南京航空航天大学自动化学院
赵修科 主编

2004 8

电话：025-84893795(H)
025-84895975(O)
Emai: jops@nuaa.edu.cn

前　言

几乎所有电源电路中，都离不开磁性元器件　电感器或变压器。例如在输入和输出端采用电感滤除开关波形的谐波；在谐振变换器中用电感与电容产生谐振以获得正弦波电压和电流；在缓冲电路中，用电感限制功率器件电流变化率；在升压式变换器中，储能和传输能量；有时还用电感限制电路的瞬态电流等。而变压器用来将两个系统之间电气隔离，电压或阻抗变换，或产生相位移(3 相 Δ—Y 变换)，存储和传输能量(反激变压器)，以及电压和电流检测(电压和电流互感器)。可以说磁性元件是电力电子技术最重要的组成部分之一。

磁性元器件—电感器和变压器与其他电气元件不同，使用者很难采购到符合自己要求的电感和变压器。对于工业产品，应当有一个在规定范围内通用的规范化的参数，这对磁性元件来说是非常困难的。而表征磁性元件的大多数参数(电感量，电压，电流，处理能量，频率，匝比，漏感，损耗)对制造商是无所适从的。相反，具体设计一个磁性元件在满足电气性能条件下，可综合考虑成本，体积，重量和制造的困难程度，在一定的条件下可获得较满意的结果。

由于很难从市场上购得标准的磁性元器件，开关电源设计工作的大部分就是磁性元件的设计。有经验的开关电源设计者深知，开关电源设计的成败在很大程度上取决于磁性元件的正确设计和制作。高频变压器和电感固有的寄生参数，引起电路中各色各样的问题，例如高损耗、必须用缓冲或箝位电路处理的高电压尖峰、多路输出之间交叉调节性能差、输出或输入噪声耦合和占空度范围限制等等，对初步进入开关电源领域的工程师往往感到手足无措。

磁性元件的分析和设计比电路设计复杂得多，要直接得到唯一的答案是困难的。因为要涉及到许多因素，因此设计结果绝不是唯一合理的。例如，不允许超过某一定体积，有几个用不同材料的设计可以满足要求，但如果进一步要求成本最低，则限制了设计的选择范围。因此最优问题是多目标的，相对的。或许是最小的体积，最低成本，或是最高效率等等。最终的解决方案与主观因素、设计者经验和市场供应情况有关。另一方面，正确的设计不只是一般电路设计意义上的参数计算。还应当包含结构、工艺和散热等设计，而且是更重要的设计。高频开关电源的很多麻烦是由于磁性元件工艺、结构和制造不合理引起的。

尽管磁性元件设计结果是相对的，不是唯一的。但至少设计结果应当是合理的。因此，开关电源设计者应当有比较好的磁学基础。遗憾的是在现今中等专业学校和高等院校中磁的讲解偏少，尤其是应用于开关电源的实际磁的概念更少涉及。为此，本书试图在讲清工程电磁的最基本概念的基础上，介绍磁性材料性能和选用以及高频条件下磁性元件工作的特殊问题、磁性元件设计的一般方法和工艺结构。给初学者初步提供理论依据和经验

数据，为进入“黑色艺术殿堂”打下必要的基础，并通过自己的不断实践，也成为开关电源磁性元件的专家。

本书由丁道宏教授主审，并提出了不少很宝贵的意见。詹晓东副教授提供不少有益的资料，给予很大帮助，在此一并表示衷心的感谢。

本书出版前后，先后受聘于多家厂商讲课，得到一致好评。很多电源工作者希望得到该书，但是销售渠道很不畅通。为此，将书稿重新整理，改正出版中的错误，并补充一些必要的例子和资料。刻制光盘，以饷读者。

2004　8

第一章 磁的基本概念

19 20

SI

MKS - - CGS - -

CGS MKS

1.1

S

N

(1)

(2)

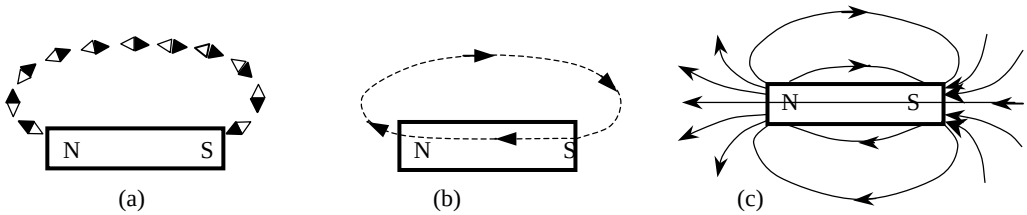
1-1(a)

N S _____(1-1(b))

N S

S N

(1-1(c))



(a) (b) (c)

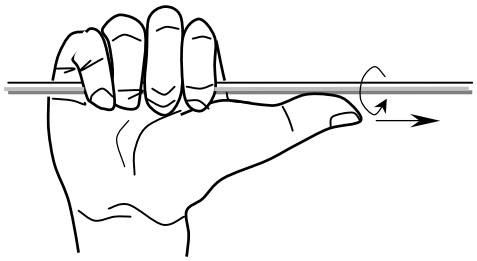
1-1

1.2

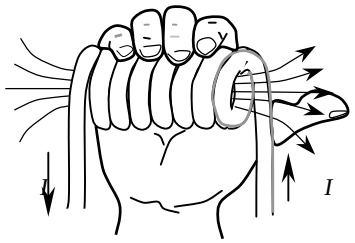
1-2

1-2(a)

1-2(b)



(a)



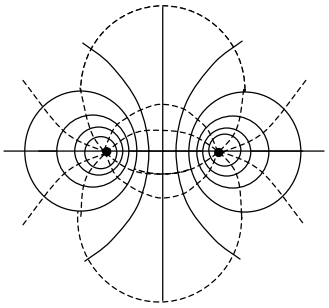
(b)

1-2

1-3

( )

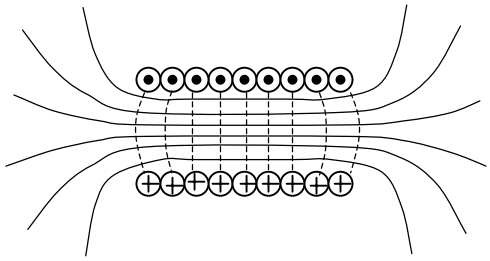
1-4



1-3

“ ”

“ ”



1-4

1-4

1.3

1.3.1 (*B*—)

2

，

($\vec{B}=\vec{F}/Il$) ($\vec{B}$)

$\vec{B}$ $\vec{F}$ I l $\vec{B}$

$\vec{B}$ (SI) (Tesla) T (CGS)

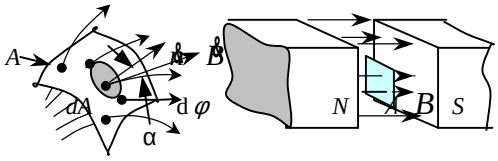
Gs $1T=10^4Gs$

1.3.2 (ϕ)

ϕ

(1-5(a)) A

$$\phi=\int_A d\phi=\int B\cos\alpha dA$$



(a) (b)

1-5

$$\phi=\int_A \vec{B}d\vec{A}$$

$d\phi$ $d\vec{A}$

α $\vec{B}$

$\vec{B}$

1-5(b)

$$\phi=BA \quad (1\text{-}1)$$

SI Wb B A

$1(Wb)=1(T)\times 1(m^2)$

CGS Mx

$1Mx=1Gs\times 1cm^2$

$1T=10^4Gs$ $1\ m^2=10^4cm^2$

$1Mx=10^{-8}Wb$

(1-1)

$$B=\frac{\phi}{A} \quad (1\text{-}2)$$

/ 2

$$1Gs=10^{-4}\,Wb/m^2=10^{-8}\,Wb/cm^2$$

1.3.3 (μ) $\vec{H}$

1. 磁介质的磁导率(μ)和磁场强度（ $\vec{H}$ ）

μ μ μ B

μ_0

μ_0 10 10^5

μ_0 1

4π

(CGS) $\mu_0 = 4\pi \times 10^{-7}$ H/m

μ_0 μ_0 4π

4π MKS

μ_r

2. 磁场强度（$\vec{H}$）

$\vec{B}$ μ

$\vec{B}$ μ $\vec{H}$,

$$\vec{H} = \frac{\vec{B}}{\mu} \qquad (1\text{-}3)$$

$\vec{H}$ $\vec{B}$.

μ $\vec{H}$

$\vec{B}$ $\vec{H}$ $\vec{H}$.

1.3.4

$\vec{H}$

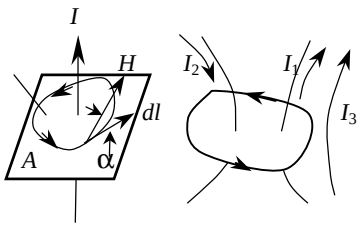
(1-6),

$$\oint_l \vec{H} \mathrm{d}\vec{l} = \oint_l H \cos\alpha \mathrm{d}l = \sum I \qquad (1\text{-}4)$$

$\vec{H}$ A $d\vec{l}$ A

α $\vec{H}$ $d\vec{l}$ Σ*I*

(1-4)



(a) (b)

1-6(a) *I* Σ*I*=*I* 1-6(b)

I_1 I_2 I_3 1-6

Σ*I*=I_1-I_2

(1-7) *N*

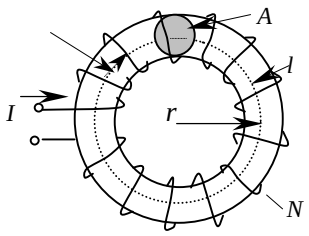
r *l* (1-4)

$$\oint \vec{H} \mathrm{d}\vec{l} = Hl = 2\pi r \times H$$ 1-5

$$\sum I = IN$$

$$H \times 2\pi r = Hl = IN \qquad (1\text{-}6)$$

$$H = \frac{IN}{2\pi r} = \frac{IN}{l} \qquad (1\text{-}7)$$



1-7

r 1

$l=2\pi r$

H r

$$l = \frac{2\pi(r2 - r1)}{\ln\frac{r2}{r1}} \qquad (1\text{-}8)$$

$\vec{B}$ $\vec{H}$

$\vec{B}$ $\vec{H}$

SI / A/m CGS Oe A/m

$$1\text{A/m} = 1\times10^{-2}\,\text{A/cm} = 0.4\pi\times10^{-2}\,\text{Oe}$$

1A/cm=0.4π Oe

(1-7) H

(1-6) IN F

$$F = IN$$

(A)

1-3

$$\mu = \frac{\vec{B}}{\vec{H}}$$

μ

μ $= \frac{\text{Wb/m}^2}{\text{A/m}} = \frac{\text{V}\cdot\text{S}}{\text{A}\cdot\text{m}} = \frac{\Omega\cdot\text{S}}{\text{m}} = \text{H/m}$ (/)

SI / H/m CGS / SI

$$1\text{H/m} = \frac{10^7}{4\pi}\text{Gs/Oe}$$

$$\mu_0 = 4\pi\times10^{-7}\,\text{H/m} = 0.4\pi\times10^{-8}\,\text{H/cm}$$

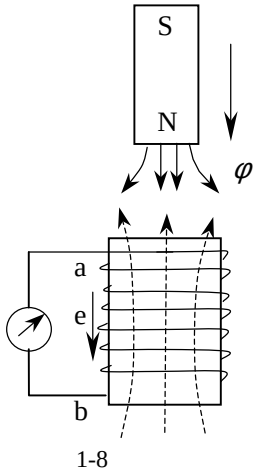
CGS , μ_0 / 1

1.3.5

(1-8)

变化

1



1-8

$$e=\left|\frac{\Delta\phi}{\Delta t}\right|$$

N

$$e=N\left|\frac{\Delta\phi}{\Delta t}\right|=\left|\frac{\Delta(N\phi)}{\Delta t}\right|=\left|\frac{\Delta\psi}{\Delta t}\right|$$

$\psi=N\phi$

1s 1Wb

1V (—Vs)

B

$$e=-N\frac{d\phi}{dt}=-\frac{d\psi}{dt} \qquad (1\text{-}9)$$

1.3.6

1-9 N D d 1

$l=\pi(D+d)/2$ A μ

u

$$u=-e=N\frac{d\phi}{dt}=NA\frac{dB}{dt} \qquad 1\text{-}10$$

$$i=\frac{Hl}{N}$$

W_e

$$W_e=\int_0^t iu\mathrm{d}t=\int_0^t\frac{Hl}{N}NA\frac{\mathrm{d}B}{\mathrm{d}t}\mathrm{d}t \qquad 1\text{-}11$$

t B

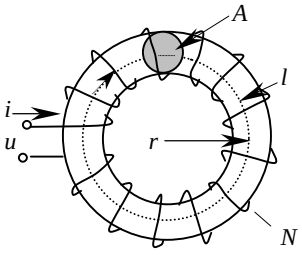
$$W_e=\int_0^B AlH\mathrm{d}B=V\int_0^B H\mathrm{d}B \qquad 1\text{-}12$$

$V=Al$ W_e

W_m μ $B=\mu H$

$$W_m=V\int_0^B\frac{B}{\mu}\mathrm{d}B=V\frac{B^2}{2\mu}=\frac{BH}{2}V=\frac{\mu VH^2}{2} \qquad (1\text{-}13)$$

1-13



1-9

1/2

例1 μ 60×10^{7} / 1-9 A=2cm^2 l 16cm N=50 1A

$$H=\frac{IN}{l}=\frac{1\times50}{16}=3.125\text{A/cm}=312.5\text{A/m}$$

$$V=l\times A=16\times2=32\text{cm}^3=32\times10^{-6}\text{m}^3$$

$$W_m=V\frac{\mu H^2}{2}=32\times10^{-6}\times\frac{60\times10^{-7}\times312.5^2}{2}=9.35\times10^{-6}$$

本章要点

-
-
-
- 1.
  2.
- CGS
  SI 10-1

1. 1985
2. 1990
3. Magnetic Powder Cores-Powder Core Division The Arnold Engineering Company.
4. Unitrode Magnetics Design Handbook Magnetics Design for Switching Power Supplies Lloyd H. Dixon
5. Permanent Magnets and Magnetism D. Hadfield London Iliffe Books LTD 1962
6. Permanent Magnets and Their Application Rollin J. Parker, Robert J. Studders . John Wiley and Sons,Inc. 1962

第二章 电路中的磁性元件

2.1

i μ $\psi(\phi)$ i

$$\psi = Li$$

(ϕ) N

$$L = \frac{\psi}{i} = \frac{N\phi}{i} \qquad (2\text{-}1)$$

L N 2-1 L

$\psi=Li$ (1-9)

$$e = -L\frac{\mathrm{d}i}{\mathrm{d}t} \qquad (2\text{-}2)$$

(2-2) 1s 1A

1V 1 H

$$L = \frac{1\mathrm{V}\times 1\mathrm{s}}{1\mathrm{A}} = 1(\mathrm{H}) \qquad (2\text{-}3)$$

(2-3) / .

(2-2) e_L

, (2-1

(a) (b))

2-1

L

(2-2) t i

$$W_e = \int_0^t ui\mathrm{d}t = \int_0^t iL\frac{\mathrm{d}i}{\mathrm{d}t}\mathrm{d}t = \int_0^i Li\mathrm{d}i = \frac{1}{2}Li^2 \quad (\mathrm{J}) \qquad 2\text{-}4$$

(1-11 1-13) (2-4)

2.2

2.2.1

N_1 N_2 2-2

N_1 i_1 ϕ_{11} N_1

N_1 N_2 ϕ_{11} N_1 ϕ_{12}

N_2 i_1 ϕ_{12} N_2 N_2 i_2

N_1

$i_1(i_2)$ $N_2(N_1)$ $\phi_{12}(\phi_{21})$

2.2.2

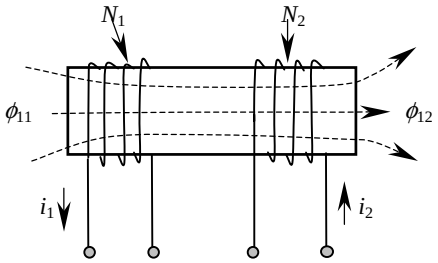
2-2 ϕ_{11} ϕ_{12} N_2

$\psi_{12}=N_2\phi_{12}$ i_1

N_2 ψ_{12} i_1

$$\psi_{12} = M_{12} i_1 \qquad (2\text{-}5)$$

M_{12} N_1 N_2



2-2

$$M_{12} = \frac{\psi_{12}}{i_1} \qquad (2\text{-}6)$$

N_2 N_1 M_{21} $M_{12} \neq M_{21}$ $M = \sqrt{M_{12} M_{21}}$

N_1 N_2 M N_1 N_2

M

μ M

M

2.2.3

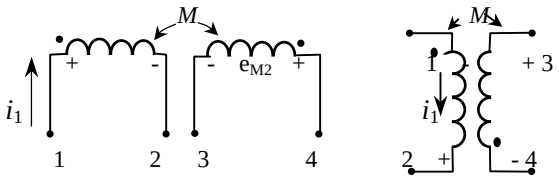
N_1

i_1 N_2

$$e_{M2} = -\frac{-\mathrm{d}\psi_{12}}{\mathrm{d}t} = -\frac{M_{12}\mathrm{d}i_1}{\mathrm{d}t} \qquad (2\text{-}7a)$$

N_2 i_2 N_1

$$e_{M1} = \frac{-\mathrm{d}\psi_{21}}{\mathrm{d}t} = -\frac{M_{21}\mathrm{d}i_2}{\mathrm{d}t} \qquad (2\text{-}7b)$$



(a) (b) ‘ . ’

2-3

2-3 M

M i_1 2-3(a) ‘ 1 ’

‘ + ’ , ‘ 2 ’ ‘ ’ ‘ 4 ’ ‘ + ’ , ‘ 3 ’ ‘ ’ i_1

2-3(b) ‘1’ ‘ ’ ‘2’
‘ ’ ‘4’ ‘ ’, ‘3’ ‘ ’

2.2.4

1. 电压平衡方程

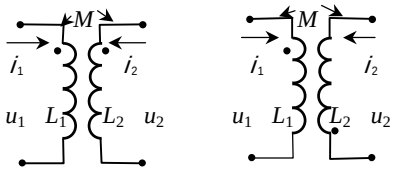
(2-1)

(2-7) i_1
i_2(2-4(a))

$$u_1 = -e_{L1} - e_{M2} = L_1 \frac{\mathrm{d}i_1}{\mathrm{d}t} + M \frac{\mathrm{d}i_2}{\mathrm{d}t} \tag{2-8}$$

$$u_2 = -e_{L2} - e_{M1} = L_2 \frac{\mathrm{d}i_2}{\mathrm{d}t} + M \frac{\mathrm{d}i_1}{\mathrm{d}t} \tag{2-9}$$

‘ . ’



(a) (b)
2-4

‘ . ’ — (2-4(b))

$$u_1 = -e_{L1} + e_{M2} = L_1 \frac{\mathrm{d}i_1}{\mathrm{d}t} - M \frac{\mathrm{d}i_2}{\mathrm{d}t}$$

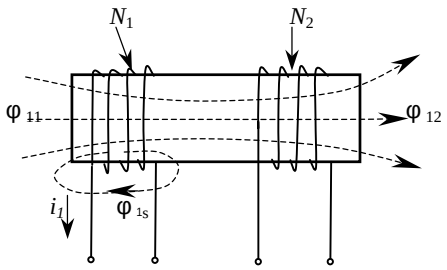
$$u_2 = -e_{L2} + e_{M1} = L_2 \frac{\mathrm{d}i_2}{\mathrm{d}t} - M \frac{\mathrm{d}i_1}{\mathrm{d}t}$$

2. 耦合系数

N_1 i_1 (2-5) N_1 ϕ_{11}(
)
ϕ_{12} N_1 N_2 ϕ_{1S}

( )

N_2 N_1



2-5

k_1

$$k_1 = \frac{\phi_{12}}{\phi_{11}}$$

N_2 ϕ_{21} ϕ_{22}
N_1 N_2 k_2

$$k_2 = \frac{\phi_{21}}{\phi_{22}}$$

k_1 k_2
k

$$k = \sqrt{k_1 k_2} = \sqrt{\frac{\phi_{12}}{\phi_{11}} \cdot \frac{\phi_{21}}{\phi_{22}}} = \sqrt{\frac{N_1 N_2}{N_1 N_2} \frac{\phi_{12}\phi_{21}}{\phi_{11}\phi_{22}} \frac{i_1 i_2}{i_1 i_2}} = \frac{M}{\sqrt{L_1 L_2}} \tag{2-10}$$

$\phi_{12}<\phi_{11}$, $\phi_{21}<\phi_{22}$ $k<1$ $k=1$ $k=1$

M

$$M_m = \sqrt{L_1 L_2} \qquad (2\text{-}11)$$

, ,

$$k = M \big/ M_m \qquad (2\text{-}12)$$

3.

