Module-7

Subject: Flexible AC Transmission System (FACTS)

Content: Thyristor Controlled Phase Angle Regulator and Thyristor Controlled Voltage Regulator

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7.0 Phase Angle Regulator (PAR)

Phase Angle Regulators are able to solve problems referred to the transmission angle which cannot be handled by the other series compensators. Even though these regulators, based on the classical arrangement of tap-changing transformers, are not able to supply or absorb reactive power they are capable of exchanging active power with the power system. Additionally, modern voltage and phase angle regulators are used to improve the transient stability, to provide power oscillation damping and to minimize the post-disturbance overloads and the corresponding voltage dips. In Fig. 7.1 the concept of a Phase Angle Regulator is shown. Theoretically, the Phase Angle Regulator can be considered a sinusoidal AC voltage source with controllable amplitude and phase angle. The angle of the voltage U_σ relative to U_1 is stipulated such that the magnitudes of U_1 and U_{1eff} are equal.

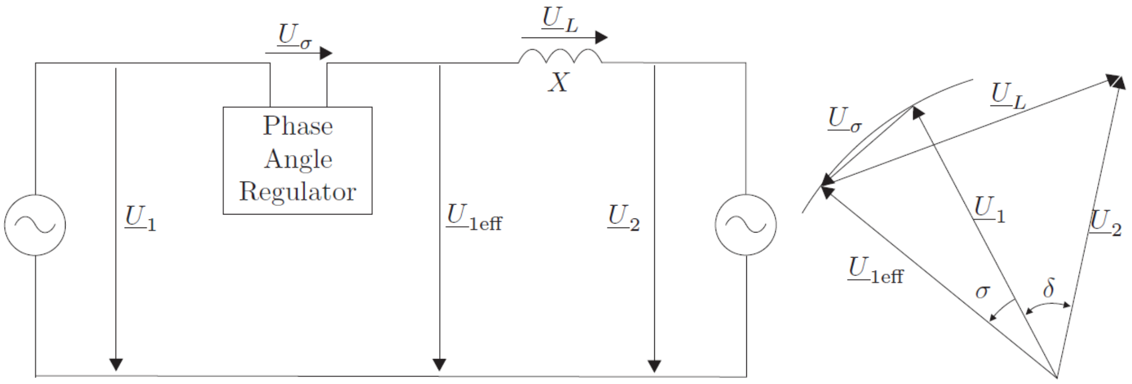


Figure 7.1: Phase Angle Regulator

The basic idea is to keep the transmitted power at the desired value independent of the prevailing transmission angle δ. If δ exceeds π/2 the amplitude of the voltage U_σ is chosen such that the effective phase angle δ+σ between the sending- and receiving- end voltages stays at π /2. This is visualized in Fig. 7.2. The formulae for active and reactive power are

$$P_\sigma = \frac{U_1 U_2}{X}\sin(\delta+\sigma) \quad (7.1)$$

$$Q_\sigma = \frac{U_1 U_2}{X}(1-\cos(\delta+\sigma)) \quad (7.2)$$

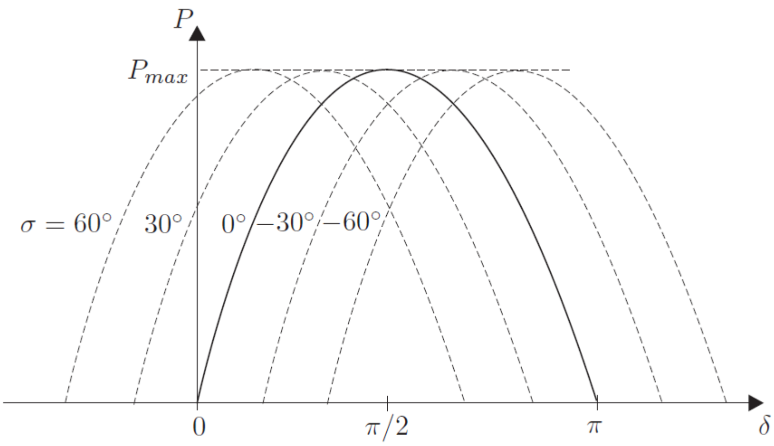


Figure 7.2: Transmitted power versus angle characteristics for a Phase Angle Regulator

