# 1 Safety

## 1.1 Hazard

Anything that can cause potential harm to you and to others.

## 1.2 Risk Level

Product of the likelihood and the severity of a hazard.

## 1.3 Safe Work Procedures

Derived from the safety and risk assessment process.

## 1.4 Hierarchy of Control

| | | |
|---|---|---|
| Elimination | Physical removal of the hazard. | Remove the dangling cable |
| Substitution | Replacing something with a with a less hazardous one. | Replace glassware to plastic ware. |
| Engineering Controls | Prevent hazard from coming into contact with people. | Fume cupboards, smoke absorbers, electrical conduits, safety guards. |
| Administrative Controls | Change the way people work. | Changes in procedure, standard operating procedures, employee training, installation of signs and warnings, inspections, and maintenance of equipment. |
| Personal Protective Equipment (PPE) | Equipment worn by worker to provide protection. | Gloves, safety goggles, laboratory coats, respirators. |

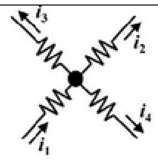
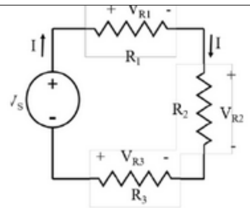
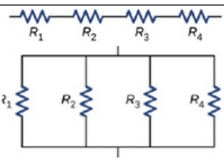
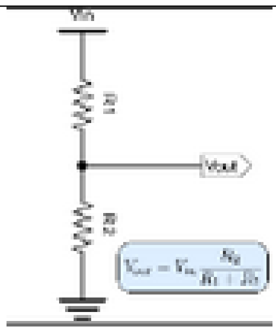
## 1.5 Electrical Safety

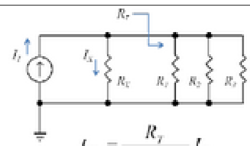
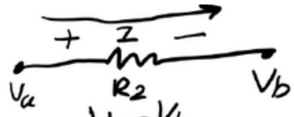
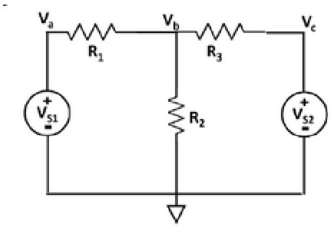
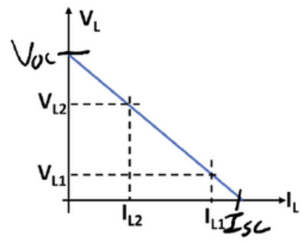
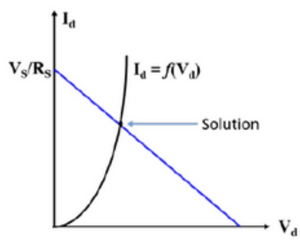
| | |
|---|---|
| 1 mA | Human can feel current |
| 5 to 10 mA | • Electrical shock and loses control of muscles<br>• Circuit cannot be broken as live object cannot be let go |

| | |
|---|---|
| 10 to 50 mA | • Human muscles fibrillate<br>• Pain<br>• Difficulty in breathing |
| More than 50 mA | • Fatal<br>• Ventricular fibrillation in heart<br>• Burns to skin and internal organs |

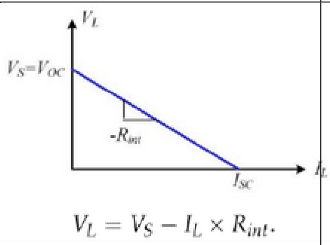
- Internal resistance to electricity of human body is 300 to 1000 ohms
- Voltages as low as 30 V is hazardous

