Reactive Power Drawn by Converters and its Application to Control of High Voltage Direct Current (HVDC) System

Sukhdeo Sao, & R.T. Thakur

***Abstract*- This paper presents a new methodology of power systems that have unique electric utility applications such as high voltage dc transmission, twelve pulse line frequency converters, reactive power drawn by converters, reactive mode of operation, inverter mode operation control of hvdc converter, harmonic filters and power factor correction factors. Electrical power generate in the form of ac voltage and currents. This power is transmitted to the load centers on three phases, ac transmission lines. It becomes desirable this power over dc transmission lines. This alternative becomes economically attractive where a large amount of power over dc transmitted over a long distance form a remote generating plant to the load center. This break-even distance for hvdc over a transmission lines usually lies somewhere in a range of 300 to 400 miles and is much smaller for under water cables. Electrical power generate power in the form of ac voltage and currents. This power is transmitted to the load centers on three phases, ac transmission lines. It becomes desirable this power over dc transmission lines. This altemative becomes economically attractive where a large amount of power over dc transmitted over a long distance form a remote generating plant to the load center. This break-even distance for hvdc over a transmission lines usually lies somewhere in a range of 300 to 400 miles and is much a smaller for under water cables.**

Even though ac side current associated with the converter contains harmonics in addition to their fundamental frequency components. The harmonic currents are "absorbed" the ac side filters whose design must be based on the magnitude of generalized harmonic current magnitudes. There fore only the fundamentals frequency components of the ac current are considered for the real power transfer and the reactive power drawn. It is necessary to consider only one of the two six-pulse converters, since the real power for the 12 pulse converter arrangement making up a pole are twice the per-converter values. If the evaluation is transmission network (66kv, 132kv and 230kv) It is clear that how the compensation can be on the transmission network as the present maximum voltage rating of the capacitor bank appears to be 33kv, if it is form of capacitor bank at 11kv or 33kv bus in the substation, does not need special transformation from the distribution voltage. If so whether the transmission need any special transformer other than one that is used normally for step up or step down transformers.

***Index Terms*--- Twelve-Pulse Line-Frequency Converters, Reactive Power, Inverter,**

I. INTRODUCTION

Problem of reactive power hvdc system for enhancement of voltage security can never be over emphasized for modern large integrated power systems which are operating under stressed conditions. In general reactive power management must be based on (i) minimizing the reactive power transfer (ii) optimizing the distance of collapse point from present operating point and (iii) keeping the voltages as high as possible near static voltage stability point [4]. Static var control is desirable is desirable to regulate the voltage within a narrow range of its nominal value. The load on the power system fluctuates and can result in voltages outside of their acceptable limits. In view of the fact that the internal impedance of the ac system seen by the load is mainly inductive (since the transmission and distribution lines, transformers, generators, etc, have mainly inductive impedance at the line frequency of 50Hz), it is the reactive power change in the load that has most adverse effect on the voltage regulation [2]. Electrical plants generate power in the form of ac voltages and currents. This power is transmitted to the load centers on three-phase, ac transmission lines. However, under certain circumstances, it becomes desirable to transmit this power over dc transmission lines. This alternative becomes economically attractive where a large amount of power is to be transmitted over a long distance from a remote generating plant to the load center.

Power flow over the transmission line can be reversed. If we assume the power flow to be from system *A* to *B*, the system A voltage, in a 69 to 230 kV range, is transformed up to the transmission level and then rectified by means of the converter terminal A and transmitted over the hvdc transmission line. At the receiving end, the dc power is inverted by means of the converter terminal B and the voltage is transformed down to match the ac voltage of system. B. The power received over the hvdc transmission line is then transmitted over ac transmission and distribution lines to wherever it is needed in system B.[5].

II. TWELVE-PULSE LINE-FREQUENCY CONVERTERS

A 12-pulse converter operation, which requires two 6-pulse converters connected through a Y-Y and ?-Y transformer. The two 6-pulse converters are connected in series on the dc side and in parallel on the ac side. The series connection of two 6-pulse converters on the dc side is important to meet the high voltage requirement of an hvdc system.