(1)

L_1 L_2

$L=L_1+L_2$ — (2-6(a))

$$U_1 = (L_1 \frac{\mathrm{d}i}{\mathrm{d}t} + M \frac{\mathrm{d}i}{\mathrm{d}t}) + (L_2 \frac{\mathrm{d}i}{\mathrm{d}t} + M \frac{\mathrm{d}i}{\mathrm{d}t})$$
$$= (L_1 + 2M + L_2) \frac{\mathrm{d}i}{\mathrm{d}t} = L_p \frac{\mathrm{d}i}{\mathrm{d}t}$$

$L_p=L_1+L_2+2M$ (2-13)

(2-6(b))

$$U_1 = (L_1 \frac{\mathrm{d}i}{\mathrm{d}t} - M \frac{\mathrm{d}i}{\mathrm{d}t}) + (L_2 \frac{\mathrm{d}i}{\mathrm{d}t} - M \frac{\mathrm{d}i}{\mathrm{d}t})$$
$$= (L_1 + L_2 - 2M) \frac{\mathrm{d}i}{\mathrm{d}t} = L_n \frac{\mathrm{d}i}{\mathrm{d}t}$$

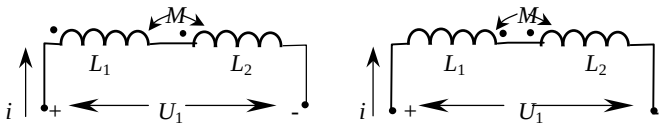
$L_n=L_1+L_2-2M$ (2-14)

$L_p>L_n$ L_n

$$M \le (L_1 + L_2)/2$$
$$L_p - L_n = (L_1 + L_2 + 2M) - (L_1 + L_2 - 2M) = 4M$$

$M = (L_p - L_n)/4$ (2-15)

(2-15)



(a) (b)

2-6

(2)

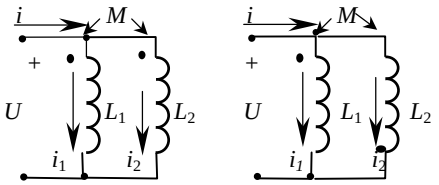
L_1 L_2

$$L = \frac{L_1 L_2}{L_1 + L_2} \qquad (2\text{-}16)$$

(2-7(a) (b))

$$U = L_1 \frac{\mathrm{d}i_1}{\mathrm{d}t} \pm M \frac{\mathrm{d}i_2}{\mathrm{d}t}$$

$$U = L_2 \frac{\mathrm{d}i_2}{\mathrm{d}t} \pm M \frac{\mathrm{d}i_1}{\mathrm{d}t}$$

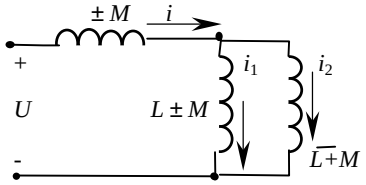


(a) (b)

±

$i=i_1+i_2$,

$$L = \frac{L_1 L_2 - M^2}{L_1 + L_2 \mp 2M} \qquad (2\text{-}17)$$



(c)

2-7

L $k<1$ $L_1L_2-M^2>0$

$M < \sqrt{L_1 L_2}$

$L_1=L_2$ $k \to 1$

$$L = \frac{L_1 L_2 - k^2 L_1 L_2}{L_1 + L_2 - 2k\sqrt{L_1 L_2}} = \frac{(1-k^2)L_l L_2}{L_1 + L_2 - 2k\sqrt{L_1 L_2}} = \frac{1+k}{2} L_1 = L_1$$

$k<1$

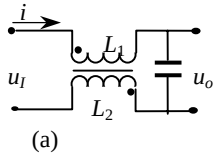
$L_2 \neq L_1$ $k \to 1,$

2-17

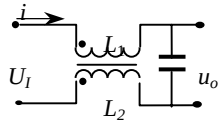
例2 1 a $L_1=0.51\text{mH}=L_2$

L 2mH M k 1(b)

2-13



(a)



(b)

1

$$M = \frac{L - (L_1 + L_2)}{2} = \frac{2 - 0.51 \times 2}{2} = 0.49\ \text{mH}$$

$$k = \frac{M}{M_m} = \frac{M}{\sqrt{L_1 L_2}} = \frac{0.49}{0.51} = 0.96$$

$$L_d = L_1 + L_2 - 2M = 0.51 + 0.51 - 2 \times 0.49 = 0.04\text{mH}$$

$$L_p = \frac{L_1 L_2 - M^2}{L_1 + L_2 - 2M} = \frac{0.51 \times 0.51 - 0.49^2}{0.51 + 0.51 - 2 \times 0.49} = 0.5\text{mH}$$

2.3

2-8(a)

(b)

N_1 ( ) N_2 ( )

2.3.1

u_i (2-8 S)

k=1 N_1

$$u_i = N_1 \frac{\mathrm{d}\phi_{11}}{\mathrm{d}t} = L_1 \frac{\mathrm{d}i_1}{\mathrm{d}t} \qquad (2\text{-}18)$$

L_1 t

$$\phi_{11t} = \int_0^t \frac{u_i}{N_1}\mathrm{d}t$$

$$i_{1t} = \int_0^t \frac{u_i}{L}\mathrm{d}t \qquad (2\text{-}19)$$

N_1 i_{1t}

ϕ_{11t} i_{1t} ϕ_{11t}

N_2 $\mathrm{d}\phi_{12}/\mathrm{d}t$ N_1 $\mathrm{d}\phi_{12}/\mathrm{d}t$ $\mathrm{d}\phi_{11}/\mathrm{d}t$ N_2

$$u_2 = e_{M2} = M\frac{\mathrm{d}i_1}{\mathrm{d}t} = N_2\frac{\mathrm{d}\phi_{12}}{\mathrm{d}t} \qquad (2\text{-}20)$$

(2-18) (2-20)

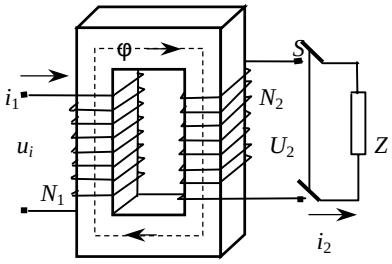
$$\frac{u_i}{u_2} = \frac{N_1}{N_2} = n = \frac{L_1}{M}$$

(2-21)

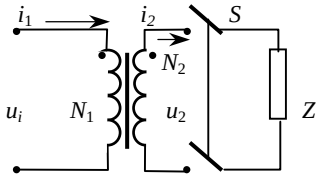
n=N_1/N_2 $M = \sqrt{L_1 L_2}$

$$n = \frac{L_1}{\sqrt{L_1 L_2}} = \sqrt{\frac{L_1}{L_2}} \qquad (2\text{-}22)$$

L_2 N_1



(a)



(b)

2-8

2.3.2

(2-8 S) i_2 u_2/Z

i_2 N_2 i_2N_2 ϕ_2 i_1N_1 ϕ_1

e_1 ϕ_{11t}=ϕ_1-ϕ_2 i_1 $i_{1t}N_1$

$$i_{1t}N_1 = i_1N_1 - i_2N_2 \qquad (2\text{-}23)$$

$$i_1 = i_{1t} + \frac{N_2}{N_1}i_2 = i_{1t} + i'_2 \qquad (2\text{-}24)$$

$$i'_2 = \frac{N_2}{N_1}i_2$$

(2-24)

$$i_1 = i'_2 = \frac{N_2}{N_1}i_2 \qquad (2\text{-}25)$$

2-8 (N_1) (N_2)

$$P_o = i_2 \times u_2$$

2-21 (2-25)

$$P_o = i_2 \times u_2 = \frac{N_1 i_1}{N_2} \cdot \frac{u_1 N_2}{N_1} = u_1 i_1 \qquad (2\text{-}26)$$

1.

2. i_{1m}

$i_{1m} N_1 = i_{2m} N_2$ i_{2m}

i_{1m} i_{2m} i_{1m} i_{2m}

3. i_{1m} $i_{1m} N_1 = i_{2m} N_2$

i_{1m}

2.3.3

1

$\mu = \infty$

2-25 2-21

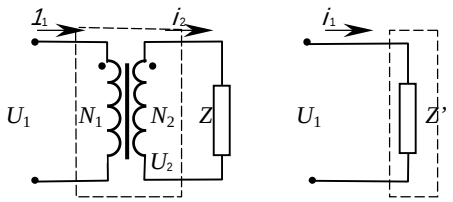
$$Z' = \frac{u_1}{i_1} = \left(\frac{N_1}{N_2}\right)^2 \frac{u_2}{i_2} = n^2 Z \qquad (2\text{-}27)$$

Z'

(2-24) (2-27)

2-9

(2)



(a) (b)

2-9

μ (2-24)

2-10(a)

2-5 φ_{12} φ_{11}

$$u_i = N_1 \frac{\mathrm{d}\phi_{11}}{\mathrm{d}t} = \frac{\mathrm{d}\Psi_s}{\mathrm{d}t} + N_1 \frac{\mathrm{d}\phi_{12}}{\mathrm{d}t} = u_s + u_1 \qquad (2\text{-}28)$$

$u_1 = N_1 \mathrm{d}\varphi_{12}/\mathrm{d}t$

$$u_2 = N_2 \frac{\mathrm{d}\phi_{12}}{\mathrm{d}t} = \frac{N_2 u_1}{N_1} \qquad (2\text{-}29)$$

$u_s = N_1 \mathrm{d}\varphi_s/\mathrm{d}t$

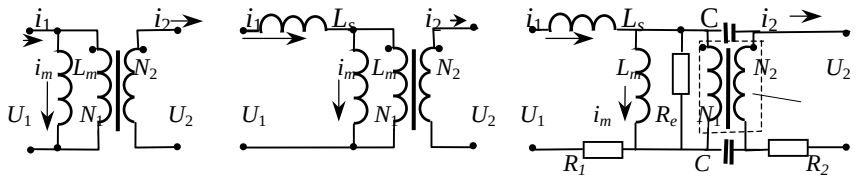
$$u_s = L_s \frac{\mathrm{d}i_1}{\mathrm{d}t} = \frac{\mathrm{d}\Psi_s}{\mathrm{d}t}$$

$$L_{1s} = \frac{\Psi_s}{i_1} \qquad (2\text{-}30)$$

i_1 2-28) L_s (2-10(b))

R_1 R_2

(C)



(a) (b) (c)

2-10

2-10(c)

●

●

1. 1985
2. 1990
3. Unitrode Magnetics Design Handbook -Magnetics Design for Switching Power Supplies Lloyd H. Dixon

第三章 磁路和电感计算

( )

3.1

( )

3.2

3-1(a) μ A l N I .

(1-7) (1-1) (1-3)

$$F = NI = Hl = \frac{Bl}{\mu} = \frac{\phi}{\mu A} l = \phi R_m \qquad (3\text{-}1)$$

$$\phi = F/R_m \qquad (3\text{-}2)$$

$F=NI$

$$R_m = \frac{l}{\mu A} \qquad (3\text{-}3a)$$

R_m— l

A μ

$$G_m = \frac{1}{R_m} = \frac{\mu A}{l} \qquad (3\text{-}3b)$$

(3-1)

3-1

SI / 1/ CGS /

3-1

F	E
ϕ	I
B	J
$R_m=l/\mu A$	$R=l/\gamma A$
$G_m=\mu A/l$	$G=\gamma A/l$
$U_m=Hl$	$U=IR$

U_m

$$U_m = \phi R_m = BA \times \frac{l}{\mu S} = Hl(\quad) \qquad (3\text{-}4)$$

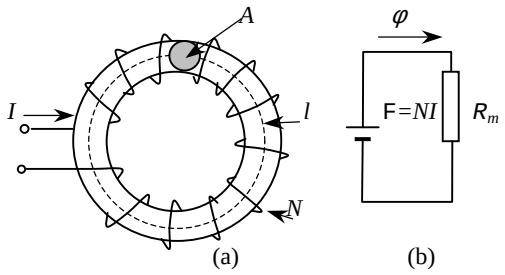
$$\sum \phi = 0 \qquad (3\text{-}5)$$

$$\sum IN = \sum \phi R \qquad (3\text{-}6a)$$

$$\sum IN = \sum Hl \qquad (3\text{-}6b)$$

(3-5)

(3-6)



3-1

(1)

(2)

10^{12} ( ) “ ” ( )

“ ”

(3)

μ

(4)

5

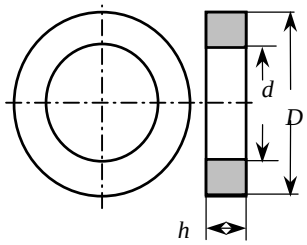
例 1 d=25mm D=41mm, h=10mm 1

μ_r μ/μ_0 50 N 50 0.5A

$$A = \frac{D-d}{2} \times h = \frac{41-25}{2} \times 10 = 80(\text{mm}^2) = 0.8(\text{cm}^2)$$

$$l=\pi\frac{D+d}{2}=\pi\frac{41+25}{2}=119.4(\text{mm})=11.94(\text{cm})$$

$$F=NI=50\times0.5=25(\text{A})$$



1

$$H_{\max}=\frac{F}{l_{\min}}=\frac{25}{\pi\times2.5}\approx3.2(\text{A/cm})$$

$$H_{\min}=\frac{F}{l_{\max}}=\frac{25}{\pi\times41}\approx1.94(\text{A/cm})$$

$$H=\frac{F}{l}=\frac{25}{11.94}\approx2.1(\text{A/cm})=210(\text{A/m})$$

$$B=\mu H=\mu_0\mu_r H=4\pi\times10^{-7}\times50\times210=0.0132T=132(\text{Gs})$$

$$\phi=BA=0.0132\times0.8\times10^{-4}=1.058\times10^{-6}(\text{Wb})=105.8(\text{Mx})$$

$$\phi=\frac{F}{R}=FG=IN\frac{\mu_0\mu_r A}{l}$$

$$\psi=N\phi=50\times1.058\times10^{-6}=5.29\times10^{-5}(\text{Wb})$$

0.8

3.3

3.3.1

3-2(a)

(1) 均匀绕线环形磁芯

( ) (x=0)

x x U_x

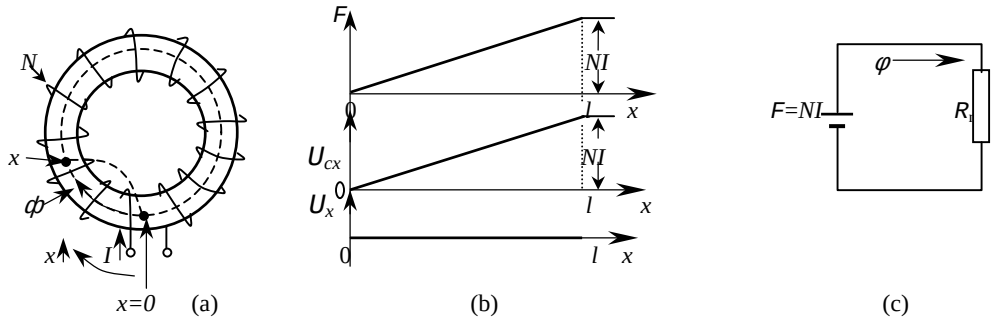
$F_x=U_{cx}+U_x$ (3-7)

F_x $0\rightarrow x$;

U_{cx} $0\rightarrow x$

x $N_x=Nx/l$ x

$$F_x=\frac{xN}{l}I \qquad (3\text{-}8)$$



3-2

$H=IN/l$

$$U_{cx}=\int_0^x H\mathrm{d}x=\frac{IN}{l}x \qquad (3\text{-}9)$$

IN— l— F_x U_{cx} 3-2(b)

3-2(b) U_{cx} F_x (3-7) x

$$U_x=F_x-U_{cx} \qquad (3\text{-}10)$$

F_x U_{cx} U_x , U_x (3-8)~(3-9)

(3-1) (3-3)

3-2(a) 3-2 c

(2) 集中绕线的等截面环形磁芯

3-3(a) l_w

F_x (3-3(b)) x $l_w/2$ $l-l_w/2$

H_x U_{cx} (3-9)

H_x U_{cx} 3-3 (b)

U_x (x=0 l/2) U_x ϕ_σ

3-3(c) x=0 $x=l/2$ 0

1-3~1-4 3-3(a)

3-3(a) x=0 x=0

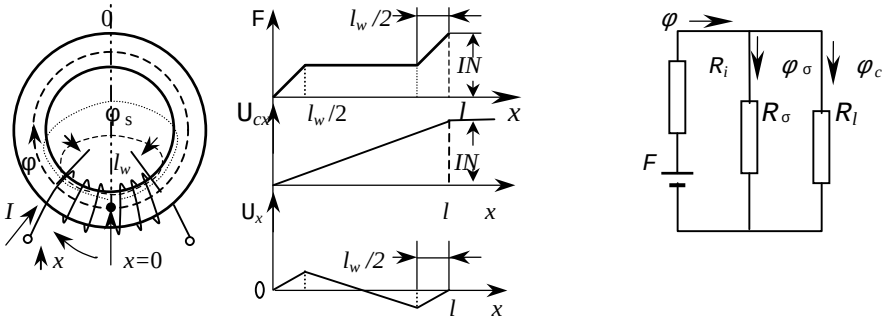
$x=l/2$ $+l_w/2$ $-l_w/2$

($\pm l_w/2$)

φ φ_c ϕ_σ

φ_c ϕ_σ “ ” ϕ_σ

ϕ_σ



(a) (b) (c)

3-3

3-3(c) $R_i = l_w / \mu A$ l_w $R_l=(l- l_w)/ \mu A$ l_k

R_s

(3) 有气隙时环形磁芯磁场

3-4(a) δ

$$F = IN = H_c l + H_\delta \delta$$

H_c H_δ

H_δ H_c $H_\delta\delta$

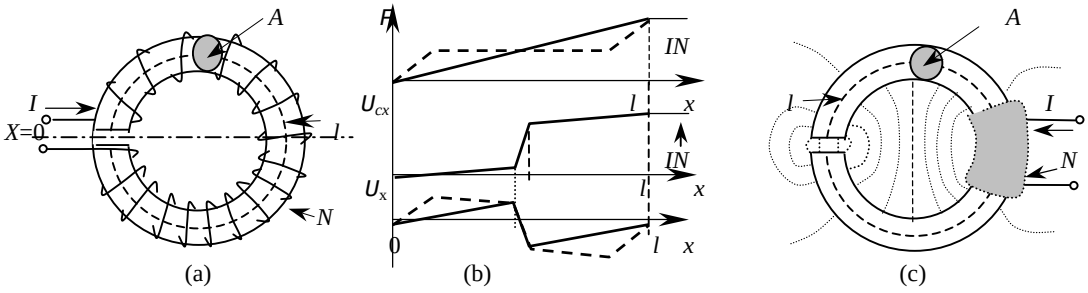
F $H_c l$ $H_\delta\delta$ 3-4(b)

H_c U_x ϕ_σ

3-4(c)) 3-4

b (c)

(b)



(a) (b) (c)

3-4

3.3.2 E

E C ETD EC RM

E “ E ”

E 3-5

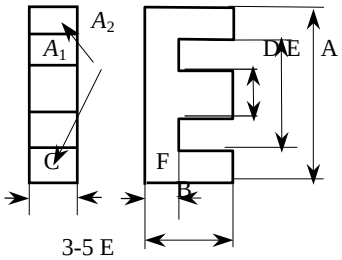
(1) 无气隙时等效磁路和磁位图

E 3-5

$A_1 = C \times D$

$A_2 = \dfrac{(A-E)}{2} \times C = \dfrac{A_1}{2}$

$A_3 = F \times C$



3-5 E

3-6(a)

N

$l_2 = 2B - F = l_1 \qquad l_3 = \dfrac{E}{2} + \dfrac{A-E}{4}$

$R_1 = \dfrac{l_1}{\mu A_1} \qquad R_2 = \dfrac{l_2}{\mu A_2} \qquad R_3 = \dfrac{l_3}{\mu A_3}$

$F=NI$ 3-6(b)

3-4

$R_2' = R_2/2 = l_2/2\,\mu A_2 \quad R_3' = R_3/2 = l_3/2\,\mu A_3$

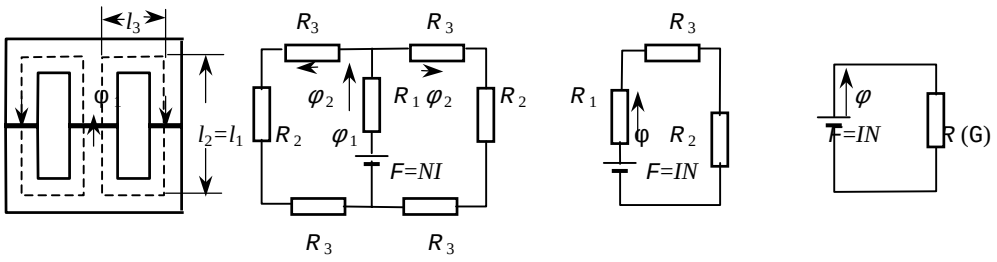
3-6(c)

$$\phi_1 = \frac{F}{R_1 + R_2 + 2R_3} \qquad \text{3-11a}$$

$A_1=2A_2=2A_3$, $R = R_1 + R_2' + 2R_3' = 2(l_1+l_3)/\mu A_1 = 1/G$ (3-11)

$$\phi_1 = \frac{F}{R} = \frac{\mu ANI}{2(l_1 + l_3)} = NIG \qquad \text{(3-11b)}$$

