Lecture 5
Converters III – operation in the inverter mode

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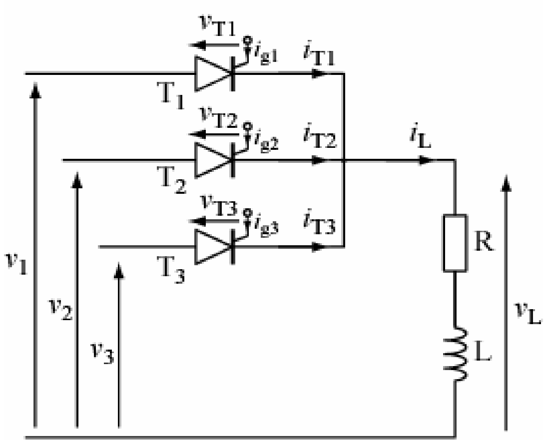
Objectives

- To consider the operation of converters in the inverter mode, i.e. when the power flow is from the DC side back to the AC supply
- To define firing advance angle which denotes thyristor firing instant for inverter mode operation
- To consider inverter-mode operation in the non-ideal case, i.e. in the presence of finite AC supply inductance and overlap
- To define the extinction angle in order to facilitate obtaining correct converter operation in the inverter mode
- To define general equations for p-phase converters in converter and inverter mode
- To consider the operation of a special type of converter called the cycloconverter

Ideal converter operation in the inverter mode

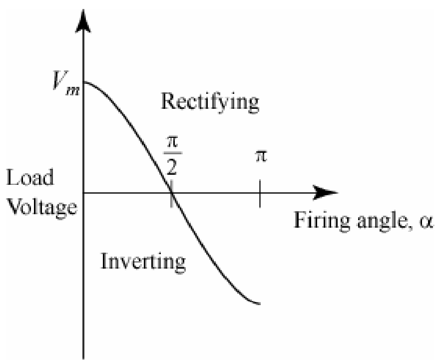
- For a converter to be operated in inverting mode it must be connected to an AC system with stable voltage and frequency
- First consider ideal case (no AC supply inductance)
  - 3-phase, half-wave converter:



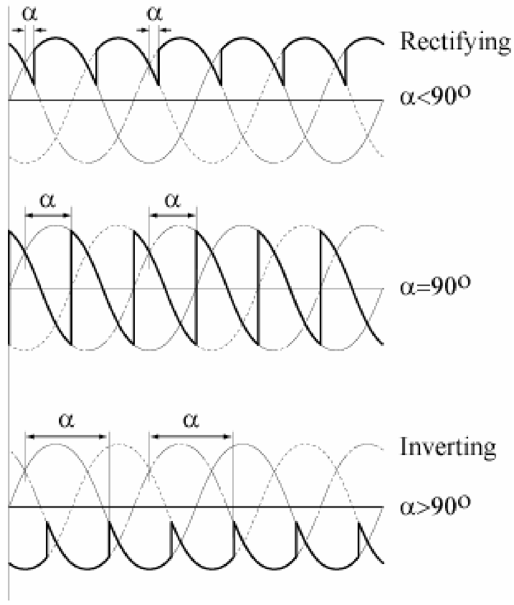
- In ideal case with no overlap, mean load voltage given by:

$$V_{mean} = \frac{3\sqrt{3}}{2\pi} V_m \cos\alpha$$

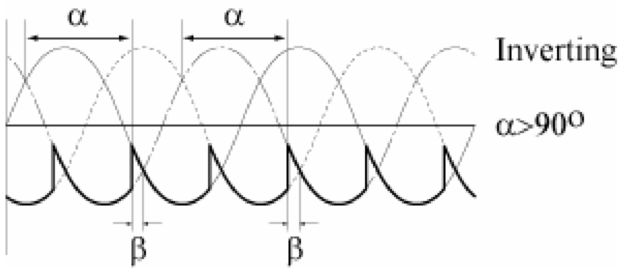
- V_m is the peak phase voltage and α is the firing angle
- Plot of mean load voltage with α:



- For α > 90º, V_{mean} becomes negative
- Since direction of current through thyristor cannot reverse, direction of power flow is now from DC side of converter back into AC supply
- Load voltage waveforms for various firing angles



- Thyristor may be fired when its anode voltage is higher than anode voltage of previously conducting thyristor, i.e. from α = 0º to α = 180º
- α is measured from first point when thyristor can possibly be fired (i.e. at α = 0º, when diode in same position would naturally conduct)
- Operation in the inverter mode corresponds to the range 90º < α < 180º
- For inverter mode, point-on-wave at which thyristor fired more usually defined by <u>firing advance angle</u> β



- β is measured backwards from latest point when thyristor can be fired
- Relationship between firing advance angle β and firing angel α:

$$\beta = 180^\circ - \alpha$$

- Relationship applies to converters of any pulse number
- In inverter mode, convenient to express mean output voltage in terms of firing advance angle rather than firing angle; replace α by 180º - β:

$$V_{mean} = \frac{3\sqrt{3}}{2\pi} V_m \cos\alpha$$

$$= \frac{3\sqrt{3}}{2\pi} V_m \cos(\pi - \beta)$$

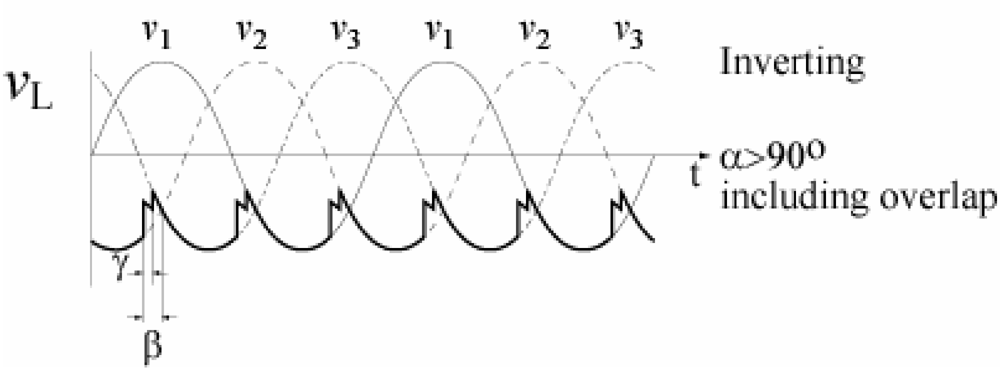
$$= -\frac{3\sqrt{3}}{2\pi} V_m \cos\beta$$

- Or integrate $-V_m \sin\omega t$ from π/6 -β to 5π/6 -β:

$$V_{mean} = \frac{3}{2\pi} \int_{\frac{\pi}{6}-\beta}^{\frac{5\pi}{6}-\beta} \left(-V_m \sin\theta\right) d\theta$$

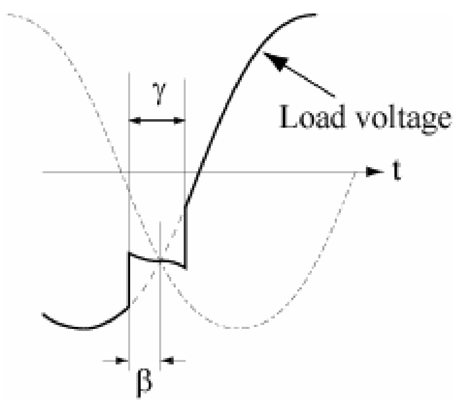
Non-ideal operation

- During overlap, both newly fired thyristor and previously conducting thyristors are conducting; load voltage follows mean of supply voltages:

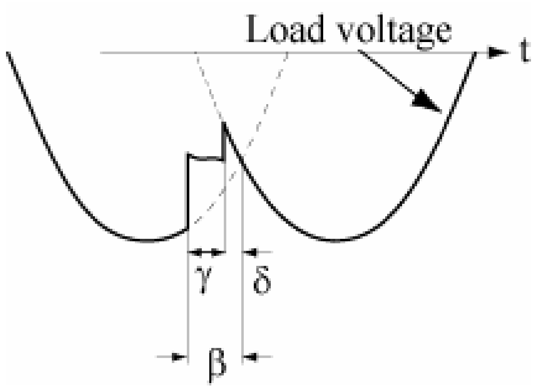


- Anode voltage of fired thyristor > anode voltage on previously conducting thyristor over overlap interval