In Fig. 1, V_{as1n1} leads V_{as2n2} by 30^0 . The voltage and current waveforms can be drawn by assuming the current I_d on the dc side of the converter to be a pure dc in the presence of the large smoothing inductor L_d as shown in Fig.1. The effects of these commutating inductances on the 12-pulse waveform. Assumptions of

R.T. Thakur
Sukhdeo Sao
Guru Nanak Dev Engg. College, Bidar, Karnataka, 585401
Email--sukhdeosao@yahoo.com

$L_s = 0$ and i_d (t) ˜ I_d , and recognizing that V_{as1n1} leads V_{as2n2} by 30^0 , we can draw the current waveforms as in Fig.2*a*. Each 6-pulse converter operates at the same delay angle *a*. The waveform of the total per-phase current $i_a = i_{a1} + i_{a2}$ clearly shows that it contains fewer harmonics than either i_{a1} *or* i_{a2} drawn by the 6-pulse converters. In terms of their Fourier components

I_{a1} = (2v3 /2N p) I_d [*cos ?-1/5 cos 5?+1/7 cos 7?-1/11 cos 11?+1/13 cos 13?….*] (1)

and

I_{a2} = (2v3 /2N p) I_d [*cos ?+1/5 cos 5?-1/7 cos 7?-1/11 cos 11?+1/13 cos 13?….*] (2)

Where *? = ?t* and the transformer turns ratio *N* Therefore, the combined current drawn is

$i_a = i_{a1} + i_{a2=}$ (2v3 /2N p) I_d [*cos ?-1/11 cos 11?+1/13 cos 13?….*] (3)

This Fourier analysis shows that the combined line current has harmonics of the order

h = 12k ± 1 (where *k* = an integer) (4)

Resulting in a 12-pulse operation, as compared with a 6-pulse operation where the ac current harmonics are of the order 6*k ± 1 (where k* = an integer). The currents on the ac side of the two 6-pulse converters add, confirming that the two converters are effectively in parallel in parallel on the ac side. On the dc side the voltage waveforms v_{d1} and v_{d2} for the two 6-pulse converters are shown in Fig.2*b* . these two voltage waveforms are shifted by 30^0 with respect to each other. Since the two 6-pulse converters are connected in series on the dc side, the total dc voltage $v_{d=}\ v_{d1} + v_{d2}$ has 12 ripple pulses per fundamental frequency ac cycle. This results in the voltage harmonics of the order *h in* v_d, where

h = 12k (k= an integer) (5)

And the twelfth harmonic is the lowest order harmonics. Magnitudes of the dc-side voltage harmonics vary significantly with the delay angle *a*.

III. REACTIVE POWER DRAWN BY CONVERTERS

The line-voltage-commutated converters operate at a lagging power factor and, hence, draw reactive power from the ac system. Even though the ac-side currents associated with the converter contain harmonics in addition to their fundamental frequency components, the harmonic currents are "absorbed" by the ac-side filters, whose design must be based on the magnitude of the generated harmonic current magnitudes. Therefore, only the fundamental frequency components of the ac currents are considered for the real power transfer and the reactive power drawn. It is necessary to consider only one of the two 6-pulse converters, since the real and the reactive power for the 12-pulse converter arrangement making up a pole are twice the per-converter values.

IV. RECTIFIER MODE OF OPERATION

With the initial assumption that $L_s = 0$ in Fig. 1, Fig 2_c, shows the phase-to-neutral-voltage v_{as1n1} and the current i_{as1} (corresponding to converter 1 in Fig.2) with i_d (t) = I_d at a delay angle a. The fundamental frequency current component $(I_{as1})_1$ shown by the dotted curve lags behind the phase voltage v_{as1n1} by the displacement power factor angle $?_1$ where

$?_1$ = *a* (6)

Therefore, the three-phase reactive power (lagging) required by the 6-pulse converter because of the fundamental frequency reactive current components, which lag their respective phase voltages by 90º, equals

Q_1 = v3 V_{LL} $(I_{as1})_1$ sin *a* *(7)*

Where V_{LL} is the line-to-line voltage on the ac side of the converter.