G 3-6(d)



(a) (b) (c) (d)

3-6 E

(2) 带气隙 E 型磁芯

E N,

$F=NI$

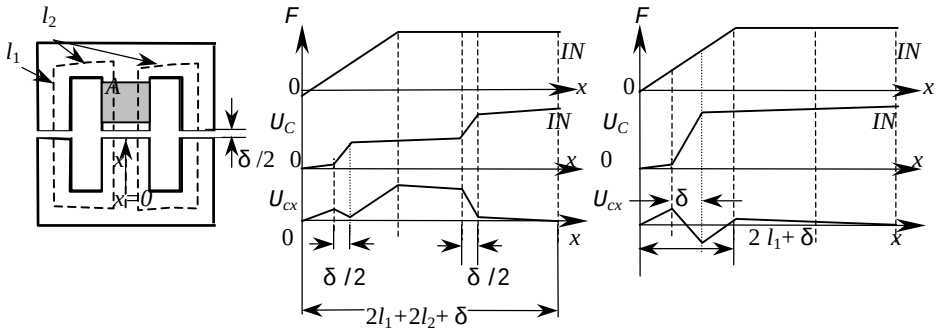
EE

3-3

3-7(b) 3-7(c) (b) (c) (b)

(c)

(b)



(a) (b) (c)

3-7 E

3.3.3

1 气隙尺寸相对端面尺寸很小时磁导计算

3-4 3-7 (<5%),

$$G_\delta = \frac{\mu_0 A}{\delta} \qquad (3\text{-}12)$$

E δ<<(*C*,*D*)

$$G_\delta = \frac{\mu_0 C \times D}{\delta}$$

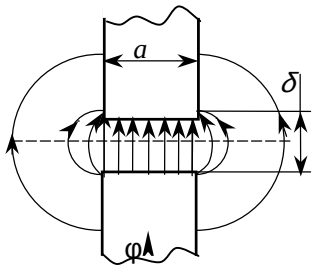
δ $G_{1\delta}$ ($G_{2\delta}$)

3-5

$$G_{1\delta} = \frac{\mu_0 C \times D}{\delta} \qquad G_{2\delta} = \frac{\mu_0 C (A-E)}{2\delta}$$

$$G = \frac{2 G_{1\delta} G_{2\delta}}{G_{1\delta} + 2 G_{2\delta}} \qquad (3\text{-}13)$$

(2) 气隙较大时，气隙磁导计算



3-8

3-8 3-12

A. 3-9

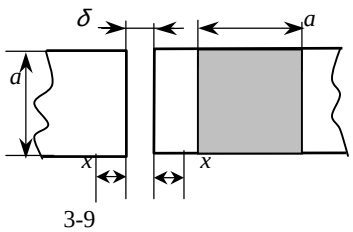
$$G = \mu_0 a \left(\frac{a}{\delta} + \frac{0.36}{2.4 + \delta / a} + \frac{0.14}{\ln(1.05 + \delta / a)} + 0.48 \right) \qquad (3\text{-}14a)$$

$\frac{\delta}{a} < 0.2$ $G = \mu_0 \frac{a^2}{\delta}$

x

$$G = \mu_0 \frac{xa}{0.17\delta + 0.4x} \qquad (3\text{-}14b)$$

x=2 3 δ (3-14),(3-14a)



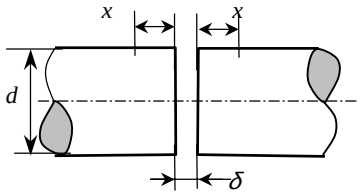
3-9

(3-14a) 3-14b

B. 3-10

$$G = \mu_0 d \left(\frac{\pi d}{4\delta} + \frac{0.36d}{2.4d + \delta} + 0.48 \right) \qquad (3\text{-}15a)$$

$$\frac{\delta}{d} < 0.2 \qquad G = \mu_0 \frac{\pi d^2}{4\delta}$$



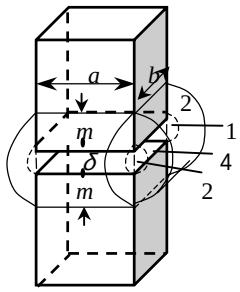
3-10

x

$$G = \mu_0 \frac{xd}{0.22d + 0.4x} \qquad (3\text{-}15b)$$

x=(2 3)δ

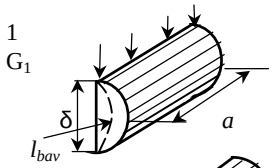
C.



3-11

$$G_{bk} = \mu_0 \frac{A_{bav}}{l_{bav}} = \mu_0 \frac{V_b}{l_{bav}^2} \qquad 3\text{-}16$$

A_{bav}— (m^2);l_{bav}—
(m);V_b— (m^3);k—



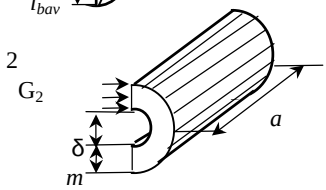
(a)

3-11

3-11 1 2 3 1/4 4 1/4

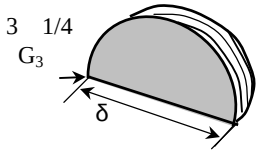
3-12

2 l_{bav}= π (δ +m)/2



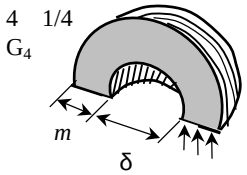
A_{bav}=$m \times a$ (3-16)

$$G_2 = \mu_0 \frac{A_{bav}}{l_{bav}} = \mu_0 \frac{m \times a}{\pi(\delta + m)/2} = \frac{2\mu_0 a}{\pi \frac{\delta}{m} + 1} \qquad (3\text{-}17a)$$



m=(1~2) δ

δ<3m , $G_2 = \mu_0 \frac{a}{\pi} \ln\left(1 + \frac{2m}{\delta}\right)$ (3-17b)



: $G_1 = \mu_0 \times 0.26a$ (3-18)

1/4 $G_3 = \mu_0 \times 0.077\delta$ 3-12

(3-19)

1/4 $G_4 = \mu_0 \times \frac{m}{4}$ (3-20)

3-12

$$G_0 = \frac{\mu_0 a^2}{\delta} \qquad (3\text{-}21)$$

$$G = G_0 + 4(G_1 + G_2 + G_3 + G_4)$$

$a \times b$ $m = \delta$

$$G = G_0 + 4(G_3 + G_4) + 2(G_{1a} + G_{2a} + G_{1b} + G_{2b})$$

$$= 4\mu_0 \left[\frac{a \times b}{4\delta} + \frac{m(a+b)}{\pi(\delta+m)} + 0.13(a+b) + 0.077\delta + \frac{m}{4} \right] \quad (3\text{-}22)$$

(b)

d δ

$$G = \mu_0 \left[\frac{\pi d^2}{4} + 1.63 \left(\frac{2d+\delta}{4} \right) + (d+\delta) \ln\left(1 + \frac{2m}{\delta}\right) \right] \quad (3\text{-}23)$$

(C)

3-4 3-7

a b A_{δ}

$$A_{\delta} = (a+\delta) \times (b+\delta) \quad (3\text{-}23a)$$

D :

$$A_{\delta} = \frac{\pi}{4}(D+\delta)^2 \quad (3\text{-}23b)$$

δ $0.1D$ A_{δ}/A 1.21 A

20

例2 E65 2 a 3mm δ 3mm

C=27mm D=19.8mm 2 a

m $m<(E-d)/2$ $m=1.5\delta$ (3-22)

$$G_{\delta} = 4\mu_0 \left[\frac{a \times b}{4\delta} + \frac{m(a+b)}{\pi(\delta+m)} + 0.13(a+b) + 0.077\delta + \frac{m}{4} \right]$$

$$= 4\mu_0 \left[\frac{19.8 \times 27}{4 \times 3} + \frac{3 \times 1.5(19.8+27)}{\pi \times 3(1+1.5)} + 0.13(19.8+27) + 0.077 \times 3 + \frac{3 \times 1.5}{4} \right] \times 10^{-3}$$

$$= 0.3062 \times 10^{-6} (\text{H})$$

3-12 3-23a

$$G = \mu_0 \frac{(a+\delta)(b+\delta)}{\delta} = \mu_0 \frac{(19.8+3)(27+3)}{3} \times 10^{-3} = 0.2865 \times 10^{-6} (\text{H})$$

μ_0 $4\pi \times 10^{-7}$H/m 10

例3 2 EE65 A=65mm B=32.6mm C=27mm D=19.8mm E=44.2mm

F=22.6mm μ $\mu_0 \times 2000$ N_1=25 N_2=5

400V T_{on}=3.6μs I_{2p}=30A

1.

2. $B_{\max}$

3. u_2

4.

0.05mm

解 (1) 3-7(a)

$$l_1=\frac{B+F}{2}=\frac{32.6+22.6}{2}=27.6\,\text{mm}=2.76\text{cm}=l_2$$

$$l_3=\frac{A+E-D}{4}=\frac{65+44.2-19.8}{4}=22.4\text{mm}=2.24\text{cm}$$

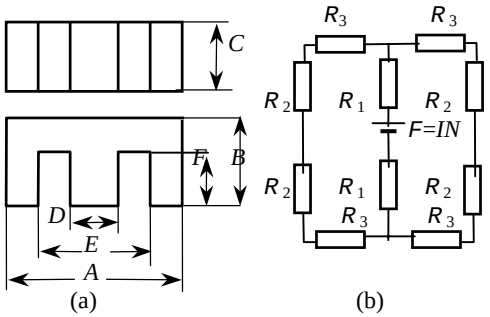
$$A_1=D\times C=1.98\times 2.7=5.35\text{cm}^2$$

$$A_2=\frac{A-E}{2}\times C=\frac{6.5-4.42}{2}\times 2.7$$

$$=2.81\text{cm}^2$$

$$A_3=(B-F)\times C=(3.26-2.26)\times 2.7$$

$$=2.7\text{cm}^2$$



(a) (b)

2 E

$$R_1=\frac{l_1}{\mu A_1}=\frac{2.76\times10^{-2}}{4\pi\times2000\times10^{-7}\times5.35\times10^{-4}}=2.045\times10^4\,(\text{H}^{-1})$$

$$R_2=\frac{l_2}{\mu A_2}=\frac{2.76\times10^{-2}}{4\pi\times2000\times10^{-7}\times2.81\times10^{-4}}=3.91\times10^4\,(\text{H}^{-1})$$

$$R_3=\frac{l_3}{\mu A_3}=\frac{2.24\times10^{-2}}{4\pi\times2000\times10^{-7}\times2.7\times10^{-4}}=3.3\times10^4\,(\text{H}^{-1})$$

R_1 R_2 R_3 2(b)

(2) 400V T_{on}=3.5 μ s 2-19

$$\phi_{11t}=\int_0^t\frac{u_i}{N_1}\text{d}t=\frac{U_1}{N_1}T_{on}=\frac{400}{25}\times3.5\times10^{-6}=56\times10^{-6}\,(\text{Wb})$$

$$B_{1\max}=\frac{\phi_{1t}}{A_1}=\frac{56\times10^{-6}}{5.35\times10^{-4}}=0.1047(\text{T})$$

( )

3. 2-21

$$u_2=\frac{u_1N_2}{N_1}=\frac{400\times5}{25}=80(\text{V})$$

4. 2-24

$$i_1=i_m+i_2\frac{N_2}{N_1}=i_m+i_2^{'}$$

$$i_2 = \frac{N_2}{N_1} i_2 = \frac{5}{25} \times 30 = 6(\mathrm{A})$$

(3-6)

$$i_m N_1 = 2R_1\phi_1 + (2R_3 + 2R_2)\phi_1 / 2$$

$$i_m = \frac{\phi_1}{N_1}(2R_1 + R_2 + R_3) = \frac{56\times10^{-6}}{50}(2\times 2.045+3.91+3.3) \times 10^4$$

=0.127(A)

$$i_1 = i_m + i_2^{'} = 0.127 + 6 = 6.127A$$

0.05mm

$$R_{\delta 2} = \frac{\delta}{\mu_0 A_2} = \frac{5\times10^{-5}}{4\pi\times10^{-7}\times2.81\times10^{-4}} = 14.2\times10^4(\mathrm{H}^{-1})$$

$$R_{\delta 1} = \frac{5\times10^{-5}}{4\pi\times10^{-7}\times5.35\times10^{-4}} = 7.44\times10^4(\mathrm{H}^{-1})$$

$$i_m = \frac{\phi_1}{N_1}(2R_1 + R_{\delta 1} + R_2 + R_3 + \frac{R_{\delta 2}}{2})$$

$$= \frac{56\times10^{-6}}{50}(2\times2.045 + 3.91 + 3.3 + 7.44 + 14.2/2)\times10^4$$

$$= 0.29(\mathrm{A})$$

50 μ m

$$i_1 = i_m + i_2^{'} = 0.29 + 6 = 6.29A$$

3.4

2-1

$$L = \frac{\psi}{i} \qquad (3\text{-}24)$$

3-24

ψ

3.4.1

A.

(1) 一定长度的导线电感

ψ

l(cm), d(cm), $\mu=\mu_0$

$$L_0 = 2l(\ln\frac{4l}{d} - 0.75) \times 10^{-7}(\text{H}) \qquad \text{3-25}$$

(l<100d) $d/2l$ (1GHz)

$$L_\infty = 2l(\ln\frac{4l}{d} - 1) \times 10^{-7}(\text{H}) \qquad \text{(3-25a)}$$

3-25

kHz 6 2

例4：求 1mm 50cm

解 (3-25)

$$L_0 = 2l(\ln\frac{4l}{d} - 0.75)\times 10^{-7} = 2\times 0.5\ \ln\frac{0.5}{0.001} - 0.75\ \times 10^{-7}$$

=0.546 μ H

2 单导线对大平面(地回路)之间电感(3-13)

d(m) l m , h(m),

$$L = 2l\ \ln\ \frac{l+\sqrt{l^2+d^2/4}}{l+\sqrt{l^2+4h^2}}\ + \ln\frac{4h}{d}\ \times 10^{-7}(\text{H})$$

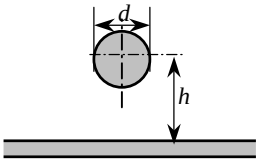
$$+2\left[\sqrt{l^2+4h^2} - \sqrt{l^2+d^2/4} + -2h + d/2\right] \times 10^{-7}(\text{H}) \qquad \text{(3-26)}$$

d<<l,

2h/l ≤ 1

$$L = 2l(\ln\frac{4h}{d} - p) \times 10^{-7}(\text{H}) \qquad \text{(3-26a)}$$

$$p = \frac{2h}{l} - 0.228\ \left(\frac{2h}{l}\right)^2$$



3-13

2h/l ≥ 1 $L = 2l(\ln\frac{4h}{d} - q) \times 10^{-7}(\text{H})$ (3-26b)

$$q = 1 + 0.5\frac{l}{2h} - 0.0352\ \left(\frac{l}{2h}\right)^2$$

p=2h/l

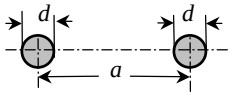
l>>h

$$L = 2l(\ln\frac{4h}{d}) \times 10^{-7}(\text{H}) \qquad \text{(3-26c)}$$

3 两根平行导线电感 3-14

l(m) d(m), a(m)

$$L = 4l\left(\ln\frac{2a}{d} - \frac{a}{l}\right) \times 10^{-7}(\mathrm{H}) \qquad (3\text{-}27)$$



3-14

例5 25 2.5mm, 15cm

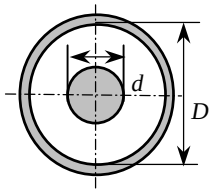
(3-27)

$$L = 4l\left(\ln\frac{2a}{d} - \frac{a}{l}\right) \times 10^{7} = 4\times 25\left(\ln\frac{2\times 15}{0.25} - \frac{0.15}{25}\right) \times 10^{-7}$$
$$= 47.8(\mu\mathrm{H})$$

(4) 单根同轴电缆的电感(3-15)

$$L = 2l\left(\ln\frac{D}{d} + 0.25\right) \times 10^{-7}(\mathrm{H}) \qquad (3\text{-}28)$$

D d l



3-15

B

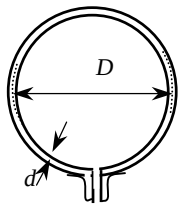
1 d m D m 3-16

$$L = 2\pi D\left(\ln\frac{8D}{d} - 2\right) \times 10^{-7}(\mathrm{H}) \qquad (3\text{-}29)$$

(2) b(m)

$$L = 2\pi D\left(\ln\frac{4D}{b} - 0.5\right) \times 10^{-7}(\mathrm{H}) \qquad (3\text{-}30)$$

(3)



3-16

$$L_c = 2l\left(\ln\frac{4l}{d} - C\right) \times 10^{-7}(\mathrm{H}) \qquad (3\text{-}31)$$

l m

d

C C=2.451 C=2.853 C=3.197

C

(1)

$$L = kN^2 D \times 10^{-7}(\mathrm{H}) \qquad (3\text{-}32)$$

D m

l (m);

k D/l ,

$$k = a\ln\frac{D}{l} + b\frac{D}{l} + C \qquad (3\text{-}32a)$$

a b c 3-2 5%

例 6 1.6mm 1 20 2cm 4cm

D/l 1 k a=1.2317 b=3.745 c=3.05 3-32a

3-2 k			
D/l	a	b	c
<1	1.2317	3.745	3.05
1 4.5	4.663	0.3803	6.4147
4.5 100	6.135	0.007	5.71

$$k = a\ln\frac{D}{l} + b\frac{D}{l} + c$$

$=1.232 \times \ln 0.5 + 0.5 \times 3.744 + 3.05 = 4.08$

3-32

$L = kN^2 D \times 10^{-7}$ $4.07 \times 20^2 \times 0.02 \times 10^{-7} = 3.256$ μH

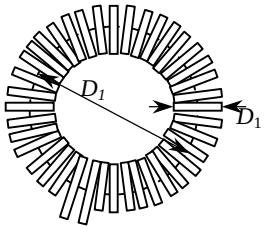
(2) 3-17

D_1 D_2 N

$$L = 2\pi N^2 \left(D_2 - \sqrt{D_2^2 - D_1^2}\right) \times 10^{-7} \text{ (H)} \qquad (3\text{-}33)$$

D_1/D_2 0.1

$$L = \frac{\pi N^2 D_1^2}{D_2} \times 10^{-7} \text{ (H)} \qquad (3\text{-}33a)$$



3-17

(3) 3-18

$$L = 2N^2 h \ln\frac{D}{d} \times 10^{-7} \text{ (H)} \qquad (3\text{-}34)$$

h (m)

d (m)

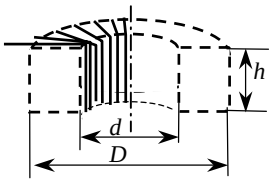
D (m)

(4) 3-19

N D w

$$L = DN^2 k \times 10^{-7} \text{ (H)} \qquad (3\text{-}35)$$

$$k = 6.194(\ln\frac{D}{w} + 0.92) \qquad (3\text{-}35a)$$



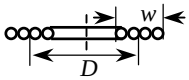
3-18

例 7 5cm, 1cm,

25

(3-35a)

$k = 6.194(\ln\frac{D}{w} + 0.92) = 6.194 \times (\ln 5 + 0.92) = 15.667$



3-19

(3-35)

$L = DN^2 k \times 10^{-7}$ $0.05 \times 25^2 \times 15.667 \times 10^{-7}$ 48.96 μH

(5)

l_1 l_2 $g = \sqrt{l_1^2 + l_2^2}$, N d

D(3-20)

$$L = 4N^2 \ (l_1 + l_2)\ln\frac{2l_1 l_2}{DN} - l_1 \ln(l_1 + g) - l_2 \ln(l_2 + g) + 2g - \frac{l_1 + l_2}{2} + 0.447ND$$

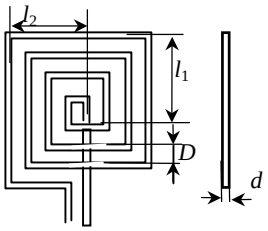
$$-4N(l_1+l_2)(A+B) \qquad (3\text{-}36)$$

A d/D

$$A=\ln\frac{d}{D}+0.557 \qquad (3\text{-}36a)$$

B N

$$B=0.33\left(0.98-e^{-N/4.95}\right) \qquad (3\text{-}36b)$$



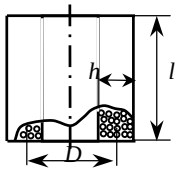
3-20

D.

(1) 长圆柱形线圈低频电感

3-21 l h

$$L=N^2D\ k-\frac{2\pi h}{l}\left(0.693+C\right)\ \times 10^{-7}\text{(H)} \qquad (3\text{-}37)$$



3-21

N

D (m)

k D/l (3-32a)

h (m) l (m)

C l/h

$$C=0.32\ \left(1-e^{-\frac{l}{4.2h}}\right) \qquad (3\text{-}37a)$$

2 矩形截面的多层线圈电感 3-22

$$L=4N^2\left(l_1+l_2\right)\ \ln\frac{2l_1l_2}{b+c}-\frac{l_1}{l_{21}+l_2}\ln\left(l_1+g\right)-\frac{l_2}{l_1+l_2}\ln\left(l_2+g\right)+\frac{2g}{l_1+l_2}-\frac{1}{2}+0.447\frac{b+c}{l_1+l_2}$$

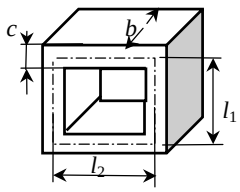
$\times 10^{-7}$(H) (3-38)

N

l_1 l_2 m

b c (m)

$g=\sqrt{l_1^2+l_2^2}$ (m)



3-22

E.

