratio of the tap section (n)

n	0	0.1	0.2	0.3	0.4
α_0, degree	0	1.57	3.00	4.31	5.50

b-Abnormal operation when the main and bypass valve are fired together, therefore the bridge reverts to the conventional control modified.

There are several modes of operation of the alternative converter with by-pass valves for different α_b ranges. The following expressions have been used in the derivation of the DC voltage:

$$V_A = \sqrt{2}V_{ph}\sin\omega t \qquad (2)$$

$$\overline{V}_A = \sqrt{2}(1+n)V_{ph}\sin\omega t \qquad (3)$$

$$V_B = \sqrt{2}V_{ph}\sin(\omega t - 120) \qquad (4)$$

$$\overline{V}_B = \sqrt{2}(1+n)V_{ph}\sin(\omega t - 120) \qquad (5)$$

$$V_C = \sqrt{2}V_{ph}\sin(\omega t + 120) \qquad (6$$

$$\overline{V}_C = \sqrt{2}(1+n)V_{ph}\sin(\omega t + 120) \qquad (7)$$

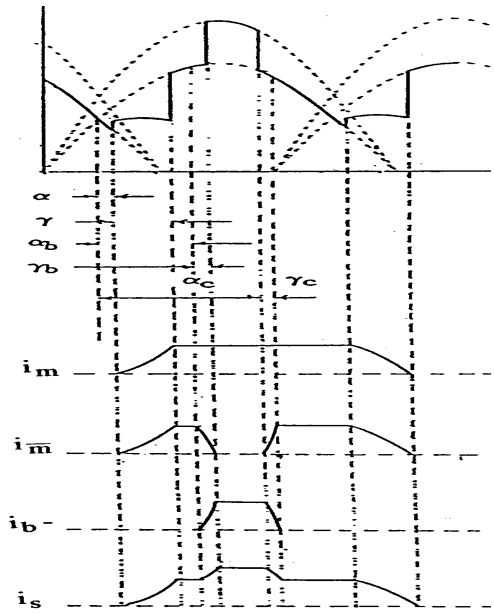


Figure.2: Rectifier current profiles for rang of α_b values from 0 to $2\pi/3$

2.2 Rectifier mode of operation

a)For $0 \le \alpha_b \prec \alpha_0$, referring to Figure (2a), the limits of the output voltage for different parts given as:

$$V_d = \frac{3}{\pi} \frac{\overline{V}_C + \overline{V}_A}{2} \Big|_{(\pi/6)+\alpha_b}^{(\pi/6)+\alpha_b+\gamma_m} \quad (8)$$

$$V_d = \frac{3}{\pi} \overline{V}_A \Big|_{(\pi/6)+\alpha_b+\gamma_m}^{(5\pi/6)+\alpha_b} \quad (9)$$

Therefore

$$V_d = (n+1)V_0[\cos\alpha_b + \cos(\alpha_b + \gamma_m)]/\sqrt{2} \quad (10)$$

Where

$$V_0 = \frac{3\sqrt{6}V_{ph}}{\pi}$$

Mean DC voltage on no-load and no by-pass valve in circuit.

$$\gamma_m = \cos^{-1}\left[\cos\alpha_b - \frac{(X_0 + 2X_b)I_d}{V_{ph}\sqrt{6(n+1)}}\right] - \alpha_b \quad 11)$$

b) For $\alpha_0 \le \alpha_b \prec (\gamma_m + \alpha_0 - \gamma_b)$, referring to Figure (2b), limits of output voltage for different part are given as:

$$V_d = \frac{3}{\pi} \frac{\overline{V}_C + V_A}{2} \Big|_{(\pi/6)+\alpha_0}^{(\pi/6)+\alpha_b+\gamma_b} \quad (12)$$

$$V_d = \frac{3}{\pi} \frac{\overline{V}_C + \overline{V}_A}{2} \Big|_{(\pi/6)+\alpha_b+\gamma_b}^{(\pi/6)+\alpha_b+\gamma_m} \quad (13)$$

$$V_d = \frac{3}{\pi} \overline{V}_A \Big|_{(\pi/6)+\alpha_b+\gamma_m}^{(5\pi/6)+\alpha_0} \quad (14)$$