- Otherwise conduction will revert to initially conducting thyristor:
- Problem due $\gamma > \beta$;



- Define the extinction angle $\delta = \beta - \gamma$



- Extinction angle $\delta \geq 5^{o}$ to ensure successful commutation
- Negative voltage on previously conducting thyristor completes turn-off

Mean load voltage

- For the ideal case:

$$V_{mean} = \frac{3}{2\pi} \int_{\frac{\pi}{6}-\beta}^{\frac{5\pi}{6}-\beta} \left(-V_m \sin\theta\right) d\theta$$

- With overlap, when thyristor fired at $\theta = \pi/6 - \beta$, load voltage follows mean of supply voltages until overlap is complete at $\theta = \pi/6 - \beta + \gamma$
- From $\theta = \pi/6 - \beta + \gamma$ until $\theta = 5\pi/6 - \beta$, load voltage follows new supply voltage

$$V_{mean} = \frac{3}{2\pi}\left\{\frac{1}{2}\int_{\frac{\pi}{6}-\beta}^{\frac{\pi}{6}-\beta+\gamma}\left\{-V_m\left[\sin\left(\theta+\frac{2\pi}{3}\right)+\sin\theta\right]\right\}d\theta + \int_{\frac{\pi}{6}-\beta+\gamma}^{\frac{5\pi}{6}-\beta} -V_m \sin\theta d\theta\right\}$$

- It can be shown that this leads to the following result:

$$V_{mean} = -\frac{3\sqrt{3}}{4\pi} V_m [\cos\beta + \cos(\beta - \gamma)]$$

- If L = 0, then γ = 0, V_{mean} = ideal case value
- Result for non-ideal case ($\gamma \neq 0$) could have obtain by substituting $\beta = \pi - \alpha$ in corresponding result for converter operating in converter mode

Equivalent circuit

- Let mean load voltage without overlap be denoted $V_{mean(ideal)}$

$$V_{mean} = V_{mean(ideal)} + \Delta V_d$$

where ΔV_d is the change in converter output voltage because of overlap

- It may be shown that:

$$\Delta V_d = V_{mean} - V_{mean(ideal)}$$

$$= -\frac{3\sqrt{3}}{4\pi} V_m [\cos\beta + \cos(\beta - \gamma)] - \frac{-3\sqrt{3}}{2\pi} V_m \cos\beta$$

$$= \frac{3\sqrt{3}}{4\pi} V_m [\cos\beta - \cos(\beta - \gamma)]$$

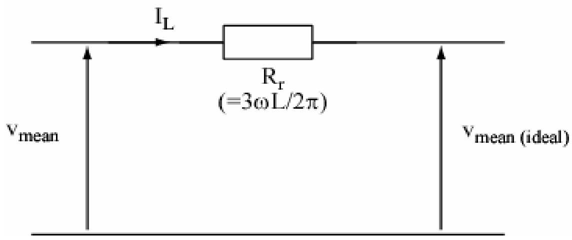
- Relate γ to load current:

$$I_L = \frac{\sqrt{3}}{2\omega L} V_m \left[\cos\beta - \cos(\beta - \gamma)\right]$$

- Hence:

$$\Delta V_d = \frac{3\omega L}{2\pi} I_L$$

- Thus loss of mean load voltage (but not power loss) may be modelled, as previously, by simple equivalent circuit