From the Fourier analysis of I_{as1} in Fig.2_c, the rms value of its fundamental frequency component is

$(I_{as1})_1$ =(v6 / p * I_d) ˜ 0.78* I_d (8)

Therefore , from Eqs. 1&2

Q_1 = v3 V_{LL}(v6 / p * I_d) sin *a*
= 1.35V_{LL} I_d sin *a* (9)

The real power transfer through each of the 6-pulse converters can be calculated from Eq. With L_s= 0 as

$P_{d1} = V_{d1}I_d$ = 1.35 V_{LL} I_d cos *a* (10)

For a desired power transfer P_{d1} the reactive power demand Q_1 should be minimized as much as possible. Similarly, I_d should be kept as small as possible to minimize I^2R losses on the dc transmission line. To minimize I_d and Q_1, noting that V_{LL} is essentially constant in Eqs. 9 & 10, we should choose a small value for the delay *a* in the rectifier mode of operation. For practical reasons, the minimum value is *a* is chosen in a range of 10 to 20 degrees.

V. INVERTER MODE OF OPERATION

In the inverter mode, the dc voltage of the converter acts like a counter-emf in a dc motor. Therefore, it is convenient to define the dc voltage polarity as shown in Fig.3*a*, so that the dc voltage is positive when written specifically for the inverter mode of operation. The extinction angle *?* for the inverter was defined in terms of *a* and *u* as

? = 180° - (*a +u*) (11)

Where *a* is the delay angle and *u* is the commutation or the overlap angle. The inverter voltages in Fig. 4 can be obtained.

$V_{d1} = V_{d2} = V_d/2$
= 1.35 V_{LL} cos *?– 3 ?* L_s/ p * I_d (12)

Again with the assumption that $L_s = 0$ for simplicity, Fig. 3b shows the idealized waveforms for v_{as1n1} and i_{as1} at an $a > 90°$, corresponding to the inverter mode of operation. The fundamental frequency component $(I_{as1})_1$ of the phase current is shown by the dotted curve. In the phasor diagram of Fig. 3c, the fundamental frequency reactive current component lags behind the phase-to-neutral voltage, indicating that even in the inverter mode, where the direction of power flow through the converter has reversed, the converter requires reactive power (lagging) from the ac system.

With $L_s – 0$, u equals zero in Eq. 11 and $? = 180° - a$. Therefore, the expressions for per-converter Q_1 and P_{d1} in Eqs. 9 & 10 and can be obtained specifically for the inverter mode in terms of *? as*

$$Q_1 = v3\ V_{LL}\ I_d\ \sin ? \qquad (13)$$

And

$$P_{d1} = 1.35\ V_{LL}\ I_d \cos ? \qquad (14)$$

Where the directions of reactive power (lagging) and the real power in fig. 3a

In Eqs. 13 & 14, *?* should be as small as possible for a given power transfer level to minimize $I^2 R$ losses in the transmission line due to I_d and to minimize the reactive power demand by the converter. The minimum value that *?* is allowed to attain is called the minimum extinction angle $?_{min}$ that is based on allowing sufficient turn-off time to the thyristors.

In a 12-pulse converter arrangement, the reactive power requirement is the sum of the reactive powers required by each of the two 6-pulse converters. The ac-side filter banks and the power-factor-correction capacitors partially provide the reactive power demand of the converters.

VI. CONTROL OF HVDC CONVERTERS

In this paper to discuss the control of converters in an hvdc system on a per-pole basis, since both the positive and the negative poles are operated under identical conditions. Fig .4*a* shows the positive pole, for example, consisting of the 12-pulse converters *A* and *B* . Terminal *A* is assumed to be operating as a rectifier, and its dc voltage $V_{dA.}$ Terminal V is assumed to be operating as an inverter, an its dc V_{dB} is shown with a polarity that is specific to the inverter mode of operation, so that V_{dB} has a positive value. In steady state in Fig. 4*a*.