To investigate the influence of a change in σ on the change of transmitted active power P at different values of P, the derivative of (7.1) with respect to σ is taken

$$\frac{\partial P}{\partial \sigma} = \frac{U_1 U_2}{X}\cos(\delta+\sigma) = \frac{U_1 U_2}{X}\sqrt{1-\sin^2(\delta+\sigma)} \qquad (7.3)$$

$$= \sqrt{\left(\frac{U_1 U_2}{X}\right)^2 - P^2} \qquad (7.4)$$

From this and the assumption that U1U2 /X is constant the graphic in Fig. 7.3 is drawn.

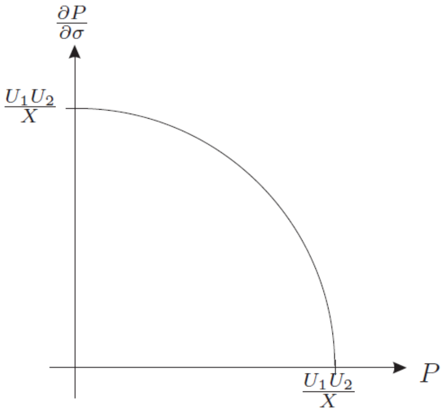


Figure 7.3: $\frac{\partial P}{\partial \sigma}$ versus P

This shows that for larger P the influence of a change in σ is rather small compared to the influence for a low transmitted active power.

7.1 THYRISTOR CONTROLLED VOLTAGE REGULATOR

The TCVR operates by inserting an in phase voltage to the main bus voltage so as to change its magnitude. The interconnection of a high voltage with a lower voltage line for increased power transmission is usually accomplished with a mechanical on-load tap changer to isolate the lower voltage system from the large voltage variation of the high voltage line Caused by seasonal or daily load changes. Similarly, voltage regulators employing on-load tap changers have been used since the early days of the ac transmission to maintain the desired user voltage in the face of changing transmission voltage and loads. In addition to voltage regulation tap changers can in general be used to control the reactive power flow in the line.

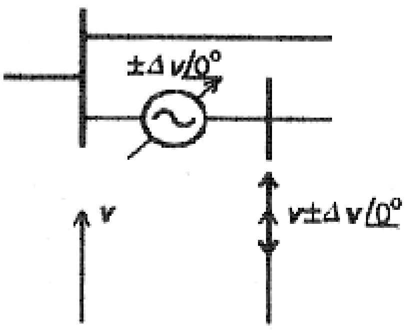
Since transmission line impedances are predominantly reactive an in phase voltage component introduced in the transmission circuit causes a substantially quadrature (reactive) current flow that, with appropriate polarity and magnitude control can be used to improve prevailing reactive power flows.

Although reactive compensation and the voltage regulation by on load tap changers appear to provide the same transmission control function, there is an important operating difference to note between them. Whereas a reactive compensator supplies reactive power to, or absorbs that from the ac system to change the prevailing reactive power flow and thereby indirectly control the transmission line voltage, the tap changer based voltage regulator cannot supply or absorb reactive power. It directly manages the transmission voltage on one side and leaves it to the power system could occur.

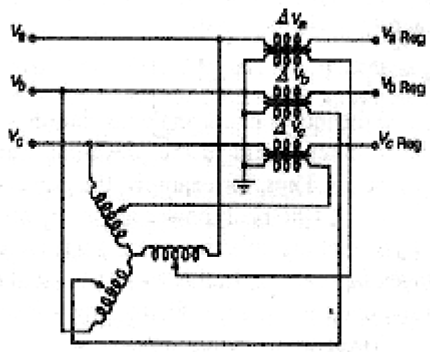
On –load tap changers contribution to voltage collapse under certain condition is well recognized. For example when the tap changers increase the transformation ratio in order to minimize the voltage drop for predominantly motor loads in the face load current at decreasing load power factor. This of course further reduces the transmission voltage and in turn further increases the current until the voltage collapses and the protection relays remove the load. Nevertheless the on-load tap changer and its electronic counterparts play a significant role in the transmission power flow control by providing the important functions of voltage regulation and reactive power management.

