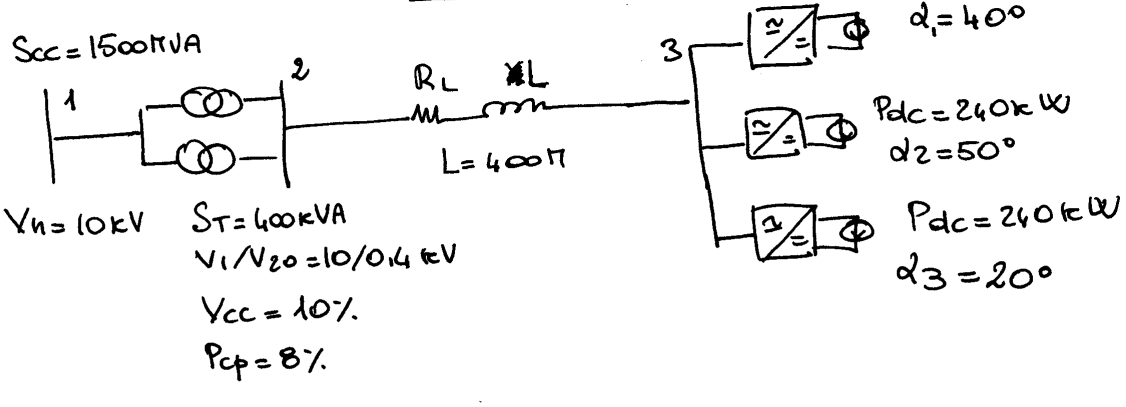
Tre convertitori a ponte esafase (Pdc= 240kW; αn1=40°, αn2=50°, αn3=20°) sono alimentati da un sistema di distribuzione (Scc= 1500 MVA, Vn = 10kV) tramite due trasformatori in parallelo di potenza pari a 400 kVA ($Vcc_{\%}$= 10%; V_1/V_{20}= 10/.4 kV, Pcp=8%). La linea in cavo, lunga 400m, ha una resistenza unitaria pari a 0.5 mΩ/m ed una reattanza unitaria alla fondamentale pari a 0.05 mΩ/m.

Verificare:

- il rispetto delle Norme IEEE 519
- la taglia del trasformatore portando in conto il K factor
-

Infine, **impostare l'analisi** del funzionamento del sistema alla fondamentale ed alle armoniche secondo il metodo iterativo.

Svolgimento



Per la verifica delle IEEE 519 (limiti sulle I_h e sulle V_h) e' opportuno disegnare il circuito equivalente alle armoniche del sistema

(A)

Current Distortion Limits for General Distribution Systems (120 V Through 69 000 V)

Maximum Harmonic Current Distortion in Percent of I_L						
Individual Harmonic Order (Odd Harmonics)						
I_{sc}/I_L	<11	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h$	TDD
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Even harmonics are limited to 25% of the odd harmonic limits above.

Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

*All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L.

where

I_{sc} = maximum short-circuit current at PCC.
I_L = maximum demand load current (fundamental frequency component) at PCC.

(B)

Table 10.4
Current Distortion Limits for General Subtransmission Systems (69 001 V Through 161 000 V)

Maximum Harmonic Current Distortion in Percent of I_L						
Individual Harmonic Order (Odd Harmonics)						
I_{sc}/I_L	<11	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h$	TDD
<20*	2.0	1.0	0.75	0.3	0.15	2.5
20<50	3.5	1.75	1.25	0.5	0.25	4.0
50<100	5.0	2.25	2.0	0.75	0.35	6.0
100<1000	6.0	2.75	2.5	1.0	0.5	7.5
>1000	7.5	3.5	3.0	1.25	0.7	10.0

Even harmonics are limited to 25% of the odd harmonic limits above.

Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

*All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L.

where

I_{sc} = maximum short-circuit current at PCC.
I_L = maximum demand load current (fundamental frequency component) at PCC.