$$I_d = (V_{dA} - V_{dB}) / R_{dc} \qquad (15)$$

Where R_{dc} is the dc resistance of the positive transmission line conductor. In practice, R_{dc} is small and I_d results as a consequence of a small difference between two very large voltages in Eq. 15. Therefore, one converter is assigned to control the voltage on the transmission line and the other to control I_d . Since the inverter should operate at a constant $? = ?_{min}$, it is natural to choose the inverter (converter *B* in Fig. 4*a)* to control V_d . Then, I_d and, hence, the power level is controlled by the rectifier (converter *A* in Fig.4*a*). Fig 4*b* shows the rectifier and the inverter control characteristics in the V_d - I_d plane, where V_d is chosen to be the voltage at the rectifier, that is, $V_d=V_{dA}$. At the constant extinction angle $?= ?_{min}$, the inverter produces a voltage V_d in Fig. 4*a*, which is given as

$$V_d = 2 *[\ 1.35 * V_{LL} * \cos ?_{min} - 3\ ?\ L_s / p * I_d] + R_{dc}.I_d$$

$$= 2 * 1.35 * V_{LL} * \cos ?_{min} - (6\ ?\ L_s / p - R_{dc})I_d \qquad (16)$$

Assuming the quantity within the bracket in Eq. 16 to be positive, the constant extinction angle operation of the inverter results in a V_d - I_d Characteristic as shown in Fig. 4_b. The power flow $P_d = V_d I_d$ from terminal *A* to terminal *B* can be controlled in Fig. 4*a* by controlling I_d, while maintaining the transmission line voltage as high as possible to minimize $I^2_d R_{dc}$ power loss in the transmission line.

VII. HARMONIC FILTERS AND POWER-FACTOR-CORRECTION CAPACITORS

(a). Dc-side harmonic filters

To minimize the inductively coupled harmonic interference produced in the telephone system and other types of control/communication channels in parallel with the hvdc transmission lines, it is important to minimize the magnitudes of the current harmonics on the dc transmission line. The voltages depend on *a*, $L_{s,}$ and I_d for a given ac system voltages. Under a balanced 12-pulse operating condition, the 12-pulse converter can be represented by an equivalent circuit as shown in Fig.5*a*. where the harmonic voltages are connected in series with te dc voltage V_d.

A large smoothing inductor L_d of the order of several hundred millineries (mH) is used in combination with a high-pass filter, as shown in Fig.5*a*, in order to limit the flow of harmonic currents on the transmission line. The impedance of the high-pass filter in Fig. 5*a* is plotted in Fig. 5*b*.

(b). Ac-side harmonic filter and power factor correction capacitors.

In a 12-pulse converter, the ac currents consist of the characteristic harmonics of the order
$12k \pm 1$ (k=an integer), The per-phase filters shown in Fig. 6*a* are commonly used. A high-pass filter as shown in Fig.6*a* is used to eliminate the rest of the higher order harmonics. The combined impedance of all the harmonic filters is plotted in Fig. 6*b* .

The harmonic filters also provide a large percentage of the reactive power required by the converters in the rectifier and the inverter mode. The effective shunt capacitance offered per-phase by the ac-filter bank at the fundamental or line frequency can be approximated as

$$C_f \tilde{}\ C_{11} + C_{13} + C_{hp} \qquad (17)$$

At the 50-H_z fundamental system frequency, the per-phase reactive power (vars) supplied by the filter bank equals

$$Q_f \tilde{}\ 377 C_f V^2_s \qquad (18)$$

Where, V_s is the rms phase voltage applied across the filters. Thus, the ac filters play an important role in meeting the reactive power demand of the converters, in addition to filtering the current harmonics.

VIII. TABLE 1

Symbol	Quantity
a	*delay angle*
V_{LL}	*line to line rms voltage*
L_s	*per-phase leakage inductance Of each of the transforms*
H	*order of the harmonics*
N.	*turns ratio*
$(I_{as1})_1$	*the fundamental frequency current component*
I_{as1}	*the current corresponding to Converter*
L_d	*Large smoothing inductor*
R_{dc}	*dc resistance of the positive transmission*

IX. CONCLUSION

The reactive power requirement is the sum of the reactive powers required by each of the two 6-pulse converters. The ac-side filter banks and the power-factor-correction capacitors partially provide the reactive power demand of the converters.

The power –factor correction capacitors are included along with the ac filter banks to supply the lagging reactive power (or the inductive vars) required by the converter in the rectifier as well as in the inverter mode of operation. On the dc side of the converter, the ripple in the dc voltage is prevented from causing excessive ripple in the dc transmission line current by means of soothing inductors L_d and the dc side filter banks. To minimize the inductively coupled harmonic interference produced in the telephone system and other types of control/communication channels in parallel with the hvdc transmission lines, it is important to minimize the magnitudes of the current harmonics on the dc transmission line. Only the fundamental frequency components of the ac currents are considered for the real power transfer and the reactive power drawn..