7.1.1 VOLTAGE REGULATION

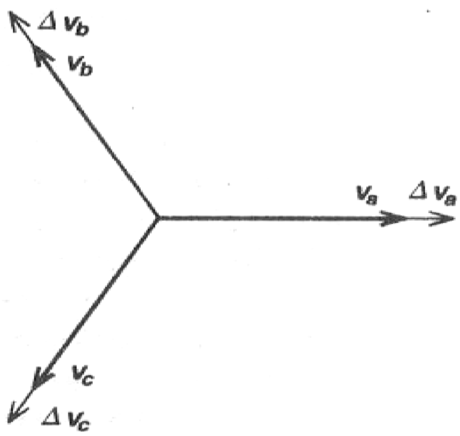
The basic concept of voltage regulation is the addition of an appropriate in-phase component to the prevailing terminal (bus) voltage in order to change (increase or decrease) its magnitude to the value specified (or desired). Thus voltage regulation could theoretically be achieved by a synchronous in-phase voltage source with controllable amplitude, ± Δ V, in series with the ac system and the regulated terminal as illustrated in fig(7.4a)a commonly used implementation of this concept is shown schematically in fig(7.4b) adjustable voltage is provided by means of a tap changer from a three phase transformer (usually referred to as regulating or excitation transformer) for the primary of a series insertion transformer which injects it to achieve the required voltage regulation. From the arrangement shown it is evident that the injected voltages ± Δva, ± Δvb ,and ± Δvc are in phase with the line to neutral voltages va , vb ,and vc respectively, as illustrated by the phasor diagram in fig(7.4c)



(a)



(b)



(c)

Fig (7.4) concept and basic implementation of a voltage regulator

7.1.2 FUNCTIONAL REQUIREMENTS

Voltage regulators are used for the reactive power flow and the terminal voltage control. Their functional capability is vital for controlling real and reactive loop power flows. Voltage regulators also play an important role in sub transmission and distribution systems in maintaining operating voltage levels.

In future flexible ac transmission systems the functional capabilities of conventional voltage regulators with modern solid state implementations will play an important role in the optimal utilization of the transmission network by real and reactive power flow management and voltage control. It will be seen that analogous to controlled shunt and series compensation, the above functional requirements can be accomplished by adapting the conventional on load tap changer concept for fast and unrestricted thyristor control , or by using a new approach in which switching converters , as voltage sources are configured to provide the desired voltage injection for voltage regulation.

7.1.3 APPROACHES TO THYRISTOR –CONTROLLED VOLTAGE REGULATORS

There are two basic approaches to modern power electronics based reactive compensators: one that uses conventional thyristors (which commutate naturally at current zeros) to control current in reactive impedances, and the other employs turn-off(GTO) thyristors(or similar devices) in switching power converters to realize controllable synchronous voltage sources. This dual approach, in a different form, extends also to voltage regulators.

The voltage regulation is generally accomplished by in-phase voltage injection. Thus the thyristor based approach insert a controlled voltage between the given bus and the controlled terminal or line. This approach obtains the insertion voltage from appropriate taps of the regulating (excitation) transformer. Thus the function of the thyristor based approach is to select the proper tap of the regulating transformer and injecting the thus obtained voltage, usually by an insertion transformer, in series with the line.

There are two main reasons for the application of Thyristor Controlled Voltage Regulators:

- Elimination of the expensive regular maintenance
- The high speed response necessary for dynamic system control

The TCVR provide a voltage with a variable magnitude from a fixed voltage source. Of course this is functionally the same as producing a voltage with fixed magnitude from a source of variable magnitude. The voltage at its output is in phase with the voltage applied at its input. The thyristor controller used as regulators is also called as thyristor tap changer.

Thyristor tap changers may be configured to provide continuous or discrete level control. Continuous control is based on delay angle control which generates harmonics. To achieve little or no harmonic generation, thyristor tap changer configuration must provide discrete level control.