# 2 Circuit Analysis Method

| | | |
|---|---|---|
| Kirchoff's Current Law | Sum of all currents entering the node must be equal to the sum of all currents leaving the node (or super node) |  $-i_1 + i_2 + i_3 + i_4 = 0.$ |
| Kirchoff's Voltage Law | Around any closed loop, at any instant of time, the sum of the voltage drops must equal to the sum of voltage rises. |  $V_S - V_{R1} - V_{R2} - V_{R3} = 0.$ |
| Equivalent Resistance | • Resistors in series<br>• Resistors in parallel |  |
| Branch current method | • Assume direction of current<br>• Apply KCL<br>• Apply KVL | |
| Voltage divider |  | $V_i = V_s \cdot \frac{R_i}{\Sigma_{i=1}^{N} R_i}$ |

| | | |
|---|---|---|
| Current divider |  $I_X = \frac{R_T}{R_X + R_T} I_T$ | $I_i = \frac{\frac{1}{R_i}}{\Sigma_{i=1}^{N} \frac{1}{R_i}}$ |
| Node voltage analysis method | • Set reference node (usually the ground)<br>• Label all node voltage<br>• Apply KCL<br>• Express current using Ohm's Law<br>• Use super-node if possible |  $I = \frac{V_a - V_b}{R_2}$ |
| Superposition Principle | In a linear circuit with a number of independent sources, the response can be found by summing the responses to each independent source acting alone, with all other independent sources set to zero. Replace voltage sources with a short circuit and current sources with an open circuit. |  $V_{b,1} = \frac{G_1}{(G_1+G_2+G_3)} V_{S1}; \quad V_{S2} = 0,$<br>$V_{b,2} = \frac{G_3}{(G_1+G_2+G_3)} V_{S2}; \quad V_{S1} = 0,$<br>$V_b = V_{b,1} + V_{b,2}.$ |
| Thevenin's Method | 1. Find open circuit voltage<br>2. Find short circuit current<br>3. Find $R_{th}$ by killing all independent sources and finding equivalent resistance seen between the terminals (be wary of any short circuits in parallel) | $V_{th} = V_{oc}, I_{sc} = \frac{V_{th}}{R_{th}}, R_{th} =$  $\frac{V_{th}}{I_{sc}}$ |
| Load Line Analysis | • The load line is the I-V characteristic of the source network found by using Thevenin's Equivalent<br>• By super positioning this graph with the I-V characteristic of the load, the intercept is the solution |  |

# 3 Battery Specifications

| Parameters | Description | Single Battery | In a battery pack of nSmP |
|---|---|---|---|
| Voltage rating | Specified voltage available between terminals without load connected | $V_{oc}$ | $nV_{oc}$ |
| Energy/Watthour rating | Watthour = Terminal Voltage x Capacity | Wh | n x m x Wh |
| Internal resistance |  | $R_{int}$ | $\frac{n}{m}R_{int}$ |
| C-rating | Maximum safe current drawn. Safe current = Capacity x C rate. Ah = Safe current x 1/C rate. nC => fully discharged in 1/n hour | C | C |
| Safe Current | Safe current = Capacity x C rate | $I_{safe}$ | $m \cdot I_{safe}$ |

**Battery Sizing**

| | |
|---|---|
| Minimum number of cells required | $N_{min} = \frac{E_{demand}}{E_{cell}}$ |
| Number of cells in series | $N_s = \frac{V_{op}}{V_{cell}}$ |
| Number of parallel strings | $N_p = \frac{N_{min}}{N_s}$ |
| Maximum battery pack power | $P_{max} = V_{op}I_{safe}N_p$ |
| If $N_p$ does not meet the power demand of the load, add extra parallel strings. Adding extra parallel strings will increase the power output, without affecting $V_{op}$ | |

# 4 Solar PV Cell

## 4.1 Peak Sun Hour (PSH)

Number of hours needed to get the same amount of energy if the irradiance would remain constant at 1000 $W/m^2$. PSH is 4.56 hours in Singapore.

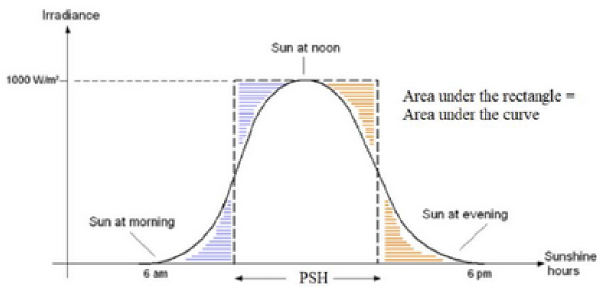



Figure 1: Peak Sun Hour

## 4.2 Energy Harvested Daily

$$E_{harvest} = \eta_{sys}\eta_{PV}\frac{1kW}{m^2}(PSH)A_{PV}$$

$\eta_{PV}$: between 10% to 25%

$\eta_{sys}$: takes account of power losses due to inverter, battery, and battery charger.