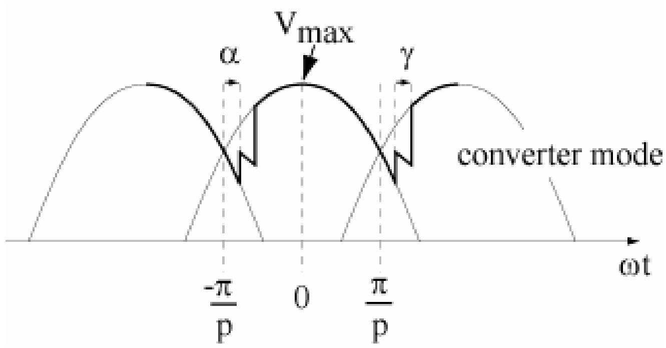
Example of converter in inverter mode

- A 3-phase, half-wave converter operating in the inverting mode is connected to a 415 V (line) 3-phase supply.
- If the firing advance angle is 18º and the overlap angle is 3.8º, find the mean voltage at the load

$$\begin{aligned} V_{mean} &= -\frac{3\sqrt{3}}{4\pi} V_m \left[\cos\beta + \cos(\beta - \gamma)\right] \\ &= -\frac{3\sqrt{3}}{4\pi} \frac{415\sqrt{2}}{\sqrt{3}} \left[\cos 18^\circ + \cos(18^\circ - 3.8^\circ)\right] \\ &= -\frac{3 \times 415}{2\sqrt{2}\pi} \left[\cos 18^\circ + \cos 14.2^\circ\right] \\ &= -269.1\,V \end{aligned}$$

General converter equations

- p-pulse, fully-controlled converter in



- Ignoring overlap:

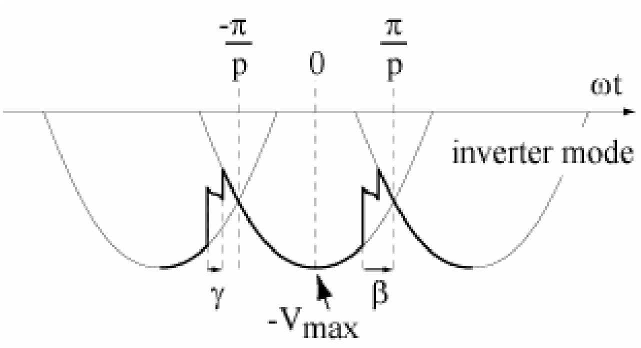
$$V_{mean} = \frac{p}{2\pi} \int_{-\frac{\pi}{p}+\alpha}^{\frac{\pi}{p}+\alpha} V_m \cos\theta d\theta = \frac{p}{\pi} V_m \sin\left(\frac{\pi}{p}\right) \cos\alpha$$

- Including overlap:

$$V_{mean} = \frac{p}{2\pi} \left\{ \int_{-\frac{\pi}{p}+\alpha+\gamma}^{\frac{\pi}{p}+\alpha} V_m \cos\theta d\theta + \frac{1}{2} \int_{-\frac{\pi}{p}+\alpha}^{-\frac{\pi}{p}+\alpha+\gamma} V_m \left[\cos\theta + \cos\left(\theta + \frac{2\pi}{p}\right) \right] d\theta \right\}$$

$$= \frac{p}{2\pi} V_m \sin\left(\frac{\pi}{p}\right) [\cos\alpha + \cos(\alpha+\gamma)] = \frac{p}{\pi} V_m \sin\left(\frac{\pi}{p}\right) \cos\alpha - \frac{p\omega L}{2\pi} I_L$$

- p-pulse, fully-controlled converter in inverter mode



- Ignoring overlap:

$$V_{mean} = \frac{p}{2\pi}\int_{-\frac{\pi}{p}-\beta}^{\frac{\pi}{p}-\beta} -V_m \cos\theta d\theta = -\frac{p}{\pi}V_m \sin\left(\frac{\pi}{p}\right)\cos\beta$$

- Including overlap:

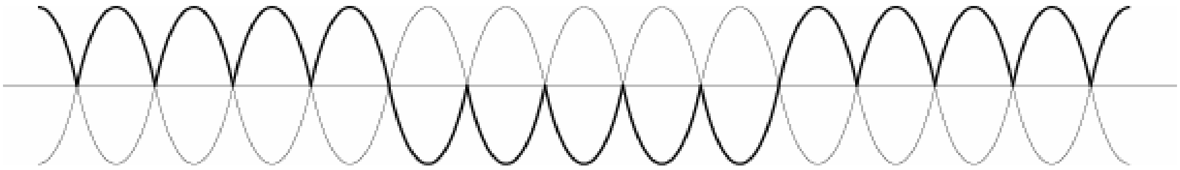
$$V_{mean} = \frac{p}{2\pi}\left\{\int_{-\frac{\pi}{p}-\beta+\gamma}^{\frac{\pi}{p}-b} -V_m \cos\theta d\theta + \frac{1}{2}\int_{-\frac{\pi}{p}-\beta}^{-\frac{\pi}{p}-\beta+\gamma} -V_m\left[\cos\theta + \cos\left(\theta+\frac{2\pi}{p}\right)\right]d\theta\right\}$$

$$= -\frac{p}{2\pi}V_m \sin\left(\frac{\pi}{p}\right)\left[\cos\beta + \cos(\beta+\gamma)\right] = \frac{p}{\pi}V_m \sin\left(\frac{\pi}{p}\right)\cos\beta + \frac{p\omega L}{2\pi}I_L$$

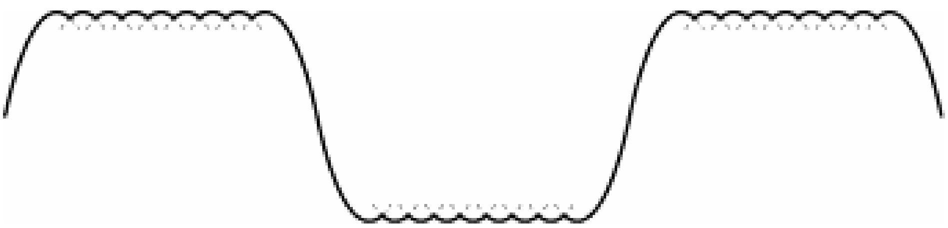
- Setting p = 3, previously derived 3-phase converter equations are obtained.

Cycloconverters

- Cycloconverter differs from converter in that it produces AC output with lower frequency than input
- Simplest form of cycloconverter is envelope cycloconverter which produces output in which each half cycle of output wave form is made up of whole number of half cycles of supply waveform
- e.g.: full-wave single-phase supply (or half-wave 2-phase supply):



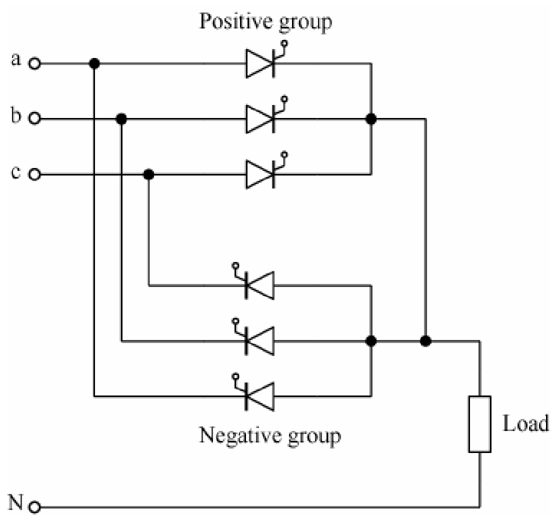
- Multi-phase supply provides output approximating to squarewave e.g. 6-pulse system:



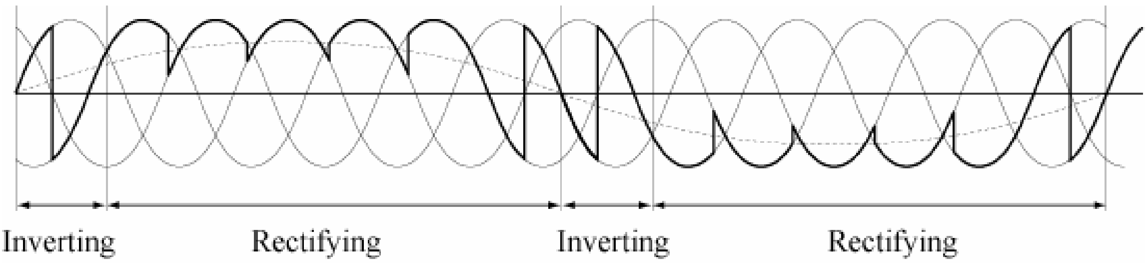
- Output no longer restricted to frequencies made up of integer numbers of half cycles or parts of cycles

