ANALYSIS OF HVDC CONVERTERS

UNIT II
The pulse number of a converter is defined as the number of pulsations (cycles of ripple) of direct voltage per cycle of alternating voltage.

The conversion from AC to DC involves switching sequentially different sinusoidal voltages onto the DC circuit.

The output voltage of the converter consists of a DC component and a ripple whose frequency is determined by the pulse number.
VALUE AND SWITCHES

A valve can be treated as a (controllable) switch which can be turned on at any instant, provided the voltage across it is positive.

A diode is an uncontrolled switch which will turn on immediately after the voltage becomes positive whereas the thyristor switching can be delayed by an angle or (alpha).

The opening of the switch(both for diode and thyristor) occurs at the current zero (neglecting the turn-off time).
CHOICE OF CONVERTER CONFIGURATION

- The configuration for a given pulse number is selected in such a way that both the valve and transformer (feeding the converter) utilization are maximized.

- The configuration shown in Fig. is not the best. In general, a converter configuration can be defined by the basic commutation group and the number of such groups connected in series and parallel.

- If there are ‘q’ valves in a basic commutation group and r of these are connected in parallel and s of them connected to in series, then

\[ P = q r s \]
• The valve voltage rating is specified in terms of peak inverse voltage (PIV) it has to withstand.
• The ratio of PIV to the average dc voltage is an index of the valve utilization.
• The average maximum dc voltage across the converter is given by

\[
V_{do} = s \frac{q}{2\pi} \int_{-\pi/q}^{\pi/q} E_m \cos \omega t \ d\omega t
\]

\[
= \frac{sq}{\pi} E_m \sin \frac{\pi}{q}
\]

------------------ (2)
• The peak inverse voltage (PIV) across a valve can be obtained as follows:

  If ‘q’ is even, then the maximum inverse voltage occurs when the valve with a phase displacement of $\pi$ radian (180°) is conducting and this is given by

  \[ \text{PIV} = 2E_m \] \hspace{1cm} (3)

  If ‘q’ is odd, maximum inverse voltage occurs when the valve with a phase shift of $\pi \pm \frac{\pi}{q}$ is conducting.

  In this case, \[ \text{PIV} = 2E_m \cos \frac{\pi}{2q} \] \hspace{1cm} (4)

• The value utilization factor is given by

  \[ \frac{\text{PIV}}{V_{do}} = \frac{2\pi}{sq \sin \frac{\pi}{2q}} \] for q even \hspace{1cm} (5)

  \[ \frac{\text{PIV}}{V_{do}} = \frac{\pi}{sq \sin \frac{\pi}{2q}} \] for q odd \hspace{1cm} (6)
TRANSFORMER RATING

• The current rating of a valve is given by

\[ I_v = \frac{I_d}{r \sqrt{q}} \]  

(7)

Where, \( I_d \) is the DC current which is assumed to be constant.

• The transformer rating on the valve side is given by,

\[
S_{v'} = p \frac{E_m}{\sqrt{2}} I_v = p \frac{V_{do}}{\sqrt{2}} \frac{\pi}{sq \sin \frac{\pi}{q}} \frac{I_d}{r \sqrt{q}}
\]

\[ = \frac{\pi}{\sqrt{2}} \frac{V_{do} I_d}{\sqrt{q} \sin \frac{\pi}{q}} \]  

\[ \]  

(8)
• The transformer utilization factor $\frac{S_{tv}}{V_{do}I_d}$ is only a function of $q$. The optimum value of $q$ which results in maximum utilization is equal to 3. It is a fortunate coincidence that the AC power supply is 3 phase and the commutation group of 3 valves is easily arranged.

For $q = 3$,

$\frac{S_{tv}}{V_{do}I_d} = 1.481 \quad (9)$

• The transformer utilization can be improved further if two valve groups can share a single transformer winding. In this case, the current rating of the winding can be increased by a factor of $\sqrt{2}$ while decreasing the number of windings by a factor of 2.

For this case,

$\frac{S_{tv}}{V_{do}I_d} = 1.047 \quad (10)$
• For a 6 pulse converter, this can be easily arranged. The Graetz circuit shown in Fig. is obtained when the two windings are combined into one.

• Thus, it is shown that both from valve and transformer utilization considerations.

  **Graetz circuit is the best circuit for a six pulse converter.**

• In HVDC transmission, the series conduction of converter groups has been preferred because of the ease of control and protection as well as the requirements of high voltage rating.

