High Voltage Engineering

The electric power transmitted on a transmission line increases as the square of the systems operating voltage. Therefore, increasing the transmission voltage permits a high power density over a given right of way. Also, for a given power to be transmitted the current decreases as the operating voltage is increased. This allows the use of conductors of lower area of cross-section and reduces I^2R loss in conductors.

Electric power transmission over long distances at increased voltage levels is therefore more economical & efficient.

Applications of High voltage.

High voltages are not only used in electrical power systems but find many applications in industry, medicine, fundamental research in physics. A few examples are:

Electron microscopy
CT scanners
X - ray
Nuclear particle accelerators
Electrostatic precipitators.

Definition of High Voltage

According to standards any voltage above 1000v is regarded as High voltage.

High voltage Engineering is concerned with technology of generation of high voltages, their measurement & the study of the means of supporting voltages. The means of Supporting high voltages are insulation system that separate & support conductors.

In power system applications insulation systems form an integral part of the generation, transmission and distribution equipment. During use an insulation system is subjected to stresses due to not only the operating voltages but also the transient voltages whose magnitude exceeds the normal operating voltage.

The transient voltages may be of external or internal nature. External voltages are associated with lightening discharges and their magnitude doesnot depend on the operating voltage of system. As a result the importance of stresses produced by Lightening overvoltages decreases as operating voltage increases.

Internal overvoltages are generated by sudden changes in the operating conditions of a system such as faults, switching operations or fluctuations in load or generation. Their magnitude depends on operating voltage, the complexity of system, the instant at which the change in the operating Conditions occur & so on. More often changes in the operating Conditions of the system are associated with switching operations. Hence, internal overvoltages are generally referred to as switching over-voltages.

In designing the insulation of a system the two areas of specific importance are :-

1) Determination of voltage stresses which the insulation must withstand.

2. Determination of response of insulation when subjected to these voltage stresses.

There has to be a proper balance between electrical stresses on insulation & dielectric strength of insulation.

Test Voltages

It is necessary to test high voltage equipment during its development stage & prior to commissioning. The magnitude & the type of test voltage varies with the rated voltage & application of a particular apparatus. The standard methods of testing are laid down in the relevant national & international standards.

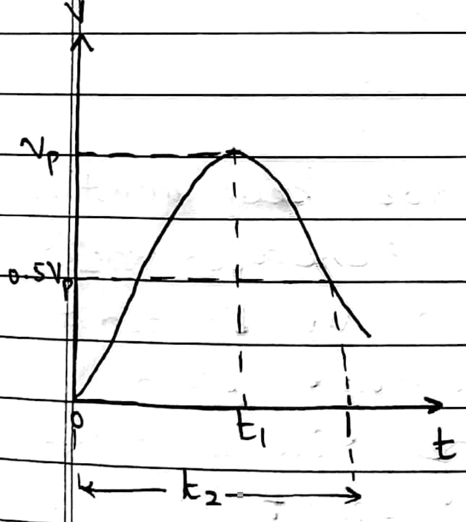
Testing with power frequency voltages

To access the ability of insulation of the apparatus to withstand under the power frequency voltage, the apparatus is subjected to 1 minute test under 50 Hz or 60 Hz voltage depending upon the country. The test voltage is set at a level higher than the normal operating voltage in order to simulate the stresses likely to be encountered over the years of service. For indoor installations the equipment tests are conduted under dry conditions only. For outdoor equipments tests may also be required under conditions of standard rain as prescribed in appropriate standards.

Date 12-03-19
Page

Testing with Lightening Impulse Voltages

Lightening strokes terminating on transmission lines induce steep rising voltages & setup travelling waves along the lines which may damage the systems insulation. The magnitude of these over voltages may reach sevel 1000kV depending upon the line surge impedence, insulation strength & over voltage protective devices. Exhaustive measurements & long term experience have shown that the lightning overvoltages are impulsive, characterised by a short front duration, ranging from a fraction of a μ sec to several 10's of μ sec, & then decreasing relatively slowly to zero.



$t_1 = 1.2\ \mu$ sec
$t_2 = 50\ \mu$ sec

For testing of power system equipment, the standard impulse voltage has been accepted as an aperiodic impulse that reaches its peak value in 1.2 μ sec & then decreases slowly in 50 μ sec to half its peak value.

Standard Lightning impulse voltage or 1.2/50 μs impulse

Testing with Switching Impulse voltages

Switching Impulse Voltages are usually the dominant factor affecting the design of insulation in high voltage power system for rated voltages of about 300 KV or more. Accordingly the various International standards recommend that the equipment design for voltages above 300 KV be tested with switching impulses. Although the wave shape of switching overvoltages occuring in the system may vary widely, the recommended switching impulse test voltage has been accepted to have a front time of about 250 μsec & time to half value of 2500 μsec (tail time)

Testing with DC voltages

In the past, DC voltages have been mostly used for purely scientific research work, industrial applications were mainly limited to testing of cables with relatively large capacitance which take a large current when tested with AC voltages. In recent years, with a rapidly growing interest in HVDC transmission, an increasing no. of industrial laboratories are being equipped with sources for producing high DC voltages.

Generation of High voltages

In the field of Electrical Engineering & applied physics, high voltages are required for several applications e.g electron microscopes / x-ray units require high DC voltages of the order of 100kV or more. Electrostatic precipitators, particle accelerators require high DC voltages of several 100 kV & even million volts. High AC voltages of the order of 1 million volt or more are required for testing power apparatus. High impulse voltages are required for testing HV equipment for simulating over voltages that occur in a power system due to lightning or switching surges.

Normally the current required in HV testing is limited to a small value (less than an ampere in case of DC & AC voltages & a few amperes in case of impulse voltages). But in certain cases like testing of surge diverters or short circuit testing of switch gear several hundred amperes or several kilo amperes of current is required. Such test facilities require high current & high voltage generators.

Specifications / Requirements of the Source

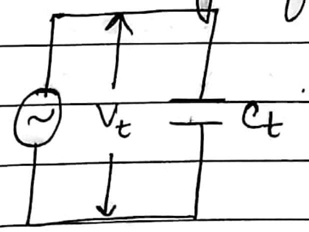
1. Test voltages are usually single phase to ground.

2. The test voltage levels required range from 10kV to 2 million volt (MV) as transmission voltages upto about 1200 kV have been reached. In general all AC voltage tests are carried out at the working frequency of the test objects. Typical exceptions are testing of iron core windings (e.g transformers) or fundamental studies on insulation systems. For iron core windings the frequency has to be raised to avoid saturation of the core.

3. wave shape :- The waveshape must be almost purely sinusoidal with both half cycles closely alike.

Ratio of peak to rms value = $\frac{Peak}{Rms} = \sqrt{2} \pm 5\%$

4. power rating of the source:-



A string of HV apparatus involves application of high voltages to capacitive loads with lower power consumption.

C_t = Capacitance of test object
V_t = Test Voltage required.

The Voltampere requirement will be given by
$$S = K\,(\omega C_t V_t^2)$$

Where $k > 1$ to account for the additional Capacitances within the whole test set & some safety factor.

Additional Capacitances are due to:-

i) HV electrodes & connections between the source and test object which usually have large dimensions to avoid high electric field intensities & partial discharges (corona)

ii) Measurement devices such as Capacitive voltage dividers.

5. Current Rating:-
The nominal current In is given by
$$I_n = \frac{S}{V_t}$$

The current ranges from some mili amperes to a few amperes.

6. The test voltages are required for a short duration. The nominal rating are therefore related to short time periods of about 15-30 minutes.

7. Due to the relatively Large thermal Constant no sophisticated Cooling arrangements are necessary.

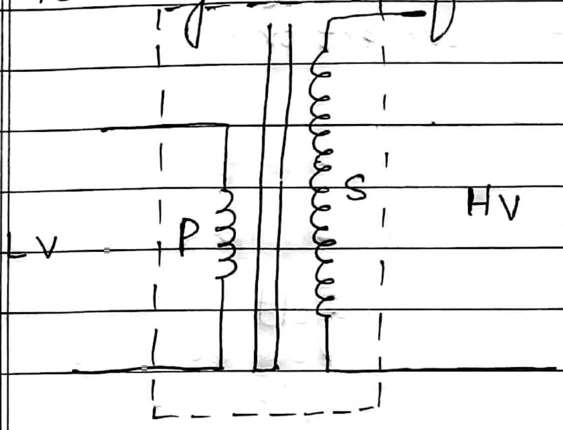
8. The test equipment should be as small as possible. For field testing portability Calls for Light weight equipment.

9. The test supply should withstand sudden collapse of the output voltage due to failure of specimen under test. The stresses to windings are usually not related to short Circuit currents & hence the magnetic forces within the windings as the currents are limited & not very large. More frequently it is the stray potential distribution between the windings which may Cause insulation failures.