- Load must be sufficiently inductive to smooth current variations over input waveform period but have inductance low enough that output voltage can change from positive to negative at output period rate
- Converter generates a DC voltage whose output voltage depends on firing angle
- If firing angle α is varied in a regular cyclic fashion, an AC output at a frequency much lower than the input frequency is produced
- By increasing pulse number of cycloconverter a better approximation to sine wave is obtained

- Circuit for one phase of three-pulse cycloconverter:



- Each group is similar to 3-phase fully-controlled converter; one group operates when output voltage positive; other group when it is negative
- Typical waveforms assuming moderate inductive load:



- Each group operates alternately in rectifying and inverting modes

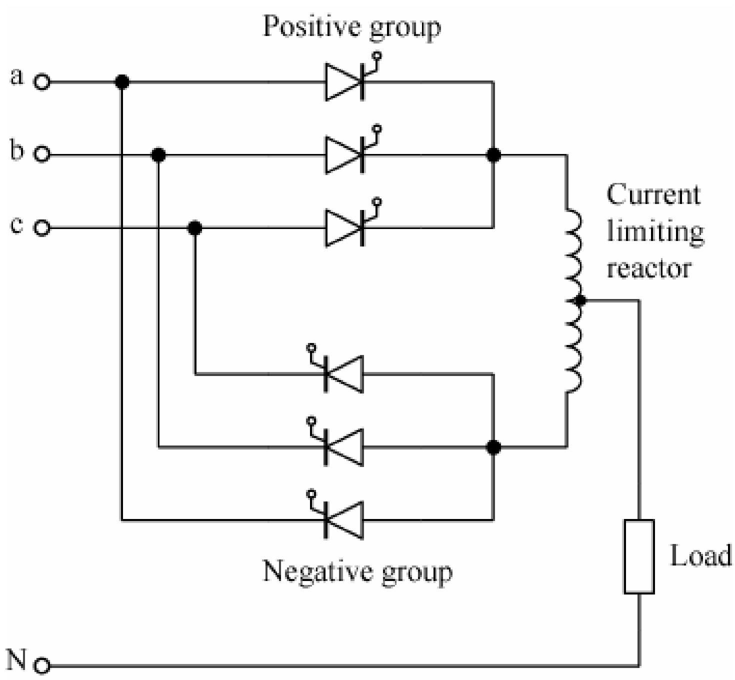
- Short term mean of output voltage indicated close to sine wave
- High frequency transients filtered out – waveform harmonically pure
- For a p-pulse cycloconverter and ignoring overlap:

$$V_0 = \frac{p}{\pi}\sin\left(\frac{\pi}{p}\right)V_m \cos\alpha$$

- From instantaneous value of output voltage V_0 required at any instant in output voltage period, cos α, and hence α, are determined

- If thyristors from positive and negative groups were fired together then supply would be short-circuited
- Blocked-group or inhibited-mode operation is used with control circuitry arranged to prevent simultaneous firing of thyristors in positive and negative groups

- Alternative is to connect reactor at output of groups



- Cycloconverter require complex control systems – used for high power systems with variable frequency requirement below frequency of an available AC supply

Summary

- Have considered operation of converters in inverter mode, defining firing advance angle to denote thyristor firing instants
- Have determined mean load voltage in presence of finite AC supply inductance and overlap and defined extinction angle in order to facilitate obtaining correct operation
- Have presented general equations for p-phase converters in converter and inverter mode, both with and without overlap

- Finally, we considered cycloconverter which converts AC waveform to controllable AC waveform with lower frequency using separate converters to synthesise positive and negative half cycles of load voltage waveform
- Next topic includes various aspects, including important one of converters with higher pulse numbers in order to obtain reduced voltage ripple