• Thus a 12 pulse converter is obtained by the series connection of two bridges. The 30° phase displacement between the two sets of source voltages is achieved by the transformer connections, Y/Y for feeding one bridge and Y/A for feeding the second bridge.

• The use of 12 pulse converter is preferable over the six pulse converter because of the reduced filtering requirements. However, increase in pulse number beyond 12 is not practical because the non-characteristic harmonics are not eliminated.
SIMPLIFIED ANALYSIS  GARETZ CIRCUIT

• Without overlap

• With overlap
WITHOUT OVERLAP

Valve 2 → fired 60° after Valve 1
Valve 3 → fired 60° after Valve 2
Each conducts for 120°.
• At any instant two valves are conducting in the bridge.
• The following assumption are made to simplify the analysis.
  • The **dc current is constant**.
  • The valves can be modelled as **ideal switch with zero impedance**, when ON, and **with infinite impedance when OFF**
  • The AC voltage at the converter bus are **sinusoidal and remains constant**.
• One period of the AC supply voltage can be divided in to 6 intervals each corresponding to the conduction of a pair of valves.
• The DC voltage waveform repeats for each interval.
• **Thus for the calculation of the average dc voltage it is necessary to consider only one interval**
Assuming the firing of 3 is delayed by an angle \( \alpha \), the instantaneous dc voltage \( V_d \) during the interval is given by

\[
V_d = e_b - e_c = e_b \cos \alpha
\]

Let,

\[
e_{ba} = \sqrt{2} E_{ll} \sin \omega t
\]

\[
e_{bc} = \sqrt{2} E_{ll} \sin (\omega t + 60^\circ)
\]

Average dc voltage,

\[
V_d = \frac{2}{\pi} \int \sqrt{2} E_{ll} \sin (\omega t + 60^\circ) \, d\omega t
\]

\[
= \frac{3\sqrt{2}}{\pi} E_{ll} \int \sin (\omega t + 60^\circ) \, d\omega t
\]

\[
= \frac{3\sqrt{2}}{\pi} E_{ll} \int \cos \omega t + 60^\circ \, d\omega t
\]
\[ V_d = \frac{3\sqrt{2}}{\pi} E_{LL} \left[ -\cos (\omega t + 60^\circ) + \cos (\omega t + 120^\circ) \right] \]

\[ = \frac{3\sqrt{2}}{\pi} E_{LL} \left[ -\cos (\omega t + 120^\circ) + \cos (\omega t + 60^\circ) \right] \]

\[ = \frac{3\sqrt{2}}{\pi} E_{LL} \left[ -\cos \alpha \cos 120^\circ + \sin \alpha \sin 120^\circ + \cos \alpha \cos 60^\circ - \sin \alpha \sin 60^\circ \right] \]

\[ = \frac{3\sqrt{2}}{\pi} E_{LL} \left[ \frac{1}{2} \cos \alpha + \frac{\sqrt{3}}{2} \sin \alpha + \frac{1}{2} \cos \alpha - \frac{\sqrt{3}}{2} \sin \alpha \right] \]

\[ = \frac{3\sqrt{2}}{\pi} E_{LL} \cos \alpha = 1.35 E_{LL} \cos \alpha \]

\[ V_d = 1.35 E_{LL} \cos \alpha \]

\[ V_d = V_{do} \cos \alpha \]
The range of alpha is from 0 degree to 180 degree and correspondingly $V_d$ can vary from $+V_{do}$ to $-V_{do}$.

- Thus the same converter can acts as a rectifier or inverter depending upon whether the dc voltage is +ve or -ve.

**AC CURRENT WAVEFORM**

- It is assumed that the direct current has no ripple.
- There is normally valid because of the smoothing reactor provided in series with the bridge circuit.
- The rms value of the fundamental components of the current is given by,
\[P_1 = \sqrt{2} \cdot \frac{3}{\pi} \int_{d} \cdot \cos \theta \cdot d\theta = \frac{\sqrt{2}}{\pi} \int_{d} \cdot \cos \theta \cdot d\theta.
\]

\[= \frac{\sqrt{2}}{\pi} \int_{-\pi/3}^{\pi/3} \sin \frac{\pi}{3} - \sin \left(\pi/3\right)\]

\[= \frac{\sqrt{2}}{\pi} \int_{-\pi/3}^{\pi/3} 2 \sin \pi/3\]
\[ P_{AC} = \sqrt{3} E_{LL} I_1 \cos \varphi \]

The DC power must match AC power, ignoring the losses in the converter, thus we get
The reactive power requirements are increased as alpha is decreased from zero.

