On the Commutation Process of Capacitor Commutated Converter (CCC)

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Abstract: Series compensated commutation is obtained by insertion a capacitor between the converter transformer and the six pulse thyristorized Graetz bridge. This arrangement will provide a reduction in the impedance of the commutation circuit. This can permit greater efficiency of commutation, reducing the reactive power consumption of the converter and the consequent necessity of large shunt compensation banks. An improvement in the susceptibility of the converter to commutation failure is achieved, when the converter is operating in the inverter mode. In this paper the valve commutation process will be studied and discussed taking into account the use of series compensated capacitor.
Key-Words: Capacitor Commutated Converter, Series Compensation, Commutation Process.

1 Introduction

There is a HVDC project, in which series compensated capacitors have been already used, as for instance, the 12 pulse [HVDC] project, Argentina – Brazil 1000 [MW] interconnection [3].

For obtaining 12-pulse converter supplying transformers whose secondary voltages are displaced thirty degrees with relation to each other, may be used. These transformers can be, for instance, transformers YY(0°) and YΔ(30°), which supply the bridges. Transformers star/extended-delta (±15°) have also already been used in the HVDC 12-pulse converter project 500 [MW], Vindyachal, India, 1988.

2 The commutation process considering the use of series compensated capacitor

Figure 1 shows the series compensated converter arrangement.

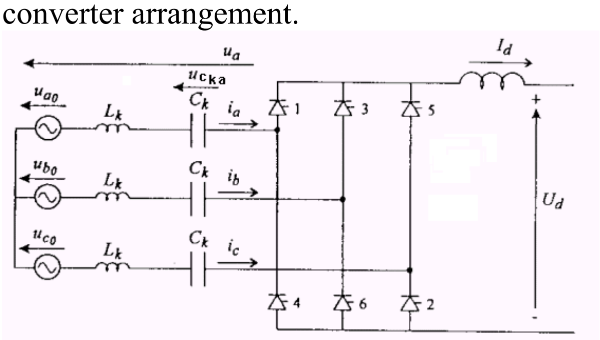

Fig. 1 – Series compensated converter.

The relative voltage drop $d_{x\ell}$ due to the inductance L_K is defined as [1]:

$$d_{x\ell} = \frac{3}{\pi}\omega . L_k . \frac{Id}{U_{dio}} \qquad (1)$$

where:
ω: Angular frequency.
Id: DC output current.
U_{dio}: DC output voltage for firing angle α equal to zero degrees.
L_K: Transformer inductance.

The relative voltage drop dx_C due to the series capacitor C_K is given by [1]:

$$d_{XC} = \frac{3}{\pi} . \frac{1}{\omega C_K} . \frac{Id}{U_{dio}} \qquad (2)$$

These expressions have been derived from the equivalent circuit of the bridge [4]:

$$U_d = U_{dio} \cos\alpha - \frac{3}{\pi} X\,Id \qquad (3)$$

where:
U_d: DC output voltage of the bridge.
X: Commutation reactance per phase.
α: Firing angle of the bridge

One way to calculate the angle of overlap (μ) refers to the analysis of the voltage time integral during the commutation time and use the fact that the time integral of the voltage across the two commutation inductances must be equal to $2L_K Id$ [1]. This gives: (commutation from valve 5 to 1).

$$2L_K Id = \frac{1}{\omega}\int_{\alpha}^{\alpha+\mu}(u_{ao} + u_{Cka} - u_{Co} - u_{Ckc})\,d\omega t \tag{4}$$

where:

u_{ao}: Phase a to neutral supply voltage;
u_{Co}: Phase c to neutral supply voltage;
u_{Cka}: Voltage across capacitor phase a;
u_{Ckc}: Voltage across capacitor phase c;

The integral of expression (4) can be split into two parts. The first one corresponding to the contribution from the source voltage and the other from the capacitor voltages. The first part is given by [1]:

$$\frac{1}{\omega}\int_{\alpha}^{\alpha+\mu}(u_{ao} - u_{Co})\,d\omega t = \frac{1}{\omega}.\frac{\pi}{3}U_{dio}\left[(\cos\alpha - \cos(\alpha+\mu)\right] \tag{5}$$

