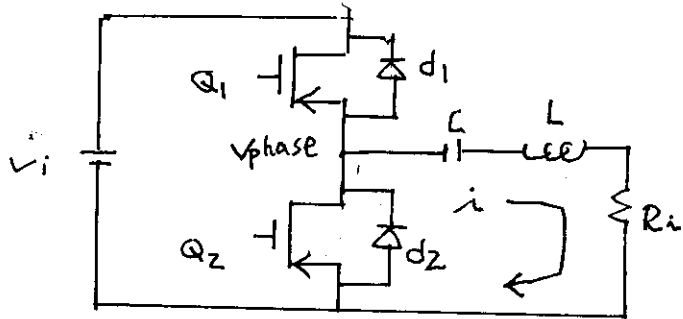


Boundary condition of ZCS & ZVS PI

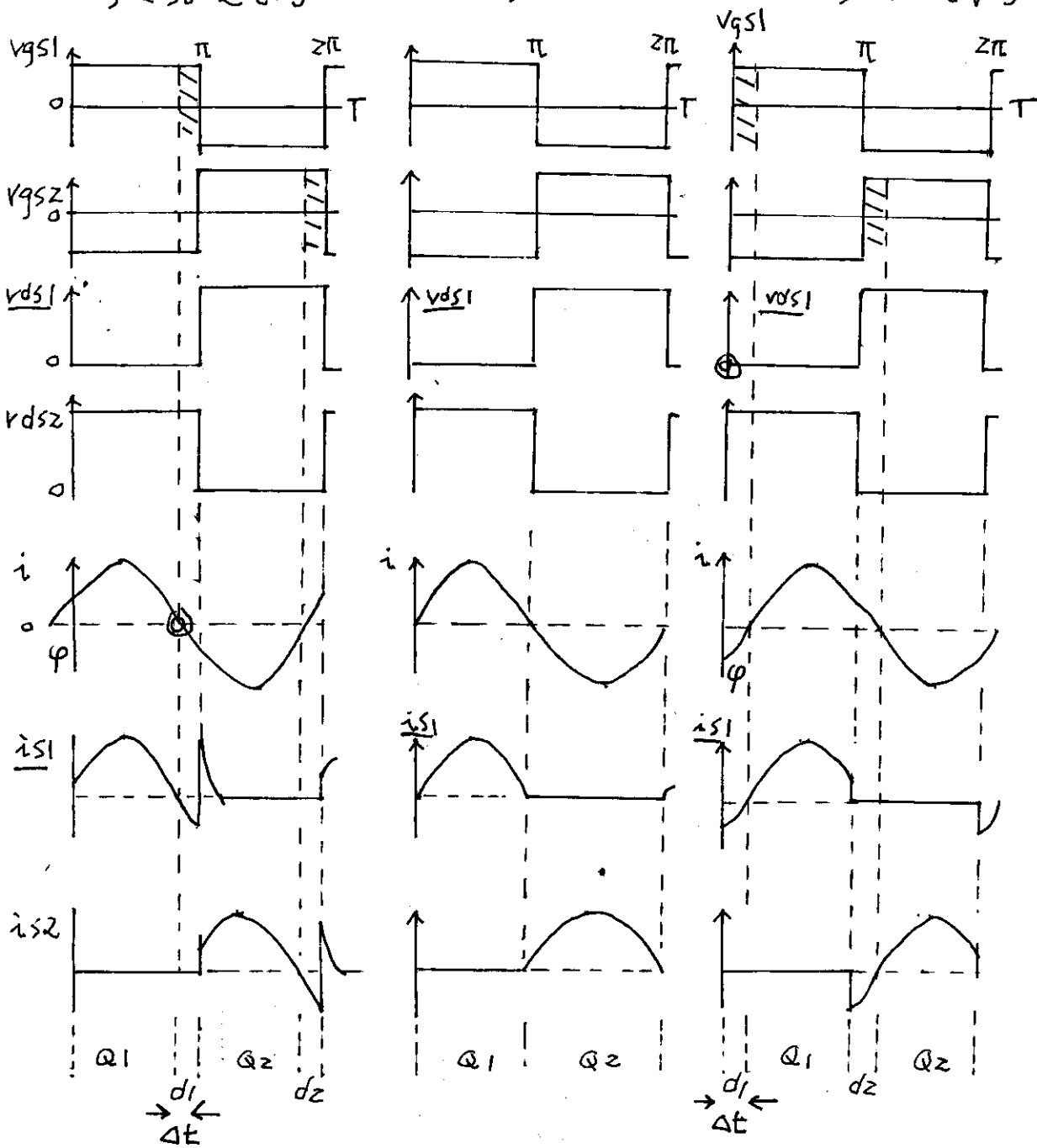


#1.

$f < f_0$ Z.C.S

$f = f_0$

$f > f_0$ Z.V.S



#2.

P2
1

We define $\omega_0 = \frac{1}{\sqrt{LC}}$

$$Z_0 = \sqrt{\frac{L}{C}} = \omega_0 L = \frac{1}{\omega_0 C}$$

• Loaded quality

$$Q_L = \frac{Z_0}{R} = \frac{\omega_0 L}{R} = \frac{1}{\omega_0 C R} = \sqrt{\frac{L}{C}} / R$$

• unloaded quality

$$Q_0 = \frac{Z_0}{r} = \frac{\omega_0 L}{r} = \frac{1}{\omega_0 C r}$$

where $r = r_{ds} + r_L + r_C$

$$R = R_i + r$$

說明

1. 當 $f = f_0$ 時, V_{phase} 看出去 Load 為 Resistive Load
i in-phase v_{ds1} , \therefore 沒有相位移.
2. 當 $f < f_0$ 時, V_{phase} 看出去 Capacitive Load, i Lead
 v_{ds1} , $\phi < 0$, 在 $T = \pi - \Delta t$ 之前 Δt 時, 此時不論 v_{gs1} 的
Level 如何, $i = 0$, 這即是 Z.C.S. 由 next stage 為 Q_2
turn on $\therefore di/dt$ 的 recovery time 會造成很大的
current-spike. [v_{ds} 尚未 turn-off, I_{ds} 已經為 0]
3. 當 $f > f_0$ 時, V_{phase} 看出去為 inductive load,
i Lag v_{ds1} , $\phi > 0$, 在 $T = 0 \sim \Delta t$ 時, 不論 v_{gs1}
的 level 如何, v_{ds1} 被 di by pass 為 0,
這是 Z.V.S. [I_{ds} 尚未 turn-on, v_{ds} 已經為 0]

CLL Resonant converter

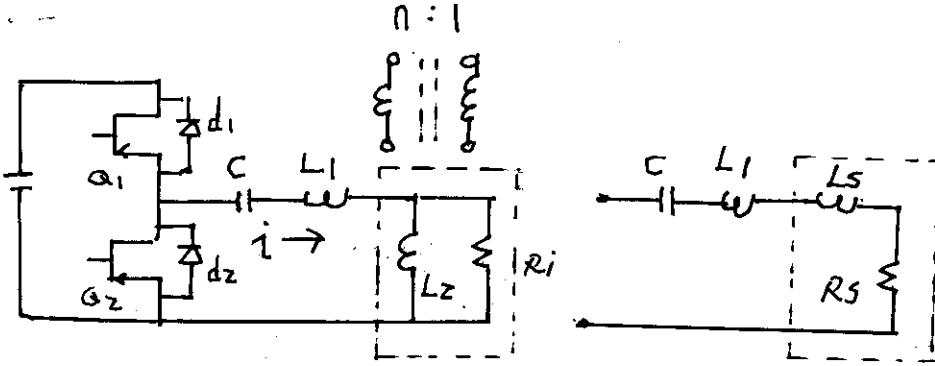


Fig 1.