Therefore

$$V_d = \frac{V_0}{\sqrt{3}} \begin{bmatrix} \frac{(n+2)\sqrt{3}}{4}\cos\alpha_0 + \frac{n}{4}\sin\alpha_0 \\ + \frac{n\sqrt{3}}{4}\cos(\alpha_b + \gamma_b) - \frac{n}{4}\sin(\alpha_b + \gamma_b) \\ + \frac{(n+1)\sqrt{3}}{2}\cos(\alpha_0 + \gamma_m) \end{bmatrix} \quad (15)$$

c)For $(\gamma_m + \alpha_0 - \gamma_b) \le \alpha_b \prec (2\pi/3 - \gamma_b)$. The limits of output voltage as shown in Figure (2c) are given asp:

$$V_d = \frac{3}{\pi} \frac{\overline{V}_C + V_A}{2} \Big|_{(\pi/6)+\alpha_0}^{(\pi/6)+\alpha_b+\gamma_m} \quad (16)$$

$$V_d = \frac{3}{\pi} V_A \Big|_{(\pi/6)+\alpha_b+\gamma_m}^{(\pi/6)+\alpha_b+\gamma_b} \quad (17)$$

$$V_d = \frac{3}{\pi} \overline{V}_A \Big|_{(\pi/6)+\alpha_b+\gamma_b}^{(5\pi/6)+\alpha_0} \quad (18)$$

Therefore

$$V_d = \frac{V_0}{\sqrt{3}} \begin{bmatrix} \frac{(n+2)\sqrt{3}}{4}\cos\alpha_0 + \frac{n}{4}\sin\alpha_0 \\ + \frac{n\sqrt{3}}{4}\cos(\alpha_b + \gamma_b) - \frac{n}{2}\sin(\alpha_b + \gamma_b) \\ + \frac{(n+1)\sqrt{3}}{4}\cos(\alpha_0 + \gamma_m) + \frac{n}{4}\sin(\alpha_0 + \gamma_m) \end{bmatrix} \quad (19)$$

Where

$$\gamma_m = \cos^{-1}\left[1 - \frac{(X_0 + X_b)I_d}{V_{ph}\sqrt{6(1 + n + n^2/3)}}\right] \quad (20)$$

$$\gamma_b = \cos^{-1}\left[\cos(\pi/6 + \alpha_b) - \frac{X_b I_d}{nV_{ph}\sqrt{2}}\right] - (\alpha_b + \pi/6) \quad (21)$$

d)For $(2\pi/3 - \gamma_b) \le \alpha_b \prec (2\pi/3)$, in this case the limits of the output voltage as shown in Figure (2d) are given As:

$$V_d = \frac{3}{\pi} \frac{\overline{V}_C + V_A}{2} \Big|_{(\pi/6)}^{(\pi/6)+\gamma_m} \quad (22)$$

$$V_d = \frac{3}{\pi} \overline{V}_A \Big|_{(\pi/6)+\gamma_m}^{(5\pi/6)} \quad (23)$$

Therefore

$$V_d = \frac{V_0}{2}[1 + \cos\gamma_m] \quad (24)$$

Where

$$\gamma_m = \cos^{-1}\left[1 - \frac{X_c I_d}{\sqrt{6}V_{ph}}\right] \quad (25)$$

2.3 Inverter mode of operation

For general case in the inverter mode of operation as shown in Figure (3), the limits of the output voltage are given by:

$$V_d = -\frac{3}{\pi}\overline{V}_A \Big|_{7\pi/6)-\beta-\delta}^{(11\pi/6)-\beta_b} \quad (26)$$

$$V_d = -\frac{3}{\pi}V_A \Big|_{11\pi/6)-\beta_b}^{(11\pi/6)-\beta_0-\delta-\gamma_m} \quad (27)$$

$$V_d = -\frac{3}{\pi}\frac{V_A+\overline{V}_B}{2} \Big|_{(11\pi/6)-\beta_0-\delta-\gamma_m}^{(11\pi/6)-\delta-\beta_0} \quad (28)$$

Therefore

$$V_d = \frac{V_0}{\sqrt{3}}\begin{bmatrix} \frac{\sqrt{3}\text{ی}}{2}\cos\beta_b - \frac{n}{2}\sin\beta_0 \\ +\frac{\sqrt{3}(n+2)}{4}\cos(\delta+\beta_0) + \frac{n}{4}\sin(\delta+\beta) \\ +\frac{(n+2)\sqrt{3}}{4}\cos(\beta_0+\delta+\gamma_m) \\ +\frac{n}{4}\sin(\beta_0+\delta+\gamma_m) \end{bmatrix} \quad (29)$$