When alpha is 90degree the power factor is zero and only reactive power consumes.
• Due to leakage inductance if the converter transformer and the impedance in the supply network, the current in a valve cannot change suddenly and the commutation from one valve to next cannot be instantaneous.

• For example: When Valve 3 is Fired.
• The Current transfer from valve 1 to valve 3 takes a finite period during which both valves are conducting.
• This is called OVERLAP and its duration is measured by the OVERLAP ANGLE ($\mu$).

• Three modes of the converter as follows.
  
  MODE 1: Two and three valve conduction ($u < 60$ degree)
  MODE 2: Three valve conduction ($u = 60$ degree)
  MODE 3: Three and four valve conduction ($u > 60$ degree)
ANALYSIS OF TWO AND THREE VALVE CONDUCTION MODE

- For the interval considered, the circuit can be reduced to that shown in diagram,
For this circuit,

\[ e_b - e_a = 1 - c \int \frac{di_3}{dt} - \frac{di_1}{dt} \]

but, \[ e_b - e_a = \sqrt{2} E_1 \sin \omega t \]

Since, \[ e_1 = I_d - i_3 \]

\[ \therefore I_d = \epsilon_1 + i_3 \]
\[ e_1 = I_d - i_3 \]

\[ \sqrt{2} E_1 \sin \omega t = \int \frac{d\epsilon_3}{dt} - \frac{d}{dt} (I_d - i_3) \]

\[ = \int \frac{d\epsilon_3}{dt} - \frac{d}{dt} \left( I_d + \frac{d^2 i_3}{dt^2} \right) \]

(neglecting \( \frac{dI_d}{dt} \) Constant \( \epsilon_3 \) \( \epsilon_1 \)

\[ \sqrt{2} E_1 \sin \omega t = 2 \pi c \frac{d\epsilon_3}{dt} \]

\[ \frac{di_3}{dt} = \frac{\sqrt{2} E_1 \sin \omega t \cdot dt}{2\pi c} \]

Integrate on both sides with a limit of \( x \) to \( x + \pi \).
\[
\int di_3 = \int \frac{\sqrt{2} E \ell L \sin \omega t}{2L - C} \cdot dt
\]
\[
\int \sin \omega t \cdot dt = \frac{\cos \omega t}{\omega}
\]

\[
\ell_3 = \frac{\sqrt{2} E \ell L}{2L - C} \left[ -\cos \omega t \right]^{x+Ht} \bigg|_{x}^{x+Ht}
\]
\[
= \frac{\sqrt{2} E \ell L}{2L - C} \left[ -\cos \left( x + Ht \right) + \cos x \right]
\]
\[
\ell_3 = \frac{\sqrt{2} E \ell L}{2L - C} \left( \cos x - \cos \left( x + Ht \right) \right)
\]
\[ P_d = P_s \int \cos \alpha - \cos (\alpha + \beta) \]

\[ P_d = P_s \int \cos \alpha - \cos (\alpha + \beta) \]

**Average Direct Voltage:** 

During commutations, the instantaneous dc voltage is \(-\frac{3}{2} V_{dc}\) instead of \(V_{dc}\).

The avg. direct voltage can be obtained as,

\[ V_d = \frac{3}{\pi} \left[ \int_{\alpha}^{\alpha + \beta} \left( \int_{-\frac{3}{2} V_{dc}}^{V_{dc}} \cdot d\theta \right) + \left( \int_{\alpha - \beta}^{\alpha} \cdot d\theta \right) \right] \]

\[ V_d = \frac{3}{\pi} \left[ \int_{\alpha}^{\alpha + \beta} \left( \int_{-\frac{3}{2} V_{dc}}^{V_{dc}} \cdot d\theta \right) + \left( \int_{\alpha - \beta}^{\alpha} \cdot d\theta \right) \right] \]

\[ V_d = \frac{3}{\pi} \left[ \int_{\alpha}^{\alpha + \beta} \left( \int_{-\frac{3}{2} V_{dc}}^{V_{dc}} \cdot d\theta \right) + \left( \int_{\alpha - \beta}^{\alpha} \cdot d\theta \right) \right] \]