X. REFERENCES

[1]. T.R. Ekambaram, “Analytical and practical approach on reactive power compensation for strenthing electric power distribution”, Journal of IE (India), vol-8,nov 1999,pp_132

[2]. K.P.Basu and B.H. Khan, “Simultaneous Ac_DC power Transmission “Journal of IE (India), vol 82 pp 32-35, june 2001.

[3]. V.P. Pawer, N.M. More & Schrotra, “measurement of transmission line parameters using time domain technic” IETE Technical Review vol 17, No_6, Nov_dec 2000, pp 347_349

[4]. LD Arya, DK Sakravadia and SC Coube, “Fast evaluation of reactive compensation index and line outage ranking “Journal of IE (India) vol_82,Dec 2001, pp-173_176.

[5]. Ned Mohan, Tore M.Undeland and William P.Robbgins, “Power electronics convertors applicatications and design”, Copy right 1994, John Wiley & Sons” PP 386_407.

[6]. C.Adamson and N.G. Hingorani, “High voltage Direct Current Transmission, Garraway, London, 1960.

[7]. I. Glyugyi and E.R Taylor,” Characteristic of Static, Thyristor Controlled shunt compensators for power transmission system applications”, IEEE Trans. On power Apparatus and system, Vol. Pas 99n0.5,PP 1795_1804, Sept/ Oct 1980.

[8]. Sukhdeo Sao and R. Devsaran, “static VAR controller – applications to modern power system”, International Conference , Dec-1998, PP 184-186.