## 4.3 Watt-peak rating

Power panel produces under standard test conditions.

Maximum electrical output of the panel with input irradiance of $\frac{kW}{m^2}$.

$$W_p = \eta_{PV}\frac{kW}{m^2}A_{PV}$$

### PV cell characteristics

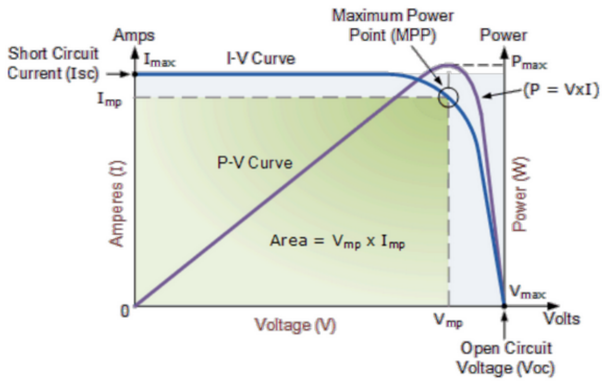



Figure 2: Maximum Power Point

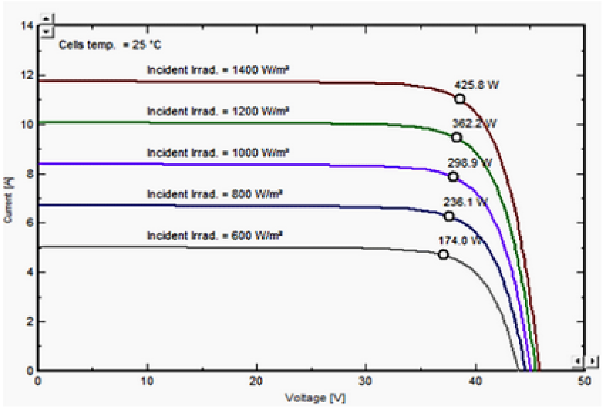



Figure 3: Different Watts, Different Whats?

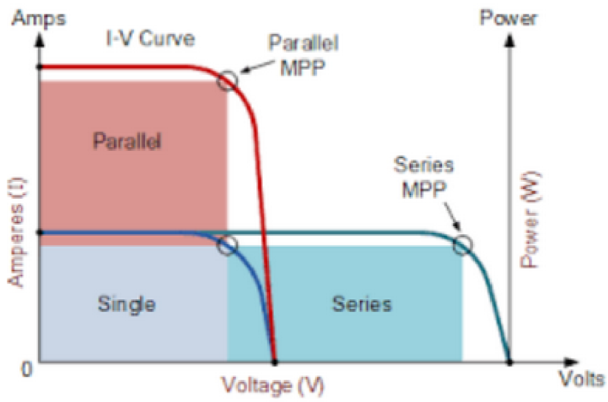



Figure 4: Series or Parallel?