\[ V_d = \frac{3}{\pi} \left[ \int_{\alpha}^{\alpha + \beta} \left( \int_{-\frac{3}{2} V_{dc}}^{V_{dc}} \cdot d\theta \right) + \left( \int_{\alpha - \beta}^{\alpha} \cdot d\theta \right) \right] \]
\[
\frac{3}{\pi} \int_{-\pi}^{\pi} e^{bc} \cdot \frac{x+60}{x+u} \, dx + \int_{-\pi}^{\pi} e^{bc} \cdot d\omega t
\]

\[
= \frac{3}{\pi} \int_{0}^{\pi} e^{bc} \cdot \frac{x+60}{x+u} \, dx + \frac{3}{2\pi} \int_{0}^{\pi} 2e^{b+ec} \cdot d\omega t
\]

\[
= V_{\theta 0} \cos \alpha - \frac{3}{2\pi} \int_{0}^{\pi} (e^{b-ec}) \cdot d\omega t
\]
\[ \begin{align*}
\theta &= \text{vd} \cos \alpha - \frac{3}{2\pi} \int_0^{\alpha+\theta} (e_b-e_a) \cdot d\omega \cdot t \\
&= \text{vd} \cos \alpha - \frac{3}{2\pi} \int_0^{\alpha+\theta} \sqrt{2} E LL \sin \omega t \cdot d\omega \\
&= \text{vd} \cos \alpha - \frac{3\sqrt{2} E LL}{2\pi} \int_0^{\alpha+\theta} \sin \omega t \cdot d\omega \\
&= \text{vd} \cos \alpha - \frac{3\sqrt{2} E LL}{2\pi} [-\cos \omega t]_0^{\alpha+\theta} \\
V_d &= \text{vd} \cos \alpha - \frac{3\sqrt{2} E LL}{2\pi} \left[ \cos \alpha - \cos (\alpha+\theta) \right]
\end{align*} \]
But, \[ \frac{3 \sqrt{2} EF}{\pi} = V_0. \]

\[ V_d = V_0 \cos \alpha - \frac{V_0}{2} \left[ \cos \alpha - \cos(\alpha + \theta) \right] \]

\[ = \frac{V_0}{2} \left[ 2 \cos \alpha - \cos \alpha + \cos(\alpha + \theta) \right] \]

\[ V_d = \frac{V_0}{2} \left[ \cos \alpha + \cos(\alpha + \theta) \right] \]

But,

\[ \frac{\partial d}{\partial s} = \frac{d_0}{s} \left[ \cos \alpha - \cos(\alpha + \theta) \right] \]

\[ \frac{\partial d}{\partial s} = \cos \alpha - \cos(\alpha + \theta) \]

\[ \cos(\alpha + \theta) = \cos \alpha - \frac{\partial d}{\partial s} \]

The above equation becomes,

\[ V_d = \frac{V_0}{2} \left[ \cos \alpha + \cos \alpha - \frac{\partial d}{\partial s} \right] \]

\[ = \frac{V_0}{2} \left[ 2 \cos \alpha - \frac{\partial d}{\partial s} \right] \]
It is analogous to armature reaction in the dc machine in the sense that in only represents a voltage drop and not a power loss.
ANALYSIS OF THREE AND FOUR VALVE CONDUCTION MODE
ANALYSIS OF THREE AND FOUR VALVE CONDUCTION MODE

- When the overlap angle exceeds 60 degree, the minimum number of valves conducting are three and there are intervals when four valves are conducting.

- This is because when a commutation process is started, the previous commutation process is not yet completed.

- For example, when valve 3 is fired to valves 1, 6 and 2 are still conducting.

- The equivalent circuit for this condition is shown in fig,
For $\alpha \leq \omega t \leq \alpha + \omega - 60^\circ$

$(\omega t = \omega) \quad L_1 = L_s \sin (\omega t + 60^\circ) + A$ (det. from init. condn)

For $\alpha + \omega - 60^\circ \leq \omega t \leq \alpha + \omega - 60^\circ$

For $\alpha + \omega - 60^\circ \leq \omega t \leq \alpha + \omega - 60^\circ$ (from final condn)

$L_1 = L_s \cos \omega t + B$. 
AVERAGE DIRECT VOLTAGE:

\[ V_d = \frac{3}{\pi} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \frac{E_c}{\alpha + \omega - 60} \cdot d\omega \]

\[ V_d = 3 \alpha + 60 \]

\[ V_d = \frac{9}{2\pi} E_m \int \sin(\omega) \left[ \sin(\alpha + 60) - \sin(\alpha + \omega - 60) \right] \]
The above equation can be written as

\[ V_d = \sqrt{3}V_{do} \cos(\alpha - 30^\circ) - 3R_cI_d \]

The equivalent commutating resistance for this case 3 times that for the case with overlap angle less than 60 degree.
CONVERTER BRIDGE CHARACTERISTICS

1. Rectifier
2. Inverter
The rectifier in general has 3 modes:

1. **1st mode**: 2 and 3 valve conduction mode (u < 60 degree)
2. **2nd mode**: 3 valve conduction mode only for (alpha < 30 degree) u = 60 degree
3. **3rd mode**: 3 and 4 valve conduction mode (alpha >= 30 degree)

As per the current continues to increase, the converter operation changes over from mode 1 to mode 2 and finally to mode 3.