Fig 2

#3. Boundary condition Between Capacitive Load & Inductive Load

① We define:

$$A = \frac{L_1}{L_2} \sim \textcircled{1}$$

$$L = L_1 + L_2 = L_2(1+A) = L_1\left(1 + \frac{1}{A}\right) \sim \textcircled{2}$$

corner frequency [undamped natural frequency]

$$\omega_0 = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{(L_1+L_2)C}} \sim \textcircled{3}$$

$$Z_0 = \omega_0 L = \frac{1}{\omega_0 C} = \sqrt{\frac{L}{C}} \sim \textcircled{4}$$

Loaded quality at ω_0

$$Q_L = \frac{R_i}{Z_0} = \frac{R_i}{\omega_0 L} = \omega_0 C R_i \sim \textcircled{5}$$

由②式的 $L_2 = \frac{L}{1+A}$ ⑤式的 $L = \frac{R_i}{\omega_0 Q_L}$

合併 $L_2 = \frac{R_i}{(1+A)\omega_0 Q_L} \sim \textcircled{6}$

② Fig 2 为 Fig 1 的串联等效电路

$$L_{eq} = L_1 + L_s \sim \textcircled{7}$$

Resonant frequency

$$\omega_r = \frac{1}{\sqrt{L_{eq} C}} = \frac{1}{\sqrt{(L_1 + L_2) C}} \sim (8)$$

Loaded quality factor at ω_r

$$Q_r = \frac{\omega_r (L_1 + L_2)}{R_S} = \frac{1}{\omega_r C R_S} \sim (9)$$

Note: 由串联共振可知，Capacitive load 或 inductive load 其 boundary 条件由 ω_r 决定之。

① 求 input impedance

由 Fig 1 知道

$$\begin{aligned} Z &= j\omega A L_2 + \frac{1}{j\omega C} + \frac{R_i j\omega L_2}{R_i + j\omega L_2} \\ &= \frac{j\omega A L_2 [j\omega C (R_i + j\omega L_2)] + [R_i + j\omega L_2] + R_i j\omega L_2 j\omega C}{j\omega C [R_i + j\omega L_2]} \\ &= \frac{[-\omega^2 A L_2 C R_i - \omega^2 L_2 C R_i + R_i] + [j\omega L_2 - j\omega^3 A L_2^2 C]}{j\omega C R_i - \omega^2 L_2 C} \\ &\quad \text{分子及分母同乘 } -\omega^2 L_2 C \\ &= \frac{[A R_i + R_i - \frac{R_i}{\omega^2 L_2 C}] + [j\omega A L_2 - j\frac{1}{\omega C}]}{1 - j\frac{R_i}{\omega L_2}} \sim (10) \end{aligned}$$

Recall $L_2 = \frac{R_i}{(1+A)\omega_0 Q_L}$; $C = \frac{Q_L}{\omega_0 R_i}$; $L_2 = \frac{L}{1+A}$

$\omega_0 = \frac{1}{\sqrt{LC}}$ 代入 (10) 式中
 Δ , Δ , Δ 式之中

由 Δ 式

$$R_i(1+A) - \frac{R_i(1+A)}{\omega^2 LC} = R_i(1+A) \left[1 - \left(\frac{\omega_0}{\omega} \right)^2 \right]$$

由 Δ 式

$$j R_i \frac{\omega}{\omega_0} \frac{A}{(1+A)} \frac{1}{Q_L} - j \frac{\omega_0 R_i}{\omega Q_L} = j \frac{R_i}{Q_L} \left[\frac{\omega}{\omega_0} \frac{A}{(1+A)} - \frac{\omega_0}{\omega} \right]$$

由 Δ 式

$$1 - j \frac{R_i}{\omega} \frac{(1+A)\omega_0 Q_L}{R_i} = 1 - j(1+A) \frac{\omega_0}{\omega} Q_L$$

合併 Δ Δ Δ 式可得

$$Z = \frac{R_i \left\{ (1+A) \left[1 - \left(\frac{\omega_0}{\omega} \right)^2 \right] + j \frac{1}{Q_L} \left[\frac{\omega}{\omega_0} \frac{A}{1+A} - \frac{\omega_0}{\omega} \right] \right\}}{1 - j Q_L (1+A) \frac{\omega_0}{\omega}} \quad \sim (11)$$

$$= Z e^{j\phi} = R_s + jX_s$$

Recall $R_i = Q_L Z_0$

$$\frac{Z}{Z_0} = Q_L \sqrt{\frac{[1+A]^2 \left[1 - \left(\frac{\omega_0}{\omega} \right)^2 \right]^2 + \frac{1}{Q_L^2} \left[\frac{\omega}{\omega_0} \frac{A}{1+A} - \frac{\omega_0}{\omega} \right]^2}{1 + [Q_L(1+A) \frac{\omega_0}{\omega}]^2}} \quad \sim (12)$$

在 (11) 式分子大括号之中乘以 $[1 + j Q_L (1+A) \frac{\omega_0}{\omega}]$ 。分母为实数。

$$(1+A) \left[1 - \left(\frac{\omega_0}{\omega} \right)^2 \right] + j \frac{1}{Q_L} \left[\frac{\omega}{\omega_0} \frac{A}{1+A} - \frac{\omega_0}{\omega} \right] \quad \Delta$$

$$+ \left[j Q_L (1+A) \frac{\omega_0}{\omega} \right] (1+A) \left[1 - \left(\frac{\omega_0}{\omega} \right)^2 \right] - \left[(1+A) \frac{\omega_0}{\omega} \right] \left[\frac{\omega}{\omega_0} \frac{A}{1+A} - \frac{\omega_0}{\omega} \right] \quad \Delta$$

其中 Δ 式又可化简

$$j Q \frac{\omega_0}{\omega} (1+A) \left[1 - \left(\frac{\omega_0}{\omega} \right)^2 \right] - A + \left(\frac{\omega_0}{\omega} \right)^2 (1+A) \quad \Delta$$

将 Δ 式与 Δ 式合併

Imagine part:

$$j \frac{1}{Q_L} \left[\frac{\omega}{\omega_0} \frac{A}{1+A} - \frac{\omega_0}{\omega} \right] + j Q_L \frac{\omega_0}{\omega} [1+A]^2 \left[1 - \left(\frac{\omega_0}{\omega} \right)^2 \right]$$