## PV Sizing

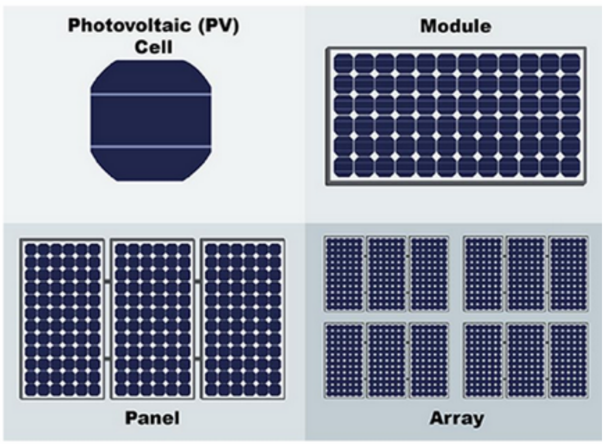



Figure 5: Cell, Module, Panel, Array

## 4.4 Power required

Find energy demand. Find PSH of location

$$P_{user} = \frac{E_{req}}{PSH}$$

## 4.5 Output power of the array

Output of PV system ¿ $P_{req}$

$$P_{array} = \frac{P_{user}}{\eta_{sys}}$$

$\eta_{sys}$: 75%-80%

## 4.6 Number of panels required

$$N = \frac{P_{array}}{P_{panel}}$$

## 4.7 Number of cells in series

$$N_s = \frac{V_{out}}{V_{mp,panel}}$$

## 4.8 Number of parallel branches

$$N_p = \frac{N}{N_s}$$

# 5 Energy and Power Demand

## 5.1 Power consumption

Energy consumption = Power demand x Duration of operation

- Duration of operation of an appliance is not always on
- Power demand of an appliance varies over time depending on the task done

## 5.2 Load curve/Load demand graph

- Graph of load (power) variation against time
- Time scale divided into equal intervals
- Power assumed constant in each interval
- Area under graph = total energy consumed

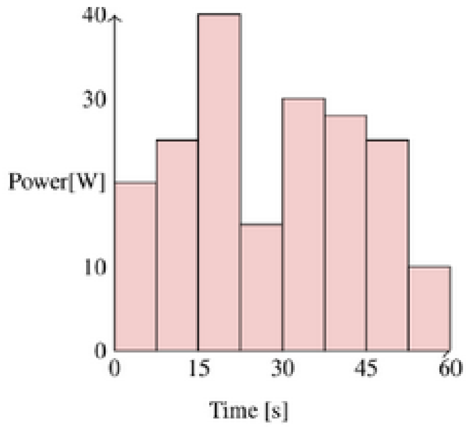



Figure 6: Load Curve

### 5.3 Load profile/ Load duration curve

- Shows how much load demand is required by time

How to get the load duration curve?

- Divide y-axis (Power) in certain number of steps
- Find time duration for each step
- Stack the powers starting with the lowest value and the longest time duration
- Top most block will have the highest power for shortest duration
- Area under plot = total energy consumed

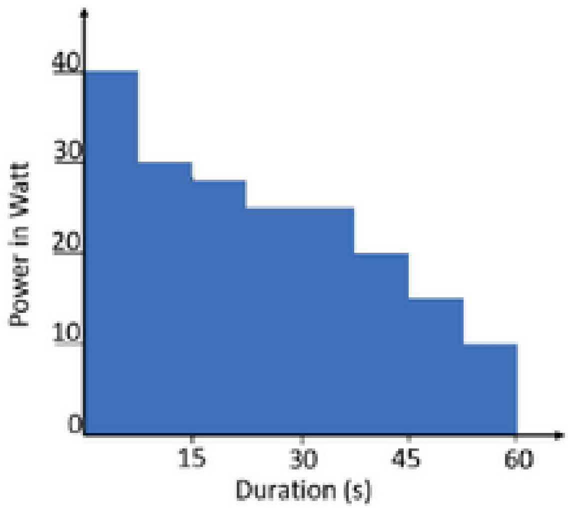
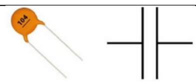
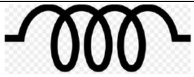
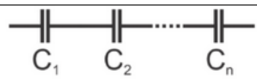
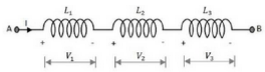
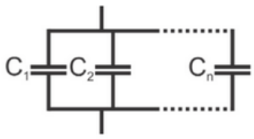
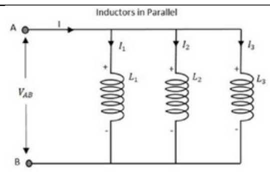
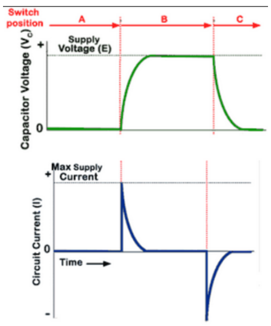
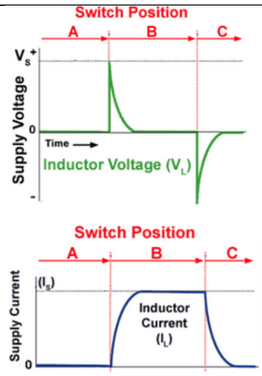