(1)

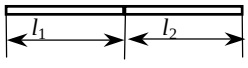
D cm l(m) D

$$M=2l\ \ln\frac{2l}{D}-1+\frac{D}{l}\ \times 10^{-7}\text{(H)} \qquad (3\text{-}39)$$

(2) 3-23

l_1 m l_2(m),

$$M=l_1\ln\frac{l_1+l_2}{l_1}+l_2\ln\frac{l_1+l_2}{l_2}\times 10^{-7}\text{(H)} \qquad (3\text{-}40)$$



3-23

D(m)

$$M=\left[\left(l_1+l_2+D\right)\ln\left(l_1+l_2+D\right)+D\ln D\right]\times 10^{-7}$$
$$-\left[\left(l_1+D\right)\ln\left(l_1+D\right)+\left(l_2+D\right)\ln\left(l_2+D\right)\right]\times 10^{-7}\quad \text{H} \qquad (3\text{-}41)$$

(3) (3-24)

l_1(m) l_2(m) D(m)

$$M = 2\ 2l_1 \cdot \ln\ \frac{l_1 + l_2 + \sqrt{(l_1 + l_2)^2 + D^2}}{D}\ + (l_1 + l_2)\ln\ \frac{l_1 + l_2 + \sqrt{(l_1 + l_2)^2 + D^2}}{l_2 - l_1 + \sqrt{(l_2 - l_1)^2 + D^2}}\ \times 10^{-7}$$

$$+\ \sqrt{(l_1 - l_2)^2 + D^2} - \sqrt{(l_1 + l_2)^2 + D^2}\ \times 10^{-7}\quad \text{H} \qquad (3\text{-}42)$$

例 8 1cm 50cm 45cm

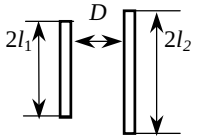
(3-42)

$$L_1 = \sqrt{(l_1 + l_2)^2 + D^2} = \sqrt{(0.45 + 0.50)^2 + 0.01^2} = 0.95m$$

$$L_2 = \sqrt{(l_2 - l_1)^2 + D^2} = \sqrt{(0.50 - 0.45)^2 + 0.01^2} = 0.051m$$

$$L_3 = l_1 + l_2 = 0.95m$$

$$L_4 = l_2 - l_1 = 0.05m$$



3-24

代入式(3-42)

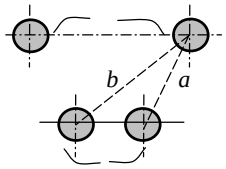
$$M = 2\ 2l_1 \times \ln\ \frac{L_3 + L_1}{D}\ + L_3 \ln\ \frac{L_3 + L_1}{L_2 + L_4}\ +\ \frac{L_3 - L_4}{2}\ \times 10^{-7}$$

$$= 2\ 2 \times 0.45 \times \ln\frac{0.95 + 0.95}{0.01} + 0.95\ln\frac{0.95 + 0.95}{0.05 + 0.051} + \frac{0.95 - 0.05}{2}\ \times 10^{-7}$$

$$= 1.6 \times 10^{\ 6}\quad \text{H}$$

(4) l 3-25

$$M = 4l \cdot \ln\frac{b}{a} \qquad (3\text{-}43)$$



3-25

(5) 3-26

$$M = \xi\sqrt{r_1 r_2} \times 10^{-7}\ (\text{H}) \qquad (3\text{-}44)$$

r_1 r_2 (m)

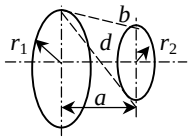
ξ b/d ;

d b

$$b = \sqrt{a^2 + (r_1 - r_2)^2} \qquad d = \sqrt{a^2 + (r_1 + r_2)^2}$$

$$\xi = m + n\frac{b}{d} + p\ \left(\frac{b}{d}\right)^{1.5} \qquad (3\text{-}44a)$$

m n p 3-3 7



3-26

(6) $l_1 \times l_2$ D

3-3 ζ

	0.01`0.1	0.1~0.5	0.5~0.99
m	57.69	32.59	18.04
n	796	153	52.6
p	4439	135.4	34.6

,

$$M = 4\ l_1\ \ln\frac{l_1 + \sqrt{l_1^2 + D^2}}{l_1 + \sqrt{l_1^2 + l_2^2 + D^2}} \times \frac{\sqrt{l_1^2 + D^2}}{D}\ + l_2\ \ln\frac{l_2 + \sqrt{l_2^2 + D^2}}{l_2 + \sqrt{l_1^2 + l_2^2 + D^2}} \times \frac{\sqrt{l_2^2 + D^2}}{D}$$

$$\times 10^{-7} + 8\left(\sqrt{l_1^2 + l_2^2 + D^2} - \sqrt{l_1^2 + D^2} - \sqrt{l_2^2 + D^2} + D\right) \times 10^{-7}\,(\mathrm{H}) \qquad 3\text{-}45$$

(3-45) $l_1=l_2$ l 3-45

(7) 3-27

$$M = \left(M_{15} + M_{26} + M_{37} + M_{48} - M_{17} - M_{28} - M_{35} - M_{46}\right) \times 10^{-7}\,(\mathrm{H}) \quad (3\text{-}46)$$

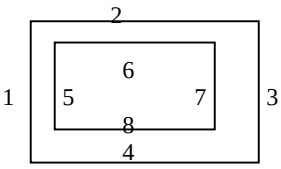
$M_{15}=M_{37}$, $M_{26}=M_{48}$, $M_{17}=M_{35}$, $M_{28}=M_{46}$,

$$M = 2\left(M_{15} + M_{26} - M_{17} - M_{28}\right) \times 10^{-7}\,(\mathrm{H}) \qquad (3\text{-}47)$$

3-24

(8) ( )((3-28))

$2l_1$ $2l_2(l_1<l_2)$, r_1 r_2 $r_1< r_2$



3-27

$$M = 2\pi^2 \frac{r_1^2 N_1 N_2}{g}\left(1 + \frac{r_2^2 r_1^2}{8g^4}\left(3 - 4\frac{l_1^2}{r_1^2}\right)\right) \times 10^{-7}\,(\mathrm{H}) \qquad (3\text{-}48)$$

$$g = \sqrt{r_2^2 + l_1^2}$$

$$k = \frac{r_1^2 \times l_1}{r_2^2 l_2}$$

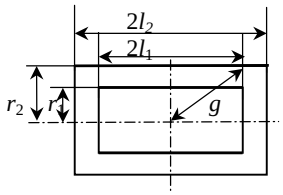
l_2 (l_1),

(9) 3-29

N_1 N_2 r_1 r_2

$$M = N_1 N_2 M_0 \qquad (3\text{-}49)$$

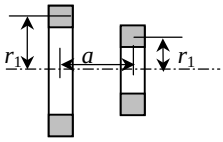
M_0 (3-44)



3-28

3.4.2

ψ $N\varphi$ $iN = \phi R_\Sigma$. R_Σ - (3-24)



3-29

$$L = \frac{\psi}{i} = \frac{N\phi}{\phi R_\Sigma / N} = N^2 \frac{1}{R_\Sigma} = N^2 G_\Sigma \qquad 3\text{-}50$$

A.

3-30(a) μ_r A

l

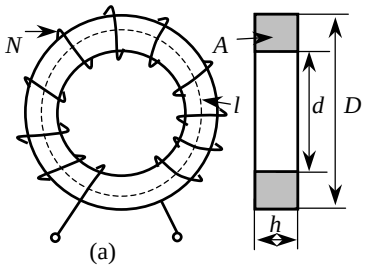
$$L = \frac{\psi}{i} = \frac{NBA}{lH / N} = N^2 \frac{\mu_0 \mu_r A}{l} = N^2 G \qquad (3\text{-}51)$$

例 9: 3-30 a d=2cm D=4cm h=1cm

40 . 100μH

:

$$l=\pi\frac{(D+d)}{2}=\pi\frac{4+2}{2}=3\pi(cm)\qquad 0.03\pi(\mathrm{m})$$



(a)

$$A=\frac{D-d}{2}h=\frac{4-2}{2}\times 1=1(cm^2)\qquad 10^{-4}(\mathrm{m}^2)$$

(3-51)

$$\mu_r=\frac{Ll}{N^2S\mu_0}=\frac{100\times10^{-6}\times0.03\pi}{40^2\times10^{-4}\times4\pi\times10^{-7}}\approx 47$$

m $\mu_0=4\pi\times10^{-7}$(H/m), cm $\mu_0=0.4\pi\times10^{-8}$(H/cm)

(b)

B.

3-31(a) δ 3-30

3-31(b)

$$L=N^2\frac{1}{\mathrm{R}_c+\mathrm{R}_\delta}$$

$$\mathrm{R}_c=\frac{l_c-\delta}{\mu A_c}\approx\frac{l_c}{\mu_0\mu_r A_c},\mathrm{R}_\delta=\frac{\delta}{\mu_0 A_\delta}.\qquad R_c<<R_\delta$$

$$L=N^2G_\delta$$

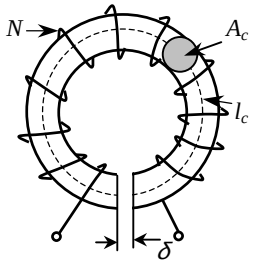
G_δ

例 10 E 2 δ 3mm

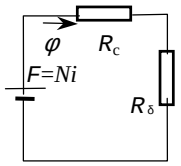
25

2

G_δ= =0.3062 × 10^{-6}(H)



(a)



(b)

3-31

$$\mathrm{R}_\delta=\frac{1}{\mathrm{G}_\delta}=\frac{1}{0.3062\times10^{-6}}=3.27\times10^6\ (\mathrm{H}^{-1})$$

5

$$\mathrm{R}_c=2\mathrm{R}_1+\mathrm{R}_2+\mathrm{R}_3$$

$$=(2\times2.045+3.91+3.3)\times10^4(\mathrm{H}^{-1})=11.3\times10^4\ (\mathrm{H}^{-1})$$

$$L=N^2\frac{1}{\mathrm{R}_c+\mathrm{R}_\delta}$$

$$=25^2\frac{1}{3.27+0.113}\times10^{-6}=0.185\times10^{-3}(H)$$

$$L=N^2\frac{1}{\mathrm{R}_\delta}=N^2\mathrm{G}_\delta=25^2\times0.3062\times10^{-6}$$

=0.191 × 10^{-3} H

$$L=N^2\frac{\mu_0 A}{\delta}=25^2\times4\times\pi\times10^{-7}\frac{2.7\times1.98}{0.3}\times10^{-2}$$

$=0.1336 \times 10^{-3}(H)$

本章要点：

-
- “ ” (
)
-
-
- 10
-

1. 1981
2. Электромагниты Постоянного Тока АВ Гордон АГСливинская 1960 МОСКВА
3. 1954
4. Unitrode Magnetics Design Handbook Magnetics Design for Switching Power Supplies Lloyd H. Dixon

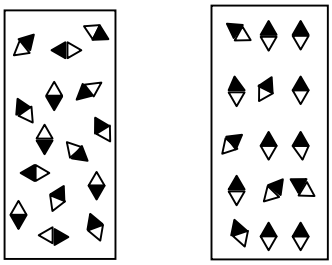
第四章 软磁材料

“ ”

“ ”

/ ( )

4.1



(a) (b)

4-1 (a)

(b)

—

(

4-1(a))

(4-1(b))

4.2

4.2.1

B

H B-H 4-2(e) C

4-2(a)

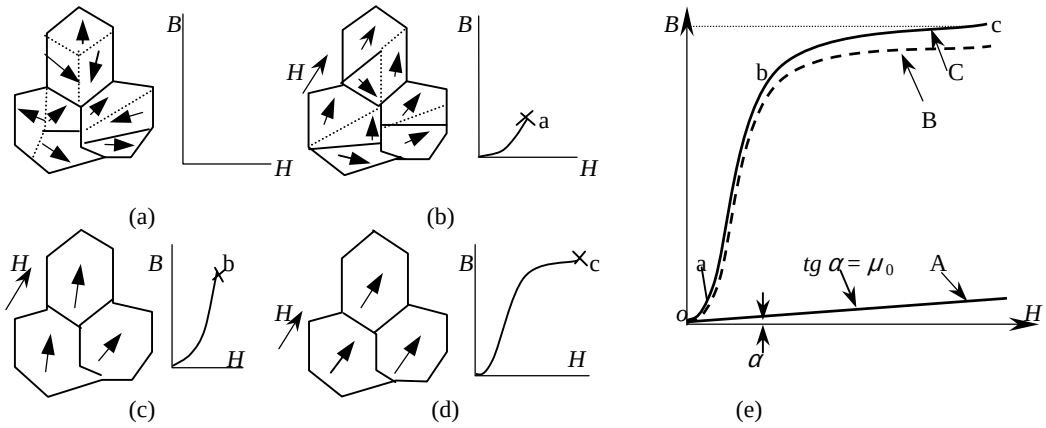
(4-2(*b*)) *B* (4-2 e oa) *H*

B ao “ ”

“ ” 4-2(c) *B* *H*

ab ab

B ba



4-2

b

B b

(4-2 d) (c)

B

B H

$$B = J + \mu_0 H \qquad (4\text{-}1)$$

μ_0— *J*— *J*(

) (

4-2(e) B) (4-2(e) A)

H *B* (4-2(e) C)

4.2.2

OS B_s 4-3

H *B* (OS) *B*

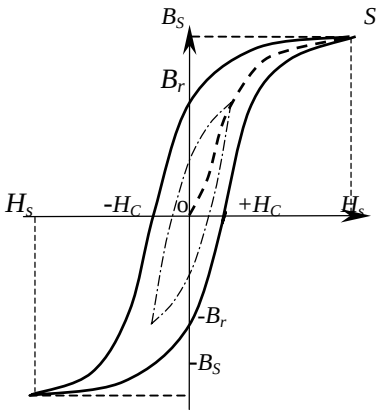
H=0 *B*≠0

B_r *B*

H

B

-*H* $-H_c$ *B*=0



4-3

-*H* *B*

$-H_s$ $B=-B_s$

-*H*=0,*B*= $-B_r$ $-B_r$ H_C *H* H_s

B B_s

$H_s \rightarrow 0 \rightarrow -H_C \rightarrow -H_s \rightarrow 0 \rightarrow H_C \rightarrow H_s$, , $B_s \rightarrow B_r \rightarrow 0 \rightarrow -B_S \rightarrow -B_r \rightarrow 0 \rightarrow B_s$ O (4-3)

4-3

1. 饱和磁感应强度 B_S

(25 100)

(, μ_r=100) B

2. 剩余磁感应强度 B_r

B_r

3. 矫顽力 H_c

B $-H$

$H_{.c}$

H_s B H

B_r H_c

H 0

H_c

,

“ ”

4.3

(P) (P_h)

(P_e) (P_c)

$P_c=P_h+P_e+P_c$

4.3.1 P_h

‘ ’

(4-4(a)) 4-4(b)

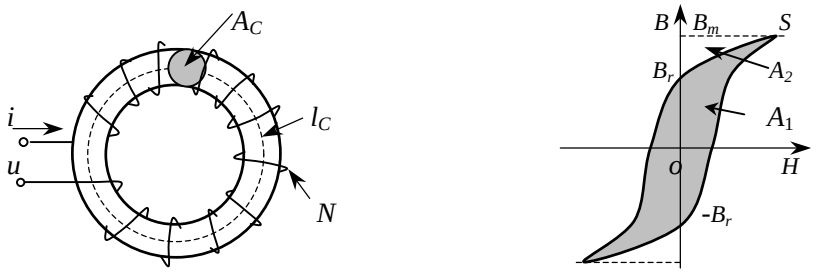
A_c l_c N u t) $i(t)$

(1-7)

$$H=\frac{iN}{l_c} \qquad i=\frac{Hl_c}{N}$$

(1-10)

$$u=N\frac{d\phi}{dt}=NA_c\frac{dB}{dt}$$



(a) (b)

4-4

$$\int_{\alpha}^{\alpha+T/2}ui\mathrm{d}t=\int_{-B_r}^{B_r}NA_c\frac{\mathrm{d}B}{\mathrm{d}t}\cdot\frac{Hl_c}{N}\mathrm{d}t=V\int_{-B_r}^{B_r}H\mathrm{d}B$$

$$=V(\int_{-B_r}^{B_s}H\mathrm{d}B-\int_{B_s}^{B_r}H\mathrm{d}B)=V\times(A_1-A_2) \qquad (4\text{-}2)$$

$V=A_cl_c$

A_1 $-B_r$ B_m $-B_r$ S B_m $-B_r$

$V\times A_1$

A_2 B_m B_r

$V\times A_2$

$V\times(A_1 \quad A_2)$ $-B_r$—S—B_r

4.3.2 P_e

φ 4-5 a φ

u_1

$$u_1=N_1\frac{\mathrm{d}\phi}{\mathrm{d}t}$$

$$\frac{u_1}{N_1}=\frac{\mathrm{d}\phi}{\mathrm{d}t} \qquad (4\text{-}3)$$

i_e

$i_e^2 R$ 4-3

50V

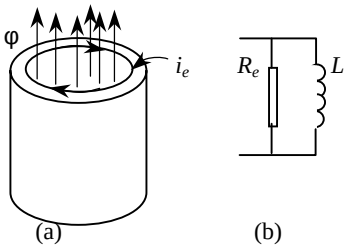
10μS 100V 5μS ΔB

4

i_e “ ”

R_e

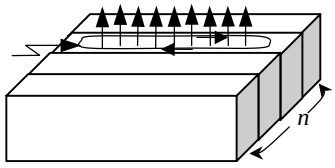
4-5(b)



4-5

1/e Δ

$$\Delta = \sqrt{\frac{\rho}{\pi \mu_0 \mu_r f}} \text{ (m)} \qquad 4\text{-}4$$



4-6

ρ Ω-m

μ_r

f Hz

ρ 55×10^{-4} Ω-m μ_r=30000

(4-4)

$$\Delta = \sqrt{\frac{\rho}{\pi \mu_0 \mu_r f}} = \sqrt{\frac{55 \times 10^{-4}}{4\pi^2 \times 10^{-7} \times 3 \times 10^4 f}} = \frac{0.22}{\sqrt{f}} \text{ (cm)} \qquad (4\text{-}5)$$

10kHz

$$\Delta = \frac{0.22}{\sqrt{f}} = \frac{0.22}{\sqrt{10^4}} = \frac{0.22}{100} = 0.022\text{mm}$$

2Δ $2 \times 0.022 \approx 0.05$mm

ρ =20Ω-m μ_r 1500

$$\Delta = \frac{5800}{\sqrt{f}} \quad \text{cm}$$

100kHz Δ=18cm

1

n

4-6 1/n

$R = \rho l/A$, ρ A l

A/n 1/2

1/n $n^2/2$

4.3.3 P_c

‘

’

ΔB_{m}

(50Hz) B_m P_h P_e

$$P_T = \eta f B_m^{1.6} V \qquad (4\text{-}6)$$

η— f— B_m— V—

200 300kHz

$$P_T = \eta f^{\alpha} B_m^{\beta} V \qquad (4\text{-}6a)$$

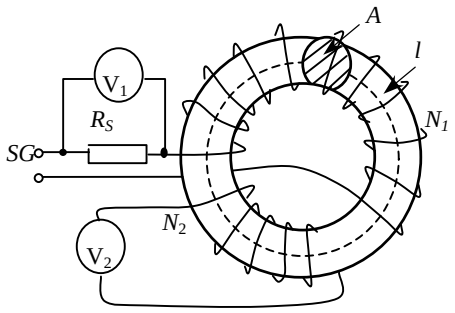
α β 1

4.4

EE42

1-10 1-7

4.4.1



4-7

4-7

N_1 N_2 A

l

R_s V_1

V_2

SG 3W

N_1 V_1 U_1 V_1 U_2

U_2

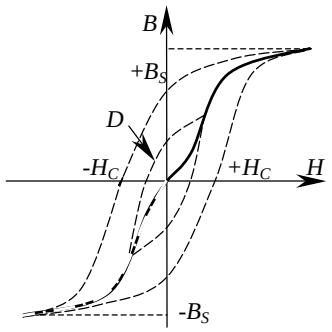
$$B = \frac{U_2}{4.44 f A N_2} = k_2 U_2 (\mathrm{T}) \qquad (4\text{-}7)$$

U_1

$$H = \frac{N_1 I}{l} = \frac{N_1}{l} \frac{\sqrt{2} \cdot U_1}{R_s} = k_1 U_1 (\mathrm{A/m}) \qquad (4\text{-}8)$$