Generation of High Alternating voltages

1. By using testing transformers.
2. By using Resonant circuits.

1. Testing Transformers.

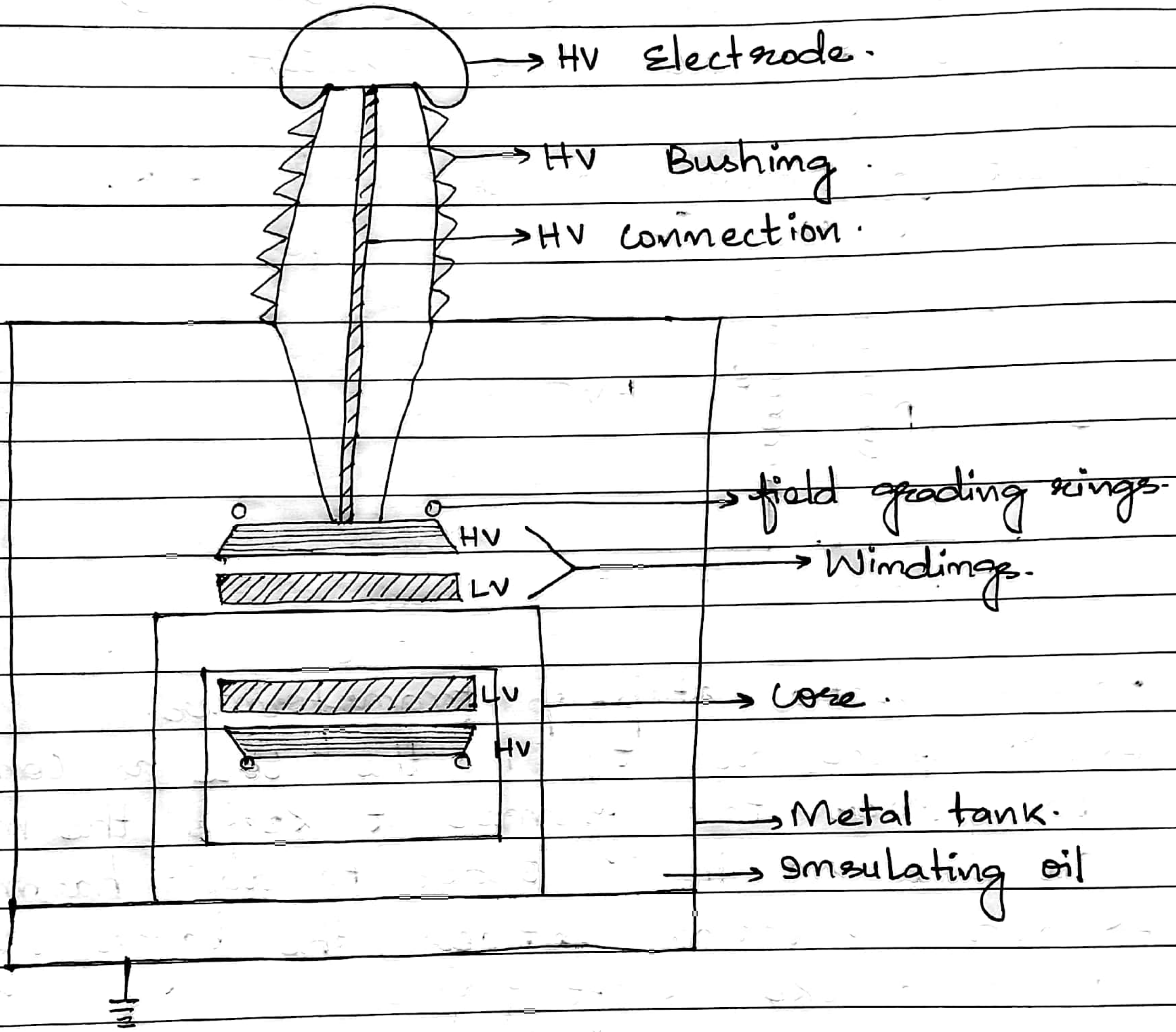


- → High ratio step-up transformer.
- → Low flux density in the core as compared to power transformer, it keeps the magnetising current small in order to avoid harmonics.
- → Solid insulation between the layers of HV winding like kraft paper.
- → The individual layers form coaxial capacitors.
- → Then the whole is placed in enclosure.

Depending upon the enclosure, we have two constructions.

1. Metal tank construction.
2. Insulating shell construction.

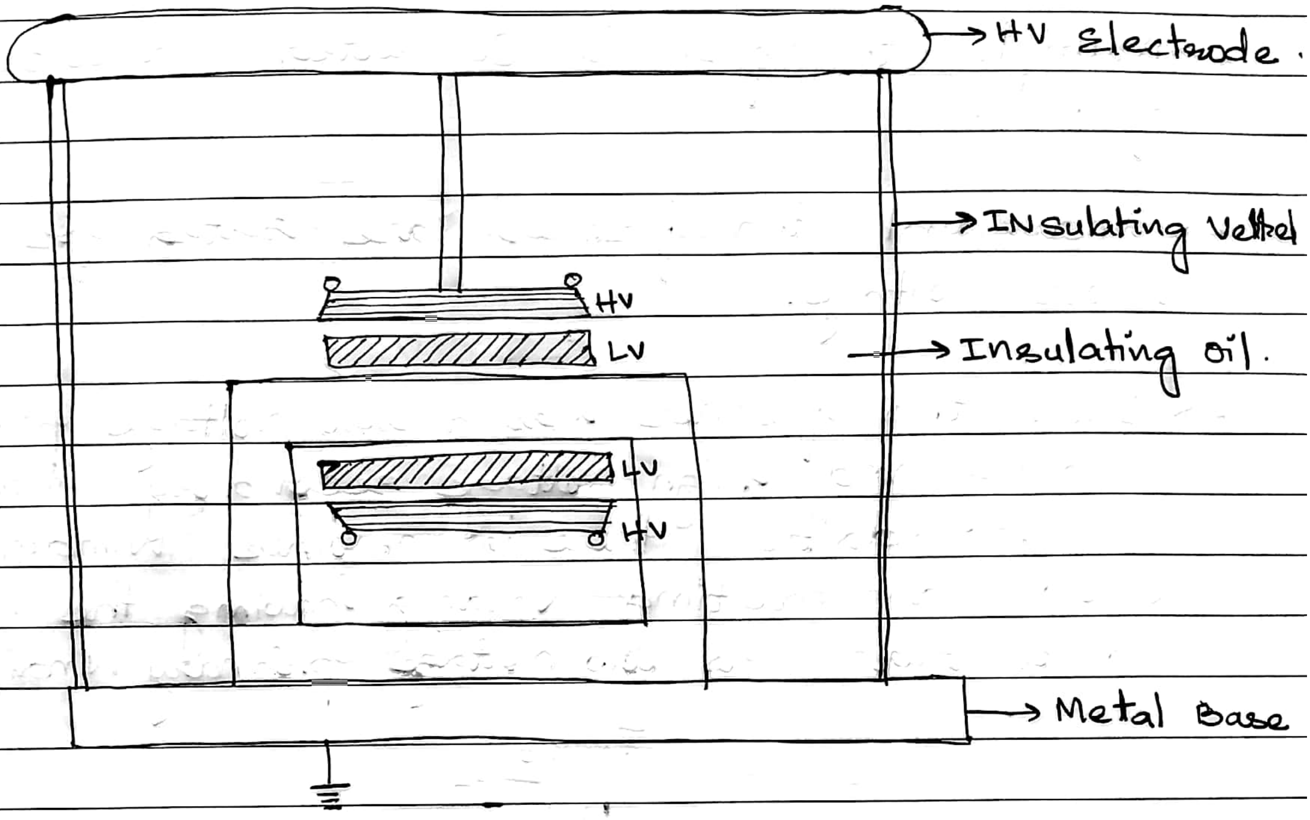
METAL TANK Construction



To provide insulation from the metal tank we provide HV Bushing in order to prevent from high electric field strength.

Since electric field intensity $\propto \frac{1}{radius}$, so high at edges so mettalurgical rings are provided to prevent from high electric field intensity.

Insulating shell construction



- No Bushing required.
- Reduced height than metal tank constrution.

Rating of testing transformers is upto about 500kV

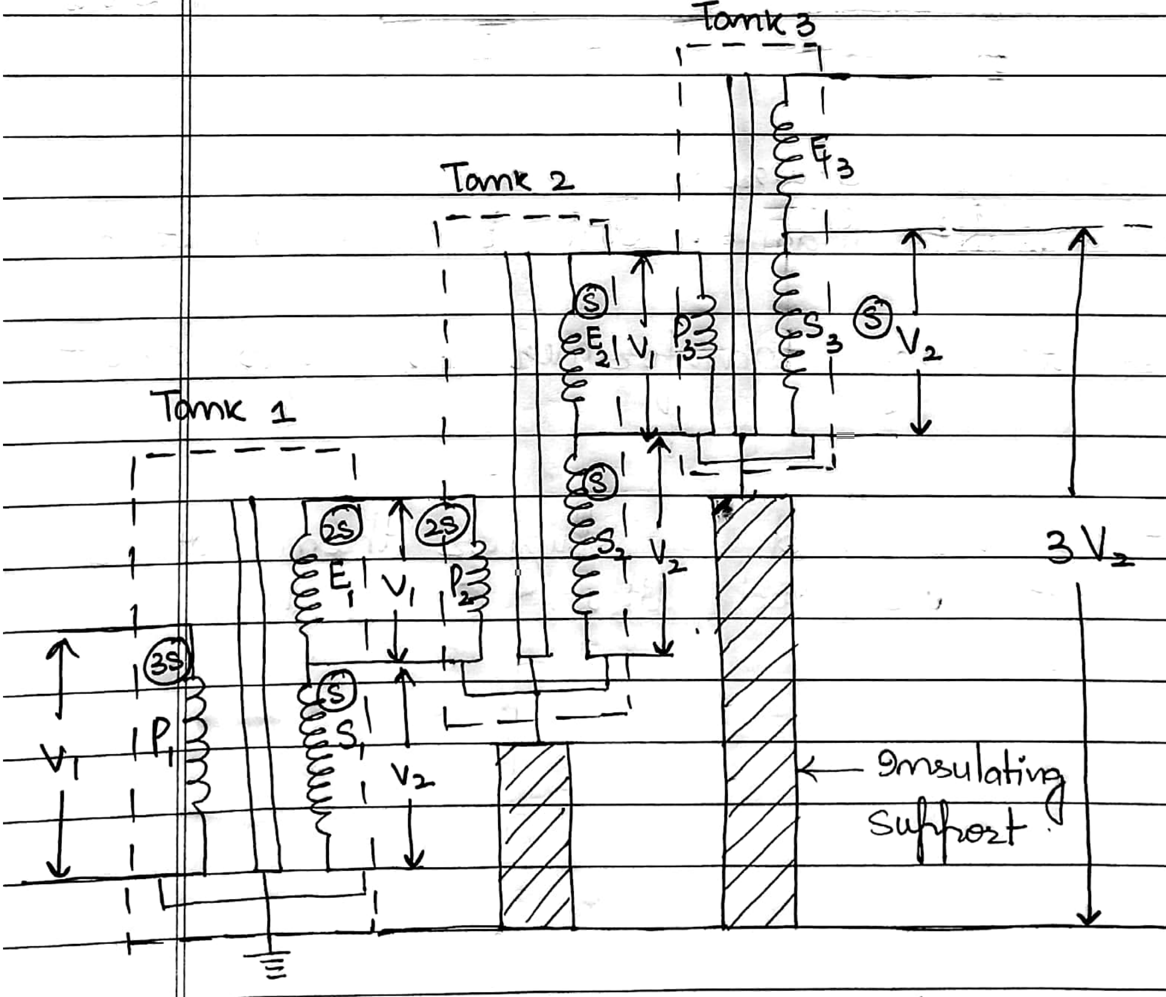
If Voltage required is higher then other arrangements are used like Cascaded transformers.