Where

$$\gamma_m = \cos^{-1}\left[\cos\delta - \frac{(X_0+X_b)I_d}{V_{ph}\sqrt{6(1+n+n^2/3)}}\right] - \delta \quad (30)$$

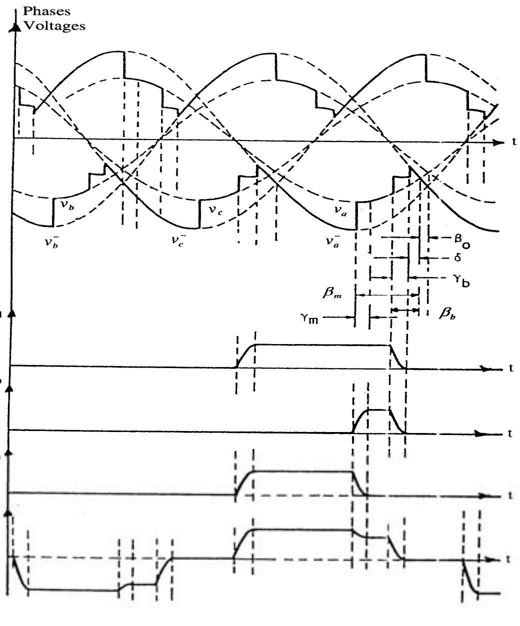


Figure.3: Inverter current profiles for modified converter

3 Microprocessor Control

Firing angle control of thyristor converters requires three basic operations: line synchronization, delay control and distribution of pulses. In microprocessor based systems, these functions can be accomplished either by software, hardware or both.

3.1 Basic function of firing angle control

Figure (4) shows the three-phase modified converter with twelve pulses, in which six pulses control the main thyristor and six pulses control the by-pass valves. The principle aim of the firing circuit is to convert the angle control input into a corresponding phase angle between the triggering pulses and the AC supply voltages.

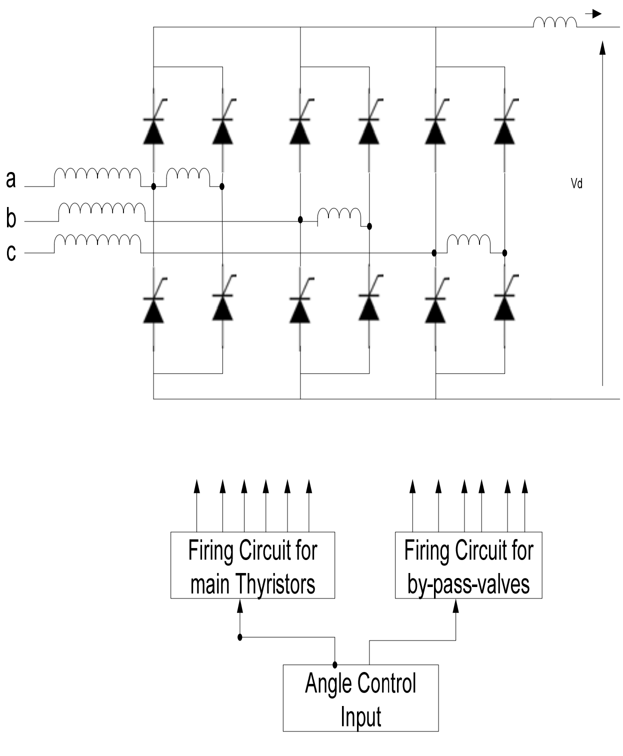


Figure.4: Three-phase modified converter

Figure (5) shows a circuit for the hardware implementation circuit. It consists essentially of a MPU+RAM, MC6802, an EPROM2716 and a PIA MC 6821. Microcomputer chip containing all these functions can be used in order to reduce the hardware further.