The main constituent parts of a thyristor tap changer offering discrete level control are transformers and the thyristor valves, together with their heat sinks, snubbers, and gate-drive control. There are a number of possible configurations capable of discrete level control with tap step sizes comparable to those generated by conventional electromechanical units. Some of these arrangements can lead to a reduction in the number

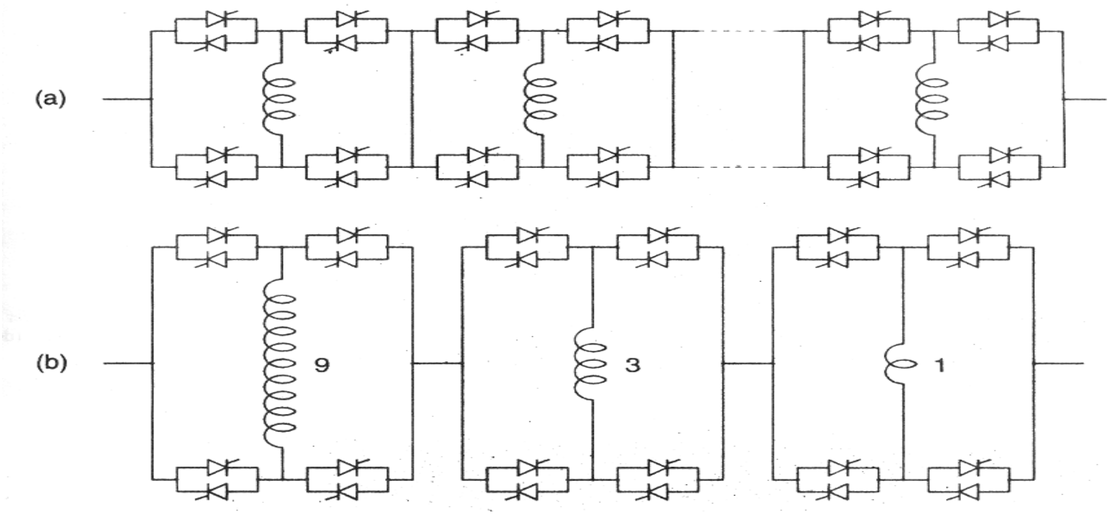


fig (7.5) Basic thyristor tap changer configuration (a) identical windings and thyristor valve ratings. (b) Windings and thyristor valve voltage ratings in ternary progression

of transformer taps required which usually is advantageous. Fig (7.5) shows the single line diagram of two basic concepts. One shown in fig (7.5a) is based on n identical windings and bi-directional thyristor bridge circuits to provide from zero to n voltage steps in either direction, since each bridge circuit can connect the related transformer winding with either polarity, or can bypass it. The other concept shown in fig (7.5b) is based on ternary progression: the transformer windings and the voltage ratings of the thyristor bridges are proportioned in the ratio of 1:3:9…and the number of steps, n, in one direction is given with the number of windings, l, by the expression

$$n = \frac{\left(3^{l} - 1\right)}{2} \tag{7.5}$$

Thus the three winding arrangement illustrated in fig (7.5b) has 13 steps in each direction. In the approaches where thyristors are to be used in utility applications the devices must tolerate the fault currents and transient voltages endemic to utility systems. Thus the number of thyristors required for a voltage regulator application is heavily influenced by the actual transient voltages and currents occurring during surges and faults. Consequently, specification requirements and protection arrangements can significantly impact the equipment cost.

7.1.4 CONTINUOUSLY CONTROLLABLE THYRISTOR CONTROLLED VOLTAGE REGULATOR

The basic power circuit scheme of a thyristor tap changer is shown in fig (7.4). This arrangement can give continuous voltage magnitude control by initiating the onset of the thyristor valve conduction. Consider fig (7.8) and assume that a resistive load is connected to the output terminals of the thyristor tap changer. This load of course could be the line current in phase with the terminal voltage. The voltages obtainable at the upper and the lower taps v_2 and v_1 respectively are shown in fig (7.9). The gating of the thyristor valves is controlled by the delay angle $\alpha = 0$, at which in the present case of a resistive load, the current crosses zero and thus the previously conducting valve turns off, valve sw1 turns on to switch the load to the lower tap. At $\alpha = \alpha_1$, valve sw_2 is gated on, which commutates the current from the conducting thyristor valve sw_1 by forcing a negative anode to cathode voltage across it and connecting the output to the upper tap with the voltage v_2. Valve sw_2 continuous conducting until the next current zero is reached. Inspection of the waveform indicates that by delaying the turn –on of sw_2 from 0 to π any output voltage between v_2 to v_1 can be attained.