The DC voltage continues to decrease until reaches to zero.
• For mode 1:

$$\frac{V_d}{V_{do}} = \cos \alpha - \frac{I_d}{2I_s}$$

• For mode 2:

• For $u = \text{constant}$, the characteristics are elliptical and the equation is given by

$$\left(\frac{V_d/V_{do}}{\cos \frac{u}{2}}\right)^2 + \left(\frac{I_d/2I_s}{\sin \frac{u}{2}}\right)^2 = 1$$
Mode 3:

- The boundary of the rectifier operation is shown in fig.
- The coordinates of point A, B, C, D and E on the boundary give in the table.
- The points E corresponding to the maximum power O/P of the converter:

\[
\frac{V_d}{V_{do}} = \sqrt{3} \cos(\alpha - 30) - \frac{3I_d}{2I_s}
\]
**INVERTER**

- The *inverter characteristics are similar to the rectifier characteristics*
- However, the operation as an inverter requires a minimum commutation margin angle during which the *voltage across the valve is negative*
- Hence the operating region of an inverter is different from that for a rectifier.

<table>
<thead>
<tr>
<th>FIRST RANGE</th>
<th>SECOND RANGE</th>
<th>THIRD RANGE</th>
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</thead>
<tbody>
<tr>
<td>$\beta &lt; 60^\circ$</td>
<td>$60^\circ &lt; \beta &lt; 90^\circ$</td>
<td>$\beta &gt; 90^\circ$</td>
</tr>
<tr>
<td>$\varepsilon = \gamma$</td>
<td>$\varepsilon = 60^\circ - u$</td>
<td>$\varepsilon = \gamma - 30^\circ$</td>
</tr>
<tr>
<td></td>
<td>$= \gamma - (\beta - 60^\circ)$</td>
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</tbody>
</table>
FIRST RANGE \( \beta < 60^\circ \)
- The commutation margin angle \( \varepsilon \) is equal to the extinction angle \( \gamma \) only values of \( \beta \leq 60^\circ \)
- The voltages across the value has a positive dent because of the secondary commutation.

SECOND RANGE \( 60^\circ < \beta < 90^\circ \)
- With increased overlap and consequently earlier ignition of the value, the dent encroaches on the period in which the valve voltage would otherwise be negative.

THIRD RANGE \( \beta > 90^\circ \)
- With Decreased commutation margin, the dent becomes entirely negative.
  If any dent changes takes places.
CHARACTERISTICS OF A TWELVE PULSE CONVERTER

• As long as AC voltage at the converter bus remains sinusoidal the operation of one bridge is unaffected by the operation of the other bridge connected in series.

• In this case, The converter characteristics are with the assumption that the AC voltage at the converter bus remains constant.

• The region of rectifier operation can be divided in to the Five modes.
• **Mode 1**: 4 and 5 value conduction
  
  \[0 \text{ degree} < u < 30 \text{ degree}\]

• **Mode 2**: 5 and 6 value conduction
  
  \[30 \text{ degree} < u < 60 \text{ degree}\]

• **Mode 3**: 6 value conduction
  
  \[0 < \alpha < 30 \text{ degree} \quad u=60 \text{ degree}\]
• **Mode 4:**
  6 and 7 value conduction
  60 degree < u < 90 degree

• **Mode 5:**
  7 and 8 value conduction
  90 degree < u < 120 degree

• It is noted that, the second mode is continuous of the 1\textsuperscript{st} mode Similarly, 5\textsuperscript{th} mode is continuous of 7\textsuperscript{th} mode

• The region of the mode 3 shrinks to a point when alpha exceeds 30 degree
• When no AC filters are provided and the source reactance is not zero the operation of either bridge is affected by the commutation process taking place in the other bridge.