Figure 7: Load Profile

# 6 First Order Systems

| Aspect | Capacitor | Inductor |
|---|---|---|

| | | |
|---|---|---|
| Symbol |  |  |
| Introduction | Separating two sheets of conductors using a thin layer of insulating material | A wire made into a coil. |
| Property | V is proportional to q, and $C = \frac{q}{V}$ | $\phi$ (flux) is proportional to $i$) and hence $V_L = \frac{d\phi}{dt} = L\frac{di}{dt}$ |
| Voltage-current relation | $i = C\frac{dV}{dt}$ | $V_L = L\frac{di}{dt}$ |
| DC steady state | Capacitor acts as open circuit, and its voltage cannot change abruptly. | Inductor acts as short circuit, and its current cannot change abruptly. |
| Energy stored | $\frac{1}{2}CV^2$ | $\frac{1}{2}LI^2$ |
| Charging | At time t=0, $V_c(0^-) = V_c(0^+) = 0$, $i_c(0^-) = 0$, $i_c(0^+) = \frac{V_s}{R}$. As t¿0, $V_c(t) = V_0e^{-\frac{t}{\tau}} + V_s(1-e^{-\frac{t}{\tau}})$, with $V_0$ the initial capacitor's voltage, and $V_s$ the source voltage, which is better defined to be $V_{th}$ | At time t=0, $V_L(0^-) = 0, V_L(0^+) = V$, $i_L(0^-) = i_L(0^+) = 0$. As t¿0, $i_L(t) = I_0e^{-\frac{t}{\tau}} + I_{ss}(1-e^{-\frac{t}{\tau}})$, with $I_0$ the initial inductor current, and $I_{ss}$ the steady state current of the inductor. |
| Time constant | $\tau = RC$ At $t = 5\tau$, the system is at steady state. | $\tau = \frac{L}{R}$ At $t = 5\tau$, the system is at steady state. |
| In series |  $\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \cdots + \frac{1}{C_n}$. |  $L_{eq} = L_1 + L_2 + L_3$. |
| In parallel |  $C_{eq} = C_1 + C_2 + \cdots + C_n$. |  $\frac{1}{L_{eq}} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3}$. |
| Graph |  |  |

# 7 Oscillations in Electrical Systems

## 7.1 No Dampers

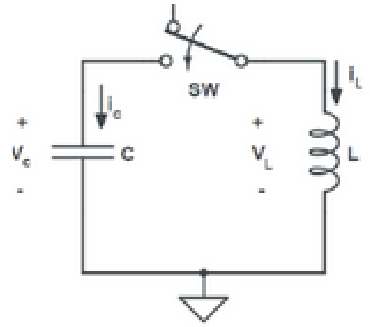



Figure 8: LC Circuit

If $V_c(0) = V_0$ and $i_c(0) = 0, i_L = 0$, then $V_L = 0$, and $i_L(0^+) = -i_C(0^+) = 0$ for $t < 0$.