(C)

Table 10.5
Current Distortion Limits for General Transmission Systems (>161 kV), Dispersed Generation and Cogeneration

Individual Harmonic Order (Odd Harmonics)						
I_{sc}/I_L	<11	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h$	THD
<50	2.0	1.0	0.75	0.3	0.15	2.5
≥50	3.0	1.5	1.15	0.45	0.22	3.75

Even harmonics are limited to 25% of the odd harmonic limits above.

Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

*All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L.

where

I_{sc} = maximum short-circuit current at PCC.
I_L = maximum demand load [illegible]

The limits listed in Table 11.1 should be used as system design values for the "worst case" for normal operation (conditions lasting longer than one hour). For shorter periods, during start-ups or unusual conditions, the limits may be exceeded by 50%.

Table 11.1
Voltage Distortion Limits

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69 kV and below	3.0	5.0
69.001 kV through 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5

NOTE: High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.

11.6 Limits of Interference With Communication Circuits. It is difficult to place specific limits on the telephone influence that the harmonic components of current and voltage in converter systems can inflict. The actual interference to voice communication systems in proximity to the power system supplying the converter is dependent upon a number of factors not under the control of the designer of the converter system. These factors will vary from location to location and from time to time as the state-of-the art of inductive coordination progresses.

There are some data available that relate to the *I·T* (see 6.9.1) performance of large converters used in telephone offices to charge batteries (see Table 11.2). It should be noted that the values shown in Table 11.2 are given for illustrative purposes and are not to be considered as requirements. Furthermore, the values shown are applicable to the secondary distribution within the telephone building. The *I·T* on the primary system would be reduced by the turns ratio in the distribution transformer, which is typically in the range of 40:1 to 60:1. For example, an *I·T* of 100 000 for a 240 V, 1600 A converter would become 2000 on a 12 kV primary. This, of course, is important because the exposure to the primary feed will be greater in length. Fig 11.3 gives typical *I·T* values for 48 V dc ferroresonant converters.

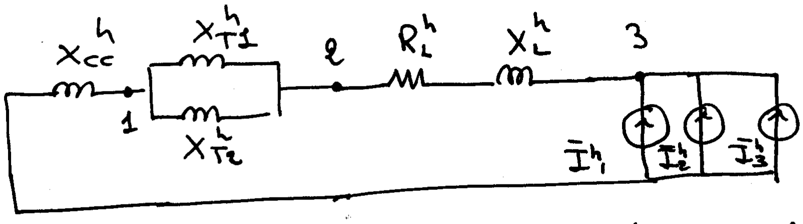
Table 11.2
Typical *I·T* Values for 48 V DC Converters

Three-Phase Line-to-Line Voltage	Rectifier Full Load Output Current Rating	*I·T* on Secondary Distribution
208/240 V	400	25 000
	800	50 000
	1600	100 000
480 V	400	12 000
	800	25 000
	1600	50 000

NOTE: For the case of ferroresonant units that do not utilize phase shifting, the *I·T* is typically much lower, as indicated in Table 11.3.

These converters were of the six-pulse type with phase-shifting taps to permit two converters to be operated in parallel on a 12-pulse basis or four converters to be operated on a 24-pulse basis. Recently, consideration has been given to lower the specified maximum values to one-half or less of the above figures, particularly where the battery plant is to be associated with an electronic switching office.

Ipotizzando nulle le "ambient harmonics" si ha:



I valori delle grandezze presenti nel circuito sono calcolati di seguito

$$X_{cc}^h = h\, X_{cc}^1 = h \frac{V_n^2}{S_{cc}} = h \cdot \frac{380^2}{1500 \cdot 10^6} \cong h\, 9.6 \cdot 10^{-2}\ m\Omega$$

$$X_{T1}^h = h\, X_{T1}^1 = h\, V_{cc}^{\%} \cdot X_{BASE} = h \cdot 0{,}1 \cdot 0{,}36 = h\ 0{,}036\ \Omega$$

$$X_{BASE} = \frac{V_n^2}{S_{T1}} = \frac{380^2}{400 \cdot 10^3} \simeq 0{,}36\ \Omega$$

$$R_L^h \cong R_1 = r * L = 0.5 \cdot 10^{-3} * 400 = 0{,}2\ \Omega$$

$$X_L^h = h X_L^1 = h \cdot x_L \cdot L = h\ 0.05 \cdot 10^{-3} \cdot 400 = 0{,}02\ \Omega$$

$$I_1^h = \frac{I_1^1}{h} = \frac{\sqrt{6}}{\pi} \cdot \frac{1}{h} \cdot I_{dc,1} \quad ; \quad \varphi_1^h = h\,\alpha = h\, 40°$$