$k_1 = \sqrt{2} N_1 / l R_s$ $k_2 = 1/(4.44 f A N_2)$ m B H 4-8

4-8



4-8

4-8

, SG

(<1Ω)

0.5% 1% V2

N2 Rs

4-8

U1 √2

U1 U1p (4-8) √2 U1 U1p

4.4.2

(1) 磁化曲线显示电路和原理

4-9

Rs

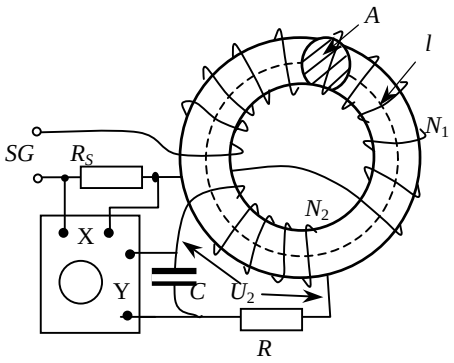
4-8 H

$$H(t)=\frac{N_1 i(t)}{l}=\frac{N_1}{l}\frac{u(t)}{R_s}=k_3 u_1(t)(\mathrm{A/m}) \qquad 4\text{-}9$$

$k_3 = N_1 / lR_s$

Rs X

X A/div



4-9

RC

Y

$R>>1/\omega C$

$$i_c \approx \frac{U_{2m}\sin\omega t}{R}=C\frac{\mathrm{d}u_c}{\mathrm{d}t} \qquad U_{2m}\sin\omega t = RC\frac{\mathrm{d}u_c}{dt} \qquad (4\text{-}10a)$$

$$U_{2m}\sin\omega t = N_2 A\frac{\mathrm{d}B}{\mathrm{d}t} \qquad 4\text{-}10b$$

4-10a 4-10b ,

$$B(t)=\frac{RC}{N_2 A}U_c(t)=k_4 U_c(t)$$

$k_4 = RC / N_2 A$

Y Y

Y T/div

2

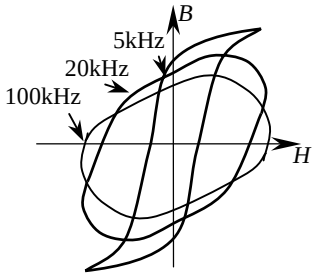
( ) —

H_m

B H

B

4-10



4-10

,

4.5 相对磁导率μ_r

(1-3) 4-11

$$\mu = \frac{B}{H}$$

μ μ_0

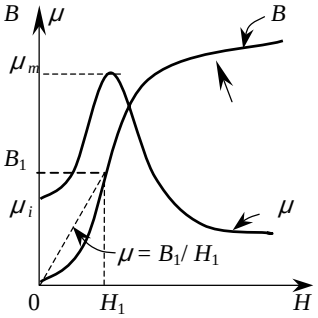
μ_r

$$\mu_r = \frac{\mu}{\mu_0} \quad (4\text{-}11)$$

μ B-H

B H

$$\mu_r = \frac{B}{\mu_0 H} = \frac{\mu}{\mu_0} \quad (4\text{-}12)$$



4-11 $B,\mu=f(H)$

4.5.1 μ_m

4-11 μ μ_r

μ_m

4.5.2 μ_i

$H \to 0$ μ_i

$$\mu_i = \frac{1}{\mu_0}\frac{\Delta B}{\Delta H}(H \to 0) \quad (4\text{-}13)$$

μ_i DIN IEC401 μ_i

f≤10kHz B<0.25mT,T=25

4.5.3 μ_Δ

(4-12), μ_Δ

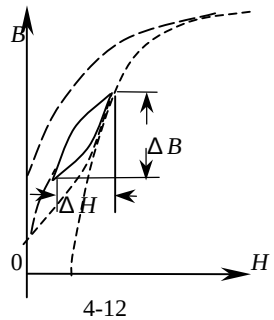
$$\mu_\Delta = \frac{1}{\mu_0}\frac{\Delta B}{\Delta H}\bigg|_{H_-}$$

4-14

(μ_{rev})

4.5.4 μ_e

(μ_r=1)



4-12

μ_i>>1)

δ (4-13(a)) A_c

l_c N I δ

$$NI = H_\delta \delta + H_c l_c$$

H_δ H_c

$$\phi = B_c A_c = B_\delta A_\delta$$

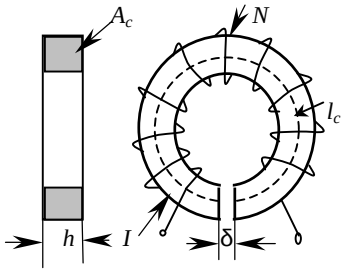
B_c=B_δ

$$NI = \frac{B_c}{\mu_0 \mu_r} l_c + \frac{B_\delta}{\mu_0} \delta = \frac{B_c l_c}{\mu_0 \mu_r} (1 + \frac{\mu_r \delta}{l_c}) = \frac{B_c l_c}{\mu_0 \mu_e} \quad (4\text{-}15)$$

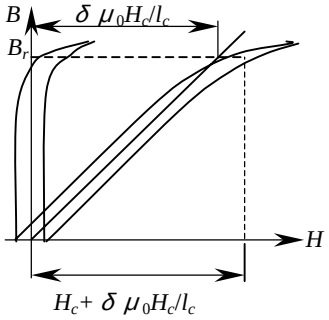
$$\mu_e = \frac{\mu_r}{1 + \frac{\mu_r \delta}{l_c}} = \frac{1}{\frac{1}{\mu_r} + \frac{\delta}{l_c}} \quad (4\text{-}16)$$

μ_e μ_r>>l_c/δ

$$\mu_e = l_c / \delta \quad (4\text{-}17)$$



(a)



(b)

4-13 (a) (b)

(4-15)

$$NI = \frac{B_c l_c}{\mu_0 \mu_e} = H_c (l_c + \mu_r \delta)$$

H_c=$B_c/\mu_0\mu_r$

H_c, H'_δ=$\mu_r\delta/l_c$,

4-13(b)

4-13 b

“ ”

(B_r)

4.5.5 (μ_a)

μ_a

$$\mu_a = \frac{1}{\mu_0}\frac{B_p}{H_p} \qquad (4\text{-}18)$$

4.6

4.6.1

(1) 磁导率要高

$B=\mu H$ (H) B μ ，μ $(\phi \propto BS)$ μ

μ_i

μ_{max}

(2) 要求具有很小的矫顽力 H_c和狭窄的磁滞回线

(3) 电阻率 ρ 要高

(4) 具有较高的饱和磁感应强度 B_s

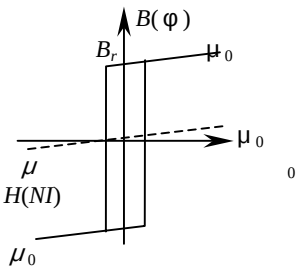
4.6.2

60000 0.6T~1.9T

(4-14),

(4-4)

，



4-14

$$k_c = \frac{A_e}{A} = \frac{nA_c}{A}$$

A_e

A_c

n

A n

$$A_e = k_c A \qquad (4\text{-}19)$$

k_c k_c 4-1

4-1

(mm)	0.35~0.20	0.1~0.08	0.05	0.025	0.01
k_c	0.95~0.9	0.9~0.85	0.8~0.7	0.75~0.65	0.65~0.5

4-1 k_c

0.01mm 0.5 0.6

ΔB

100 200kHz

1 硅钢片

B_s

4-2 YB901-78

GB11255-89

DQ DG D Q 50Hz G 400Hz

4-2 (a)

	(mm)	B(T)						P(W/kg)		H_c(A/m)
		$B_{0.4}$	$B_{0.8}$	B_2	B_4	B_{10}	B_{25}	$P_{1/400}$	$P_{1.5/400}$	
DG1	0.05	0.60	0.90	1.20	1.35	1.55	1.70	10.0	21.0	0.36
DG2	0.05	0.80	1.00	1.30	1.42	1.60	1.75	8.5	19.0	0.34
DG3	0.05	0.85	1.10	1.40	1.50	1.66	1.82	7.5	16.0	0.32
DG4	0.05	0.90	1,20	1.50	1.57	1.70	1.84	7.0	15.0	0.32
DG1	0.08 0.10	0.60	0.90	1.20	1.35	1.55	1.70	10.0	22.0	0.36
DG2	0.08 0.10	0.80	1.00	1.30	1.42	1.60	1.75	8.5	19.0	0.32
DG3	0.08 0.10	0.90	1.10	1.40	1.50	1.66	1.82	7.5	17.0	0.28
DG4	0.08 0.10	1.00	1.20	1.50	1.57	1.70	1.84	7.0	16.0	0.26
DG1	0.20	0.60	0.90	1.20	1.35	1.55	1.70	12.0	27.0	
DG2	0.20	0.80	1.00	1.30	1.42	1.60	1.75	11.0	25.0	
DG3	0.20	0.90	1.10	1.40	1.50	1.66	1.82	10.0	23.0	
DG4	0.20	1.00	1.20	1.50	1.57	1.70	1.84	9.0	21.0	

Hc ρ 0.20mm $B_{0.4}$ $B_{0.8}$ B_2

4-2(b)

	(mm)	*B*(T)				P(W/kg)		
		B_5	B_{10}	B_{25}	B_{50}	$P_{1/50}$	$P_{1.5/50}$	$P_{1.7/50}$
DQ1	0.35	1.50	1.57	1.70	1.80	0.90	2.00	2.90
DQ2	0.35	1.56	1.62	1.75	1.83	0.80	1.80	2.60
DQ3	0.35	1.64	1.67	1.80	1.86	0.70	1.60	2.30
DQ4	0.35	1.66	1.72	1.84	1.89	0.60	1.40	2.00
DQ5	0.35	1.68	1.74	1.87	1.91	0.54	1.25	1.83
DQ6	0.35	1.71	1.77	1.89	1.93	0.50	1.15	1.66

B_{10} B_{25} $P_{15/50}$

B *H* *H* /m

25cm

P *B/f* B -*B* +*B* -*B*

f $P_{1/400}$ 1T 400Hz

DG4 0.2mm $P_{1/400}$ 9W/kg 1T 400Hz 1kg

9W B 0.4

0.4A/m

B_s=2.03T (μ =100) T_c=740 d=7.65g/cm^3

ρ=47 × 10^{-8} Ω m λ_s=5 × 10^{-6}

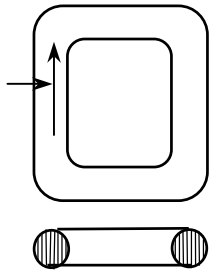
CD EC O

7

C O

R 4-14

O



4-15 R

R

B_r

2 铁镍软磁合金

4-3

IJ85 : d=8.75g/cm^3 T_c=400

4-3

		mm					
			μ i	μ m	H_c (Oe)	B_s (T)	B_r/B_s
IJ46		0.02~0.04 0.05~0.09 0.1~0.19	2000 2300 2800	18000 22000 25000	0.40 0.30 0.25	1.5 1.5 1.5	
IJ51		0.01 0.02~0.04 0.05~0.09 0.10		25000 35000 50000 60000	0.30 0.25 0.20 0.18	1.5 1.5 1.5 1.5	0.90 0.90 0.90 0.90
IJ79		0.01 0.02~0.04 0.05~0.09 0.1	12000 15000 18000 20000	70000 90000 110000 150000	0.06 0.05 0.035 0.025	0.75 0.75 0.75 0.75	
IJ86		0.01 0.02~0.04 0.05~0.09 0.1~0.19	10000 30000 40000 50000	80000 110000 150000 180000	0.050 0.030 0.018 0.015	0.60 0.60 0.60 0.60	

3 非晶合金和微晶合金

20 70

10^6 /

4-4 GB n 292-89

1k101			1k203		
1k102			1k204		
1k103			1k205		
1k104			1k206		
1k105			1k501		
1k106			1k502		
1k201			1k503		
1k202			1k601		

1k200

4-5

	B_s(T)	(H_c) A/m	μ m	(W/kg)			T_c( )	T_x( )
				$P_{1/60}$	$P_{1/400}$	$P_{0.4/10k}$		
1k101	1.55	6.4	120000	0.2	1.7	30	390	485
1k102J	1.60	6.4	150000	0.16	2.0	30	420	490
1k103	1.40	4.0	250000		1.5	35	435	450
1k104	1.30	5.0	100000			25	318	528
1k105	1.32	6.4			1.8		312	550
1k105J	1.32	3.2			1.4		310	550
1k106	1.58	8.0	200000		1.5	20	405	515

d=7.3g/cm^3 ρ $1.3 \times 10^{-4}\ \Omega$m

4-4

B_s(0.5 0.8T)

B_s(1.4T~1.8T)

1/3~1/5

B_s(0.7

1.2T)

IJ79

4-5~4-8

4-5

	B_s(T)	(H_c) A/m	μ	(W/kg) $P_{1/60}$	$P_{1/400}$	$P_{0.4/10k}$	T_c( )	T_x( )
1k101	1.55	6.4	120000	0.2	1.7	30	390	485
1k102J	1.60	6.4	150000	0.16	2.0	30	420	490
1k103	1.40	4.0	250000		1.5	35	435	450
1k104	1.30	5.0	100000			25	318	528
1k105	1.32	6.4			1.8		312	550
1k105J	1.32	3.2			1.4		310	550
1k106	1.58	8.0	200000		1.5	20	405	515

d=7.3g/cm^3 ρ $1.3 \times 10^{-4}\,\Omega$m

4-6

	B_s(T)	(H_c) A/m	μ	(W/kg) $P_{0.5/20k}$	$P_{0.3/100k}$	T_c( )	T_x( )
1k201H	0.70	1.2		25		340	530
1k202J	0.68	1.2	400000	35		320	510
1k203	0.80	1.2		20		320	530
1k204	0.60	1.6	200000		110	300	540
1k205	0.60	1.2		20		260	480
1k206	0.53	1.6	150000			320	520

d=7.9g/cm^3 ρ $1.5 \times 10^{-4}\,\Omega$m

4-7

	B_s(T)	(H_c) A/m	μ	(W/kg) $P_{1/400}$	$P_{1/5k}$	$P_{0.2/20k}$	T_c( )	T_x( )
1k501	0.75	1.2	400000	1.5	65	15	243	410
1k50H	0.75	1.6	3000	35		15	258	421
1k502	0.90	1.2	400000	20			300	500
1k503	0.80	0.56	520000			110		360

d=7.9g/cm^3 ρ $1.9 \times 10^{-4}\,\Omega$m λ 0

10 20nm

10^5

(1.2T) $P_{0.2/50k}$=15W/kg

B_s

20kHz kHz

O CD

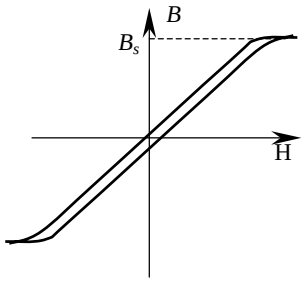
4-8

		B_s (T)	B_r/B_s %	H_c (A/m)	μ_m $\times 10^4$	(W/kg) $P_{0.5/20k}$	$P_{0.5/50k}$	$P_{0.5/100k}$	T_c( )	T_{cr}( )
		1.35	60	1.3	30	≤ 25	≤ 15	≤ 50	845	788
			85	0.8	60	≤ 40	≤ 35	≤ 120		
			7	1.6		≤ 20	≤ 10	≤ 40		
		1.25	55	1.5	20	≤ 45	≤ 20	≤ 60	840	770
			85	1.0	50					
			7	3.0	3					

d=7.25g/cm^3 ρ $0.8 \times 10^{-4}\Omega$

4.6.2.4

4-16



4-15

4-9

4-9

	H (Oe)	μ_e	* α	B_s (T)	B_r (T)
IJ67h	0 3	2000		1.25	0.15
IJ34h	0 10	1000	<15~20	1.5	0.1
IJ34kh	0 20	500	<20	1.6	0.1
IJ50h	0 100	100	<20	1.5	0.1

$*\alpha = \frac{\alpha_{e\max} - \alpha_{e\min}}{\alpha_{e\max}}$ μ_e

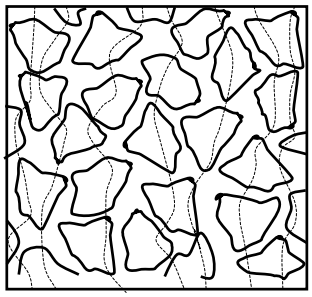
C

，

4.6.3

4-15

15 550

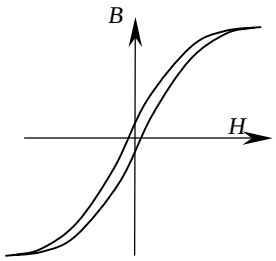


， 4-17

4-16 μ 0

B-H 4-12

4-18



μ_e

B_s

μ_e

4 (Kool mu) MPP

4-17

1. 铁粉芯

a)

b) 10 75

c)

d)

e)

2. Sendust 磁芯（铁硅铝） Arnold MSS Magnetics Inc. Kool mu

a) 6 9 85

b)

c)

d) 26 60 75 90 125

3. 高磁通密度－铁镍磁粉芯

a) 50 50

b)

c)
d)
e) 14 200

4. Mpp-钼皮莫合金－粉末

a) 2 81 17
b)
c)
d)
e)
f) 14 550

,

Δ /

EMC

4.6.4

1. 组成和基本特性

$MeFe_2O_3$ Me 2 (Mn) (Zn) (Ni) (Co) (Cu) (Fe) (Mg)

(MnZn) (NiZn)

Philipps MnZn 3C85 Fe_2O_3 71% MnO 20% ZnO NiZn 4A11 Fe_2O_3 50% NiO 24% ZnO.

(1000)

(T_c)

(NiZn) 1MHz (MnZn) 1MHz (μ_i) (B_s)

10.3

2. 铁氧体应用参数

(4.5) .

A. ($\Sigma(1/A)$,A_e,l_e,V_e)

(A_e) (l_e) (V_e)

$R_m=l_e/\mu_e A_e$

$$R_m = \frac{1}{\mu}\cdot\sum\frac{l}{A} = \frac{l_e}{\mu_e A_e} \qquad (4\text{-}20)$$

$$L = \frac{N^2}{R_m} = \frac{0.4\pi\times10^{-9}\mu_e N^2 A_e}{l_e}\ (\mathrm{H}) \qquad (4\text{-}21)$$

例 1 N A_e l_e $\sqrt{2}\,U\sin\omega t$

$$B_p = \frac{U\sqrt{2}\times10^9}{\omega\cdot A_e\cdot N} = \frac{2.25U\times10^9}{f\cdot A_e\cdot N}(\mathrm{mT})$$

A_e (mm^2) U (V) f $\omega/2\pi$ (Hz) N

$$H_p = \frac{IN\sqrt{2}}{l_e}(\mathrm{A/m})$$

I A

A_{min}

B (A_L)

A_L 1 ,

1000 N

$$L = N^2 A_L \qquad 4\text{-}22$$

A_L 1000 N

$$L = N^2 A_L\times10^{-6} \qquad (4\text{-}23)$$

A_L

(N^2)

$$A_L = \frac{0.4\pi\mu_e}{\sum A/l} = \frac{0.4\pi\mu_e A_e}{l_e}\ (\mathrm{nH}) \qquad (4\text{-}24)$$

δ (4-16) (4-17)

$$\mu_e = \frac{l_e}{\delta}$$

$$A_L = \mu_0\frac{A}{\delta}(nH) \qquad (4\text{-}25)$$

4-24) μ_e

2 材料性能

1 (ρ)

(MnZn) $10^{-3}\Omega m$

(NiZn) $30\Omega m$

0.1 $20\Omega m$ NiZn 10^4 $10^6\Omega m$ 4-11 4-12

4-11 —3C80

( )	-20	0	20	50	100
(Ωm)	≈10	≈7	≈4	≈2	≈1

4-12 —4C6

	0	20	60	100
($\Omega m \times 10^5$)	≈500	≈100	≈10	≈1

4-13 4-14

4-13 —

(MHz)	0.1	1	10	100
(Ωm)	≈2	≈0.5	≈0.1	≈0.01

4-14 —

(MHZ)	0.1	1	10	100
(Ωm)	$\approx 10^5$	$\approx 5 \times 10^4$	$\approx 10^4$	$\approx 10^3$

(2)

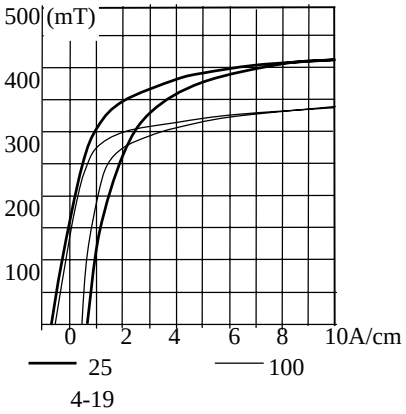
4-19

H_s=1200A/m

B_s

4-19 100

25 0.42T 0.34T



4-19

(3)