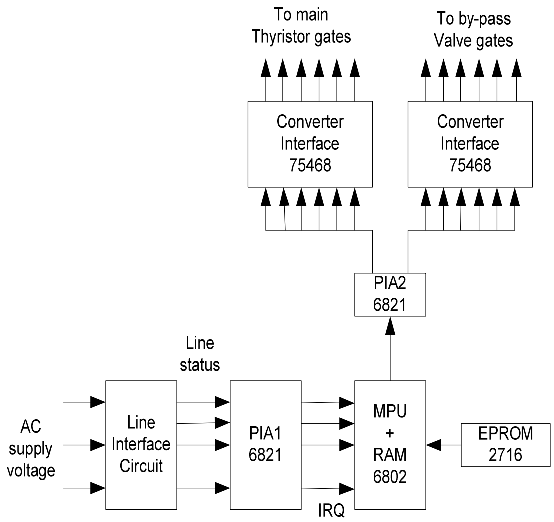


Figure.5: Hardware implementation

A simplified diagram of the line interface circuit is shown in Figure (6). It consists essentially of three zero-crossing detectors which provide line status signal LA, LB, LC and an edge detector which produces a synchronization signal IRQ as shown in Figure (7). The implementation program is executed upon reception of synchronization pulse IRQ provided by the line interface circuit every zero-crossing of the line voltage. The MPU reads the line status and the control angles α and α_b, then it determines the mode of operation whether is rectifier or inverter. If $\alpha \prec 90$ the converter operated is rectifier mode, if $\alpha \succ 90$ the converter operated is inverter mode. It also determines the kind of control whether normal or abnormal as shown in Figure [8].

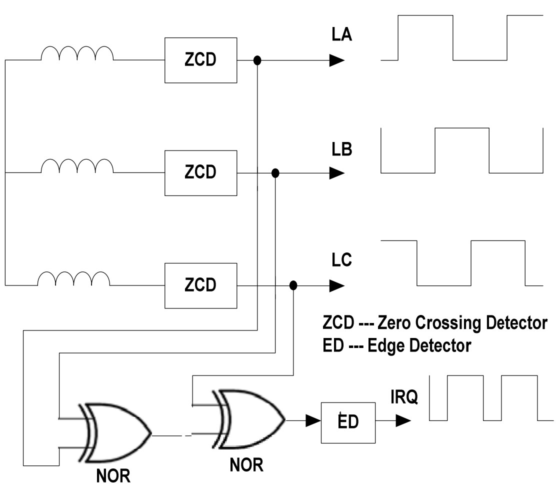


Figure.6: Line interface circuit

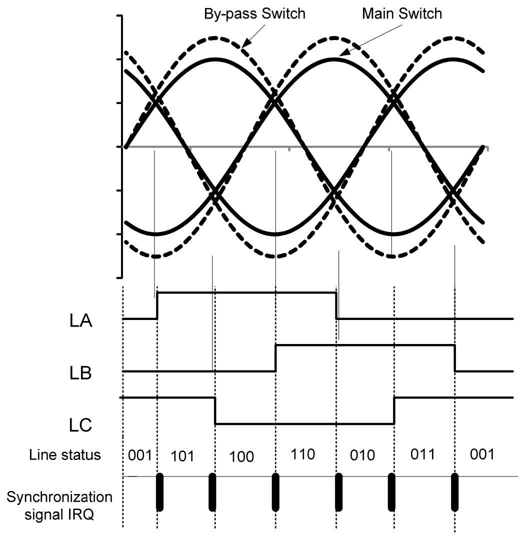


Figure.7: Principle of firing angle control

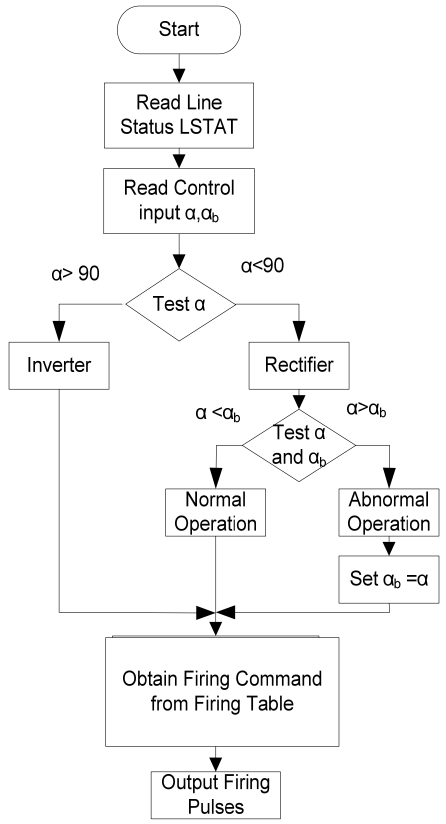
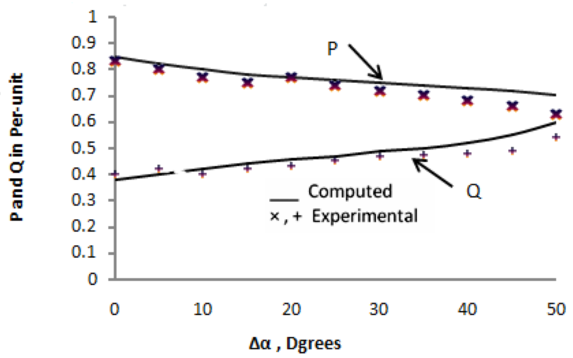