Real part = 1

$$\text{For } \varphi = \tan^{-1} \left\{ \frac{1}{Q_L} \left(\frac{\omega}{\omega_0} \frac{A}{1+A} - \frac{\omega_0}{\omega} \right) + Q_L \left(\frac{\omega_0}{\omega} \right) (1+A)^2 \left[1 - \left(\frac{\omega_0}{\omega} \right)^2 \right] \right\}$$

(13)

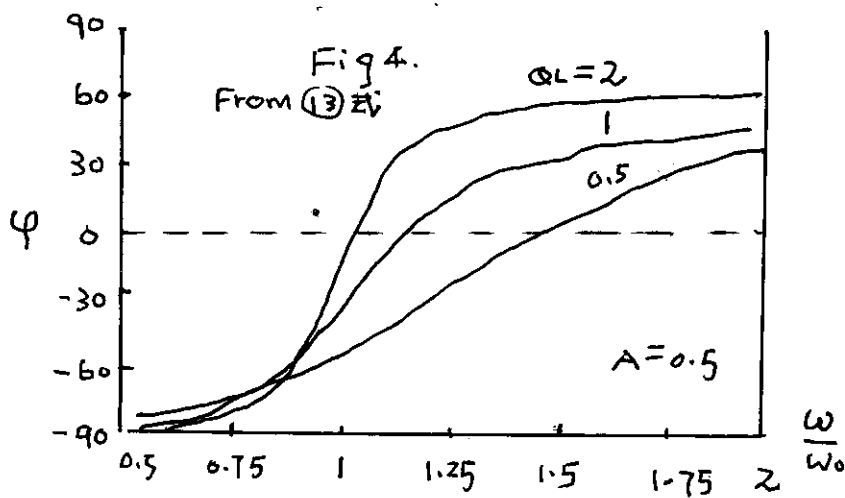
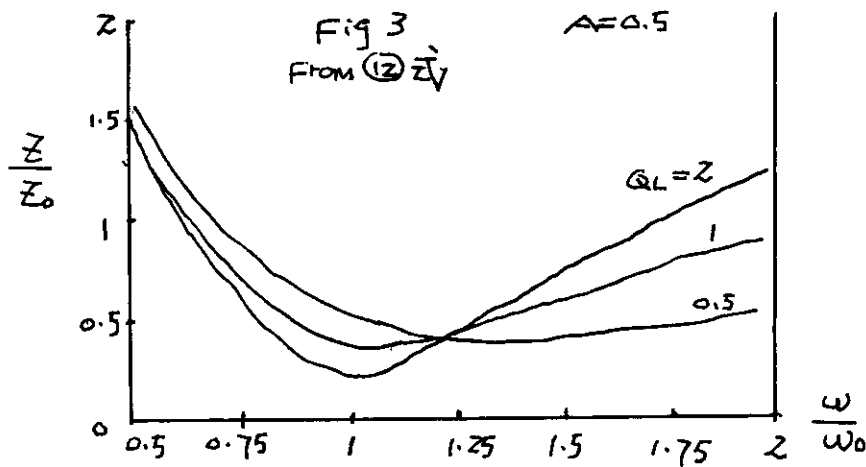
∴ $R_s = Z \cos \varphi$; $X_s = Z \sin \varphi$.

假如 $\omega = \omega_0$ 时

$$\varphi = \tan^{-1} \frac{1}{Q_L} \left(\frac{A}{1+A} - 1 \right) = -\tan^{-1} \frac{1}{Q_L} \left(\frac{1}{1+A} \right) < 0 \quad (14)$$

由 (14) 式说明了 $\omega = \omega_0$ 或 $\omega < \omega_0$ 时

Resonant converter 呈现了 Capacitive load 的特性。



求 Boundary condition 的 ω_r .

由 Fig 4 可知道 LLC Resonant Converter 在不同的 Q_L 值, 它的 $\frac{\omega_r}{\omega_0}$ 是不一樣的, 並不像 LC Resonant Converter 不同的 Q_L 值只有 $\frac{\omega_r}{\omega_0}$ 值, 我們必須求出 $\frac{\omega_r}{\omega_0}$ 值.

由 (13) 式

令 $\varphi=0, \omega \rightarrow \omega_r, \frac{\omega_r}{\omega_0} = k$

$$\text{則 } \frac{1}{Q_L} \left(k \frac{A}{1+A} - \frac{1}{k} \right) + \frac{Q_L}{k} (1+A)^2 \left(1 - \frac{1}{k^2} \right) = 0$$

$$\frac{kA}{1+A} - \frac{1}{k} + \frac{Q_L^2}{k} (1+A)^2 \left(1 - \frac{1}{k^2} \right) = 0$$

$$\frac{k^2 A}{1+A} - 1 + Q_L^2 (1+A)^2 - \frac{Q_L^2 (1+A)^2}{k^2} = 0$$

$$\frac{k^4 A}{1+A} + k^2 [Q_L^2 (1+A)^2 - 1] - Q_L^2 (1+A)^2 = 0$$

$$\therefore k^2 = \frac{1 - Q_L^2 (1+A)^2 \pm \sqrt{[Q_L^2 (1+A)^2 - 1]^2 - 4A Q_L^2 (1+A)}}{2A(1+A)}$$

$$\therefore \frac{\omega_r}{\omega_0} = \sqrt{\frac{(1+A) \left\{ 1 - Q_L^2 (1+A)^2 \pm \sqrt{[Q_L^2 (1+A)^2 - 1]^2 - 4A(1+A) Q_L^2} \right\}}{2A}}$$

(15) 式

由 (15) 式可知, 當 $Q_L \rightarrow 0$ 時 $\frac{\omega_r}{\omega_0} \rightarrow \sqrt{\frac{1+A}{A}}$

除了由 (15) 式可知道 $\frac{\omega_r}{\omega_0}$, 我們也可以應用 Fig 2 等效電路求出 ω_r .