Cascaded transformers

- Multiple transformers connected in a certain fashion.

- Individual transformers are rated for a lower voltage.

- Each transformer has a low voltage primary winding and high voltage secondary winding and in addition there is another winding known as exciting winding having the same no. of turns as low voltage primary winding.



3 - stage Cascaded transformers.

Insulating support is provided in order to prevent from short circuiting because tank 2 is at a potential of V_2 w.r.t ground, if it is grounded i,e insulating support is not provided, it will result in short circuiting of S_1 (secondary of Ist transformer).

$$S_{total} = 3V_2 I = 3S$$

Primary rating increases as we move from higher transformers to lower transformer (i,e 3 to 1).

For Cascade, all the transformers should be identical because then the capacitance will be different and hence potential which will lead to failure of transformers.

Series Resonant Circuits

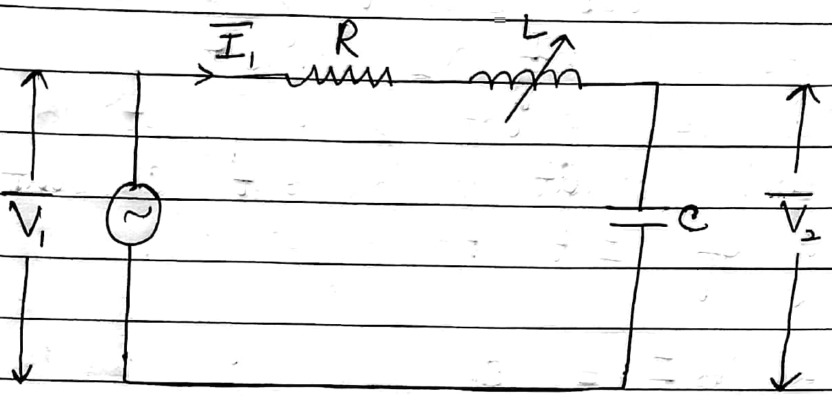


Fig. 1

Resonance will occur when

$$\omega L = \frac{1}{\omega C} \quad — ①$$

Current, $$\overline{I}_1 = \frac{\overline{V}_1}{R} \quad — ②$$

output voltage, $\overline{V}_2 = \overline{I}_1 X_c = \frac{\overline{V}_1}{R} \cdot \frac{1}{\omega C}$

$$V_2 = Q V_1 \quad — ③$$

Where $Q = \frac{1}{\omega RC}$, Quality factor — ④

For generating high voltages

$Q \doteq 20 - 50$

e.g $V_1 = 10$ kV, $Q = 50$

$V_2 = Q V_1$

$V_2 = 50 \times 10$ kV

$V_2 = 500$ kV.

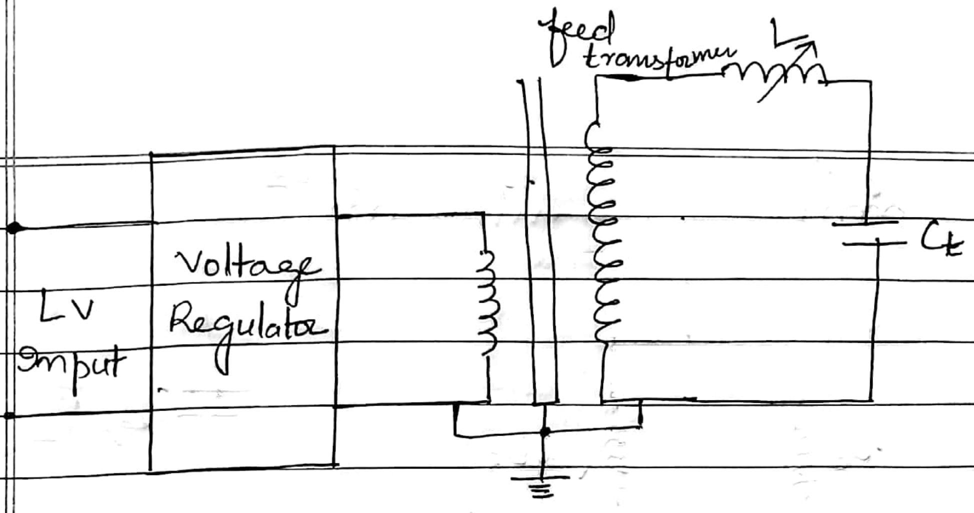


Fig. 2

Circuit arrangement of a practical resonant circuit for generating high voltages.

- → Here Ct is the Capacitance of test object which is fixed, therefore we use variable inductor in order to achieve resonant frequency, it must be continuously variable rated for full voltage & current.

- → Since input voltage is low (upto 240V) so we need a step up transformer to step up the low input voltage because we need to generate very high voltages.

- → Voltage regulator is used to control the magnitude of voltage (both input and output voltage).

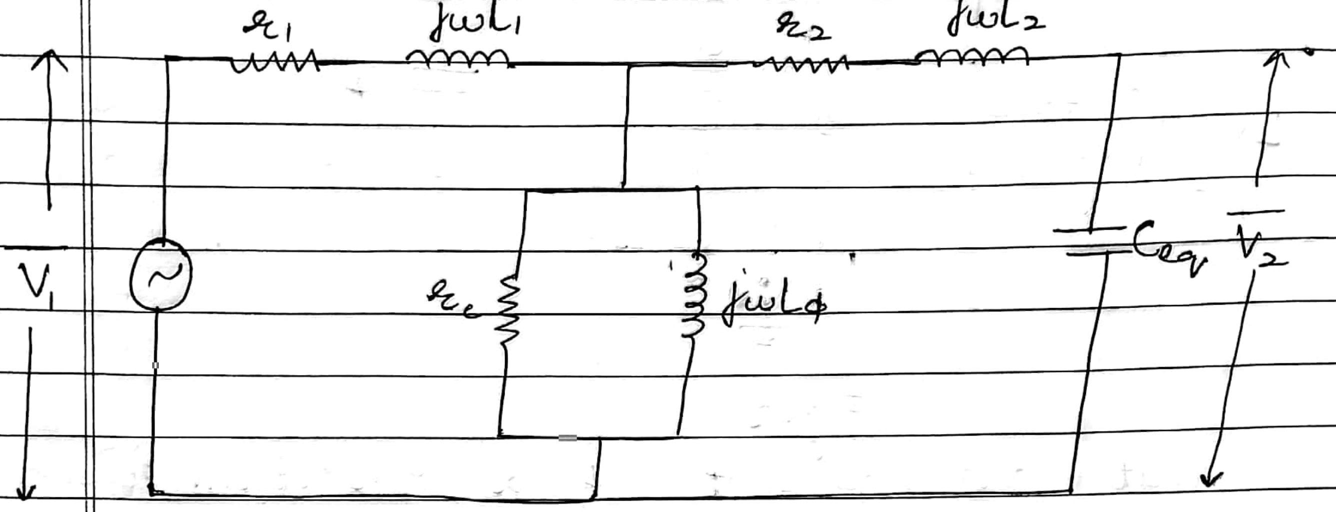


Fig. 3

Equivalent circuit of Fig. 2

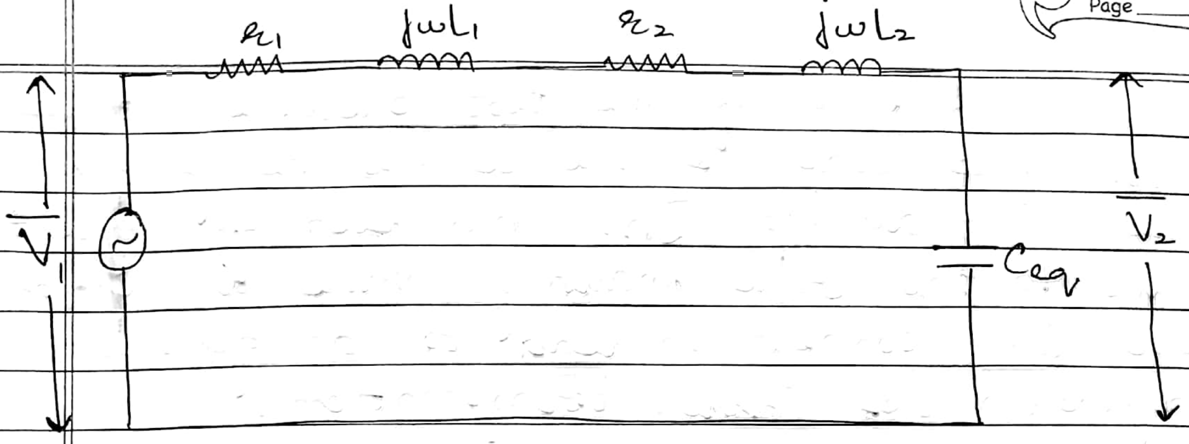
V_1 → input low voltage.