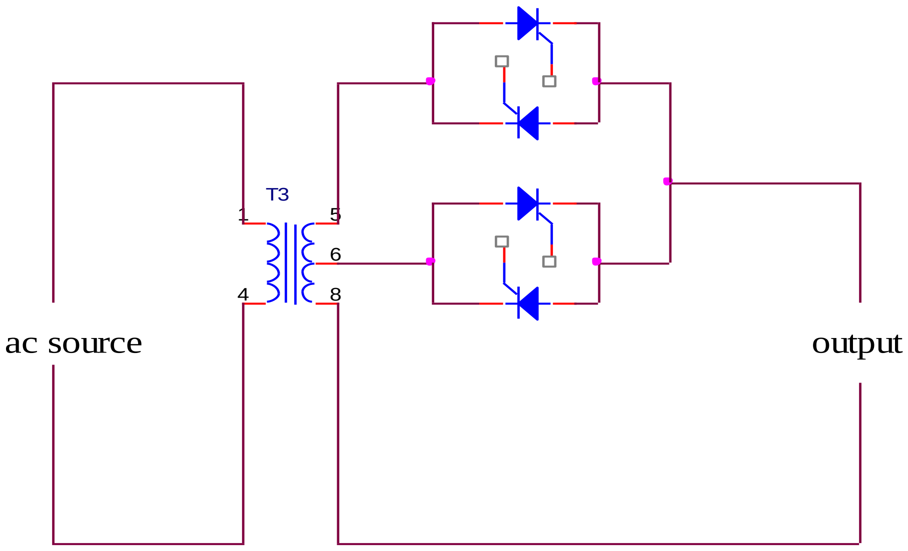


Fig (7.7) Basic TCVR circuit

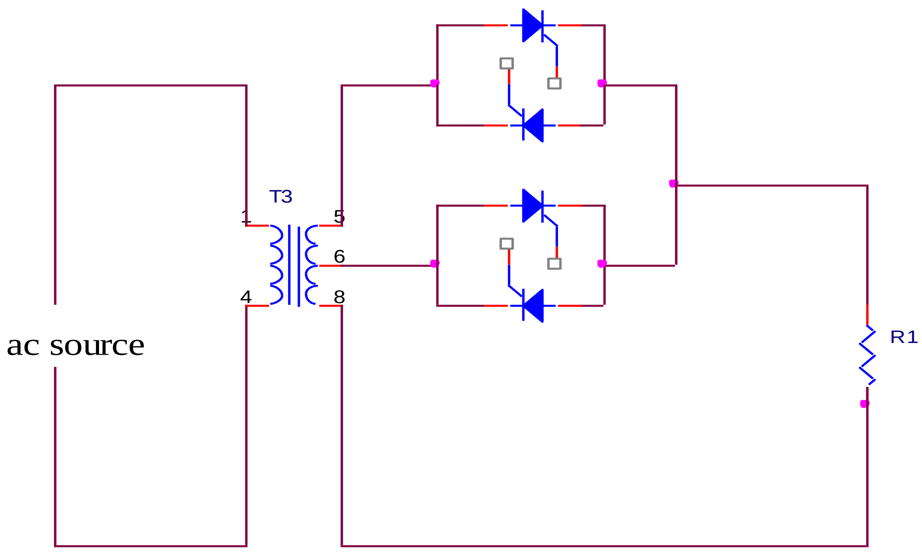


Fig (7.8) TCVR supplying a resistive load

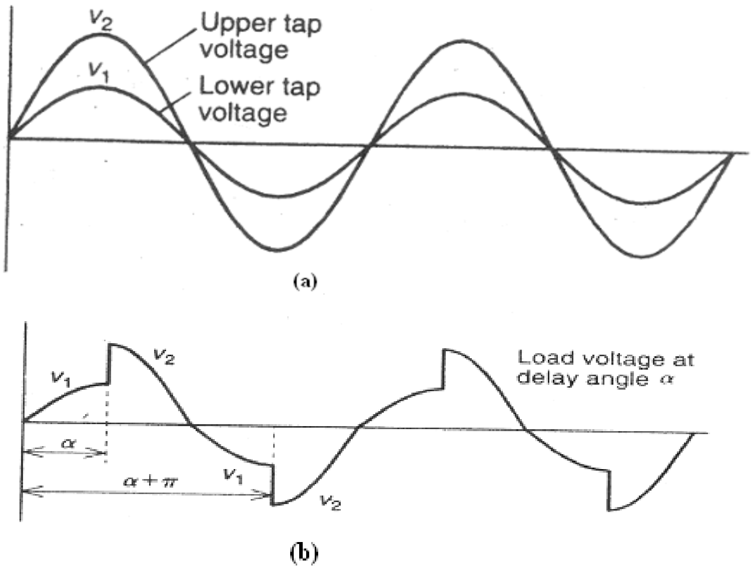


Fig (7.9) Output voltage waveform of the delay angle controlled TCVR supplying a resistive load

7.1.5 MATHEMATICAL ANALYSIS OF TCVR

Fourier analysis of the output voltage waveform for an idealized controlled thyristor tap changer operating between voltages v_1 and v_2 with resistive load and delay angle α with respect to zero crossing of the voltage can be easily carried out, yielding the following expressions for the fundamental component

$$v_{of} = \sqrt{a_1^2 + b_1^2} \tag{7.6}$$

$$\psi_{of} = \tan^{-1}\left(\frac{a_1}{b_1}\right) \tag{7.7}$$

Where V_{of} is the amplitude of the fundamental and ψ_{of} is the phase angle of the fundamental with respect to the unregulated voltage and

$$a_1 = \left(\frac{v_2 - v_1}{2\pi}\right)\left(\cos 2\alpha - 1\right) \tag{7.8}$$

$$b_1 = v_1 + \left(\frac{v_2 - v_1}{\pi}\right)\left(\pi - \alpha + \frac{\sin 2\alpha}{2}\right) \tag{7.9}$$

The variation of amplitude V_{of} and ψ_{of} of the fundamental voltage V_{of} with delay angle α for an assumed ±10% regulation range (V_1=0.9 and V_2=1.1 p.u.) is shown in fig (7.10). The maximum phase shift is in the vicinity of α = 900 is proportional to the regulation range.