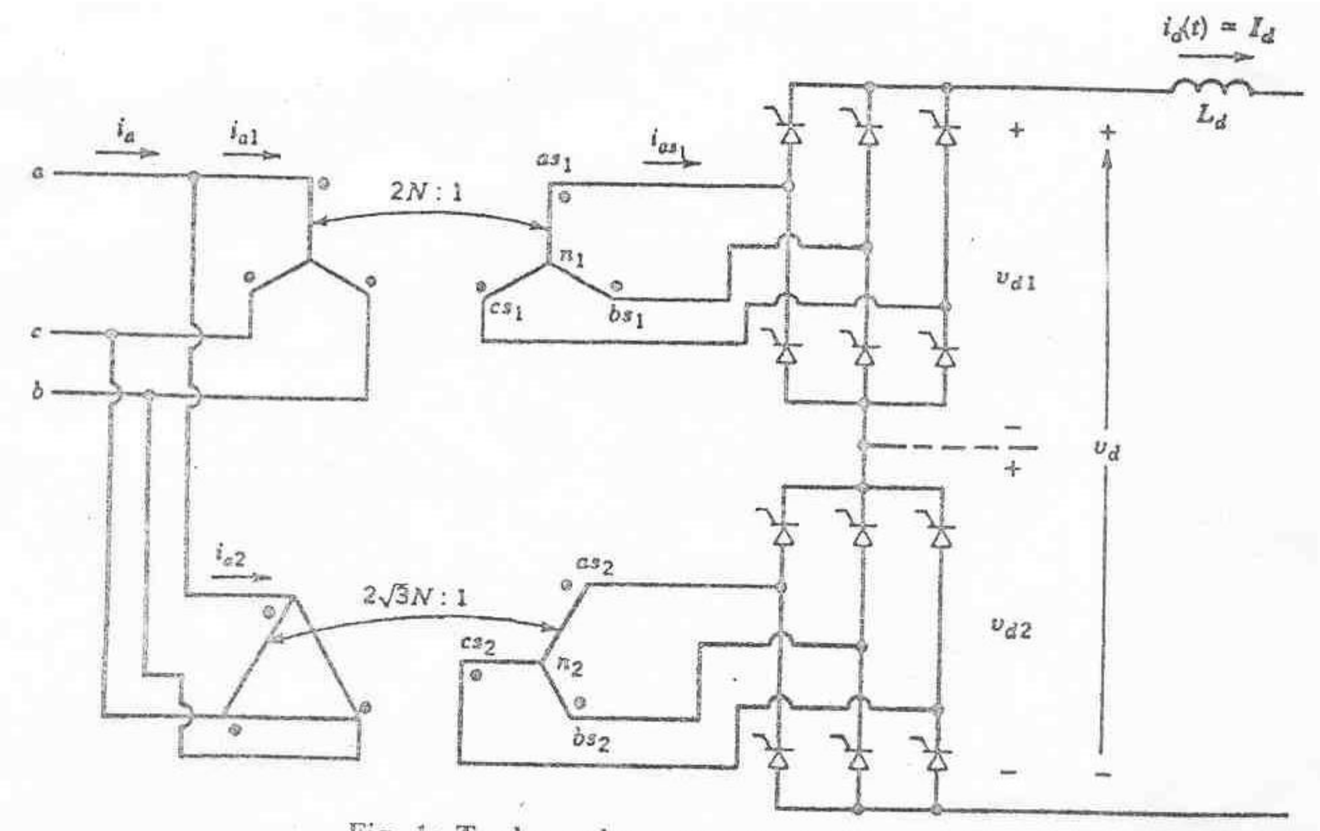

Fig. 1: Twelve-pulse converter arrangement.