(4-6a) p_t $mW/cm^3=kW/m^3$

$p_t = P_T / V = \eta f^{\alpha} B_m^{\beta}$ 4-26

50kHz (4-25) α 1.5 1.7 β 2 2.7

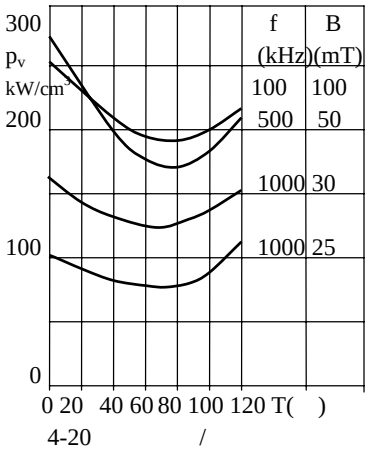
4-15

4-20

4-20 100

4-20

80~100



4-20 /

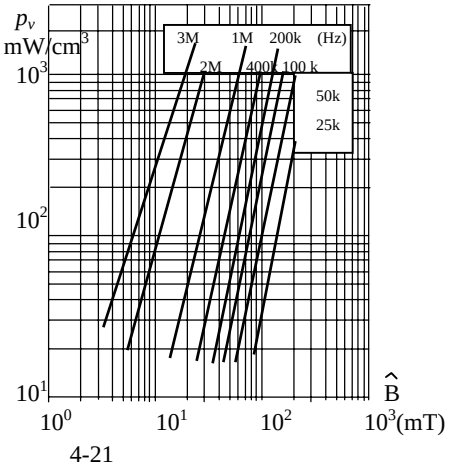
4-20 4-21

4-15 100

		mW/cm^3,	mT

(kHz)		160	140	120	100	80	60
	Ferroxcube 3C80	85	60	40	25	15	
	Ferroxcube 3C85	82	25	18	13	10	
	Ferroxcube 3F3	28	20	12	9	5	
	Magnetics R	20	12	7	5	3	
	Magnetics P	40	18	13	8	5	
	TDK H7C1	60	40	30	20	10	
	TDK H7C4	45	29	18	10		
	Siemens N27	50			24		
	Ferroxcube 3C8	270	190	130	80	47	22
	Ferroxcube 3C85	80	65	40	30	18	9
50	Ferroxcube 3F3	70	50	30	22	12	5
	Magnetics R	75	55	28	20	11	5
	Magnetics P	147	85	57	40	20	9
	TDK H7C1	160	90	60	45	25	20
	TDK H7C4	100	65	40	28	20	
	Siemens N27	144			96		
	Ferroxcube 3C8	850	600	400	250	140	65
	Ferroxcube 3C85	260	160	100	80	48	30
100	Ferroxcube 3F3	180	120	70	55	30	14
	Magnetics R	250	150	85	70	35	16
	Magnetics P	340	181	136	96	57	23
	TDK H7C1	500	300	200	140	75	35
	TDK H7C4	300	180	100	70	50	
	Siemens N27	480			200		
	Siemens N47				190		
	Ferroxcube 3C8				700	400	190
	Ferroxcube 3C85	700	500	350	300	180	75
200	Ferroxcube 3F3	600	360	250	180	85	40
	Magnetics R	650	450	280	200	100	45
	Magnetics P	850	567	340	227	136	68
	TDK H7C1	1400	900	500	400	200	100
	TDK H7C4	800	500	300	200	100	45
	Siements N27	960			480		
	Siemens N47				480		
	Ferroxcube 3C85				1800	950	500
	Ferroxcube 3F3		1800	1200	900	500	280
500	Magnetics R		2200	1300	1100	700	400
	Magnetics P		4500	3200	1800	1100	570
	TDK H7F						100
	TDK H7C4		2800	1800	1200	980	320
	Ferroxcube 3C85						2000
	Ferroxcube 3F3				3500	2500	1200
1000	Magnetics R				5000	3000	1500
	Magnetics P						6200

0.5T



4-21

4.7

.

, , , , .

100kHz

10kW 1MHz

本章要点

- B_s B_r H_c μ
-
-
-
-
- 3

B_s

200kHz

1MHz

-

1. 1996
2. Philips Magnetic Components 1996 (Mannul)
3. Magnetic Powder Cores-Powder Core Division The Arnold Engineering Company
4. Soft Ferrite Hand Book Core Gain Developments LTD.
5. TDK Ferrite Cores (Mannul)
6. Ferrites and Accessories S+M Siemens Matsushita Components Data Book 1997
7.
8.
9. Amorphous Magnetic Parts Toshiba 1997
10. 1999
11. Unitrode Magnetics Design Handbook Magnetics Design for Switching Power Supplies Lloyd H. Dixon
12. 1998
13. Permanent Magnets and Their Application Rollin J. Parker, Robert J. Studders . John Wiley and Sons,Inc. 1962
14. “ ” B
15. 1999

第五章 变换器中磁芯的工作要求

EMC

—Buck .

5.1 Buck

5-1(a) Buck R_1 R_2 U_r

PWM

S

U_o L S

U_i U_o L (

5-1(b)) D

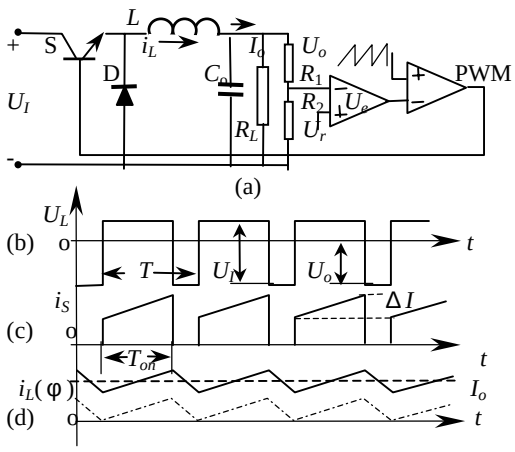
((d))

D

$\Delta I=(U_i- U_o)T_{on}/L$ U_oT_{of}/L ,

U_o $T_{on}U_i/T=DU_i$

D



5-1 Buck

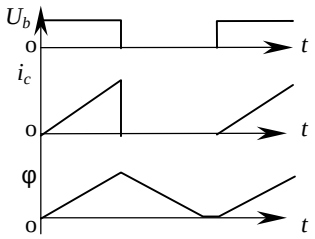
5-1(d)

I_o

(5-1(d)

)

(5-2)



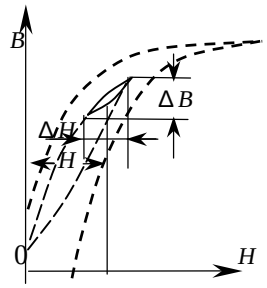
$U_o=DU_i(D=T_{on}/T$) 5-2

$U_o=DU_i$

(2-4)

$$W_m=\frac{1}{2}LI_p^2 \quad (5\text{-}1)$$

I_p



5-1(d)

5-3

$L=N^2 \mu_0 \mu_e A_e/l_e$ μ_e 5-3

ΔB

$$\Delta B = \frac{L\Delta I}{NA_e} \qquad (5\text{-}2)$$

ΔI

N

A_e

$$B = \frac{\mu_0 \mu_e NI}{l_e} = \frac{LI}{NA_e} \qquad (5\text{-}3)$$

$$\frac{\Delta I}{I} = \frac{\Delta B}{B} = 2k \qquad (5\text{-}4)$$

10 k=0.1

$$I_{o\,min} = \frac{\Delta I}{2} = \frac{(U_i - U_o)T_{on}}{2L} = 0.1I_o \qquad (5\text{-}5)$$

$D=T_{on}/T$ $U_o=DU_i$ (5-1)

$$L = \frac{(U_i - U_o)T_{on}}{0.2I_o} = \frac{5(U_i - U_o)U_o T}{U_i I_o} \qquad (5\text{-}6)$$

($I_o+\Delta I/2$ $=(1+k)I_o$ $1.1I_o$)

$(1+k)B<B_s$

k

Boost Boost/Buck

—

5-4

S S

$$i_1 N_1 = i_2 N_2 \qquad (5\text{-}7)$$

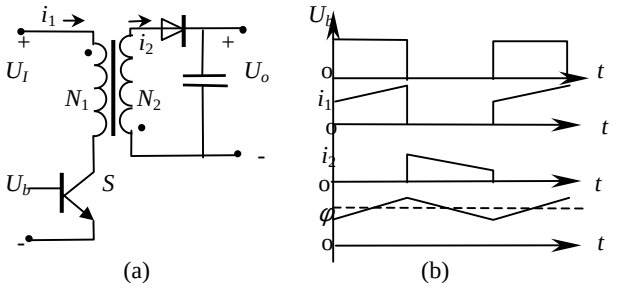
N_1 N_2

i_1

i_2 i_1

i_2

( )



(a) (b)

5-4

5-4(b)

:

1. , , , ,

( ) $\Delta B/2$

4-20 ΔB

50kHz

2. H

μ_e

3. $D/2$

B_m

30% 40%

4 5-1

$$L = \frac{U_i T_{of}}{2 I_{o\,min}}$$

U_i-

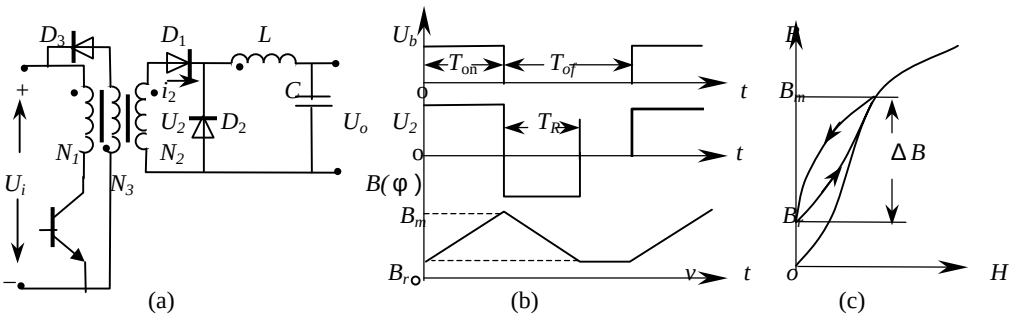
T_{of}-

$I_{omin} = \Delta I/2$

5.2

5-5(a) N_1 D_1 D_2 L C

Buck , N_1



(a) (b) (c)

5-5

N_2 D_1

$$U_i = N_1 A \frac{\mathrm{d}B}{\mathrm{d}t}$$

$$\Delta B = \frac{U_i T_{on}}{A N_1} \qquad (5\text{-}8)$$

T_{on} (S)

N_1

A m^2

$$i_2 = I_o + \frac{U_2 - U_o}{2L} T_{on} \qquad (5\text{-}9)$$

$$i_2' = \frac{N_2 i_2}{N_1} \qquad (5\text{-}10)$$

L_m , , :

$$i_m = \frac{U_i}{L_m} t = i_1 - i_2' = i_1 - \frac{i_2 N_2}{N_1} \qquad (5\text{-}11)$$

D_1

$(Li_m^2/2)$

$L_m i_m / t_f$ t_f

N_3 D_3 D_3

D_3

$$T_R \geq \frac{U_i T_{on}}{E_3} \approx \frac{N_3 T_{on}}{N_1} \qquad (5\text{-}12)$$

E_3— N_3 N_3 N_1

5-5 b

$\pm B_S$ 5-5(c)

5-5(c)

$\Delta B < B_S - B_r$

B_s B_r 100 0.3T

0.1T 0.2T

4-12(b) B_r

0.05~0.1mm 0.02T ΔB 0.2T

(4-14)

$$\mu_e = \frac{\mu_r}{1+\frac{\mu_r \delta}{l_e}} = \frac{l_e}{\frac{l_e}{\mu_r}+\delta}$$

$$L_1 = N_1^2 A_L = N_1^2 \frac{\mu_0 \mu_r A_e}{l_e}$$

$$L_\delta = N_1^2 \frac{\mu_e \mu_0 A_e}{l_e} = N_1^2 \frac{\mu_0 A_e}{l_e} \cdot \frac{l_e}{\frac{l_e}{\mu_r}+\delta} = L_1 \cdot \frac{l_e/\mu_r}{\delta + l_e/\mu_r} \approx \frac{L_1 l_e}{\delta} \qquad (5\text{-}13)$$

δ

l_e

A_e

A_L μ_r

5-5(c)

25 TDK 100kHz 34 60kHz 35 20kHz 39%

(1)

B_s B_r $\Delta B = B_m - B_r$ B_r B_r

(2)

$\Delta B_m = B_s - B_r$

B_r

ΔB_m

μ_e B_s B_r

(3)

B_m 30% 40% B

B 2 B_m

5.3

S_2

S_1 ( ) S_2 B_m B_m S_2 S_1 B_m B_m

5.3.1

PWM

A.

5-6 (a) (b) t=0 S_1 S_2 $N_{11}= N_1$

$$e_2 = \frac{N_2}{N_1} U_i \qquad (5\text{-}14)$$

L

$$i_1 = \frac{1}{L_m} + \frac{N_2^2}{N_1^2 L} U_i t \qquad (5\text{-}15)$$

L_m

L—

($t=T_{on}$) S_1

( )

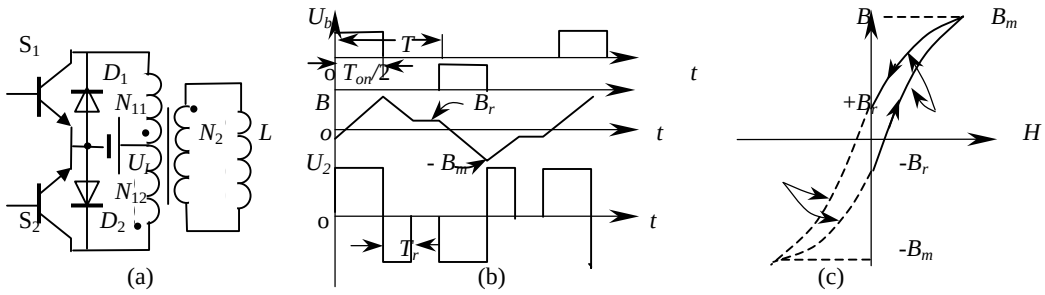
S_1 D_2

(5-6(b))

B_r B_m (5-6(c))

$$B_m + B_r = \frac{U_i T_{on} / 2}{AN_1} \qquad 5\text{-}16$$

$$-B_r - B_m = \frac{U_i T_r}{AN_1} \qquad (5\text{-}17)$$



5-6

$$T_r = \frac{T_{on}}{2} - \frac{2B_r AN_1}{U_i} \qquad (5\text{-}18)$$

A

B_r=0 ,T_r=T_{on}/2

π/2

B_r=B_m

PWM

B. SPWM

5-6

SPWM

SPWM

5-7 a

(+) (-)

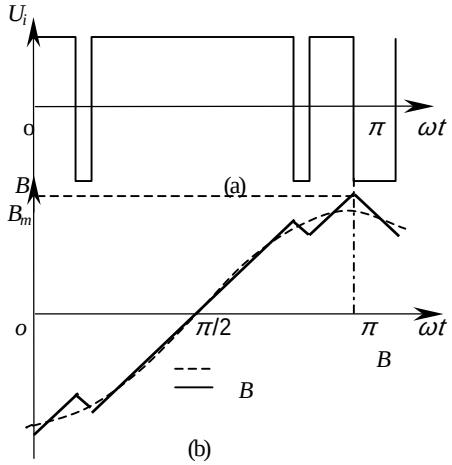
$$\frac{dB}{dt} = \pm\frac{2U_i}{N_1 A} \qquad (5\text{-}19)$$

$+B_m$

B_m 5-7(b)

(5-7(b)) B

5-19 U_i



5-7 B

C. **SPWM**

5-8(a) S_1

S_3 S_4 S_2 SPWM SPWM

$t \le 0$ S_3 S_1 S_4 S_2

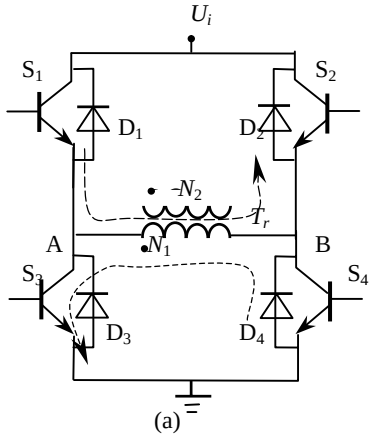
S_3 D_4

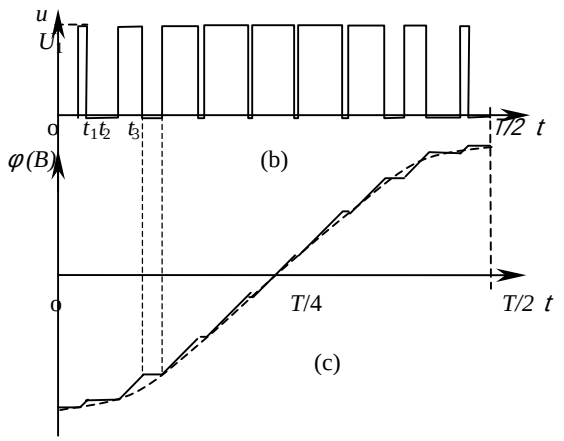
$-B_m$ 0 t_1 S_1 S_3

S_2 S_4 S_1 D_2 5-8(a)

$-B_m$ t_1 t_2 5-8(b) S_2 S_4 U_i S_1 S_4

$$U_1 = N_1 A\frac{dB}{dt} = U_i \qquad (5\text{-}20)$$





5-8 B

$$\frac{\mathrm{d}B}{\mathrm{d}t}=\frac{U_i}{N_1 A} \qquad (5\text{-}21)$$

B $t=t_2$

$$U_2=\frac{N_2}{N_1}U_1 \qquad (5\text{-}22)$$

$T/2$ S_1 S_3 S_2 S_4 $T/4$

S_2 D_1 $T/4$ D_3 S_4

N_2 SPWM (5-8(b)) $T/2$ $+B_m$

(5-21) (5-19)

D.

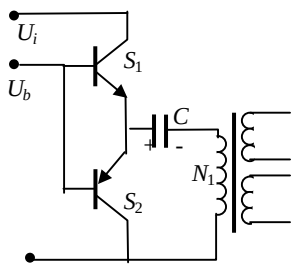
5-9(a) C

$U_c=U_iT_{on}/T$ U_b S_1 S_2

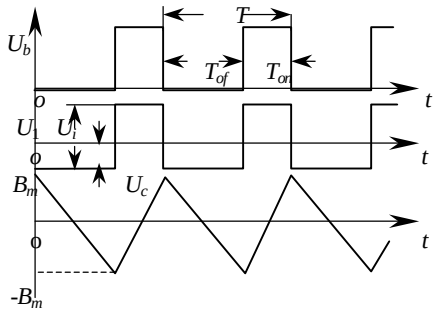
$$U_{1+}=U_i-U_c=(1-D)U_i=N_1\frac{\Delta\phi_{on}}{T_{on}} \qquad (5\text{-}23)$$

U_b S_1 S_2

$$U_{1-}=U_c=DU_i=N_1\frac{\Delta\phi_{of}}{T_{0f}} \qquad (5\text{-}24)$$



(a)



(b)

5-9

5-23 ,(5-24) $\Delta\varphi_{on}=\Delta\varphi_{of}$

5.3.2 SPWM

5-8 AB SPWM *LC*

5-10

$$u_L = u_{AB} - u_o$$

L

$$\Delta B_L = \frac{1}{NA}\int_0^{\pi/2}\left(u_{AB} - \sqrt{2}U_o \sin \omega t\right)dt \qquad (5\text{-}25)$$

N

A

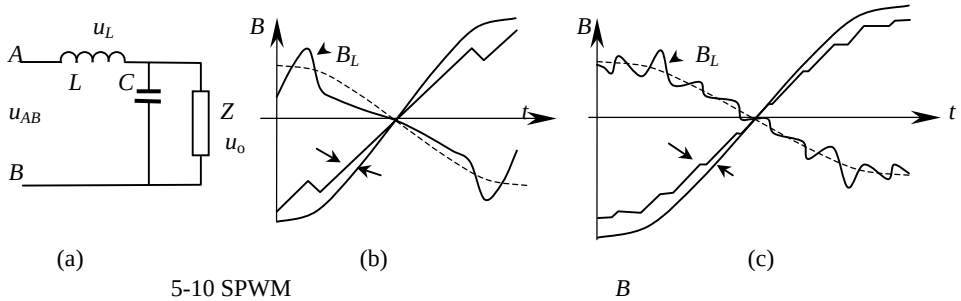
U_o

(5-25) 5-7 b 5-8 c

5-7( ) 5-8

u_{AB} B 5-25

5-10(b) (c)



(a) (b) (c)

5-10 SPWM B

5-10

5.3.3

— 5-11 a

200V LC S_1

S_2(5-11)