The second part can be determined [1].

$$\frac{1}{\omega}\int_{\alpha}^{\alpha+\mu}(u_{Cka} - u_{Ckc})\,d(\omega t) = \frac{1}{\omega}.\frac{2\pi}{3}(1-\frac{\mu}{2\pi}).\mu\frac{Id}{\omega C_K} \tag{6}$$

This integral has been obtained assuming that the voltage u_{Cka} and u_{Ckc} are linear during the interval $i_a = I_d$ and $i_c = I_d$ and constant when these currents (i_a and i_c), remain null. Also, the commutation currents have been considered linear, during the commutation process.

From equations (4), (5) and (6), results:

$$\frac{3}{\pi}\,\omega L_K\,\frac{Id}{U_{dio}} = \frac{1}{2}\left[\cos\alpha - \cos(\alpha+\mu)\right] + \frac{\mu}{\omega C_K}(1-\frac{\mu}{2\pi})\frac{Id}{U_{dio}} \tag{7}$$

The determination of the commutation angle μ can be made using the Newton-Raphson method, as follows:

$$F(\mu) = \frac{3}{\pi}\omega L_K\frac{I_d}{U_{dio}} - \frac{1}{2}\left[\cos\alpha - \cos(\alpha+\mu)\right] - \frac{\mu}{\omega C_K}(1-\frac{\mu}{2\pi})\frac{I_d}{U_{dio}} \tag{8}$$

$$F'(\mu) = -\frac{1}{2}\text{sen}(\alpha+\mu) - \frac{1}{\omega C_K}.\frac{I_d}{U_{dio}}\left(1-\frac{\mu}{\pi}\right) \tag{9}$$

The Newton-Raphson method is applied as follows:

$$\mu_{i+1} = \mu_i - \frac{F(\mu_i)}{F'(\mu_i)} \tag{10}$$

Considering the expressions (1) and (2), expression (7) can be written as:

$$d_{X\ell} = \frac{1}{2}\left[\cos\alpha - \cos(\alpha+\mu)\right] + \frac{\pi}{3}.\mu(1-\frac{\mu}{2\pi})d_{XC} \tag{11}$$

and expression (8) as:

$$F(\mu) = d_{X\ell} - \frac{1}{2}\left[\cos\alpha - \cos(\alpha+\mu)\right] - \frac{\pi}{3}.\mu(1-\frac{\mu}{2\pi})d_{XC} \tag{12}$$

The interactive process is continued until the expression ABS(F(μ)), (8) remains lower-equal of a given maximum tolerance value (TOL). The developed program flowchart using the Newton-Raphson method, is shown in figure 2.

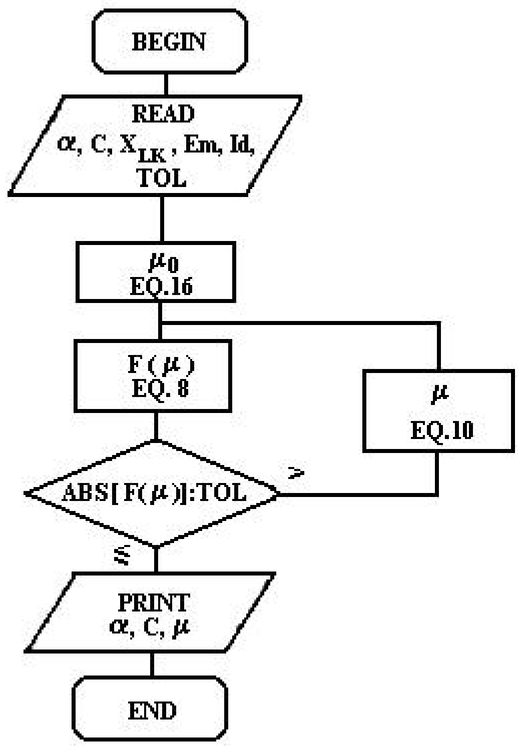

Fig. 2 – Developed program flowchart.