$(r_1 + j\omega L_1)$ → Comprises of the series impedance of the source, voltage regulator & transformer primary winding.

$(r_c \parallel j\omega L_\phi)$ → Transformer magnetising impedance.

$(r_2 + j\omega L_2)$ → series impedance of transformer secondary of the series reactor.

C_{eq} → Capacitance of the test object, transformer secondary, bushing Capacitance and Connections.



For this circuit resonance will occur when

$$\boxed{\omega(L_1 + L_2) = \frac{1}{\omega C_{eq}}}$$

Advantages of Series Resonant Circuit

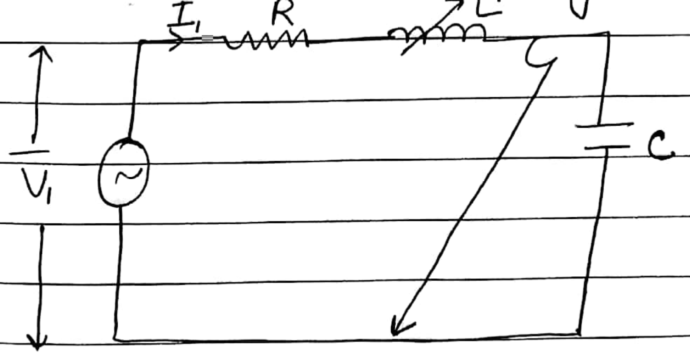
1. $V_2 = Q V_1$

$$\Rightarrow V_1 = \frac{V_2}{Q}$$

The voltage rating of the feed transformer can be as low as $\frac{V_2}{Q}$ as such the volt-ampere requirement of the source is reduced by a factor $\frac{1}{Q}$.

2. The voltage wave shape is improved not only by elimination of unwanted resonances but also by attenuation of harmonics already present in the supply.

3.



Series RLC circuit

of the failure of the test specimen occurs, resonance ceases & hence no heavy power arc will develop. This has been of great value to the cable industry where a power arc can sometimes lead to dangerous explosion of cable termination.

This has also proved helpful for the development work as weak part of the insulation will not be completely destroyed. The arc is self extinguishing due to the voltage collapse. This results in a recurring flashover condition with little energy, thus making it simple to observe the path of an air flashover.

4. The series resonant circuits are compact and light weight compared with testing transformers.

5. Resonant circuits are used for testing at high voltages requiring high current outputs such as cable testing & also for dielectric loss measurements, partial discharge measurements etc where wave shape considerations are important.

High Direct Voltages

They are used in:-

1. Pure scientific research in physics e.g Nuclear particle accelerators, electron microscopy etc.

2. Electromedical equipment e.g CT scanners, X - rays.

3. Industrial applications -
   i) Electrostatic precipitators used for filtering of exhaust gases in thermal power stations and cement industry.
   ii) Electrostatic painting & powder coating.
   iii) mineral separation.

4. Communication electronics like TV & broadcasting stations.

5. Testing of HVDC transmission equipment.

6. Testing of HV AC power Cables of long length.

7. Charging supply for impulse generators.

According to IEC 60-2 (International Electrotechnical commission), the value of direct test voltage is defined by it's arithmatic mean value.

$$\overline{V} = \frac{1}{T}\int_0^T V(t)\,dt$$

where T is the time period, if V(t) is not constant but oscillating ripple is present in the voltage.

$$\text{Ripple, } \delta V = \frac{1}{2}\left[V_{max} - V_{min}\right]$$

$$\text{Ripple factor} = \frac{\delta V}{\overline{V}} = \frac{\text{ripple voltage}}{\text{average voltage}}.$$

Different values of ripple factor are possible e.g.

for industrial applications.
$R.F = 2 - 5\%$

for test voltages
$R.F < 5\%$

for impulse generator charging, R.F upto 10%

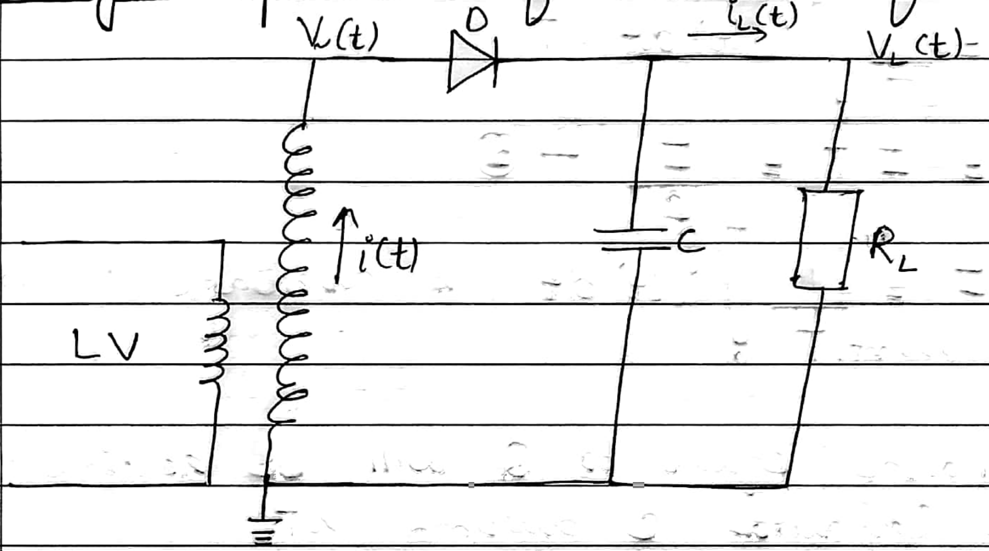
for Nuclear particle accelerators, R.F < 0.0001%

Generation of High Direct Voltages

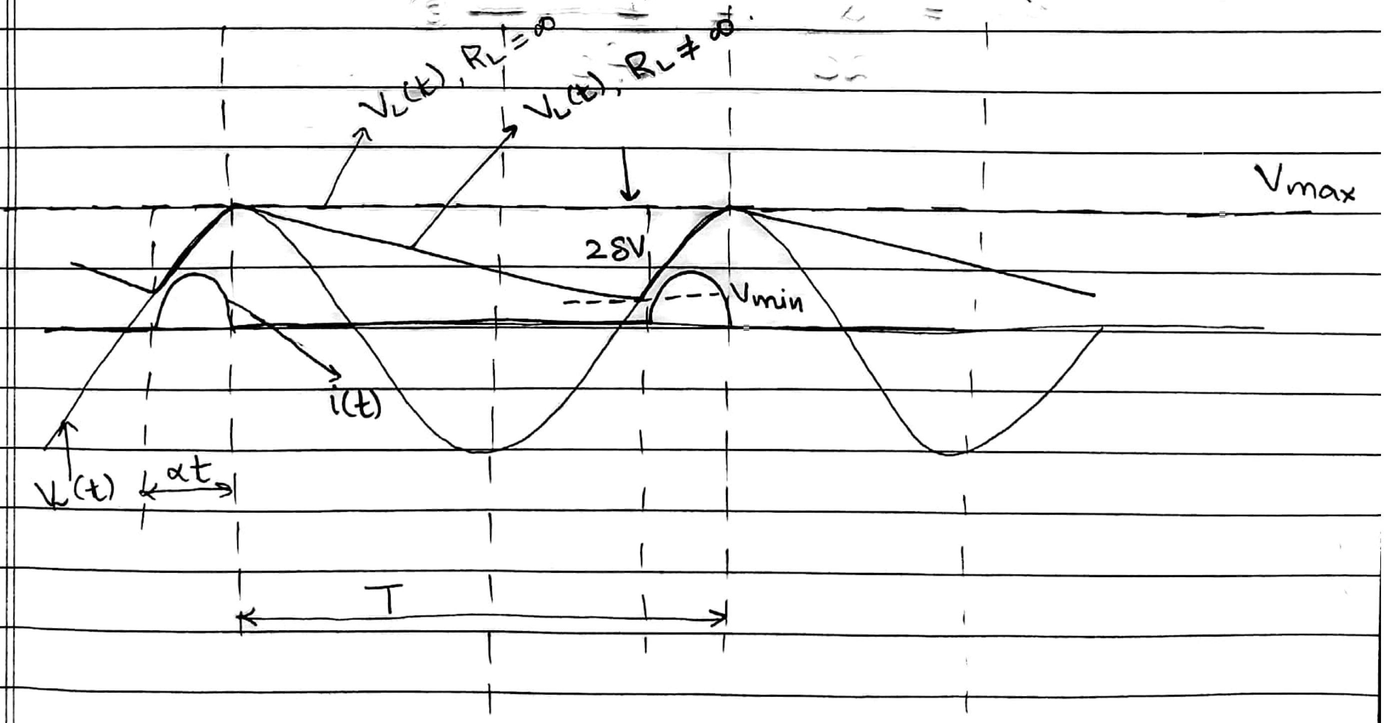
Rectifying circuits

Series connected diodes are used provided with equilizing circuits.

1. Single phase Half wave Rectifier



i) $R_L = \infty$, unloaded.
ii) $R_L \neq \infty$, loaded.