S_1 S_2 S_1 N_{11}

$N_{11}=N_{12}=N_1$, $N_{21}=N_{22}=N_2$ N_{21}

$$U_{21} = \frac{N_2}{N_1}U_1 = \frac{N_2}{N_1}U_i \qquad 5\text{-}26$$

D_1 $U_{21}>U_o$, i_L B_m B_m D_1

i_2' i_m B H

i_m $+i_m$

S_1 S_2 U_{21}

D_1 D_2 i_L

S_1 ( )$N_{11}i_{m1}$

“ • ”

$$i_{m1}N_{11} = i_{22}N_{22} - i_{21}N_{21}$$

$$i_{22} - i_{21} = \frac{N_1}{N_2}i_{m1} \qquad (5\text{-}27)$$

$$i_{21} + i_{22} = i_L \qquad (5\text{-}28)$$

(5-27) (5-28)

$$i_{21} = \frac{1}{2}(i_L - \frac{N_1}{N_2} i_{m1}) \qquad (5\text{-}29a)$$

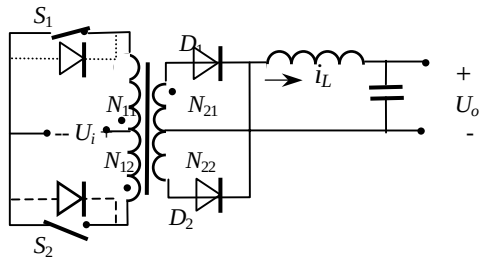
$$i_{22} = \frac{1}{2}(i_L + \frac{N_1}{N_2} i_{m1}) \qquad (5\text{-}29b)$$

i_L—

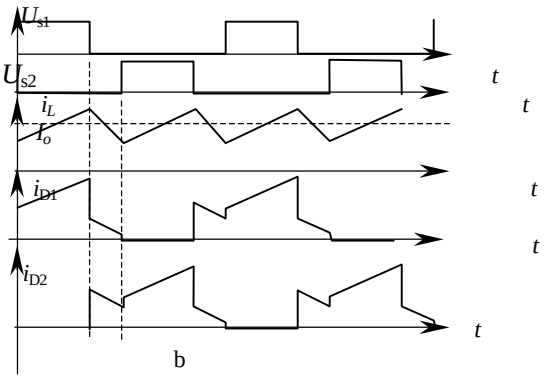
i_{21}— $N_{21}(D_1)$

i_{22}— $N_{22}(D_2)$

i_{m1}—



(a)



5-11 b

S_2 S_1 5-29

(5-29a) $D_1(D_2)$ $i_{21}(i_{22})$ $S_2(S_1)$

$D_1(D_2)$ $+B_m$ $(-B_m)$ D_2 D_1

5-11(a)

DC DC

(1) $\pm B_m$ $2B_m$ $B_m <$

B_S B_m

(2)

B_m

B_m B_S

>100kHz

(3) SPWM

dB/dt

4-3

(4) DC/AC

( )

(5) ρ B_r H_C

B_S μ

5.4

5.4.1

5-12(a) L S U_i R

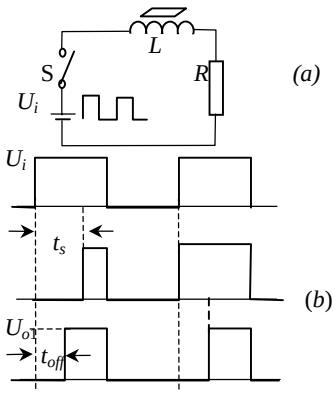
50 5-12 c $-B_s$ S

U_i $+B_s$(5-12 $-B_s$~3)

$$t_s = \int_{-Bs}^{+Bs} \frac{NA}{U_i} \mathrm{d}B = \frac{2B_s NA}{U_i}$$ 5-30

A

N



L

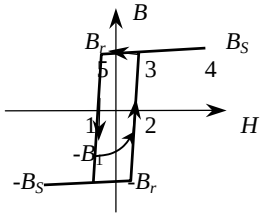
(t_s) $+B_s$ (

5-12 3~4) L μ_0

(5-12 4~B_r=B_s)

$+B_s$

$\rightarrow B_r$ $B_r \rightarrow B_s$



(c)

$+B_s$ $-B_1$(5-12

B_r~1,B_1 $+B_s$~$-B_s$

c B_1

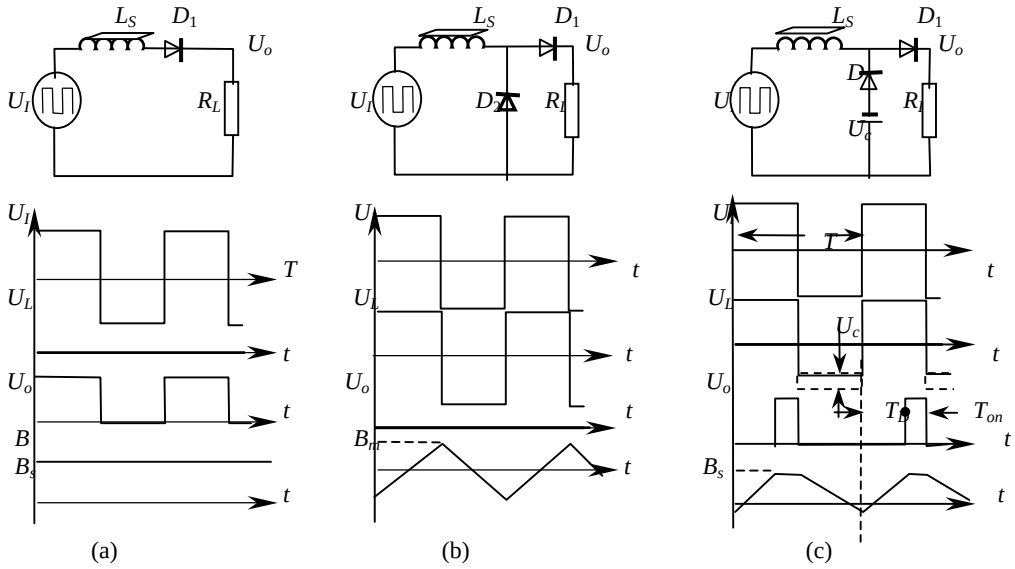
U_i (5-30) 2 5-12

B_s t_{off} t_s

(B_1) t_{off}

t_s

5-12(c)



5-13

5-13 U_i L_s D_1( ) R_L

B_r

5-13(a)

B_s

D_2 5-13(b) ,

D_2

D_2 U_c 5-13(c)

U_i U_c

T_D

T_{on} U_o

T_D,

($T_{on}=T/2-T_D$) (5-13 c)

$$U_i T_D - (U_i - U_c)\frac{T}{2} = U_i(\frac{T}{2} - T_{on}) - (U_i - U_c)\frac{T}{2} = 0$$

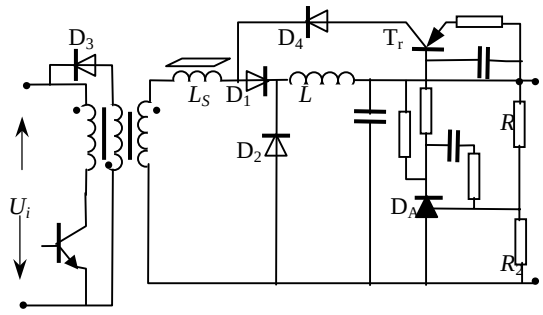
$$U_i T_{on} = U_c T / 2$$

$$U_o = U_i D = \frac{U_i T_{on}}{T} = \frac{U_c}{2}$$

$D=T_{on}/T$ U_c

5.4.2

5-14



R_1 R_2

D_A TL431

T_r D_4 L_S

5-14

0.9

Philips 3R1

-
-

1/5

-

2

-

- dB/dt

-

1. Philips Magnetic Components 1996 (Mannul)
2. 1999
3. Swiching Power Supply Design Abraham I. Pressman Second Edition McGraw-Hill 1998
4. Amorphous Magnetic Parts TOSHIBA
5. 1991

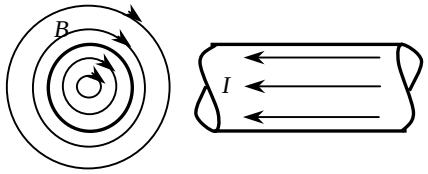
第六章　线圈

6.1

6-1(a)

I

B



6-1

$H=I/\pi d$

d

6-1

i

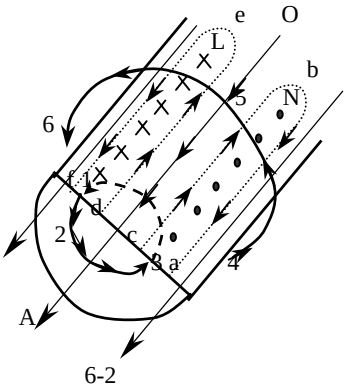
(6-2 1 2 3 4 5 6)

L

N a

b c a d e f d a b

e f O A b c d e O A



6-2

6-3(a)

A_n *n*

$$\phi_n = B_n A_n$$

B_n,A_n *n* *n* *n*

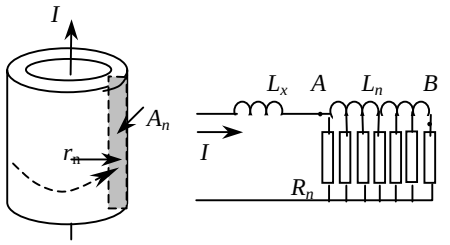
n

$$L_n = \frac{\phi_n}{\sum i_n}$$

L_x

$$R_n = \rho \frac{1}{A_n} \qquad (6\text{-}1)$$

L R L 6-3(b) A



(a) (b)

6-3 n (a)

(b)

Skin effect

0.368 1/e

Δ Δ Δ

Δ f ω

$$\Delta = \sqrt{\frac{2k}{\omega\mu\gamma}} \qquad (6\text{-}2)$$

μ

γ $1/\rho$

k μ μ_0 $4\pi \times 10^{-7}$H/m 20 ρ 0.01724 $\times 10^{-6}\Omega$-m 1/234.5 1/ k=(1+(T-20)/234.5)

T 20

$$\Delta = \frac{6.6}{\sqrt{f}} (\text{cm}) \qquad (6\text{-}2a)$$

6-1

6-1 20

f(kHz)	1	3	5	7	10	13	15	18	20	23
Δ(mm)	2.089	1.206	0.9346	0.7899	0.6608	0.5796	0.5396	0.4926	0.4673	0.4358
f(kHz)	25	30	35	40	45	50	60	70	80	100
Δ(mm)	0.4180	0.3815	0.3532	0.3304	0.3115	0.2955	0.2697	0.2497	0.2336	0.2089

20 100 ρ_{100} $2.3 \times 10^{-6}\Omega$-cm

$$\Delta = \frac{7.65}{\sqrt{f}} (\text{cm}) \qquad (6\text{-}2b)$$

R_{dc}

R_{ac}

$$\frac{R_{ac}}{R_{dc}}=\frac{\pi d^2/4}{\pi d^2/4-\pi(d-2\Delta)^2/4}=\frac{(d/2\Delta)^2}{(d/2\Delta)^2-(d/2\Delta-1)^2} \qquad (6\text{-}3)$$

6-2 (6-3)

R_{ac}/R_{dc} 100 25kHz 0.48mm 1.5mm

6-3 R_{ac}/R_{dc} 1.149 200kHz 0.017mm, R_{ac}/R_{dc} 2.488

(6-3) R_{ac}/R_{dc} R_{ac}

d^2 d

$d=D/\sqrt{2}$ D π d

Δ $\sqrt{2}$ π dΔ 41

50kHz 100kHz

15 20A

37

Venkatramen

3 2 3 Δ ’ (6-3) R_{ac}/R_{dc}

70

6.2

1-3

a × b i_A i_B 6-4 a “ ·”

“ ” 1-3

6-4 *a* Δ i_A i_B

A i_A ϕ_A *B* *B* i_{AB} A

i_B A i_B

A B i_B B

w 6-4(b)

b>>*w*

$$L = N^2 \mu_0 \frac{w \times l}{b \times l} = 4\pi \frac{w}{b} (\text{nH/cm}) \qquad (6\text{-}4)$$

N=1

l (cm)

b cm

w (cm)

$$W_m = \frac{\mu_0}{2} H^2 V / l = \frac{\mu_0}{2} \left(\frac{I}{b} \right)^2 bw = \frac{\mu_0 w}{2b} I^2 \qquad 6\text{-}5$$

I

H

b

(6-5) 6-5

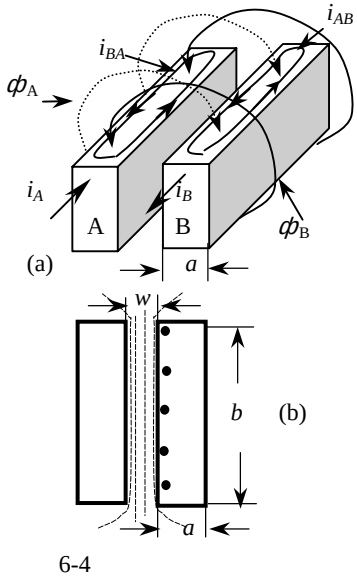
b

w (a)

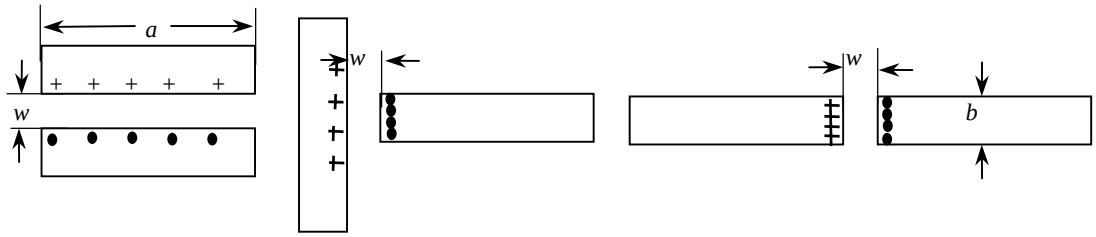
c (6-5)

c a (c)

(a) (b) (c)



6-4



6-5

例 1 6-5(a) a (c) b 5

解 6-5

$$W_m = \frac{1}{2} \mu_0 H^2 w / b$$

(a) (c) 5 (c) (a) 5

6.3

6.3.1

6-6 E 4 1

I_2(10A)

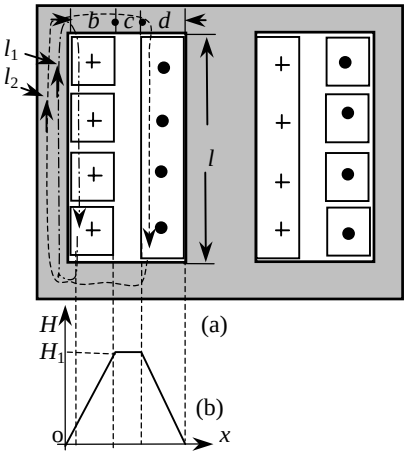
$I_1=I_2N_2/N_1$(2.5A)

b

, d c ,

I_1N_1

l_1



6-6

$$\frac{I_1N_1}{b}x = H_x l$$

$$H_x = \frac{I_1N_1}{bl}x = H_1\frac{x}{b} \qquad 6\text{-}6$$

I_1N_1

H_1

l

6-6) x $x=b$

H_1 H_1

$x=b+c$

$x>b+c$ l_2

$$H_x = H_1 - \frac{N_2I_2}{dl}\left(x-(b+c)\right)$$

$N_2I_2=N_1I_1$,

$$H_x = H_1 - \frac{N_2I_2}{dl}\left(x-(b+c)\right) = H_1\ 1-\frac{x-b-c}{d} \qquad (6\text{-}7)$$

$$W_m = W_b + W_c + W_d \qquad (6\text{-}8)$$

W_b W_c W_d

$$W_b = \int_0^b \frac{\mu_0}{2}H_x^2 l_{av1}ldx = \frac{\mu_0 l_{av1}l}{2}\int_0^b \left(\frac{N_1I_1}{bl}x\right)^2 dx$$

$$= \frac{\mu_0 l_{av1}(N_1I_1)^2}{2b^2l}\times\frac{x^3}{3}\Big|_0^b = \frac{\mu_0 l_{av1}b(N_1I_1)^2}{6l} \qquad (6\text{-}9a)$$

$$W_d = \frac{\mu_0 l_{av2}d}{6l}(N_2I_2)^2 \qquad (6\text{-}9b)$$

$$W_c = \frac{\mu_0}{2}\times\left(\frac{N_1I_1}{l}\right)^2 \times ll_{av3}c = \frac{\mu_0 l_{av3}c(N_1I_1)^2}{2l} \qquad (6\text{-}9c)$$

l_{av1} l_{av2} l_{av3}

$$W_e = \frac{1}{2}L_{s1}I_1^2 = W_m \qquad (6\text{-}10)$$

(6-9) (6-10) $N_2I_2=N_1I_1$

$$L_{s1} = \frac{\mu_0 N_1^2}{l} \; cl_{av3} + \frac{bl_{av1}}{3} + \frac{dl_{av2}}{3} \qquad \text{6-11}$$

l_{av} ,

6-11

$$L_{s1} = \frac{\mu_0 N_1^2 l_{av} k_s}{l} \; c + \frac{b+d}{3} \qquad \text{(6-11a)}$$

$$k_s = 1 - \frac{c+b+d}{\pi l} + 0.35 \left(\frac{c+b+d}{\pi l} \right)^2 \qquad \text{(6-11b)}$$

6-11a N l

6-6

c H

6.3.2

6-6

E

E

3.2

,

E

3-4 3-7

6.3.3

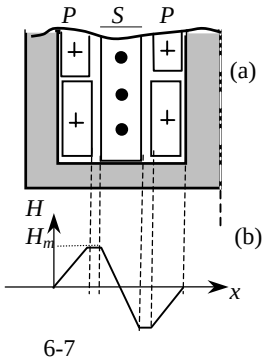
6-7(a)

6-6 (6-7) (6-7(b)) 6-6

6-6 6-7 (H_m=H_1/2)

6-7 6-6 1/2

6-6 1/4 1/4,



6-7

1/3→ 1/2→ 1/3→

1/2→ 1/3 1/3→ 2/3→ 2/3→ 1/3

1/9

RM PM

6.4

6.4.1

6-8 (p) (s) Δ

Δ

6-6 b x=0

$x=b-\Delta$ Δ 0 $H_1=N_1I_1/2l$

δ $x>b+\delta$

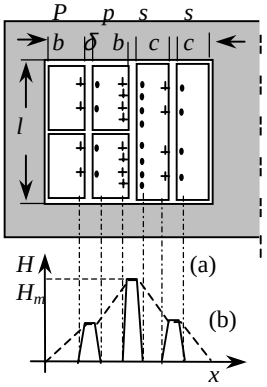
δ H_1 Δ

$x=2b+\delta-\Delta$ $2b+\delta$ Δ

Δ

(1 2^2) (I^2r ,

5 6-8 b



6-8

n n n

n-1 n

((n-1)^2 n^2)

例2 6-8 3 200kHz

0.84mm 100

解：1. 100

$$\Delta=\frac{7.6}{\sqrt{f}}=\frac{7.6}{\sqrt{200\times10^3}}=0.017cm$$

2.

$Q=d/\Delta=0.84/0.17\approx5$( )

3 $(n\text{-}1)^2+n^2$

m_1=1 , m_2=1 2^2 5 m_3=2^2 3^2 13

$F_R=R_{ac}/R_{dc}$

$$F_R=Q\times\frac{m_1+m_2+m_3}{3}=5\times\frac{1+5+13}{3}=31.67$$

Δ .

Δ

I^2R Dowell

6-9 $F_R=R_{ac}/R_{dc}$ Q

Δ

d 0.83

$0.83d\sqrt{d/s}$,d s Q

$$Q=\frac{h\sqrt{F_l}}{\Delta} \quad (6\text{-}12)$$

h=0.83d;

d

Δ

F_l $N_l d/w$;

N_l

w

F_l 1

2 Q 5 6-9 Q=5

3 F_R 31.67

6-9

Δ F_R

Δ F_R 1

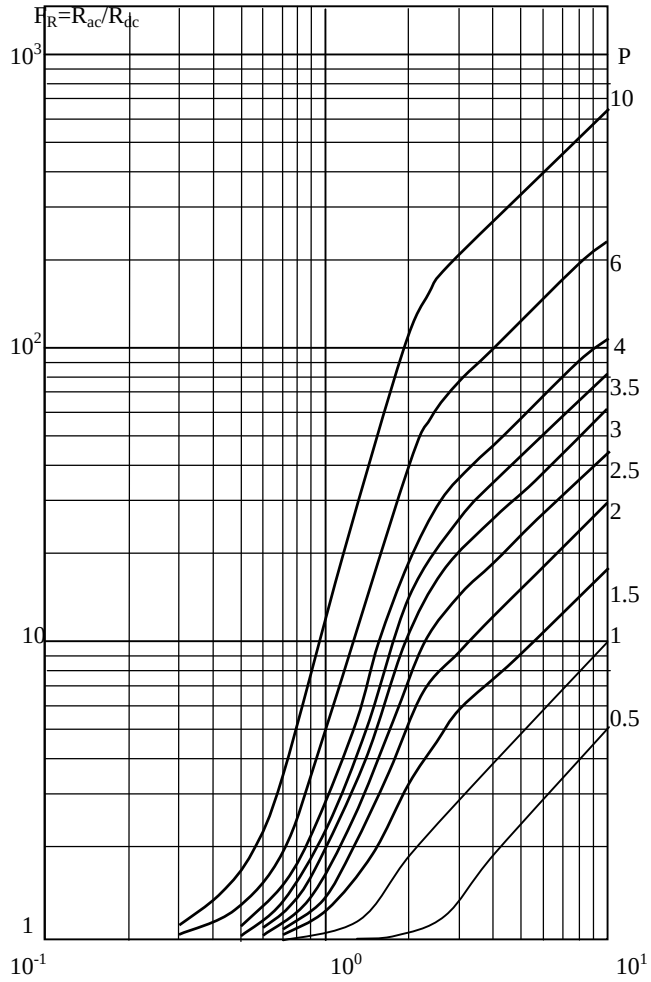
Q

F_R 1.5 F_R

1.5

F_R 1.5

1 Q 1.6 10 0.4 6-9



Q

Q= /Δ

6-9

F_R

6-10 (a)

Q 4 6-9 F_R=13

(b) (a) 1 Q=4, 6-9 F_R=4

(c) 1/3 2/3 2/3 1/3

(b)

3 I_P 20A D 0.5 90kHz 10 l=24mm.

$I_a=DI_p=0.5\times 20=10$A

$I \quad \sqrt{D} I_p = \sqrt{0.5} \times 20 = 14\ \text{A}$

$$I_{\text{rms}} = \sqrt{I^2 - I_a^2} = \sqrt{0.5 \times 20^2 - 10^2} = 10\ \text{A}$$

j=4A/mm^2

$$A_{cu} = \frac{I_{\text{rms}}}{j} = \frac{10}{4} = 2.5\ \text{mm}^2$$

1.