$I_{dc,1} = \dfrac{P_{dc,1}}{V_{dc,1}}$ dove, trascurando la commutazione, $V_{dc,1}$ e' pari a

$$V_{dc,1} \cong 1{,}35\, V \cos\alpha = 1{,}35\ 380 \cos 40° = 3{,}9\ 10^2\ V \Rightarrow$$

$$I_{dc,1} = \frac{240 \cdot 10^3}{3{,}9\ 10^2} \cong 610\ A \Rightarrow I_1^h \cong \frac{1}{h}\, 476\ A$$

$I_2^h = \dfrac{I_2^1}{h} = \dfrac{\sqrt{6}}{\pi} \cdot \dfrac{1}{h} \cdot I_{dc,2}$ dove, nelle stesse ipotesi, $V_{dc,2}$ e' pari a

$$V_{dc2} \cong 330\ V \Rightarrow I_{dc,2} = \frac{240\ 10^3}{330} \cong 728\ A$$

$\dot{I}_2^h \simeq 568 \cdot \frac{1}{h}\ A \quad ; \quad \varphi_2^h = h\,50°$

$I_3^h = \frac{I_3^1}{h} = \frac{\sqrt{6}}{\pi}\, I_d^3 \cdot \frac{1}{h}$

$I_d^3 = \frac{P_{dc}}{V_{dc}} \simeq 498\ A \Rightarrow I_3^h \simeq 388\ A \quad ; \quad \varphi_3^h = h \cdot 20°$

Nel nodo ③ la generica armonica complessivamente iniettata è pari alla <u>somma vettoriale</u> delle tre armoniche di corrente

$\bar{I}_1^h = I_1^h e^{-jh40°} \quad ; \quad \bar{I}_2^h = I_2^h e^{-j50°h} \quad ; \quad \bar{I}_3^h = I_3^h e^{-jh20°}$ ossia:

$$\bar{I}^h_{TOT} = \frac{1}{h}\left[476\, e^{-j40°h} + 568\, e^{-j50°h} + 388\, e^{-j20°h}\right] \cdot [A]$$

$$\bar{I}^h_{TOT} = \frac{1}{h} \cdot \left[1{,}0658\ 10^3 - j\,8{,}7378\ 10^2\right] \quad [A]$$

$$\bar{I}^h_{TOT} = \frac{1}{h} 1{,}3782 \cdot 10^3\, e^{-j39°h}\ A \qquad ①$$

Per semplificare i calcoli e per verificare l'errore che si commetterebbe ipotizzando i 3 vettori non sfasati tra di loro, è possibile calcolare la corrente $(\bar{I}^h_{TOT})'$ ottenuta dalla relazione

$$|\bar{I}^h_{TOT}|' = \sum_{1}^{3}{}_i\, |\bar{I}_i^h| = \frac{476 + 568 + 388}{h} = \frac{1432\ A}{h} \qquad ②$$

La differenza tra la ① e la ② è pari a 53,7A

Ponendo $h=1$ nella relazione ① è possibile calcolare la massima corrente alla fondamentale assorbita dal sistema di utenza, pari a

③ $$\begin{cases} \bar{I}_L = 1378{,}2\, e^{-j39°}\ A \quad a\ 380\,V \\ \bar{I}_L = \dfrac{1378{,}2}{t} e^{-j39} \quad con\ t = \dfrac{10\,10^3\,V}{380\,V} \cong 52{,}4\ A\, e^{-j39°}\ a\ 10\,kV \end{cases}$$