$$\omega_r = \frac{1}{\sqrt{L_{eq} \cdot C}}, \text{ where } L_{eq} = L_1 + L_5$$

also, we define $g_r = \frac{\omega_r L_5}{R_5} = \frac{R_i}{\omega_r L_2} = Q_L (1+A) \left(\frac{\omega_0}{\omega_r} \right)$

where $L_2 = \frac{R_i}{(1+A) \omega_0 Q_L}$

(16) 式

○ 求出 L_s, R_s

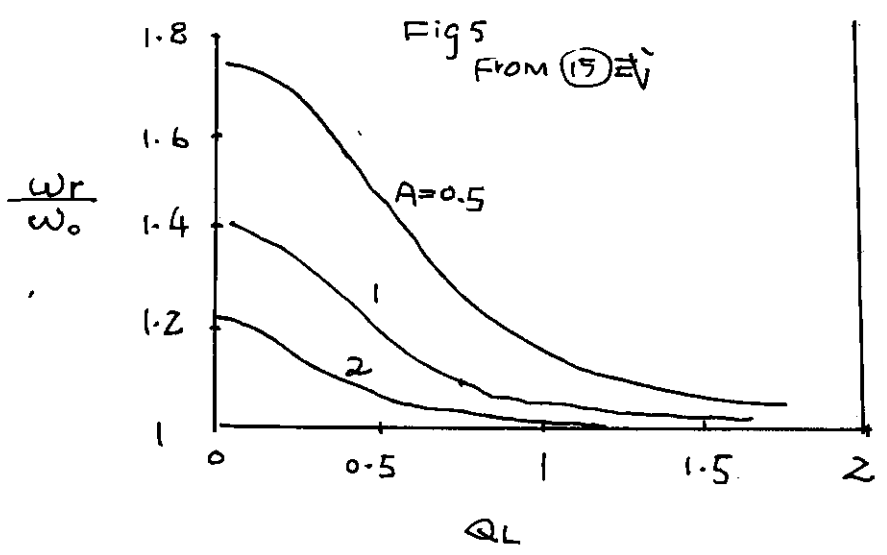
$$R_i // X_{L_2} = \frac{R_i j\omega_r L_2}{R_i + j\omega_r L_2} = \frac{R_i(\omega_r L_2)^2 + j\omega_r L_2 R_i}{R_i^2 + (\omega_r L_2)^2}$$

$$= \frac{R_i}{1 + (\frac{R_i}{\omega_r L_2})^2} + j \frac{\omega_r L_2}{1 + (\frac{\omega_r L_2}{R_i})^2}$$

$$R_s = \text{Re}[R_i // X_{L_2}] = \frac{R_i}{1 + (\frac{R_i}{\omega_r L_2})^2} = \frac{1}{1 + \frac{1}{Q_r^2}} \quad \text{--- (17)}$$

$$X_{L_s} = \text{Im}[R_i // X_{L_2}] = \frac{X_{L_2}}{1 + (\frac{\omega_r L_2}{R_i})^2} = \frac{X_{L_2}}{1 + \frac{1}{Q_r^2}} \quad \text{--- (18)}$$

當 $Q_r^2 \gg 1$ 時 $L_s \approx L_2, R_s \approx R_i \therefore \omega_r \approx \omega_0$



#.4 voltage transfer function.

$$v_{ds2} = V_I \text{ for } 0 < \omega t \leq \pi$$

$$0 \text{ for } \pi < \omega t \leq 2\pi$$

where, V_I fundamental component $\frac{1}{\pi}$

$$v_{i1} = V_m \sin \omega t, \quad V_m(\text{peak}) = \frac{2}{\pi} V_I$$

$$V_{rms} = \frac{V_m}{\sqrt{2}} = \frac{\sqrt{2}}{\pi} V_I$$

$$\text{we define } MVS = \frac{V_{rms}}{V_I} = \frac{\sqrt{2}}{\pi} \sim (19)$$

From Fig 1, We define ac to ac voltage transfer function

$$MVR = \frac{V_{Ri}(rms)}{V_{rms}} = \frac{R_i // X_{L2}}{Z} \sim (20)$$

$$Z_{L2} \quad R_i // X_{L2} = \frac{R_i j\omega L_2}{R_i + j\omega L_2} = \frac{R_i}{1 + \frac{R_i}{j\omega L_2}}$$

$$\text{将 } L_2 = \frac{R_i}{(1+A)\omega_0 Q_L} \quad A \gg 1 \text{ 式}$$

$$\text{可得 } R_i // X_{L2} = \frac{R_i}{1 - j Q_L \frac{\omega_0}{\omega} (1+A)} \sim (21)$$

Recall (20) 式 与 (21) 式 $A \gg 1 \sim (20) \text{ 式}$

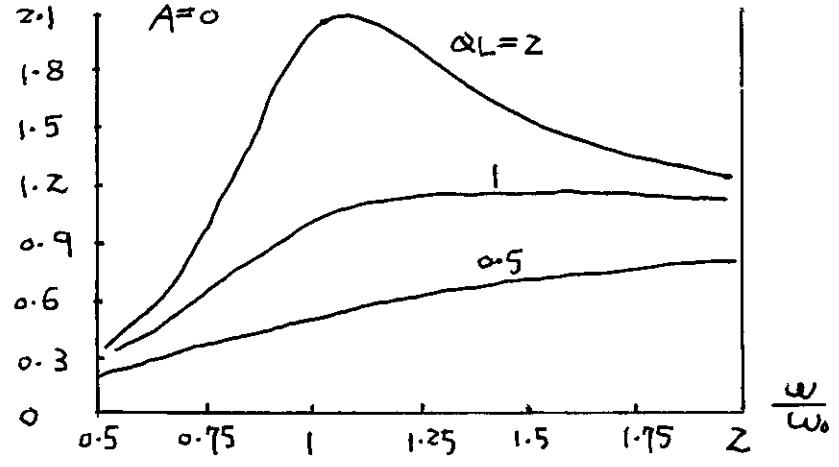
$$MVR = \frac{V_{Ri}(rms)}{V_{rms}} = \frac{1}{(1+A) \left[1 - \left(\frac{\omega_0}{\omega} \right)^2 \right] + j \frac{1}{Q_L} \left(\frac{\omega}{\omega_0} \frac{A}{1+A} - \frac{\omega_0}{\omega} \right)} = MVR_e^{j\varphi} \sim (22)$$

where MVR \neq phasor.

$$MVR = \frac{1}{\sqrt{(1+A)^2 \left[1 - \left(\frac{\omega_0}{\omega} \right)^2 \right]^2 + \frac{1}{Q_L^2} \left(\frac{\omega}{\omega_0} \frac{A}{1+A} - \frac{\omega_0}{\omega} \right)^2}} \sim (23)$$

$$\varphi = -\tan^{-1} \left\{ \frac{\frac{1}{Q_L} \left(\frac{\omega}{\omega_0} \frac{A}{1+A} - \frac{\omega_0}{\omega} \right)}{(1+A) \left[1 - \left(\frac{\omega_0}{\omega} \right)^2 \right]} \right\} \sim (24)$$

Fig 6 From (23) ZV

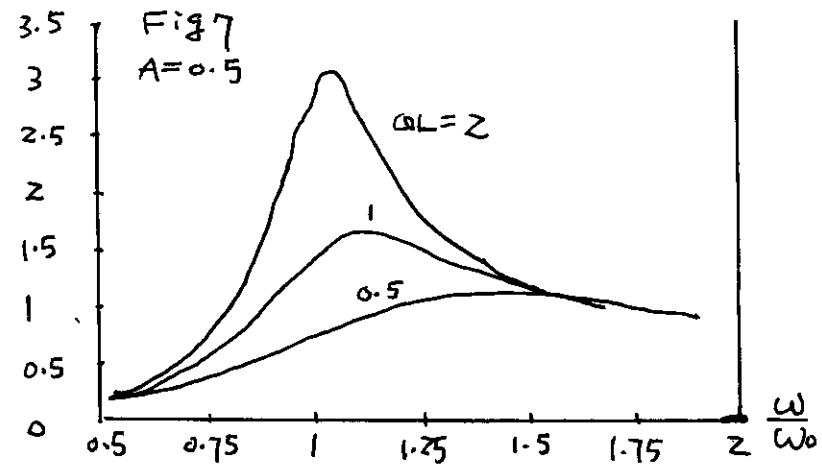


Note
 1. A 愈小
 MVR 愈不受
 ω 的影响

2. 以相同的 Q_L
 为条件 MVR 较低

3. 以 ZVS/ZCS Boundary
 $\frac{\omega}{\omega_0}$ 较高
 Q_L 愈高 MVR
 愈高
 ω 愈高, MVR
 愈低