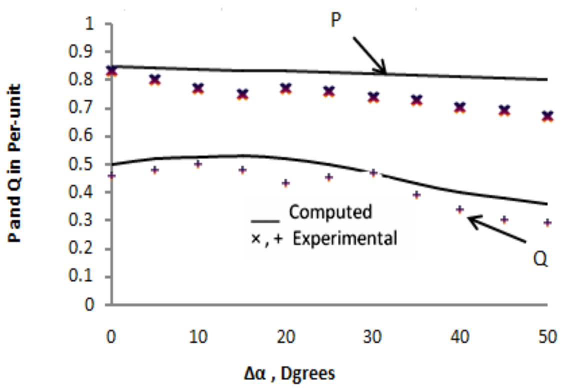
Figure.8: Firing control software

4 Results and Discussion

A suite of computer program was written to determine the theatrical performance of the converter bridge using equation (1) to (15). Harmonics analysis of the supply current waveforms was obtained using a Matlab. Theoretical and experimental results for the converter with conventional control and by-pass-valve control are shown in Figures (9) and (10) for reactive power absorption and harmonics content respectively. All results are obtained for a fixed value of I_d. The measured and experimental results were in good agreement and showed the general characteristic obtained using by-pass valve control. A voltage range of about $\pm 10\,\%$ was possible by varying α_b over 120° with a near constant reactive power absorption. Two bridges are invariably used with delta and star connected primary windings to eliminate the 5th , 7th and 19th harmonics etc. A delta-connected tertiary winding reduced the triple harmonic content with by-pass control. A large installation may reduce the residual triple harmonic content to an insignificant level. The proposed firing scheme has a response time less than one-sixth of the control of thyristor converter, dual converter, or cycloconverter.

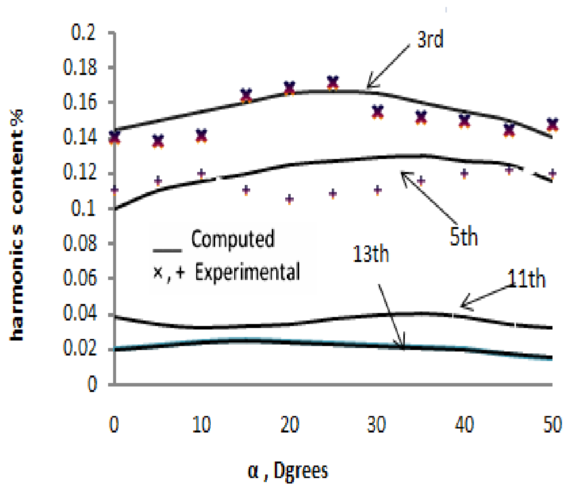


(a) Conventional Control

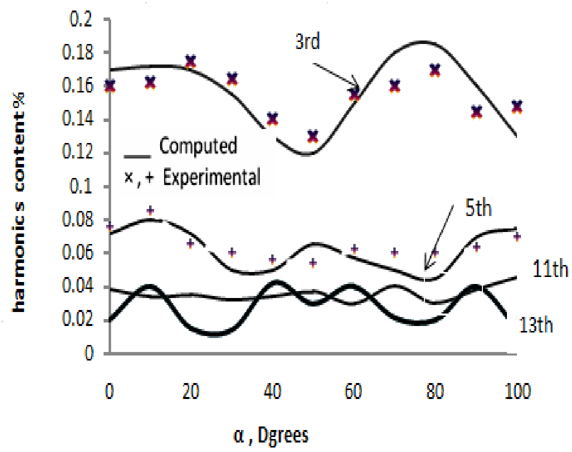


(b) By-Pass Valve Control

Figure.9: Active and reactive power



(a) Conventional Converter Δ / Y Transformer



(b) By-Pass Converter Δ / Y Transformer

Figure.10: Harmonic content of supply current

5 Conclusions

A novel bridge arrangement for use in HVDC converters is described. Computed values and experimental results from a laboratory model are in reasonable agreement and illustrate typical performance characteristics. A microprocessor-based firing control scheme for a modified converter has been presented. Also, a very compact, precise and fast –microprocessor controller has been described. Comparison of results obtained with the by-pass valve arrangement and a conventional converter indicates that there is a reduction in the VAR absorption. At normal operating point, the harmonics content of the supply current is generally reduced.