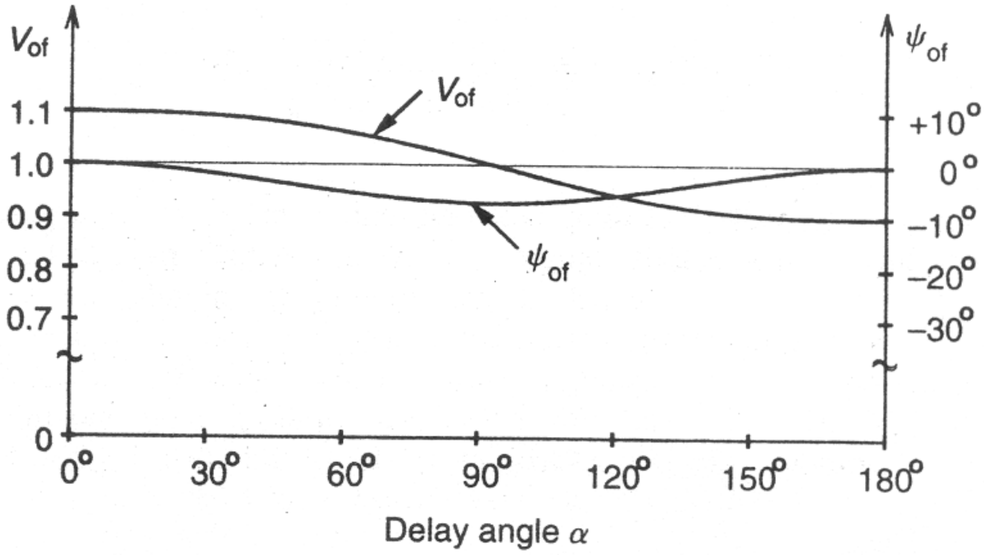


Fig (7.10) variation of the amplitude and phase angle of the fundamental output voltage obtained with a delay angle controlled thyristor tap changer supplying a resistive load

The harmonics in the output voltage can be expressed in the following way:

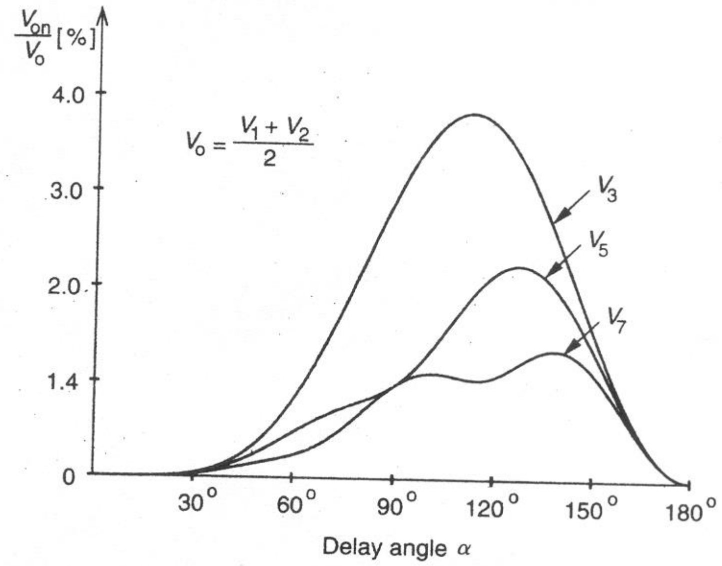
$$v_n = \sqrt{a_n^{\ 2} + b_n^{\ 2}} \tag{7.10}$$

$$a_n = \left(\frac{v_2 - v_1}{\pi}\right)\left(\frac{1}{n-1} - \frac{1}{n+1} + \frac{\cos\{n+1\}\alpha}{n+1} - \frac{\cos\{n-1\}\alpha}{n-1}\right) \tag{7.11}$$

$$b_n = \left(\frac{v_2 - v_1}{\pi}\right)\left(\frac{\sin(n+1)\alpha}{n+1} - \frac{\sin(n-1)\alpha}{n-1}\right) \tag{7.12}$$

Where n=2k+1 and k=1, 2, 3…..

Figure (7.11) shows the dominant harmonic components as a percentage of the nominal fundamental output voltage $(V_1 + V_2)/\ 2$ for the stipulated tap voltage difference $(V_2\text{-}V_1) = 0.2$ p.u. which as mentioned corresponds to a ±10% regulation range. The amplitudes of the harmonics at any given α are of course proportional to the regulation range for example with a ±20% regulation range the amplitudes plotted in fig (7.11) would double.



Fig(7.11) Amplitude variation of the dominant harmonics vs. delay angle present in the output voltage of a Thyristor Controlled Voltage Regulator

7.1.6 MODELLING OF TCVR

TCVR is considered as the common voltage regulator. It is able to smoothly vary voltage magnitude with a tap changing in the control range of $-\alpha_{min} < \alpha_l < \alpha_{max}$. A static model of TCVR with a tap ratio is connected in a series impedance of the distribution line

The TCVR operates by inserting an in-phase voltage to the main bus voltage so as to change its magnitude. It is modeled by an ideal tap changer transformer in series with the branch. Its value depends on the main bus voltage magnitude V_b of the line in which the device is located. The additional voltage is in the range $-0.15\ V_b \leq V_{TCVR} \leq 0.15\ V_b$ p.u

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