• In this case operation of the twelve pulse converter is quite complex and there could be additional modes

• 5 value conduction

• 6-7 – 8-7 valve conduction

• Also there could be new modes of 5-6-7-6 valve conduction, depending on the value of coupling factor $K$ is defined by

$$K = \frac{X_s}{X_s + X_T}$$

Where $X_s$ is the source reactance

$X_T$ is the converter transformer leakage reactance
• It is to be noted that the interaction between adjacent bridges can be neglected if the converter bus voltages are sinusoidal.

• However, the presence of source reactance results in the variation off the magnitude of the bus voltage.

• This can affect the shape of the converter characteristics.
DETAILED ANALYSIS OF CONVERTERS

• Some of the assumptions can be made

  • The system is described by sets of linear differential equations, and each set is applicable for particular conduction pattern of the values in bridge.

  • AC system is symmetrical and source voltages are balanced

  • Firing pulses are generated at equal interval of time.
• The solution is periodic in steady state, each period can be divided into \( p \) intervals where \( p \) is the pulse number of the converter.

• Each interval in general can be subdivided into sub-intervals as follows:
  
  • \( 0 < t < t_1 \) corresponding to the conduction of \( (m+1) \) valves.
  • \( t_1 < t < T_1 \) corresponding to the conduction of \( m \) valves.
• For Example, 6pulse converter
• Normal mode consists of 3 and 2 valve conduction.
• First computing from a non linear equation to form

\[ f(t_1) = 0 \]

Once \( t_1 \) is obtained initial conditions can be calculated from linear equation
• Some of the assumptions can be made for calculating boundary conditions.

• Magnetic fluxes and electric charges must be continuous function of time.
• The current in the outgoing valve is zero at \( t = t_1 \)

DEVELOPMENT OF THE METHOD FOR STEADY STATE ANALYSIS

• It contains there are two sub intervals, it is described as equations

\[
\begin{align*}
x'_1(t) &= A_1 x_1(t) + B_1 u(t) \quad 0 < t < t_1 \\
x'_2(t) &= A_2 x_2(t) + B_2 u(t) \quad t_1 < t < T_1
\end{align*}
\]
• The orders of the state vector $x_1$ and $x_2$ are $(n+1)$ and $n$ respectively.
• Since outgoing valve current becomes zero at $t=t_1$, one state variable is eliminated in second outgoing.
• Solutions for above equations are

$$
x_1(t) = x_{s_1}(t) + e^{A_1(t)} [x_1(0) - x_{s_1}(0)]
$$

$$
x_2(t) = x_{s_2}(t) + e^{A_2(t-t_1)} [x_2(t_1) - x_{s_2}(t_1)]
$$

• Where $x_{s_1}(t)$ is the forced response in sub interval I
• From the boundary conditions, We have

\[ x_2(t_1) = [I_n : 0] x_1(t_1) = [K] x_1(t_1) \]

• \( I_n \) is the identity matrix of \( n \)th order

\[ Cx_1(t_1) = 0 \]

• Where \( C = [0:1] \)

• From the consideration of symmetry, We have
From considerations of symmetry, we have
\[ x_1(0) = [S_n]x_2(T_1) \]
where \( S_n \) is a constant matrix.

After some manipulations, we get
\[ x_1(0) = Q^{-1}g \]
where
\[
Q = \begin{bmatrix}
I_{n+1} & -S_n e^{A_2(T_1 - t_1)} Ke^{A_{11}} \\
S_n & e^{A_2(T_1 - t_1)} - e^{A_{11}}
\end{bmatrix}
\]
\[
g = [S_n] \left\{ \left[ xS_2(T_1) + e^{A_2(T_1 - t_1)} \right] \left[ -xS_2(t_1) + kxS_1(t_1) - ke^{A_{11}t_1}xS_1(0) \right] \right\}
\]
and \( t_1 \) is determined from the nonlinear equation
\[
[C] \left\{ xS_1(t_1) + e^{A_{11}t_1} \left[ Q^{-1}g - xS_1(0) \right] \right\} = 0
\]
SMOOTHING REACTOR

• Smoothing reactors are intended to provide a high impedance to the flow of harmonic currents, and to reduce the rate of current rise on failures in direct current (d.c.) systems.

• Two main application fields are defined as follows:
  • The direct current has superimposed harmonic components. This situation occurs in d.c. systems for industrial applications. Since the system voltages are generally not higher than 10kV, these reactors are usually designed for indoor application.
  • The direct current has small superimposed harmonic components. This situation occurs in HVDC transmission systems. The d.c. system voltages are generally 50kV or higher.