Per la verifica delle norme IEEE519 sulle armoniche di corrente è necessario calcolare la I_{cc} nel punto di connessione comune, assunto corrispondente al nodo 1. In tale nodo si ha:

$$I_{cc}^{10kV} = \frac{S_{cc}}{\sqrt{3}\,V_n} = \frac{1500 \cdot 10^6}{\sqrt{3} \cdot 10 \cdot 10^3} \cong 87\ kA$$

$$I_{cc}^{380V} = \frac{S_{cc}}{\sqrt{3}\,V_n'} = \frac{1500 \cdot 10^6}{\sqrt{3} \cdot 380} \cong 2{,}3\ MA$$

Il rapporto $\frac{I_{cc}}{I_L}$ nel nodo 1 è pari a $\frac{I_{cc}^{10kV}}{52{,}4} \cong 1.7\ 10^3$

Dalla tabella Ⓐ delle norme si entra nell'ultima riga poiché $\frac{I_{cc}}{I_L} > 1000$ e si ricava per le armoniche di ordine $h < 11$ il limite pari a 15.0% della I_L calcolata entrambi allo stesso livello di tensione, ovviamente).

Dalle relazioni ① e ③ si ricava

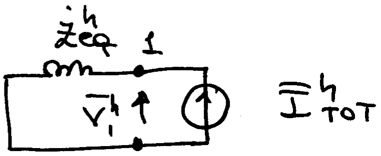
$$\frac{I_{TOT}^5}{I_L} = \frac{1}{5} \cdot \frac{1378}{1378} = 0{,}2 > 0{,}15 \Rightarrow \text{il limite non è rispettato}$$

$$\frac{\dot I^7_{TOT}}{I_c} = \frac{1}{7}\,\frac{1378}{1378} = 0,14 < 0,15 \Rightarrow$$ il limite è rispettato

Per $h > 11$ i limiti sono, ovviamente, rispettati.

Per la verifica della IEEE 519 sulle armoniche di tensione è necessario verificare che ogni armonica di tensione sia inferiore al 3% della V_n (Tabella D)

Il calcolo della V_h si effettua con il metodo per equivalenti



$\dot Z^h_{eq} = j h X_{cc}$ [Ω];

$\dot I^h_{TOT} = \frac{1}{h}\,\frac{1378{,}2}{t}\, e^{-j39°h}$ [A]; $\forall h$

$$\left|\bar V^h_1\right| = h X_{cc} \cdot \frac{1}{h}\,\frac{1378.2}{t} = X_{cc}\cdot\frac{1378{,}2}{t}$$

$$V^h_1 = \frac{(10.10^3)^2}{1500.10^6}\cdot\frac{1378.2}{\left(\frac{10.10^3}{380}\right)} \cong 6.6\,10^{-2}\cdot 52.3 \cong 3,5\ V;\ \forall h$$

$$\frac{V_1^h}{V_n} = \frac{3,5}{10.10^3}\cdot 100 \cong 3.5\cdot 10^{-2} < 3\% \Rightarrow$$ il limite è rispettato

Il "k factor" e' dato dalla relazione

$$K = \frac{\sum_{1}^{h_{MAX}} I_{h,pu}^2 \cdot h^2}{\sum_{1}^{h_{MAX}} I_{h,pu}^2} = \frac{\sum_{1}^{h_{MAX}} \left(\frac{1}{h}\right)^2 h^2}{\sum_{1}^{h_{MAX}} \left(\frac{1}{h}\right)^2}$$

nel caso specifico in esame (ci sono solo convertitori esafase senza carichi lineari)

Ponendo $h_{MAX} = 13$ si ottiene

$$k = \frac{5}{1,07} \cong 4,6$$

La taglia del trasformatore S_T e' pari a:

$S_T = \sqrt{3}\, V_n\, I_{RMS}^{MAX}$ ed e' legata alla I_{RMS}^{MAX} (p.u.) pari a:

$$I_{RMS}^{MAX} (p.u.) = \sqrt{\frac{1 + P_{cp}}{1 + K\, P_{cp}}} = \sqrt{\frac{0,08 + 1}{1 + 4,6 \cdot 0,08}} =$$

$I_{RMS}^{MAX} (p.u.) \cong 0,88$ ciò significa che il trasformatore può continuativamente alimentare carichi non lineari puri sfruttando l'88% della sua corrente nominale.