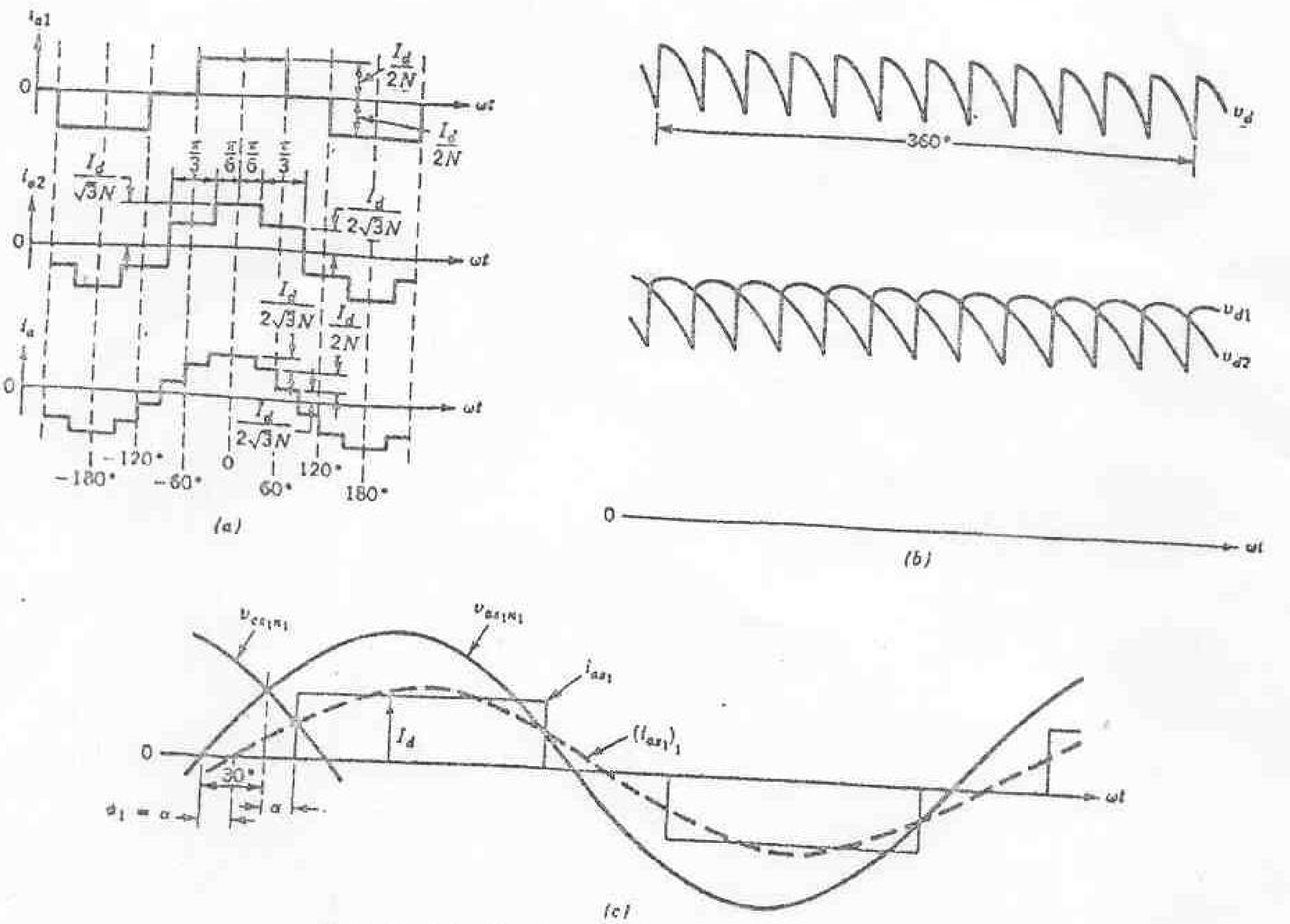

Fig. 2: Idealized waveforms assuming $L_s = 0$

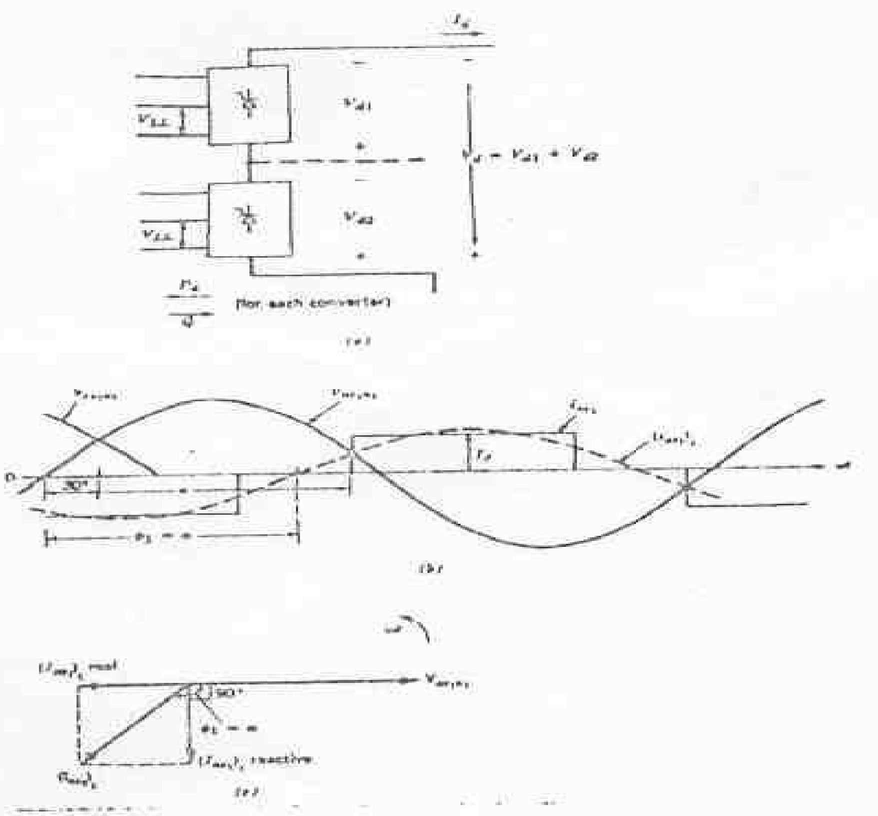

Fig. 3: Inverter mode of operation (assuming $L_s = 0$)