The expression of the commutation angle (μ) without the use of series capacitor is given by [4]:

$$I_d = I_{S2}(\cos\alpha - \cos\delta) \tag{13}$$

$$\delta = \alpha + \mu \tag{14}$$

$$I_{S2} = \frac{\sqrt{3}\,Em}{2\omega\, L_K} \tag{15}$$

Where Em: Peak value of the phase-neutral converter supply voltage.

Results:

$$\mu = \cos^{-1}\left[\cos\alpha - \frac{Id}{I_{S2}}\right] - \alpha \tag{16}$$

3 Obtained Results

Considering the transformer with the following data:

S = 2 [KVA] (rated power)
U_2 = 190 [V] (rated secondary voltage)
$X_{LK}\%$ = 8% (reactance)

Results:

$X_{LK} = 0.08 \text{ x } (190)^2/2000$

$$X_{LK} = 1.44\ [\Omega] \tag{17}$$

$$\text{Where } X_{LK} = \omega L_K \tag{18}$$

3.1 Bank Dimensioning

The characteristic U_d x I_d of CCC is given by [1]:

$$U_{di} = U_{dio}\left[\cos\alpha - \left(d_{x\ell N} - \frac{\pi}{3}.\mu.\left(1 - \frac{\mu}{2\pi}\right).d_{xcN}\right).\frac{I_d}{I_{dN}}.\frac{U_{dioN}}{U_{dio}}\right] \tag{19}$$

Where the index N is related with rating conditions of the considered term. For instance, considering $d_{xcN}/d_{x\ell N} = 4$ and μ = 15^o ($15\pi/180$ rad), which is a satisfactory value for HVDC systems, results in a slope characteristic U_d x I_d almost equal to zero. So, the output voltage will be practically constant, independent of the DC current.

Results (according to [4]):

$$S = 1.047\ U_{dio}\ I_d \tag{20}$$

$$U_{dio} = 1.35\ U_2 \tag{21}$$

$$I_{dN} = \frac{2000}{1.047 \text{x} 1.35 \text{x} 190}$$

$$I_{dN} = 7.45[A]$$

$$I_1 = \frac{\sqrt{6}}{\pi} I_d \tag{22}$$

$$I_1 = 5.81\ [A] \tag{23}$$

$$X_{CK} = 4X_{LK} \tag{24}$$

$X_{CK} = 5.76[\Omega]$, resulting:

$$C_K = 460.5\ [\mu F/\text{per phase}] \tag{25}$$

For this value of C_K and taking into account rating conditions, the commutation angle for α = 155^o will be calculated, using the developed program (flowchart figure 2):

$\mu \cong 6.5^o$

For the conventional converter, without capacitor, the angle μ is:

$\mu \cong 15.5^o$ (using (16)).

The reactive power generated by the capacitors for rating conditions is:

$$Q_{CN} = 3X_{CK}\, I_1^2 \tag{26}$$

$$Q_{CN} = 583.3[VAr]$$

According to [1] α_{min} can be calculated for rating conditions, and considering the commutation angle $\mu = 6.5^o$.

$$\sin\alpha_{min} = -\frac{2X_{CK}\,I_d}{U_{dio}}\left(1-\frac{3\mu}{4\pi}\right) \tag{27}$$

$$\sin\alpha_{min} = -0.3255$$

$$\alpha_{min} = -19^o \tag{28}$$

(considering μ)

Neglecting the commutation angle ($\mu = 0$).

$$\sin\alpha_{min} = -0.3347$$

$$\alpha_{min} = -19.55^o \tag{29}$$

(Neglecting (μ)).

3.2 Inverter Commutation Failures

The more common inverter commutation failures of the conventional converter are shown in figures 4, 5, 6 [5]. These failures are minimized in the CCC converter, consisting, so, this fact, an advantage of the CCC converter.

Figure 3 shows the conventional DC inverter output voltage for a single commutation failure (valves 5 and 3).