$$\frac{d^2V_C}{dt^2} + \frac{1}{LC}V_C = 0$$

Thus,

$$V_C(t) = V_0\cos(\omega_n t)$$

with natural frequency

$$\omega_n = \frac{1}{\sqrt{LC}}$$

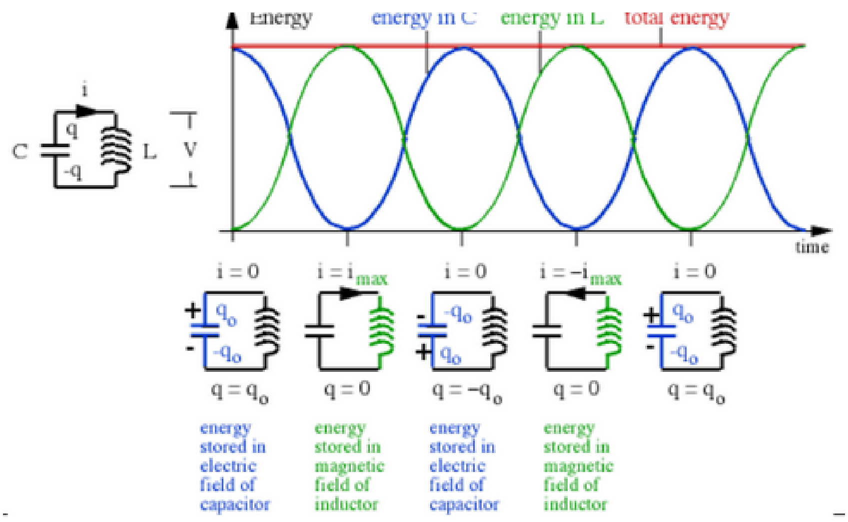



Figure 9: LC Time Evolution

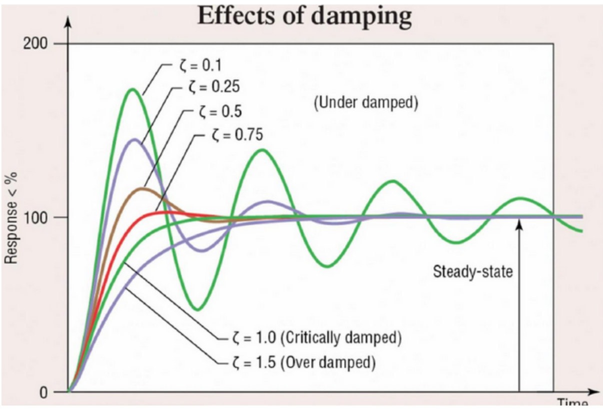



Figure 10: Different Profiles for Different Values of $\zeta$

## 7.2 Damped oscillation without voltage source

$V_C = V_0, i_C(0) = 0, i_L(0) = 0$

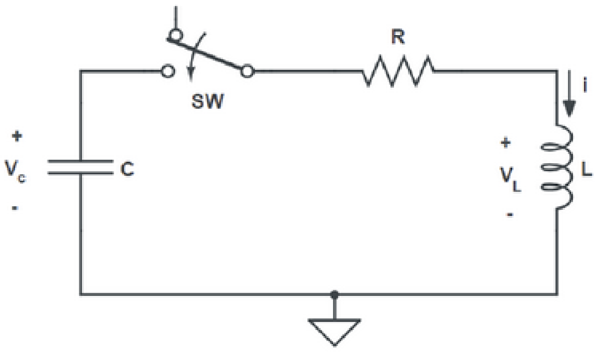



Figure 11: RLC without Voltage Source

$$V_C - RI - L\frac{di}{dt} = 0$$

$$\frac{d^2V_C}{dt^2} + \frac{R}{L}\frac{dV_C}{dt} + \frac{1}{LC}V_C = 0$$

$$\frac{d^2V_C}{dt^2} + 2\zeta\omega_n\frac{dV_C}{dt} + \omega_n^2 V_C = 0$$

Damping coefficient

$$\zeta = \frac{R}{2L\omega_n} = \frac{R\sqrt{LC}}{2L} = \frac{R}{2}\sqrt{\frac{C}{L}}$$

Damped frequency

$$\omega_d = \omega_n\sqrt{1-\zeta^2}$$

## 7.3 Underdamped response

$0 < \zeta < 1$,

$$V_C(t) = \frac{V_0}{\sqrt{1-\zeta^2}}e^{-\zeta\omega_n t}\cos(\omega_d t - \theta),$$

$$\theta = \tan(\frac{\zeta}{\sqrt{1-\zeta^2}})$$

## 7.4 Critically damped response

$\zeta = 1$,

$$V_C(t) = V_0 e^{-\zeta\omega_n t}(1 + \zeta\omega_n t)$$

## 7.5 Overdamped response

$\zeta > 1$,

$$V_C(t) = Ae^{-\lambda_1 t} + Be^{-\lambda_2 t}$$
$$\lambda_1 = -\zeta\omega_n + \omega_n\sqrt{\zeta^2 - 1}$$
$$\lambda_2 = -\zeta\omega_n - \omega_n\sqrt{\zeta^2 - 1}$$