Ripple

charge transferred to load per cycle

$$Q = \int_0^T i_L(t)\,dt \quad — ①$$

$$Q = \frac{1}{T}\int_0^T i_L(t)\,dt \cdot T$$

$$Q = I\,T = \frac{I}{f} \quad — ②$$

where $I = \frac{1}{T}\int_0^T i_L(t)\,dt$ is average value of load current.

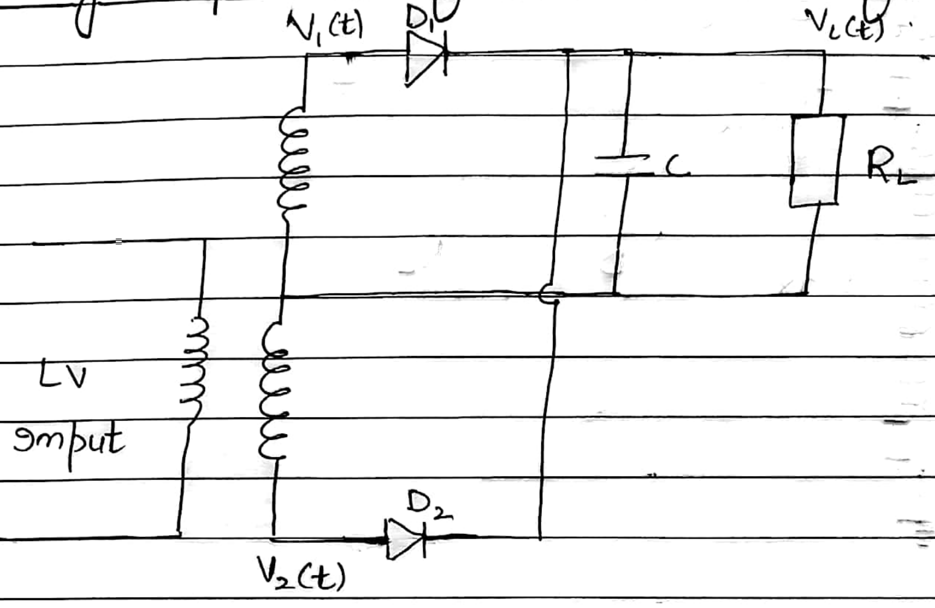
The charge equal to Q will be received by the Capacitor C during αT

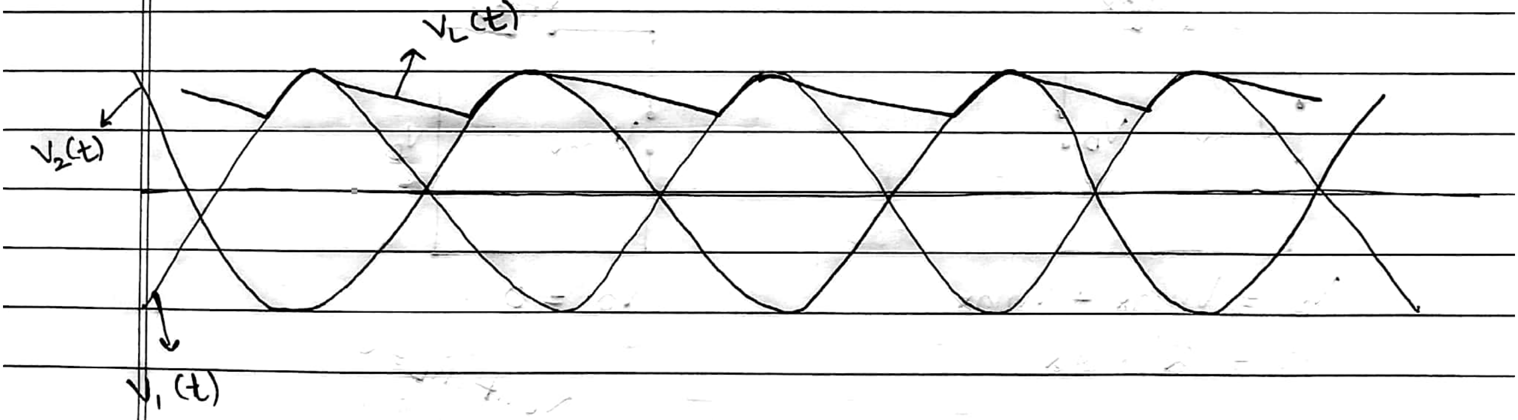
$$\alpha T << T$$

$$Q = C(2\,\delta V) \qquad (\because Q = CV)$$

$$\delta V = \frac{Q}{2C} = \frac{I}{2fC} \quad — ③$$

2. Single phase full wave rectifier.





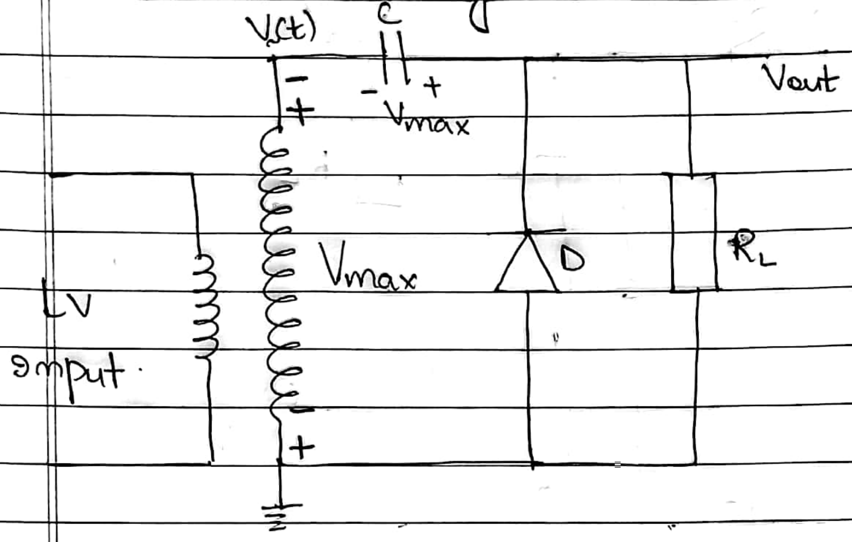
$T' = T/_2$; $f' = 2f$ (∵ Capacitor is charging twice both in positive half cycle & negative half cycle)

∴ Ripple voltage, $\delta V = \dfrac{I}{4fC}$.

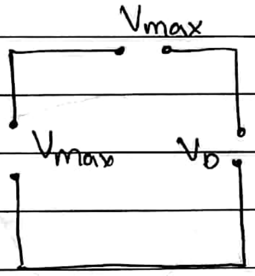
→ More turns used in single phase full wave rectifier. It is therefore costly.

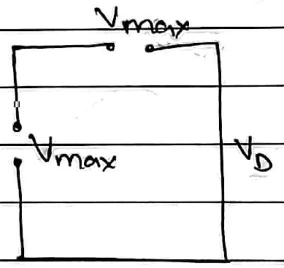
→ Transformer will not go into saturation in this case (because at one time only one diode is active & other becomes open circuit).

Villard Voltage Doubler Circuit



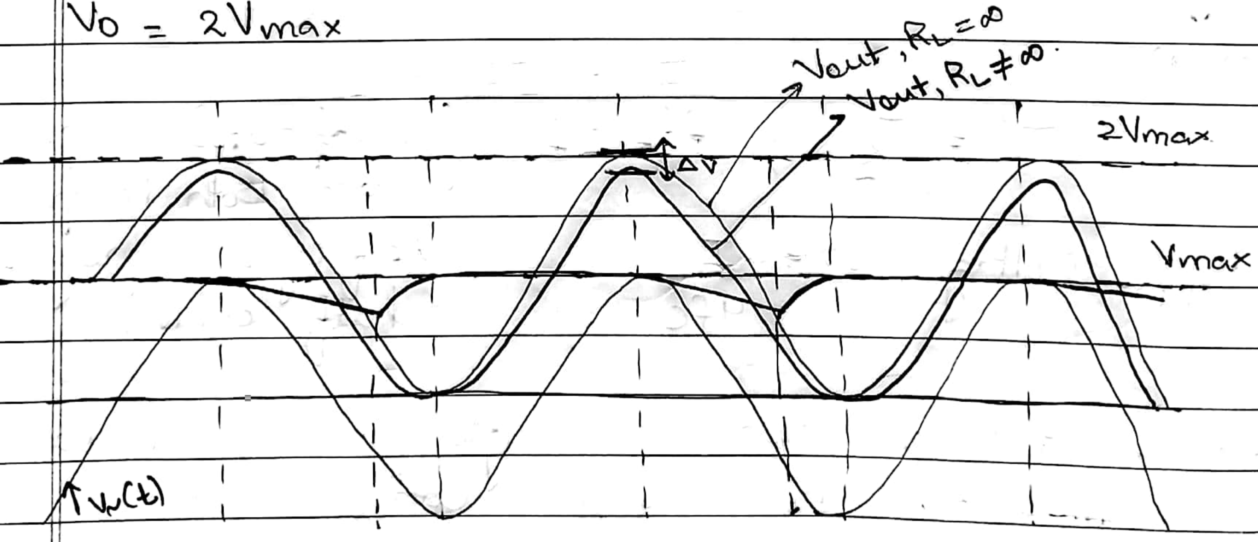
In +ve half cycle. In −ve half cycle.





$V_D = V_{max} + V_{max}$ $\qquad$ $V_D = 0$.

$V_D = 2V_{max}$



Voltage drop, ΔV :- Difference of peak voltage at no loaded condition & peak voltage at loaded condition.