Fig 7
 A=0.5

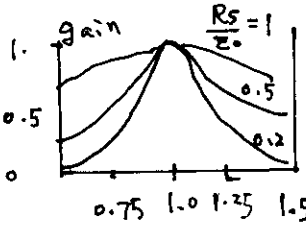
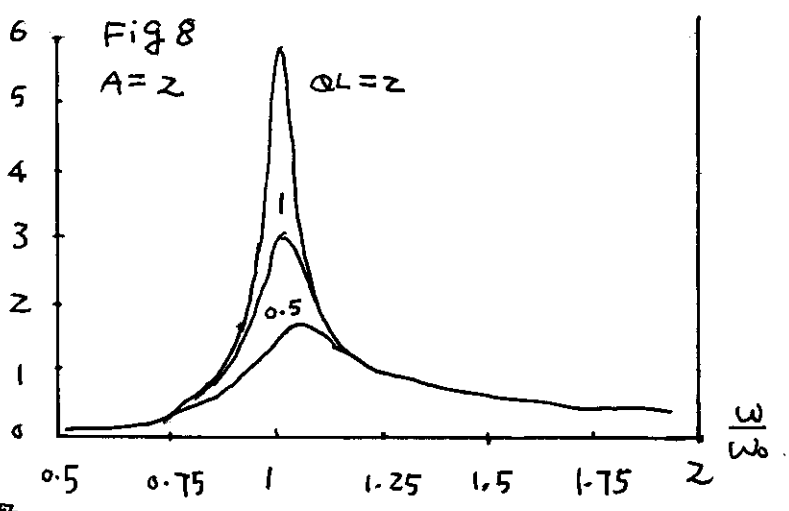


以 Fig 7 为例
 $\frac{\omega}{\omega_0} = 1.5$ 时

MVR 不受 Q_L 值影响
 为定数。

这是 CLL 共振
 与 CL 共振
 非常不一样的
 地方。

Fig 8
 A=2



$\frac{\omega}{\omega_0} > 1.0$ 才有 ZVS, \therefore 为过频

由(22)式知道, 如果 $MVR=1$, 其必要條件為

$$\text{Image part} = 0$$

$$\text{Real part} = 1, \omega \rightarrow \omega_{rs}$$

$$\therefore 1 - \left(\frac{\omega_0}{\omega_{rs}}\right)^2 = \frac{1}{1+A}, \left(\frac{\omega_0}{\omega_{rs}}\right)^2 = \frac{A}{1+A} \therefore \frac{\omega_{rs}}{\omega_0} = \sqrt{1 + \frac{1}{A}} \sim (25)$$

From (25) 式

$$\omega_{rs} = \omega_0 \sqrt{1 + \frac{1}{A}} = \sqrt{\frac{1}{LC}} \times \sqrt{\frac{L}{L_1}} = \frac{1}{\sqrt{L_1 C}} \sim (26)$$

由(26)式可知在共振時 $X_{L_1} + X_C = 0$

$$MVR \text{ 永遠} = 1.$$

如果要求 dc to AC voltage transfer function:

$$MVI = \frac{V_{ri}(\text{rms})}{V_i} = \frac{V_{ri}(\text{rms})}{V_{\text{rms}}} \times \frac{V_{\text{rms}}}{V_i} = MVR \cdot MVS$$

(9)式与(23)式合併即可

$$MVI = \frac{\sqrt{2}}{\pi \sqrt{(1+A)^2 \left[1 - \left(\frac{\omega_0}{\omega}\right)^2\right]^2 + \left[\frac{1}{Q_L} \left(\frac{\omega}{\omega_0} \frac{A}{A+1} - \frac{\omega_0}{\omega}\right)\right]^2}} \sim (27)$$

#5. Energy parameters

流经 resonant capacitor C 的电流, 定义为

$$i = I_m \sin(\omega t - \varphi)$$

$$\textcircled{1} I_m = \frac{V_m}{Z} = \frac{2VI}{\pi Z}$$

将 (2) 式代入上式可得

$$I_m = \frac{2VI}{\pi Z_0 Q_L} \times \sqrt{\frac{1 + [Q_L(\frac{\omega_0}{\omega})(1+A)]^2}{(1+A)^2 \left[1 - (\frac{\omega_0}{\omega})^2\right]^2 + \frac{1}{Q_L^2} \left(\frac{\omega}{\omega_0} \frac{A}{A+1} - \frac{\omega_0}{\omega}\right)^2}}$$

观察分母为 MVr^2 ,

$$\therefore I_m = \frac{2VI M V r}{\pi Z_0 Q_L} \sqrt{1 + [Q_L(\frac{\omega_0}{\omega})(1+A)]^2} \sim (28)$$

② output current 的 i_{r1}

$$I_{om}(\text{peak}) = \frac{\sqrt{2} V r i}{R_i} = \frac{\sqrt{2} \cdot M V I \cdot V I}{V I}$$

将 (28) 式代入上式

$$I_{om}(\text{peak}) = \frac{2VI}{\pi Z_0 Q_L} \sqrt{(1+A)^2 \left[1 - (\frac{\omega_0}{\omega})^2\right]^2 + \left[\frac{1}{Q_L} \left(\frac{\omega}{\omega_0} \frac{A}{A+1} - \frac{\omega_0}{\omega}\right)\right]^2}$$

~ (29)

where $Z_0 Q_L = R_i$

③ output power

$$P_{ri} = \frac{V r i^2}{R_i} = \frac{M V I^2 V I^2}{R_i} \quad \text{(28) 式代入}$$

$$= \frac{2VI^2}{\pi^2 Z_0 Q_L} \left\{ (1+A)^2 \left[1 - (\frac{\omega_0}{\omega})^2\right]^2 + \left[\frac{1}{Q_L} \left(\frac{\omega}{\omega_0} \frac{A}{A+1} - \frac{\omega_0}{\omega}\right)\right]^2 \right\}$$

~ (30)