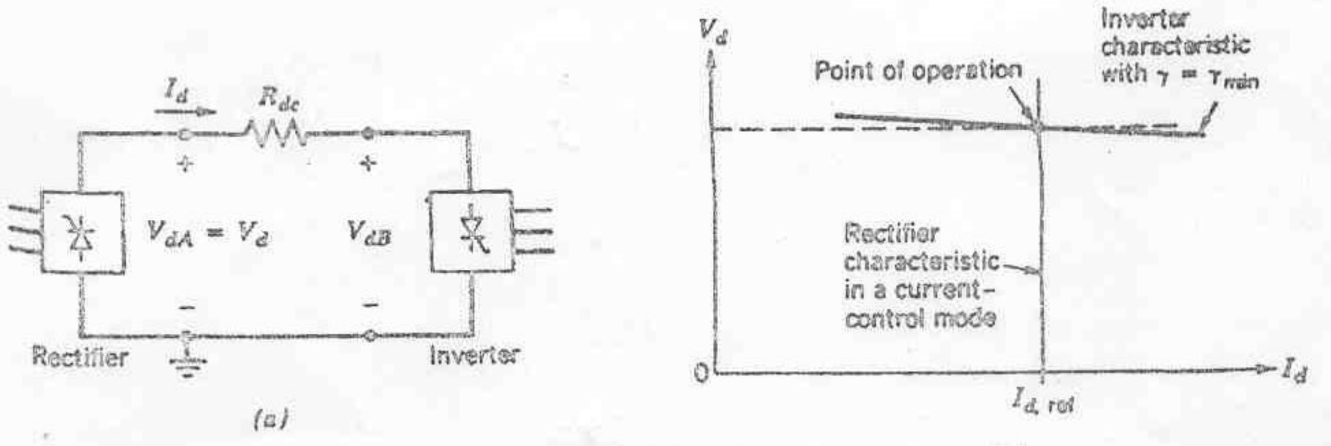

Fig. 4: Control of HVDC system

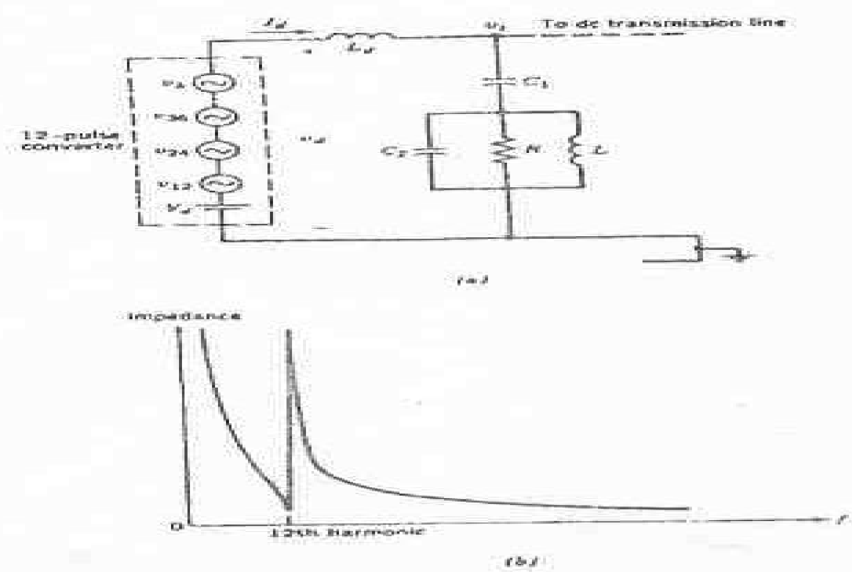

Fig. 5: Filter for dc-side volatage harmonics
(a) dc-side equivalent circuit;
(b) high-pass filter impedance versus frequency

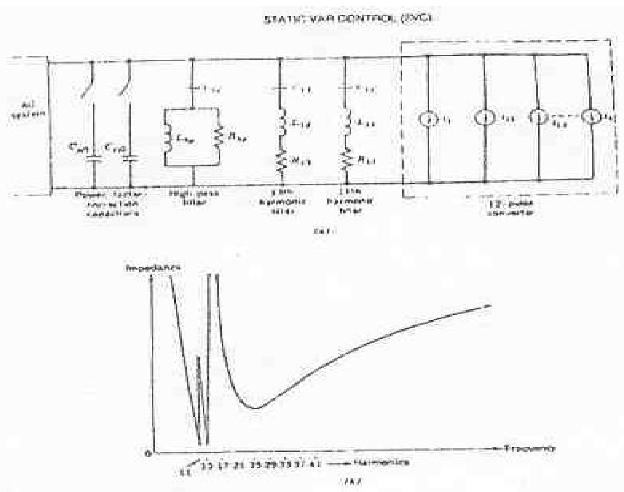

Fig. 6: AC side filters and power-factor-correction capacitors: (a) per-phase equivalent circuit; (b) combined per-phase filter impedance versus frequency.