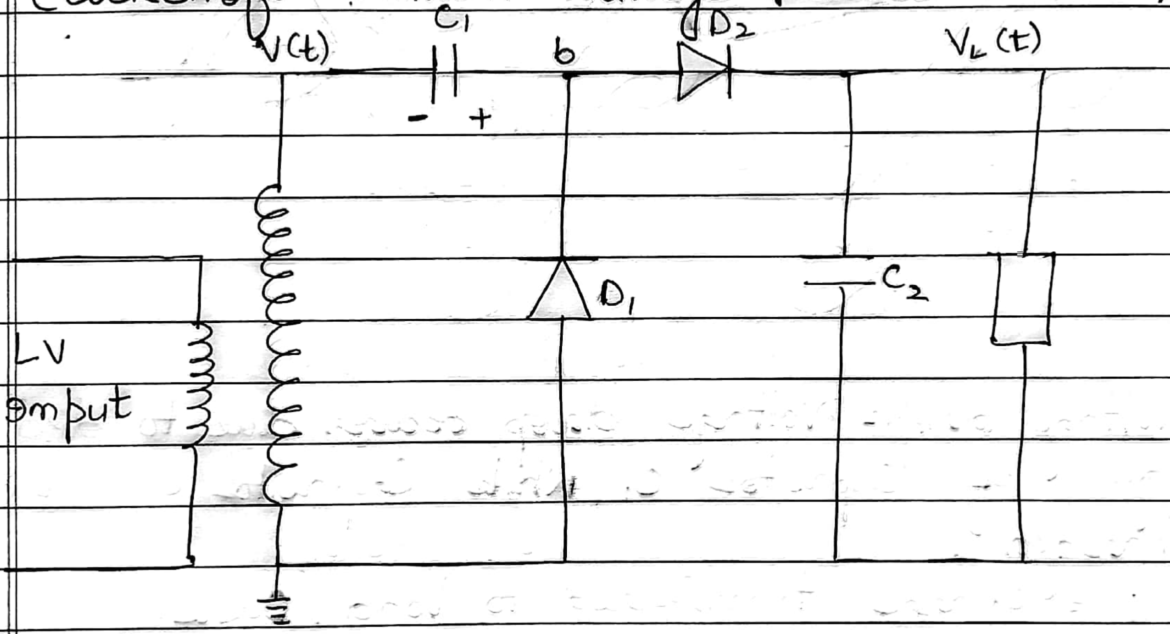
$\overline{V} = V_{max}$

$\delta V = V_{max}$

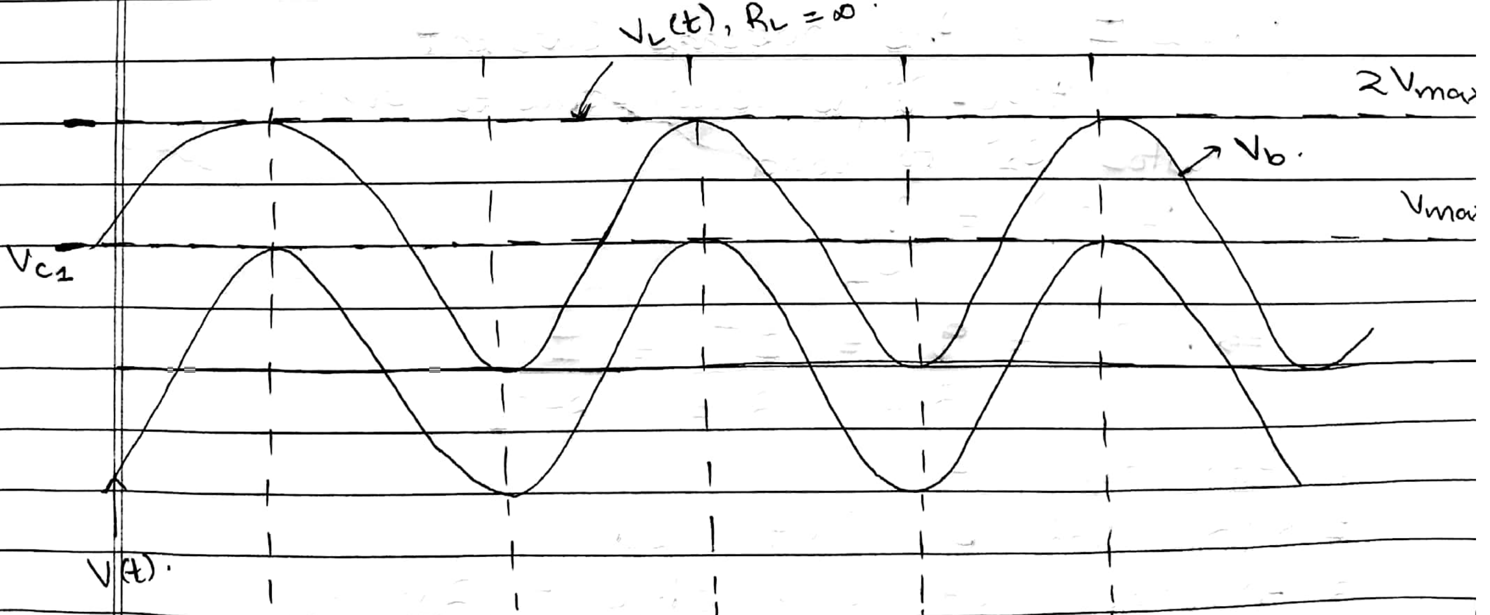
<u>Disadvantage</u> :- Ripple is Large.

Date : 27-03-19

Greinacher Voltage Doubler Circuit
(Cockcroft - Walton Voltage Doubler circuit)

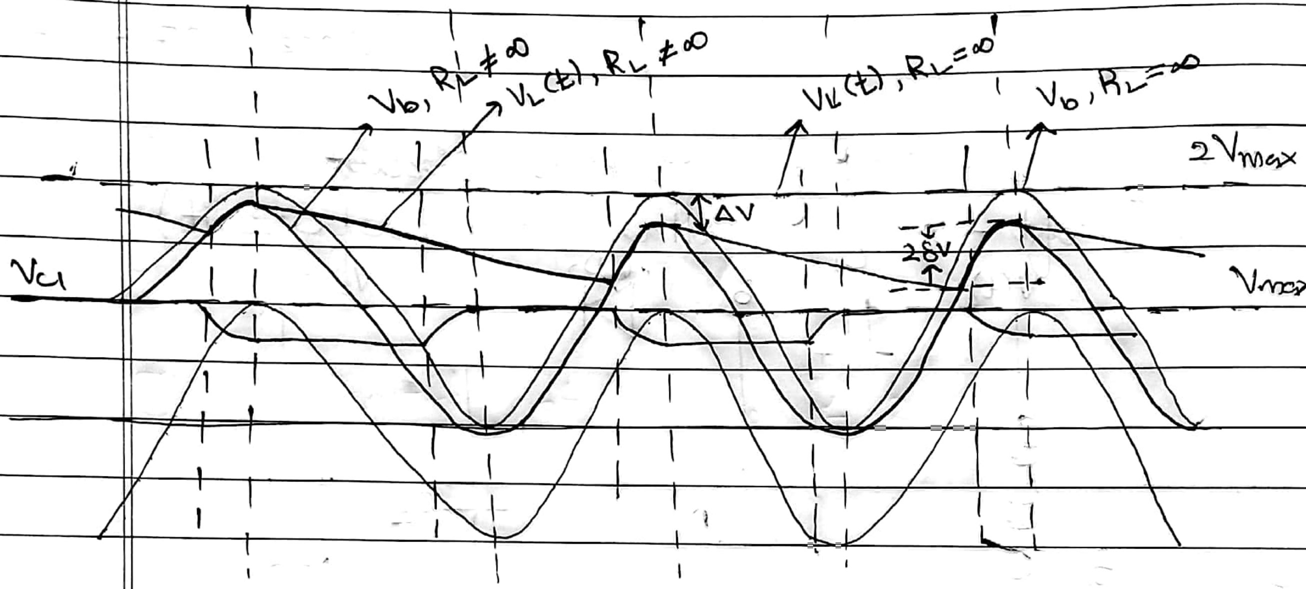


i) No loaded condition, $R_L = \infty$.



ii) Loaded Condition , $R_L \neq \infty$.

C_1 will charge close to -ve peak.
& C_2 will charge close to +ve peak.



i) Voltage drop:- Voltage drop occurs due to discharging of Capacitor C_1, while Capacitor C_2 is being charged.

q = charge transferred to load / cycle.

$$\Delta V = \frac{q}{C_1} = \frac{IT}{C_1} = \frac{I}{fC_1}$$

where I is the average current.