① conduction loss

$$P_r = \frac{r I_M^2}{2}$$

将 (28) 式代入上式

$$P_r = \frac{2r V_I^2 M V_r^2 \left\{ 1 + \left[Q_L \left(\frac{\omega_0}{\omega} \right) (1+A) \right]^2 \right\}}{\pi^2 Z_0^2 Q_L^2} \sim (31)$$

where $r = r_{ds} + r_{cr} + r_{L1} + r_{Ls}$

$$= r_{ds} + r_{cr} + r_{L1} + \frac{r_{L2}}{1 + \left(\frac{\omega L_2}{R_i} \right)^2}$$

② efficiency

$$\eta_I = \frac{P_{ri}}{P_{ri} + P_r} = \frac{1}{1 + \frac{P_r}{P_{ri}}} \sim (32)$$

$$\text{where } \frac{P_r}{P_{ri}} = \frac{2r V_I^2 M V_r^2 \left\{ 1 + \left[Q_L \left(\frac{\omega_0}{\omega} \right) (1+A) \right]^2 \right\}}{\pi^2 Z_0^2 Q_L^2} \times \frac{R_i}{M V_I^2 \cdot V_I^2}$$

where $R_i = Z_0 Q_L$

$$\left(\frac{M V_r}{M V_I} \right)^2 = \frac{1}{M V_s^2} = \frac{\pi^2}{Z} \quad \text{将 (28) 式代入上式}$$

再合并 (32) 式

$$\eta_I = \frac{1}{1 + \frac{r}{R_i} \left\{ 1 + \left[Q_L \left(\frac{\omega_0}{\omega} \right) (1+A) \right]^2 \right\}} \sim (33) \text{ 式}$$

from (33) 式

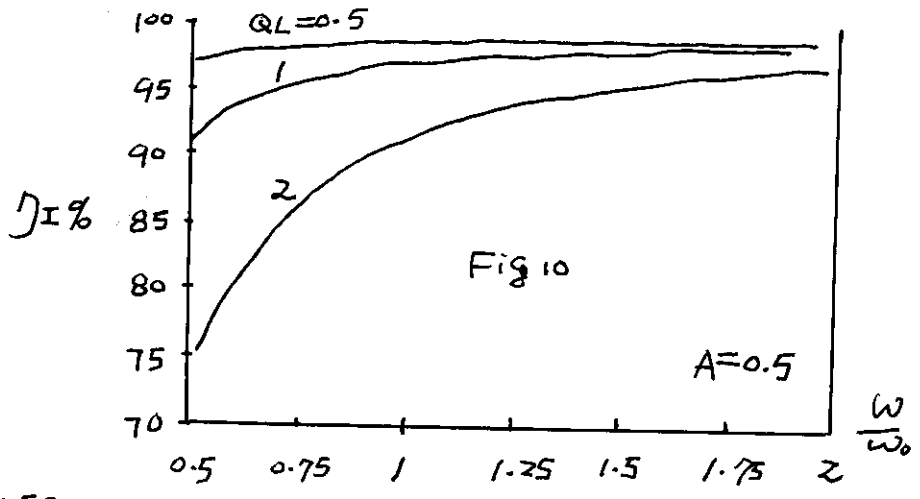
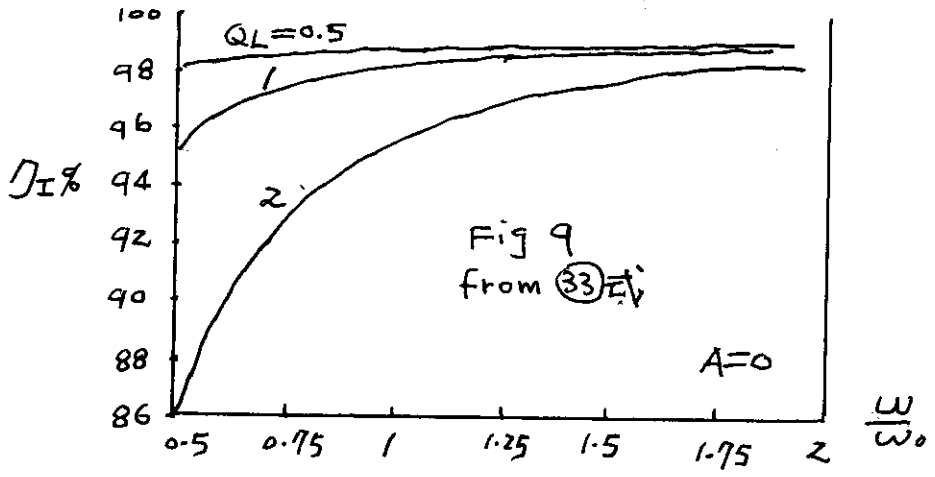
$$\hat{\omega} = \frac{\omega_0}{\omega} = \frac{1}{k} \lambda \text{ (33) 式}$$

$$\eta_I = \frac{1}{1 + \frac{r}{Q_L Z_0} \left[1 + \frac{Q_L}{k} (1+A) \right]^2} = \frac{1}{1 + \frac{r}{Q_L Z_0} \left[1 + \left(\frac{Q_L}{k} \right)^2 (1+A)^2 + \frac{2Q_L}{k} (1+A) \right]}$$

$$= \frac{1}{1 + \frac{r}{Z_0} \left[\frac{1}{Q_L} + \frac{Q_L}{k^2} (1+A)^2 + \frac{2}{k} (1+A) \right]}$$

$$\text{令 } \frac{d\eta_I}{dQ_L} = 0 \therefore \frac{1}{Q_L^2} - \left(\frac{1+A}{k} \right)^2 = 0$$

$$\therefore \text{在最高效率时 } Q_L = \frac{k}{1+A} = \frac{\omega}{\omega_0} \rightarrow \sim \text{(34)}$$



$r_{ds} = 0.5 \Omega$, $r_{cr} = 0.08 \Omega$
 $r_{L1} = r_{L2} = 0.8 \Omega$
 $Z_0 = 212 \Omega$