## 7.6 Damped oscillation with voltage source

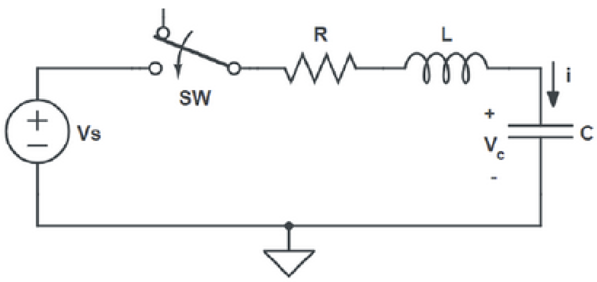



Figure 12: RLC with Voltage Source

$V_C(0) = 0$, $i(0) = 0$

$$V_R + V_L + V_C = V_s$$
$$Ri + L\frac{di}{dt} + V_C = V_s$$
$$\frac{d^2V_C}{dt^2} + \frac{R}{L}\frac{dV_C}{dt} + \frac{1}{LC}V_C = \frac{1}{LC}V_s$$
$$\frac{d^2V_C}{dt^2} + 2\zeta\omega_n\frac{dV_C}{dt} + \omega_n^2 V_C = \frac{1}{LC}V_s$$
$$V_C(t) = V_{C,t} + V_{C,ss}$$

1. $V_{C,ss}$ represents the steady state response, and
2. $V_{C,t}$ is the solution of the homogeneous ODE

$$\frac{d^2V_C}{dt^2} + 2\zeta\omega_n\frac{dV_C}{dt} + \omega_n^2 V_C = 0$$

, that describes the nature of the oscillatory response.

## 7.7 Steady state response

$$\frac{1}{V_C}V_{C,ss} = \frac{1}{LC}V_S \to V_{C,ss} = V_s$$

## 7.8 Complete response

### 7.8.1 Underdamped

$$V_C(t) = V_s - V_s\frac{\omega_n}{\omega_d}e^{-\zeta\omega_n t}\cos(\omega_d t - \theta)$$

$$\theta = \arctan\frac{\zeta}{\sqrt{1-\zeta^2}}$$

### 7.8.2 Critical

$$V_C(t) = K_1 e^{-\zeta\omega_n t} + K_2 e^{-\zeta\omega_n t} + V_s$$

### 7.8.3 Overdamped

$$V_C(t) = Ae^{-\lambda_1 t} + Be^{-\lambda_2 t}$$
$$\lambda_1 = -\zeta\omega_n + \omega_n\sqrt{\zeta^2 - 1}$$
$$\lambda_2 = -\zeta\omega_n - \omega_n\sqrt{\zeta^2 - 1}$$

# 8 DC-DC Converter

## 8.1 PWM

PWM signal is a repetitive pulse train, alternating between HIGH and LOW. The switch will be turned ON when the PWM signal is at HIGH state. The duration for which the switch is ON is called on-time $t_{on}$. The remaining time in one switching period is known as off-time $t_{off}$. This process is repeated every $T_s$ (switching time period), where $T_s = t_{on} + t_{off}$. The ratio of on-time $t_{on}$ to switching time period $T_s$ is known as duty cycle, D:

$$D = \frac{t_{on}}{T_s} \Rightarrow t_{on} = DT_s$$

The duty cycle, D can be varied from zero to one i.e. $0 < D < 1$.

## 8.2 Output Voltage

$$V_0 = V_i\frac{1}{1-D}$$

## 8.3 Sizing of inductor and capacitor

The inductor and capacitor being energy storage devices act as energy buffers during the switching. They smoothen the current and voltage in the converter. The current ripple and voltage ripple will be small when larger inductors and capacitors are used.

Input current ripple is inversely proportional to the inductor value $L$. We can reduce the input current ripple by having a large inductor. Alternatively, we can reduce the input current ripple by having a switching at high frequency.

Output voltage ripple is inversely proportional to the capacitor value $C$. We can reduce the output voltage ripple by having a large capacitor. Alternatively, we can reduce the ripple by having a high switching frequency.

However, a higher switching frequency leads to higher power loss. Hence, there is a trade-off between the size of the inductor/capacitor and that of the heat sink.

# THE END