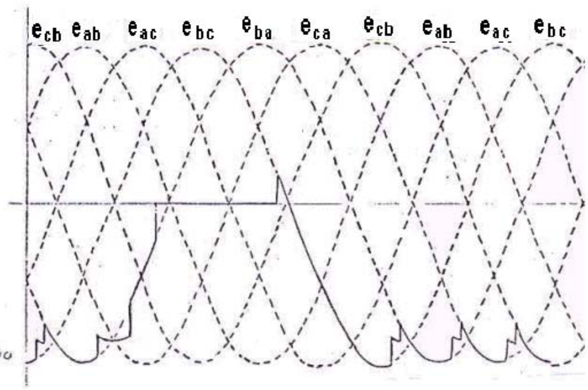

Fig. 3 – Inverter DC output voltage for single commutation failure.

Figure 4 shows the inverter DC output voltage for double successive commutation failure (valves 5-3; 6-4).

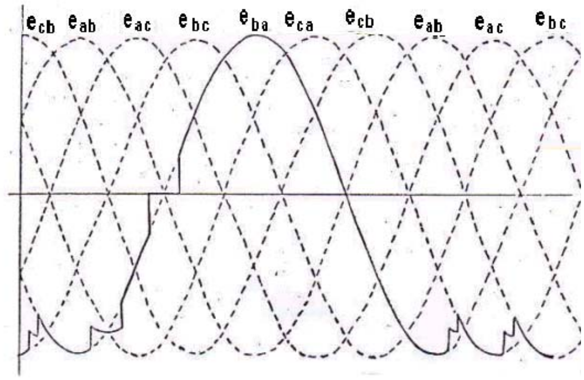

Fig. 4 – Inverter DC output voltage for double successive commutation failure (valves 5-3; 6-4).

Figure 5 shows the inverter DC output voltage for double non successive commutation failure (valves 5-3; 2-6).

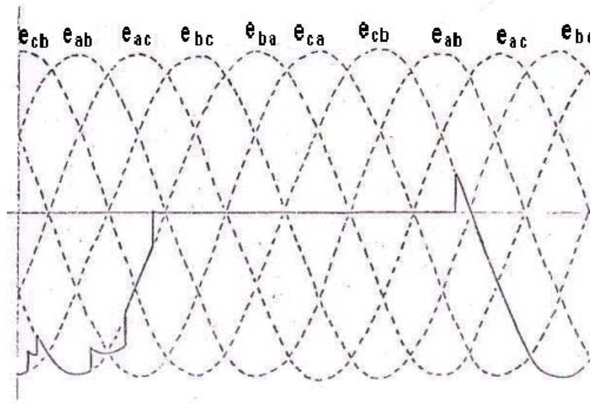

Fig. 5 – Inverter DC output voltage for double non successive commutation failure (valves 5-3; 2-6).

3.3 Operation as Rectifier

Table 1 shows the commutation angle (μ) for rectifier operation, and considering, for instance, $I_d = 0.5$ [A].

Firing Angle (α)	Capacitor (μF)	Commutation angle (μ) (degrees)
$\alpha = 20^o$	50	0.57
	60	0.60
	70	0.63
	80	0.66
	90	0.68
	100	0.70
Firing Angle (α)	Capacitor (μF)	Commutation angle (μ) (degrees)
$\alpha = 30^o$	50	0.44
	60	0.46
	70	0.48
	80	0.50
	90	0.51
	100	0.52
Firing Angle (α)	Capacitor (μF)	Commutation angle (μ) (degrees)
$\alpha = 40^o$	50	0.37
	60	0.38
	70	0.40
	80	0.41
	90	0.41
	100	0.42
Firing Angle (α)	Capacitor (μF)	Commutation angle (μ) (degrees)
$\alpha = 50^o$	50	0.32
	60	0.33
	70	0.34
	80	0.35
	90	0.36
	100	0.36
Firing Angle (α)	Capacitor (μF)	Commutation angle (μ) (degrees)
$\alpha = 60^o$	50	0.29
	60	0.30
	70	0.31
	80	0.32
	90	0.32
	100	0.32

Table 1: CCC Commutation angle (μ) for rectifier operation.

3.4 Operation as Inverter

Table 2 shows the commutation angle (μ) for inverter operation.