說明：

1. 由 Fig 9, Fig 10 效率圖說明了, A 愈小, Q_L 愈小, 會有比較高的效率。

而且由 Fig 11 看來, Q_L 比較小, I_m 會比較小。

但是由 Fig 12, Fig 13 看來 Q_L 比較小, 輸出功率以及流經負載電流會小得很多。

不利於 Heavy power 設計。

2. 將 ω 的^值拉高會有比較好的效率,

而且效率不易受 Q_L 的影響

但由 (34) 式觀察 $Q_L = \frac{\omega}{\omega_0} [最高效率原則]$

$|+A$

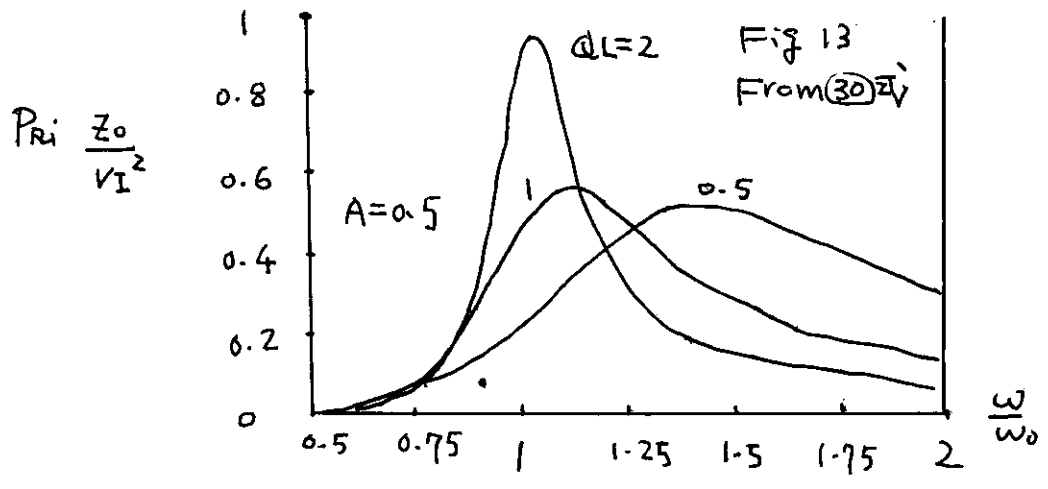
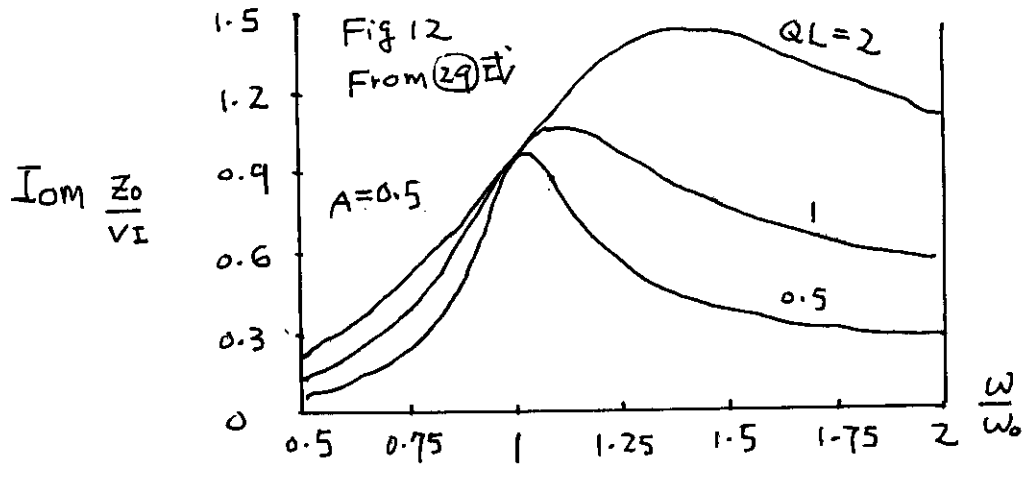
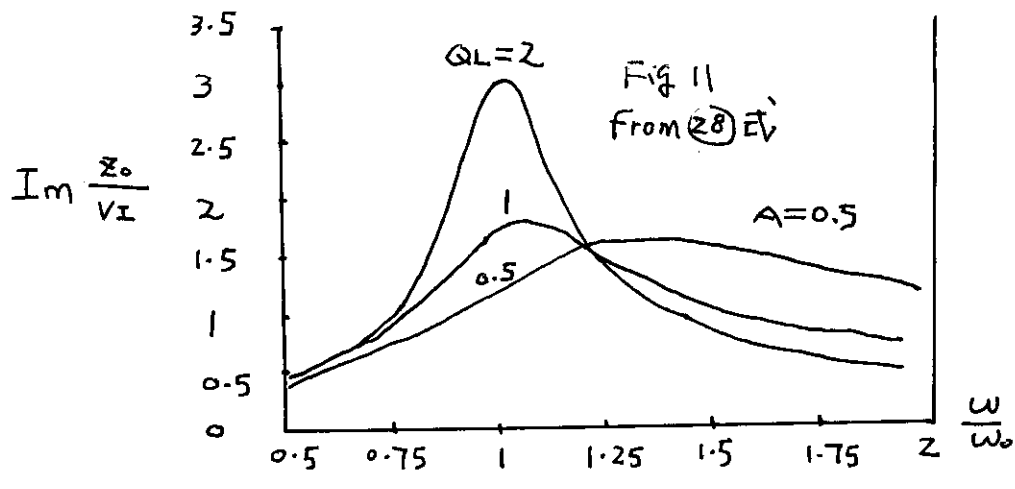
$\frac{\omega}{\omega_0}$ 要大, A 要小, 而且要使 Q_L 小, 似乎是背道而馳, 只能做 optimized 設計。

3. 由 Fig 6, 7, 8 觀察 A 愈小, Q_L 愈低

表現出來的是對 frequency response 是很慢的,

也表示了對於增益反應是很慢的,

不利 transient 以及 variation of V_L 。



#6. Voltage Stress.

P17

$$\textcircled{1} V_{L1m} = X_{L1} \cdot I_m$$

$$\text{已知 } X_{L1} = \omega \frac{A}{1+A} L = \omega \frac{A}{1+A} \frac{Z_0}{\omega_0}$$

将本式与 (28) 式合并

可得

$$V_{L1m} = \frac{\omega}{\omega_0} \frac{A}{1+A} \frac{ZVI Mvr}{\pi Q_L} \sqrt{1 + \left[Q_L \frac{\omega_0}{\omega} (1+A) \right]^2} \sim (35)$$

$$V_{L1m} = (\omega L_1) \frac{V_m}{Z} = \left(\frac{\omega}{\omega_0} \right) (\omega_0 L_1) \frac{ZVI}{\pi Z} \sim (36)$$

$$\textcircled{2} V_{L2m} = \sqrt{Z} V_{Ri} = \sqrt{Z} Mvr \cdot MV_s \cdot VI = \sqrt{Z} MVI \cdot VI$$

将本式与 (27) 式合并

$$V_{L2m} = \frac{ZVI}{\pi \sqrt{(1+A)^2 \left[1 - \left(\frac{\omega_0}{\omega} \right)^2 \right]^2 + \left[\frac{1}{Q_L} \left(\frac{\omega}{\omega_0} \frac{A}{1+A} - \frac{\omega_0}{\omega} \right) \right]^2}} \sim (37)$$