6 Nomenclature

V_d = DC voltage

V_{ph} = RMS value of phase voltage

V_0 = DC line voltage with zero delay angle on no-load

I_d = DC current in HVDC line

i_m = instantaneous value of main thyristor current

i_p = instantaneous value of by-pass thyristor current

n = transformer tap-section turns (p.u)

X_C = main thyristor commutation reactance

X_b = by-pass thyristor commutation reactance

α = delay angle of main thyristor

α_0 = delay angle due to unequal thyristor voltages

α_b = delay angle of by-pass thyristor

γ = commutation angle due to main thyristor

γ_b = commutation angle due to by-pass thyristor

β_0 = angle of advance due to unequal thyristor voltages

δ = safety angle in inverter operation

References

1. J. D. Ainsworth. “The phase-locked Oscillator – A new control method for control static converter”, *IEEE transactions on power Apparatus and systems*, Vol. PAS-87, , 1968, 859 - 865.
2. H. D. Al-Majali and B. H. Al-Majali, “Control of AC/DC converter under unbalanced System Conditions”, *Jordan Journal of Electrical Engineering (JJEE)*, Vol.1, No.1, 2015, 25 -36.
3. Y. Wang and L. Pierrat, probabilistic modeling of current harmonics produced by a AC/DC converter under voltage unbalance. *IEEE Transactions on power Delivery*, Vol.8, No.4, 1993, 2060-2066.
4. F. A. Farret and L. L. Freris, Minimization of uncharacteristic harmonics in HVDC converter through firing angle modulation, *IEE proceedings (Generation, Transmission and Distribution)*, Vol.137, Pt.C, No.1, 1990, 45-52.
5. Alves. J. E. R, Pilotto. L. A. S and Watanabe. E. H, An adaptive digital controller.
6. S. Al-Dhalaan, H. D. Al-Majali and D. O’Kelly,HVDC converter using self commutated devices, *IEEE Trans on Power Electronics*, Vol.13, No.6, 1998, 1164 – 1173.
7. H. D. Al-Majali, Voltage control of modified series-connected HVDC bridges, *Electric Power Systems Research (Elsevier, Vol.43*, 1997, 37-44
8. H. D. Al-Majali, Voltage control of series-connected modified HVDC bridges using GTO thyristor by-pass valves, , *Electric Power Systems Research (Elsevier), Vol.49*, No.2, 1999, 79-86
9. H. D. Al-Majali , S. Al-Dhalaan, “Transient of Modified HVDC Converter”, *Electric Power Systems Research (Elsevier)*, Vol.77, No. 10, 2007, 1329 – 1336.
10. H. D. Al-Majali , S. Al-Dhalaan, “A Snubber Configuration for Modified Bridge Converter” *Electric Power Components and Systems (Taylor & Francis)* Vol.34, No.11, 2006, 1177-1190.
11. H. D. Al-Majali, “Abnormal Harmonics Generated by Modified HVDC Converters” *Electric Power Components and Systems (Taylor & Francis*). Vol.35, No.6, 2006, 639 – 654.
12. X.Wilsun, J. E. Drakos, Y. Mansour and A. Chang, A three-phase converter model for harmonic analysis of HVDC systems, *IEEE Transaction on power Delivery*, Vol.9, No.3, 1994, 1724-1731
13. H.D. Al-Majali and D. O'Kelly, "Control of an HVDC Converter Using GTO Thyristor By-Pass Valaves*", 26th UPEC, Brightan Polytechnic*, U.K, 1991, PP 26-39.
14. H. D. Al-Majali and D. O'Kelly, "Control of an HVDC Converter Using By-Pass Valves", *25th UPEC, Robert Gordon's Institute of Technology*, Aberdeen, U.K, 1990, PP 652-656.