Firing Angle (α)	Capacitor (μF)	Commutation angle (μ) (degrees)
$\alpha = 160^o$	50	0.57
	60	0.61
	70	0.64
	80	0.66
	90	0.69
	100	0.70
Firing Angle (α)	Capacitor (μF)	Commutation angle (μ) (degrees)
$\alpha = 150^o$	50	0.44
	60	0.47
	70	0.48
	80	0.50
	90	0.51
	100	0.52
Firing Angle (α)	Capacitor (μF)	Commutation angle (μ) (degrees)
$\alpha = 140^o$	50	0.37
	60	0.38
	70	0.40
	80	0.41
	90	0.41
	100	0.42
Firing Angle (α)	Capacitor (μF)	Commutation angle (μ) (degrees)
$\alpha = 130^o$	50	0.32
	60	0.33
	70	0.34
	80	0.35
	90	0.36
	100	0.36
Firing Angle (α)	Capacitor (μF)	Commutation angle (μ) (degrees)
$\alpha = 120^o$	50	0.29
	60	0.30
	70	0.31
	80	0.32
	90	0.32
	100	0.32

Table 2: CCC Commutation angle for inverter operation.

3.5 Operation as Rectifier (without capacitor – conventional converter)

Table 3 shows the commutation angles (μ) of the conventional converter for rectifier operation.

Firing Angle (α)	δ Angle	Commutation angle (μ) $\mu = \delta - \alpha$
$\alpha = 20^o$	$\delta = 20.88^o$	$\mu = 0.88^o$
$\alpha = 30^o$	$\delta = 30.61^o$	$\mu = 0.61^o$
$\alpha = 40^o$	$\delta = 40.48^o$	$\mu = 0.48^o$
$\alpha = 50^o$	$\delta = 50.40^o$	$\mu = 0.40^o$
$\alpha = 60^o$	$\delta = 60.35^o$	$\mu = 0.35^o$

Table 3: Conventional converter commutation angles (μ) for rectifier operation.

3.6 Operation as Inverter - conventional converter

Table 4 shows the commutation angles (μ) of the conventional converter for inverter operation.

Firing Angle (α)	δ Angle	Commutation angle (μ) $\mu = \delta - \alpha$
$\alpha = 160^o$	$\delta = 160.92^o$	$\mu = 0.92^o$
$\alpha = 150^o$	$\delta = 150.62^o$	$\mu = 0.62^o$
$\alpha = 140^o$	$\delta = 140.48^o$	$\mu = 0.48^o$
$\alpha = 130^o$	$\delta = 130.40^o$	$\mu = 0.40^o$
$\alpha = 120^o$	$\delta = 120.36^o$	$\mu = 0.36^o$

Table 4: Conventional converter commutation angles (μ) for inverter operation.

4 Conclusion

The capacitor commutated converter provides a reactive power compensation, and so large shunt filter banks are no longer required for this purpose.

Better commutation failure immunity is achieved due to the increase of the inverter commutation margin, when series capacitors are used. Also increasing the DC current, results in an increasing voltage across the capacitor, compensating this way the drop in the AC network voltage.

The developed program using the Newton-Raphson method (flowchart figure 2) for calculation of CCC commutation angles (μ), has presented convergence in the interactive process.

The commutation angle (μ) is lower for capacitor commutated converter, when compared with the conventional no compensated converter, as seen comparing the commutation angles (μ) of tables 1 and 2 (CCC) with the commutation angles (μ) of tables 3 and 4 (no compensated converters), for each considered firing angle (α).

The series capacitor's impedance provides also an increasing in the total secondary side impedance, reducing, in this way, the DC side short circuit currents. The capacitor commutated converter (CCC), can operate with a good power factor. As well in some cases, it can until present to the network a leading power factor. In these cases the firing angle α is negative in the rectifier and higher than 180 degrees in the inverter.

At the moment maximum capacitors per phase 100 [μF] are available in our laboratories. Because of this fact, tables 1 and 2 present values of commutation angles for this maximum considered capacitor. However we are providing the acquisition of the rated capacitors (460 μF/per phase), which provide the operation of the CCC with rating conditions of the supply transformer (Id_N = 7.45 [A]), resulting in a lower RMS capacitor voltage. The slope characteristic (U_d x I_d) being almost equal zero to the inverter, will result favorable with respect to the stability of the system.

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