$$\textcircled{3} V_{Cm} = X_C \cdot I_m$$

$$\text{已知 } X_C = \frac{1}{\omega C} = \frac{\omega_0 Z_0}{\omega}$$

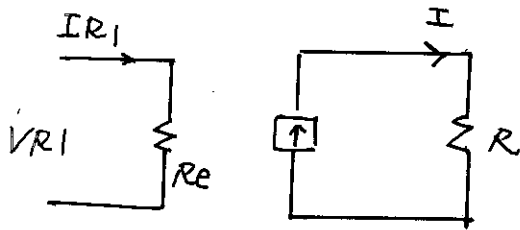
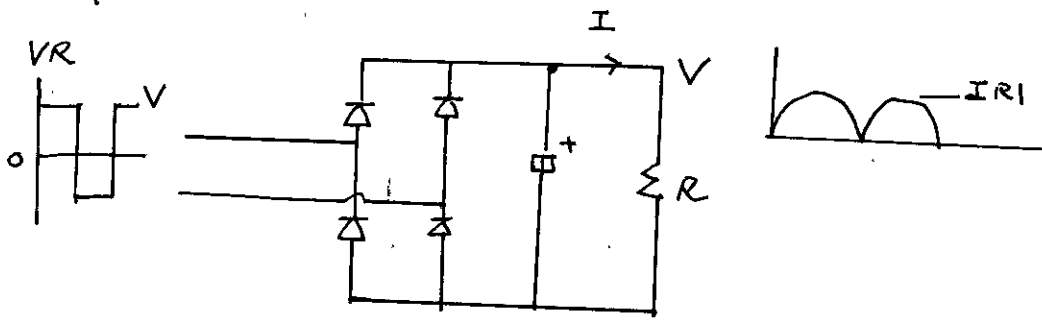
将本式与 (28) 式合并

$$V_{Cm} = \frac{\omega_0}{\omega} \left(\frac{ZVI Mvr}{\pi Q_L} \right) \sqrt{1 + \left[Q_L \frac{\omega_0}{\omega} (1+A) \right]^2} \sim (38)$$

$$V_{Cm} = \frac{1}{\omega C} \frac{V_m}{Z} = \left(\frac{\omega_0}{\omega} \right) \left(\frac{1}{\omega_0 C} \right) \frac{ZVI}{\pi Z} \sim (39)$$

#7. Emulated Resistor

P18



由於串聯共振 Secondary 為 Current driving.

可以知道輸入電源為 V .

V_R fundamental component

$$V_{R1} = \frac{4}{\pi} V \sin(\omega t - \varphi) = V_{R1} \sin(\omega t - \varphi)$$

I 為正弦波之 fundamental component, 並與 V_{R1} in-phase.

$$\therefore I = \frac{2}{T_s} \int_0^{T_s/2} I_{R1} |\sin(\omega t - \varphi)| dt$$

$$= \frac{2}{\pi} I_{R1}$$

$$R_e = \frac{V_{R1}}{I} = \frac{V_{R1}}{V} \times \frac{I}{I_{R1}} \times \frac{V}{I}$$

$$= \frac{4}{\pi} \times \frac{2}{\pi} \times R$$

$$\therefore R_e = \frac{8}{\pi^2} \times R \quad \sim \text{④}$$

實際設計的應用

P19

規格 $V_o = 24V$, $I_o = 10A$, Rectifier $V_f = 0.7V$
 $V_i(\min) = 380V$, $V_i(\max) = 420V$
 $f_s = 100kHz$.

① 共振的計算非常複雜，只能作 compromise 的設計，先決定 $A = \frac{L_k}{L_m}$ 的比值。

ST's 建議 $A = \frac{1}{3.5} \sim \frac{1}{7.0}$

這裏我們定義 $A = \frac{1}{5} = 0.2$

$$n = \frac{n_p}{n_s} \geq \frac{V_i(\max) \times d_1}{V_o + V_f} = \frac{420 \times 0.5}{24 + 0.7} = 8.5$$

We choose $n = 9$

from (4) 式

$$R_i = \frac{8}{\pi^2} \times n^2 \times \frac{V_o + V_f}{I_o} = \frac{8}{\pi^2} \times 81 \times \frac{24 + 0.7}{10} = 162.17 \Omega$$

from (2) 式

MVR = 1. 其必要條件 $\frac{f_s}{f_0} = \sqrt{1 + \frac{1}{A}} = \sqrt{6} = 2.45$

$$\therefore f_0 = \frac{100k}{2.45} = 40.82k$$

from (3) 式，如果以最大效率為設計的必要條件

$$Q_L = \frac{f_s/f_0}{1 + A} = \frac{2.45}{1.2} = 2.04$$

from (5) 式

$$C = \frac{Q_L}{\omega_0 R_i} = \frac{2.04}{2\pi \times 40.82k \times 162.17 \Omega} = 0.049 \mu F$$

$$L = (L_k + L_m) = \frac{R_i}{\omega_0 Q_L} = \frac{162.17 \Omega}{2\pi \times 40.82k \times 2.04} = 309.6 \mu H$$

$$L_k = \frac{1}{6} \times L = 51.6 \mu H$$

$$L_m = \frac{5}{6} \times L = 258 \mu H$$

from page 10

我們可以觀察得知, Q_L 愈高, M_{VR} 愈高, voltage-stress 也會愈高, 並且以 1. 信号而言, phase-margin 也會較小。

假如, 定義 $Q_L = 1.0$ 為設計條件。

$$C = \frac{Q_L}{\omega_0 \cdot R_i} = \frac{1}{2\pi \times 40.82\text{K} \times 162.17\Omega} = 0.024\mu\text{F}$$

$$L = \frac{R_i}{\omega_0 \cdot Q_L} = \frac{162.17\Omega}{2\pi \times 40.82\text{K}} = 631.7\mu\text{H}$$

$$L_K = \frac{1}{6} \times L = 105.3\mu\text{H}$$

$$L_M = \frac{5}{6} \times L = 526.4\mu\text{H}$$

$$f_r = \frac{1}{2\pi \sqrt{L_K \times C}} = \frac{1}{2\pi \sqrt{105.3\mu\text{H} \times 0.024\mu\text{F}}} = 100.02\text{K} = f_s$$

$$Z_0 = \sqrt{\frac{L}{C}} = \frac{R_i}{Q_L} = 162.17\Omega$$

① from (28) 式 以 fourier 第一、二谐波计算流经 MOS 的 peak current.

$$I_M = \frac{V_M}{Z} = \frac{2VI}{\pi Z}$$

$$= \frac{2VI \cdot M_{VR}}{\pi Z_0 Q_L} \sqrt{1 + \left[Q_L \times \frac{\omega_0}{\omega} \times (1+A) \right]^2}$$

$$= \frac{2 \times 400 \times 1}{\pi \times 162.17 \times 1} \times \sqrt{1 + \left(\frac{1}{2.04} \times 1.2 \right)^2} = 1.82\text{A}$$

from (35) \vec{z}_v

P2/

$$V_{L_{km}} = \omega L_k \cdot I_m \\ = 2\pi \times 100K \times 105.3 \mu H \times 1.82A = 120.4V$$

$$V_{C_m} = \frac{1}{\omega C} \cdot I_m = \frac{1}{2\pi \times 100K \times 0.024 \mu F} \times 1.82A = 120.57V$$

from (37) \vec{z}_v

$$V_{L_{m.m}} = \frac{zV_i}{\pi \sqrt{(1+A)^2 [1 - (\frac{\omega}{\omega_0})^2]^2 + [\frac{1}{Q_L} (\frac{\omega}{\omega_0} \frac{A}{1+A} - \frac{\omega_0}{\omega})]^2}} \\ = \frac{2 \times 400}{\pi \sqrt{0.8536}} = 275.6V$$