2. Ripple voltage:- Ripple occurs due to discharge of Capacitor C_2 to load

$$2(\delta V) = \frac{q}{C_2}$$

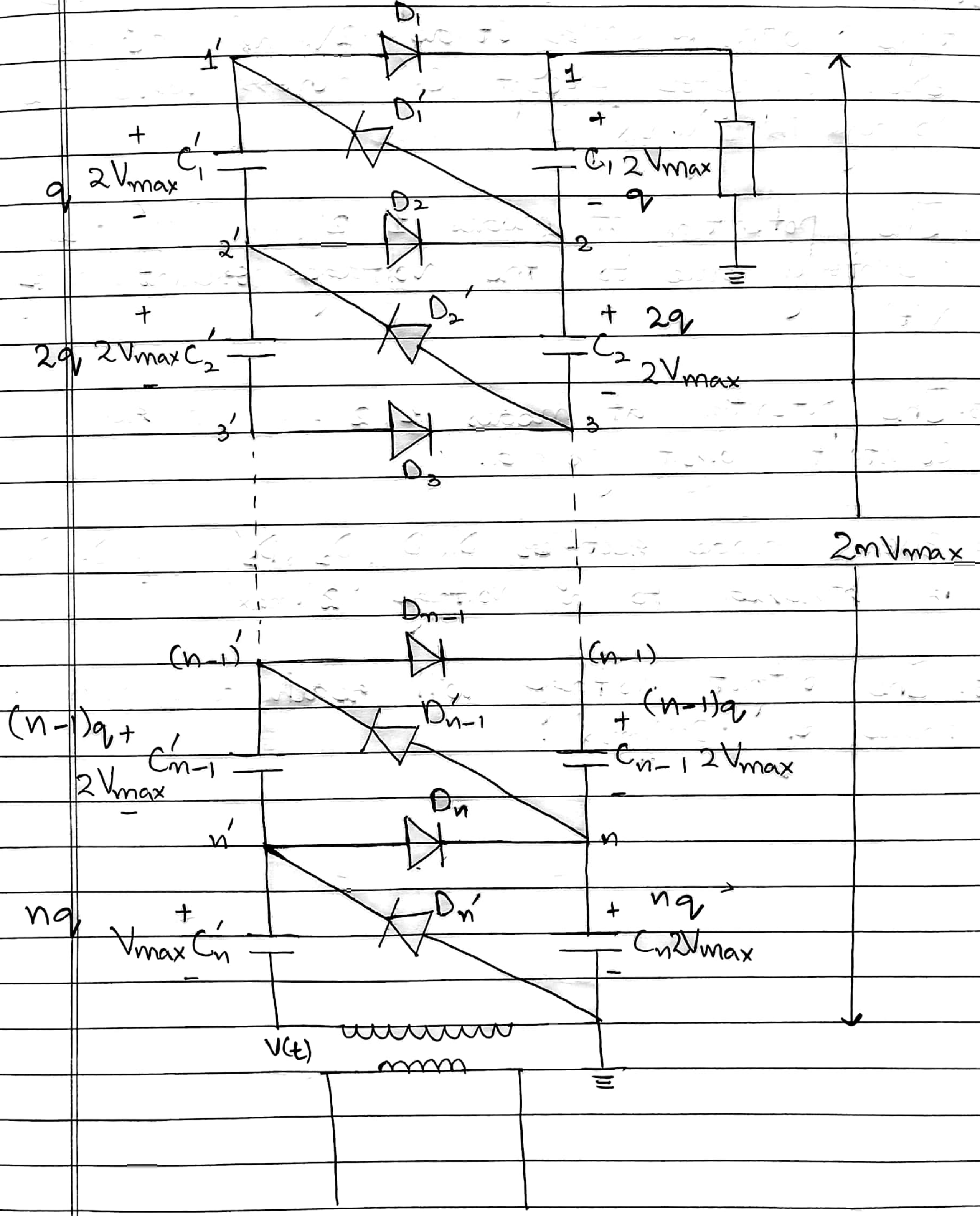
$$\Rightarrow \quad \delta V = \frac{q}{2C_2} = \frac{IT}{2C_2} = \frac{I}{2fC_2}.$$

⇒ Advantages :-

1. Ripple can be controlled.
2. Average voltage is close to 2Vmax

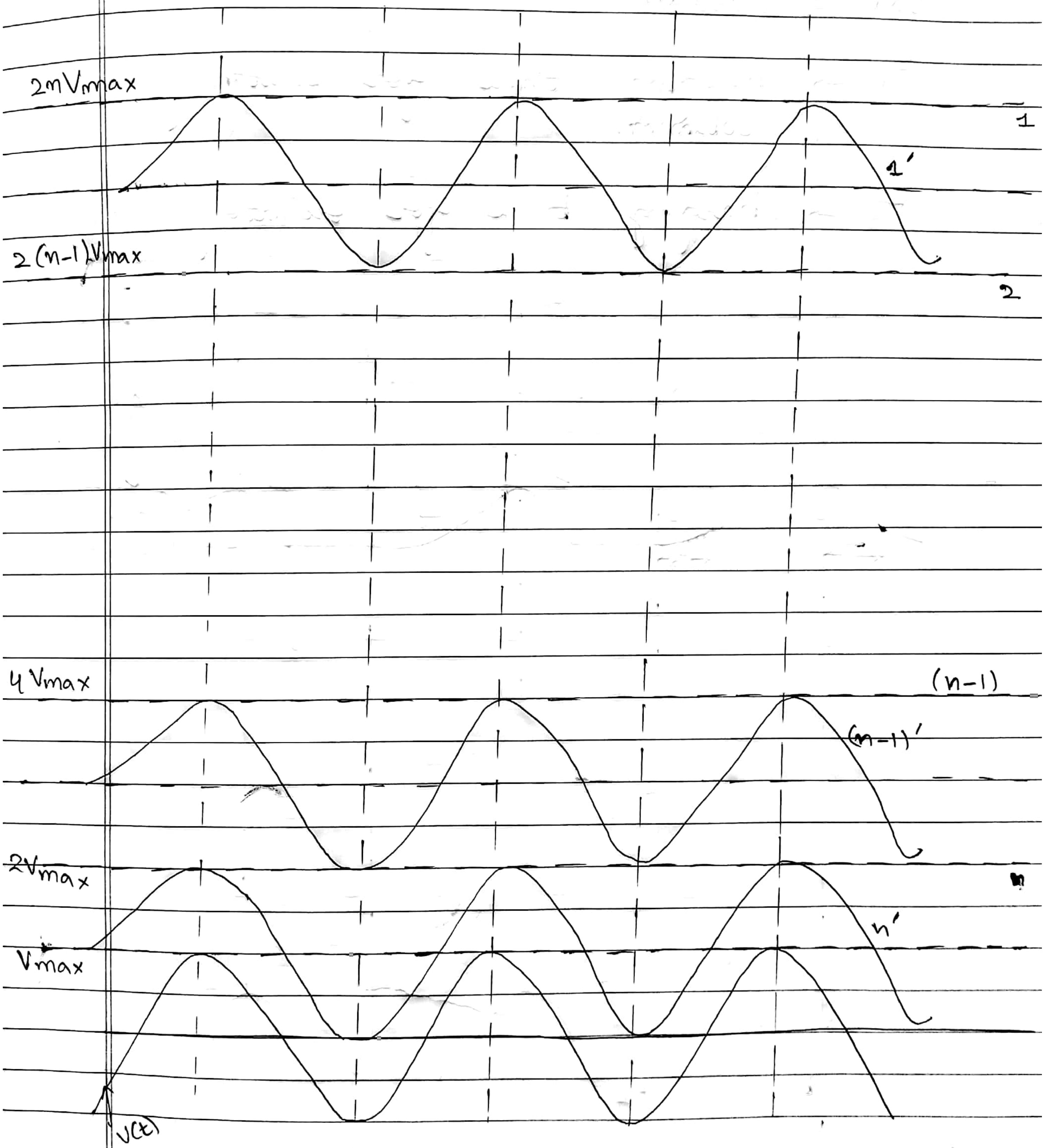
But still we donot get very high voltages.

Cockcroft - Walton Voltage Multiplier Circuit



Circuit observations (For the unloaded circuit)

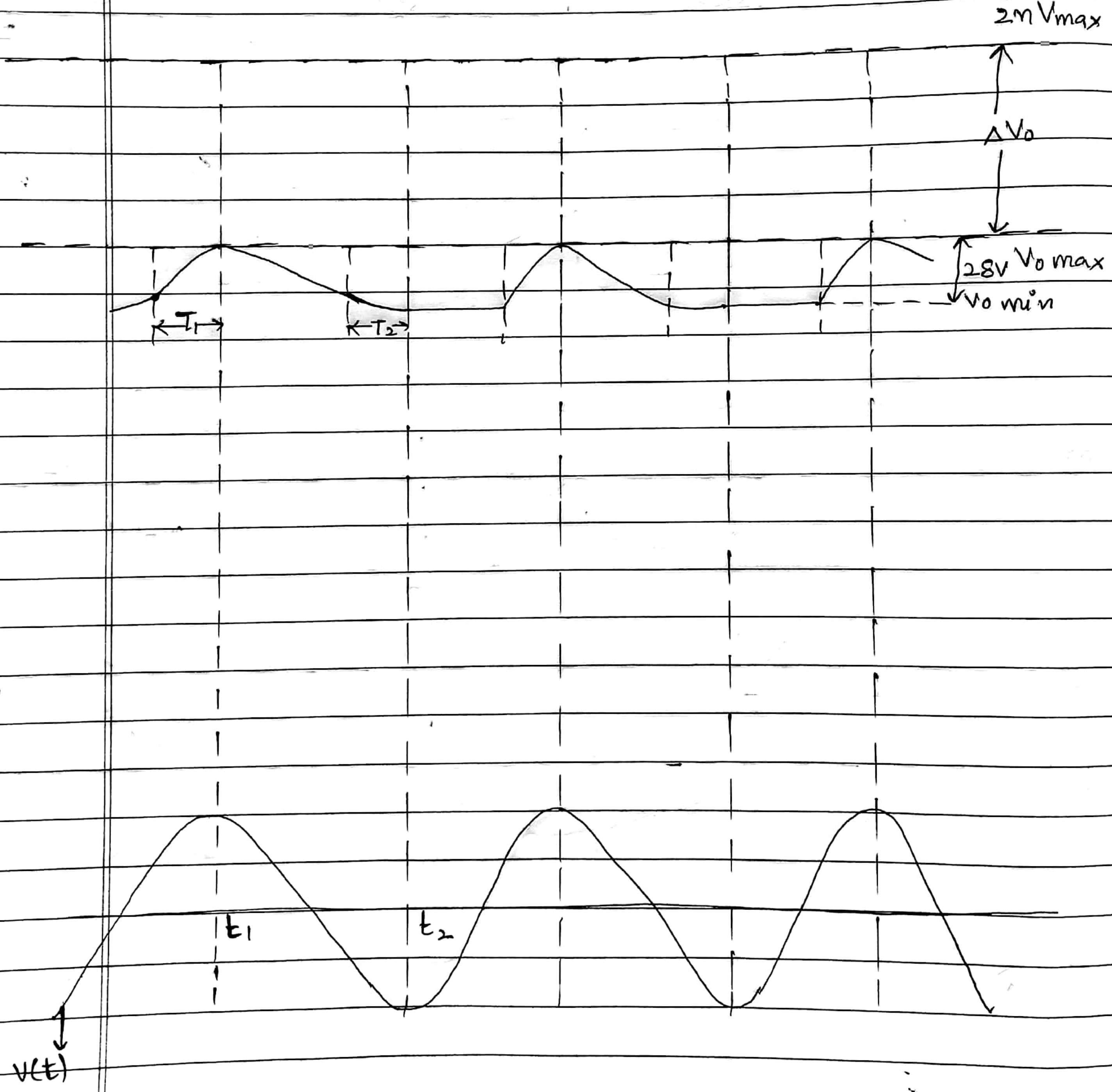
1. Voltage across all the Capacitors are of dc type with a magnitude '$2V_{max}$' across each Capacitor except C_n' across which the Voltage is 'V_{max}'.
2. The potential at nodes $1', 2', \ldots n'$ are oscillatory due to the voltage oscillations of $V(t)$.
3. The potential at nodes $1, 2, \ldots, n$ remain Constant w.r.t ground.
4. Every diode rectifier $D_1, D_1', D_2, D_2', \ldots, D_n, D_n'$ is stressed to a voltage '$2V_{max}$'
5. The output voltage will reach a maximum value of '$2nV_{max}$'.


2nVmax
1
1'
2(n-1)Vmax
2
4Vmax
(n-1)
(n-1)'
2Vmax
n
n'
Vmax
v(t)

Loaded Circuit

T_1 → charging time for smoothing column.

T_2 → charging time for oscillatory column.



Ripple Voltage

There is ripple present in the output voltage ripple is because of discharging of smoothing column.

Charge transfer associated with each Capacitor per cycle is shown in the figure.

If q is charge transferred to load per cycle.

$$\therefore 2(\delta V) = \frac{q}{C_1} + \frac{2q}{C_2} + \frac{3q}{C_3} + \cdots\cdots + \frac{nq}{C_n}$$

$$2(\delta V) = q\left[\frac{1}{C_1} + \frac{2}{C_2} + \frac{3}{C_3} + \cdots\cdots + \frac{n}{C_n}\right]$$

lower Capacitors are more responsible for Causing more ripple.

In order to reduce the ripple Voltage & to make a Convenient design.

$C_1 = C_2 = C_3 = \cdots\cdots = C_n = C.$

$$2(\delta V) = \frac{q}{C}\left[1 + 2 + 3 + \cdots\cdots + n\right].$$

$$2\,\delta V = \frac{q}{C}\,\frac{n(n+1)}{2}$$

$$\delta V = \frac{q}{4C}\,n(n+1) \quad \text{— ①}$$

$$\text{or} \quad \boxed{\delta V = \frac{I}{4fC}\,n(n+1)} \quad \text{— ②}$$

Voltage Drop

The output Voltage Cannot reach '$2nV_{max}$', therefore there is voltage drop.

Maximum voltage to which the Capacitor is charged

$$(V_{cn})_{max} = 2V_{max} - \frac{nq}{C_n'} \quad \text{— ③}$$

Voltage drop of Ist stage

$$\Delta V_n = \frac{nq}{C_n'} \quad \text{— ④}$$

$$(V_{cn-1}')_{max} = (V_{cn})_{max} - \frac{nq}{C_n}$$

$$(V_{cn-1}')_{max} = 2V_{max} - \frac{nq}{C_n'} - \frac{nq}{C_n} \quad \text{— ⑤}$$

$$(V_{cn-1})_{max} = (V_{cn-1}')_{max} - \frac{(n-1)q}{C_{n-1}'}$$

$$(V_{cn-1})_{max} = 2V_{max} - \frac{nq}{C_n'} - \frac{nq}{C_n} - \frac{(n-1)q}{C_{n-1}'} \quad \text{— ⑥}$$

$$\Delta V_{n-1} = \frac{nq}{C_n'} + \frac{nq}{C_n} + \frac{(n-1)q}{C_{n-1}'} \quad \text{— ⑦}$$

$$C_1' = C_2' = \dots = C_n' = C.$$

$$\therefore \Delta V_n = \frac{nq}{C} \quad \text{— ⑧}$$

$$\Delta V_{n-1} = \frac{2nq}{c} + \frac{(n-1)q}{c} \quad ⑨$$

$$\Delta V_{n-2} = \frac{2nq}{c} + \frac{2(n-1)q}{c} + \frac{(n-2)q}{c}$$

$$\vdots$$

$$\Delta' V_1 = \frac{2nq}{c} + \frac{2(n-1)q}{c} + \cdots + 2 \times \frac{2q}{c} + \frac{q}{c}$$

or $\Delta V_n = \frac{q}{c} n$

$$\Delta V_{n-1} = \frac{q}{c} \{2n + (n-1)\}$$

$$\Delta V_{n-2} = \frac{q}{c} \{2n + 2(n-1) + (n-2)\}$$

$$\vdots$$

$$\Delta V_1 = \frac{q}{c} \{2n + 2(n-1) + 2(n-2) + \cdots + 2 \times 2 + 1\}$$

$$\Delta V_0 = \Delta V_n + \Delta V_{n-1} + \cdots + \Delta V_1$$

$$\Delta V_0 = \frac{q}{c} \left\{ \frac{2n^3}{3} + \frac{n^2}{2} - \frac{n}{6} \right\}$$

$$\Delta V_0 = \frac{I}{fc} \left\{ \frac{2n^3}{3} + \frac{n^2}{2} - \frac{n}{6} \right\}$$

If $C_n' = 2C$

$$\Rightarrow \Delta V_n = \frac{q}{2C} n$$

$$\Delta V_0 = \frac{I}{fc} \left\{ \frac{2n^3}{3} + \frac{n^2}{2} - \frac{n}{6} \right\} - \frac{I}{2fc} n^2$$

$$\Rightarrow \Delta V_0 = \frac{I}{fc}\left\{\frac{2n^3}{3} - \frac{n}{6}\right\}$$

for $n > 3$; 2nd term can be neglected.

$$\Delta V_0 = \frac{I}{fc} \cdot \frac{2n^3}{3}$$

since $\Delta V_0 = 2nV_{max} - V_{0,max}$

$$\Rightarrow \boxed{V_{0,max} = 2nV_{max} - \frac{I}{fc}\frac{2n^3}{3}}$$

For maximum output voltage.

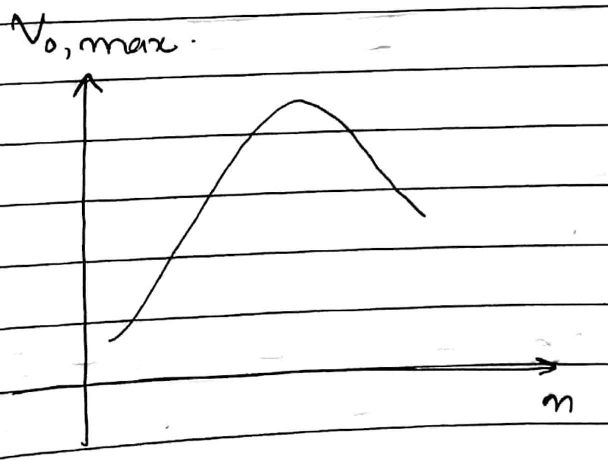
$$\frac{d}{dn}V_{0,max} = 0$$

$$2V_{max} - \frac{I}{fc} \cdot \frac{6n^2}{3} = 0$$

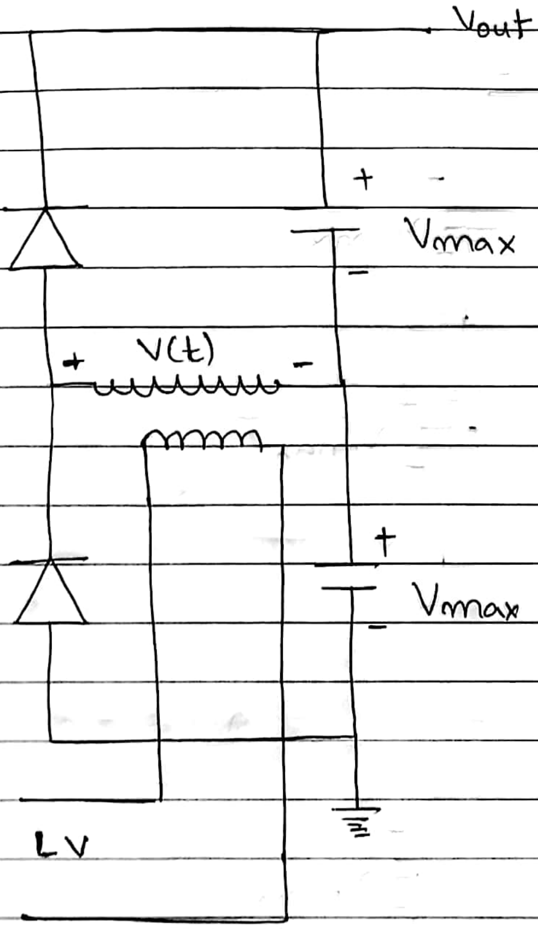
$$\frac{I}{fc}n^2 = V_{max}$$

$$\boxed{n = \sqrt{\frac{fc\,V_{max}}{I}}}$$

maximum no. of stages for which we get maximum output voltage.



Voltage Doubler Circuit



Voltage Multiplier Circuits with Cascaded Transformers