10-2 d=1.8mm(A_{cu}=2.545mm^2), d'=1.92mm 10

10 × 1.92=19.2mm<24mm 2mm

90kHz 100 ,

$$\Delta = \frac{7.6}{\sqrt{f}} = \frac{7.6}{\sqrt{90 \times 10^3}} = 0.0253\text{cm} \quad 0.253\text{mm}$$

F_{l}=d/d'=1.8/1.92

$$Q = \frac{0.83 \times d\sqrt{F_l}}{\Delta} = \frac{0.83 \times 1.82 \times \sqrt{1.8/1.92}}{0.253} = 5.7$$

6-9 Q 5.7 1 $F_{\text{R}} \approx 5.7 = R_{\text{ac}}/R_{\text{dc}}$

2.

d<2 Δ =2 × 0.253=0.506mm 10-2

d=0.45mm, d'=0.51mm A_{cun}=0.159mm^2

$$N = \frac{A_{\text{cu}}}{A_{\text{cun}}} = \frac{2.5}{1.59} = 15.7 \qquad n=16$$

16 4 × 4 4 × 10=40 40 × 0.51 20.4mm<24mm

$$Q = \frac{0.83 \times d\sqrt{F_l}}{\Delta} = \frac{0.83 \times 0.45 \times \sqrt{0.45/0.51}}{0.253} = 1.39$$

6-9 Q 1.39 4 $F_{\text{R}} \approx 7$

4 Q 1.39 $F_{\text{R}} \approx 2.3$

3.

0.18 × 100 10 × 10 Q 0.57 6-9 $F_{\text{R}} \approx 1.9$

F_{R} 1.5, 0.18

4.

b=20mm

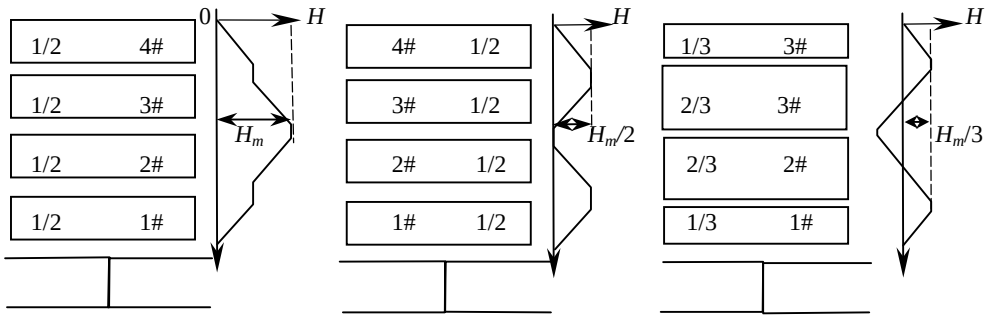
$$\delta = \frac{A_{cu}}{b} = \frac{2.5}{20} = 0.125\ \text{mm}$$

$$Q = \frac{\delta}{\Delta} = \frac{0.125}{0.253} \approx 0.5$$

1 Q 0.5 $F_{\text{R}} \approx 1$

6-9 6-9

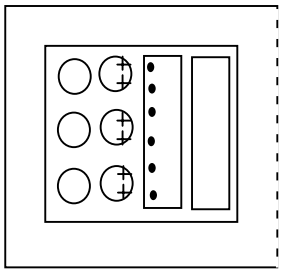
6-9 50



(a) (b) (c)

6-10

6.4.2



2-17

6-4 6-8

全部电流高频分量将在初级与次级直接面对的里层的内表面和相邻的外表面流动 6-11

6-11

零

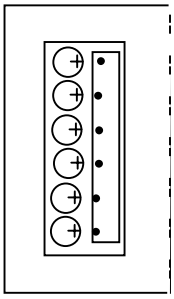
1.

6-12 6-11 6-9

6-11 6-12

6-12 6-11 ,

4



6-12

2.

6-7 6-13 6-12

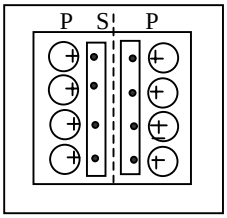
6-12 6-7

6-13 P (S) 1/2

P-SS-PP-S 6-10(c)

3. 并联准则

6-8



n

Litz Wire 6-13

6-9 $\sqrt{n}$ 100kHz

6-13 6-8(b) 6-13

6-8(c) 2/3 2/3

6.4.3

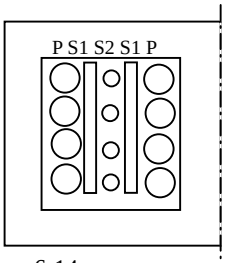
1. 无源导体的邻近效应

“ ” Δ

- ;
-
- Δ/3

Δ

6-14 S1 S2 S1

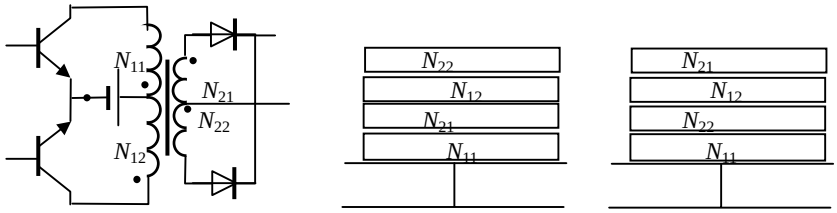


6-14

2. 尽量避免中心抽头线圈

6-15(a)

6-15(b)



(a) (b) (c)

6-15 (a) (b) (c)

6-9 F_R

3. 减少散磁通

$\delta/2$ δ

$\delta/2$ $\delta/2$ 3-7(b)

1. 2.

3.

3-8(c)

3-8

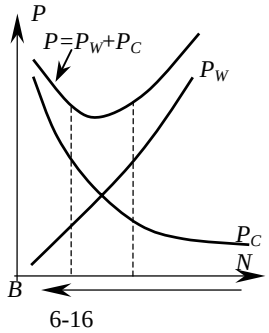
1 3mm

1 3 3 4

2mm μ_r=10 2cm

2cm 2cm

6.5



6-16

6-16

ΔB P_c

P_W P_c P_W

P $N(B)$

P_W P_C

6-16

4 0.25 80 90 90

1

6.5.1

1.绝缘

, IEC

7 6-2

6-2 IEC

	Y	A	E	B	F	H	C
	90	105	120	130	155	180	>180

A B 8 8 B

8 H 12

$$t = Ne^{\frac{b}{T}} \quad (6\text{-}13)$$

t— (h);

T— (k)

N,*b*— A B $N=1.3\times10^{-8}$,$b=1.14\times10^{4}$ H $N=1.29\times10^{-8}$ $b=1.7\times10^{3}$

T_a

$\Delta T=T_{max}-T_a$ 6-14

T_{max} A 90

T_a

250

B 250 100

100 120

E 100

40 $100mW/cm^3$

2. 热阻

R_i, R_{th}

“ ” R_i

R_i

R_{th}( )

R_{th} R_{th}

R_{th} “ ”

R_{th} R_i

“ ”

$$\Delta T = R_{th} P \qquad (6\text{-}15)$$

R_{th} W/

10

$$R_{th} = 295A^{-0.7} P^{-0.15} \qquad (6\text{-}16)$$

$$\Delta T = R_{th} P = 295A^{-0.7} P^{0.85} \qquad (6\text{-}17)$$

P (W)

A cm^2

R_{th} 10 15

4 E55 , 3F3 200kHz B 0.08T 3W $106.5cm^2$

3F3 100 0.08T $80mW/cm^3$

E55 $43.5cm^3$

P_W=0.08 × 43.5=3.48W

P=P_c+P_w=3.48+3=6.48W

6-17

$$\Delta T = 295A^{-0.7} P^{0.85} = 295 \times 106.5^{-0.7} \times 6.48^{0.85} = 55$$

$$R_{th} = \frac{800}{A_s\left(cm^2\right)} \quad (\quad /W) \qquad 6\text{-}18$$

A_S EE

EC ETD PM PR 22

A_W

$$R_{th} = \frac{36}{A_W\left(cm^2\right)} \quad (\quad /W) \qquad (6\text{-}18a)$$

PQ A_S/A_W=25~50, R_{th} 16 32 $/A_W$

3.电流密度

$$P_W = RI^2 = \frac{\rho_t l}{A_{cu}} I^2 = j\rho_t Il \qquad (6\text{-}19)$$

R= ρ l/A_{cu}

I

j=I/A_{cu}

A_{cu}

ρ_t t

l

Il

A

2.5~3A/mm^2(250~300A/cm^2) E 4.50/mm^2

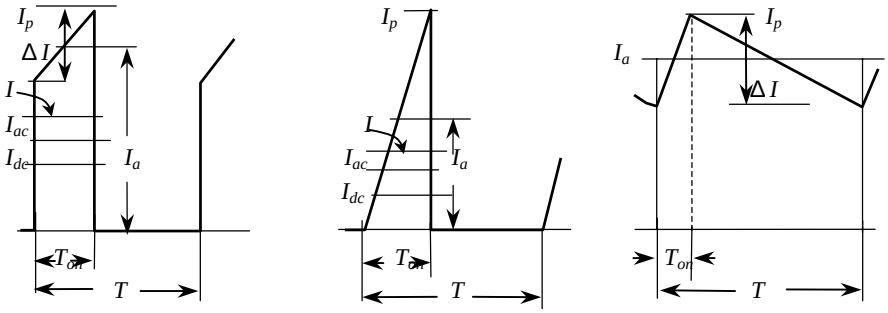
4~6.5A/mm^2

8A/mm^2 10A/mm^2

P_W P_C

6.5.2

6-17 I_p I_{dc} I



6-17 I_p I_{dc} I_{ac} I

1. 梯形波

(6-17(a))

T_{0n} T

I_p ΔI $D=T_{on}/T$ $I_a=I_p$ $\Delta I/2$

$$i = I_a - \frac{\Delta I}{2} + \frac{\Delta I}{T_{on}} t \left(0 < t < T_{on}\right)$$

$$i = 0\left(T_{on} < t < T\right) \qquad (6\text{-}20)$$

I_{dc}

$$I_{dc} = \frac{1}{T}\int_0^{T_{on}} i\mathrm{d}t = \frac{1}{T}\int_0^{T_{on}} \left(I_a - \frac{\Delta I}{2} + \frac{\Delta I}{T_{on}} t\right) \mathrm{d}t = DI_a \qquad (6\text{-}21)$$

I

$$I = \sqrt{\frac{1}{T}\int_0^{T_{on}} i^2 \mathrm{d}t} = \sqrt{\frac{1}{T}\int_0^{T_{on}} \left(I_a - \frac{\Delta I}{2} + \frac{\Delta I}{T_{on}} t\right)^2 \mathrm{d}t}$$

$$= \sqrt{D\left(I_a^2 + \frac{(\Delta I)^2}{12}\right)} \qquad 6\text{-}22$$

$\Delta I/2$ kI_a k=0.05~0.2,

$$I = I_a\sqrt{D} \qquad (6\text{-}22a)$$

$$I_{ac} = \sqrt{I^2 - I_{dc}^2} = \sqrt{DI_a^2 - D^2 I_a^2} = I_a\sqrt{D(1-D)} \qquad (6\text{-}22b)$$

6-17(a) 6-21~6-22

D 1-D

(2)

(6-17(b)) (6-20)~(6-22)

$$I_{dc} = \frac{DI_p}{2} \qquad (6\text{-}23)$$

$$I = \sqrt{\frac{DI_p^2}{4} + \frac{DI_p^2}{12}} = I_p\sqrt{\frac{D}{3}} \qquad (6\text{-}23a)$$

$$I_{ac} = \sqrt{\frac{DI_p^2}{3} - \frac{D^2 I_p^2}{4}} = I_p\sqrt{\frac{D}{3} - \frac{D^2}{4}} \qquad (6\text{-}23b)$$

(3)

6-17(c) $\Delta I/2$

$$I_{dc} = I_a \qquad (6\text{-}24)$$

$$I = \sqrt{I_a^2 + \frac{(\Delta I)^2}{12}} \approx I_a \qquad (6\text{-}24a)$$

$$I_{ac} = \frac{\Delta I}{2\sqrt{3}} \qquad 6\text{-}24b$$

6.5.3 k_w

$$k_W = \frac{\sum NA_{cun}}{A_W} \qquad (6\text{-}25)$$

A_W

$\sum NA_{cun}$ N A_{cun}

k_w

6-18 E

1/2

1/2

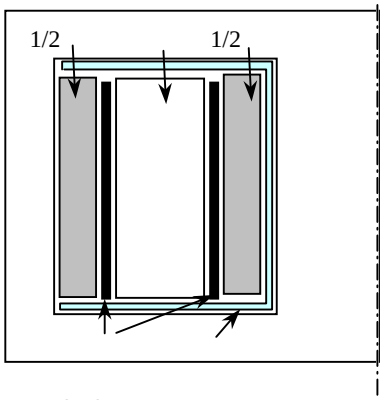
10.6

IEC65 VDE0860 3

6 8mm. 1cm

6-19 (a) b
2mm
2mm (a)
0.3mm
(b)
0.866d_1 d_1
0.8mm

0.9~0.95 d_1 0.3mm

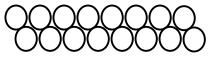


6-18

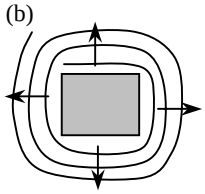
V/
21

0.1mm


(a)


0.25~0.5
(b)

6.5.4


50
(c)

6-19

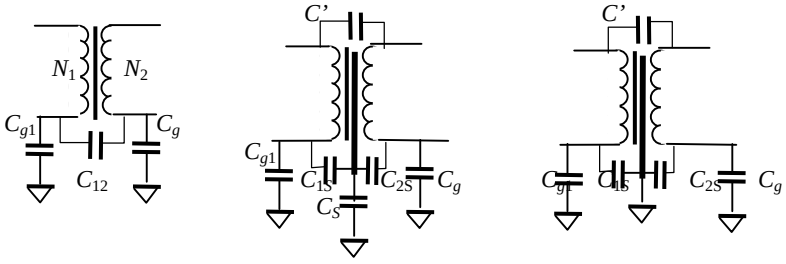
40 60

6.6

1. 线圈间电容和屏蔽

6-18

Δ Δ/3
“ ”



(a) (b) (c)

6-20

6-20

C_{12}

C_{g1} C_g

C_{1S} C_{2S}

C' U_{i1}

$$U_2 = \frac{C_{12}}{C_{12} + C_g} U_{i1} \qquad (6\text{-}26)$$

, C_S U_S

$$U_2^{'} = \frac{C_{2S}}{C_{2S} + C_g} U_S \qquad (6\text{-}27)$$

$$U_S = \frac{C_{1S}}{C_{1S} + C_S + C_{2S} C_g \left(C_{2S} + C_g\right)} U_{i1} \qquad (6\text{-}28)$$

6-28 (6-27)

$$U_2^{'} = \frac{C_{1S} C_{2S}}{\left[C_{1S} + C_S + C_{2S} C_g \left(C_{2S} + C_g\right)\right]\left(C_{2S} + C_g\right)} U_{i1} \qquad (6\text{-}29)$$

$C_{1S} >> C_S$ $C_{1S} >> (C_g // C_{2S})$

$$U_2'' \approx \frac{C_{2S}}{C_{2S} + C_g} U_{i1} > U_2^{'} \qquad (6\text{-}30)$$

$C_S \approx$ U_S=0 U_2'=0

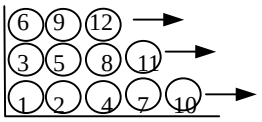
C'

$$U_2''' = \frac{C'}{C' + C_{2S} + C_g} U_{i1} \approx \frac{C'}{C_{2S} + C_g} U_{i1} \qquad (6\text{-}31)$$

C'<<C_{2S}

“ ” “ ”

2. 端部之间电容



6-21

6-21

本章要点

-
- Δ
- Δ
-
-
-
- Δ
- Dowell
  R_{AC}/R_{DC}=1.5
- /
-
-
-
-
-

1. Unitrode Magnetics Design Handbook Magnetics Design for Switching Power Supplies Lloyd H. Dixon
2. Swiching Power Supply Design Abraham I. Pressman Second Edition McGraw-Hill 1998
3. 1998
4.
5. 1990
6. Magnetics Handbook
7. 1991

第七章 功率变压器设计

7.1

7.1.1

7.1.2

EMI

(ZVT)

7.1.3

“ ”

6-15 ΔT R_{th} / W P

W

$$\Delta T = R_{th} P$$

40

A E 40 50 100

1.磁芯损耗

(1)

$U_o=DU_i/n$ $n=N_1/N_2$

U_i

(2) I^2R

/ U_i I^2R 4

I^2R U_i

2 .线圈损耗

1/5

$I_{2p}=I_o$

$I_{1p}=I_{2p}/n$

U_i I^2R

D U_i D

U_i

3.铁氧体磁芯

50kHz

0.16T 50kHz 1.6~2 2 2.7

4-20

100 200mW/cm^3

200 300kHz

200 300kHz

U_i

4-20

U_i

$R_{ac}/R_{dc}(F_R=1.5)$

U_i

U_i

4.带料合金磁芯

U_i

U_i

40 60 50

/ / /

1.5 1

6-16 E

6-18

7.1.4

70 75 75

7 7 0.75 × 0.75 × 0.75 42

80 90

0.35~0.5

0.25 0.5

7.1.5

0 150W 50

500W 100W 1000W 500W

1500W

7.1.6

“ ” “ ” f_s

“ ” IC

IC IC

50

1/2

“ f_T ”

,

7.1.7

D T_{on} T $D=T_{on}/T$

U_{imin} 0.45

45 0.9

90 D=0.9 90 90

45

$D=0.5T_{on}/0.5T=T_{on}/T$ D

D $U_o=U_2'D$ $U_2' \approx U_i/n$

$$U_i T_{on} = \frac{U_i D}{f_s} = \frac{nU_o}{f_s}$$ 7-1

$f_S=1/T$

U_{imin}

U_i 50

100

1

D_{lim}

U_i D_{lim}

$D_{max} < D_{lim}$

D_{lim}

D_{lim}

U_{imax}

B_S(B_s-B_r)

3:1 ΔB 0.08T 3 ΔB =0.24T<B_S

7.1.8

1．匝数的取整

5V 1V 5V 1
2 1 2 1.5 2
25
1 1/3
U_iD

12V 5V 2.5:1 5V
2 12V 5 5V 1 12V 3

2. 分数匝

1.2~1.8V 100kHz
1 1

1

U N

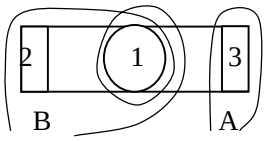
$$\frac{\Delta BA_e}{T_{on}}=\frac{U}{N} \tag{7-2}$$

T_{on} U (s)
A_e (m^2)
ΔB T_{on} T
E 7-1 E
1(a) A 1(a) B “X”
(1(b) A B C) 7-1(a) A

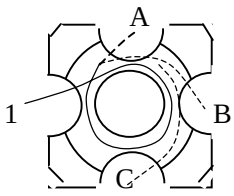
$$U_F=\frac{\Delta B}{T_{on}}\cdot\frac{A_e}{2} \tag{7-3}$$

7-2 *N*=1 (7-3) 7-2 A

7-1(a) B



(a) E



(b) X

7-1

B 1.5

7-1(b) 1/4

A,B,C 1.25 1.5 1.75

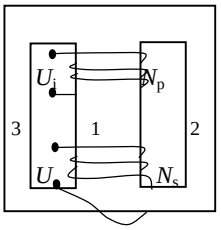
7-2 E

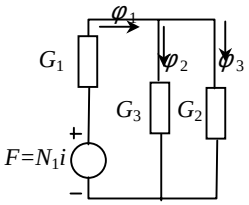
$G_1=\mu A_1/l_1$ $G_2=\mu A_2/l_2$ G_3 $A_3=A_2$ $l_3=l_2$

$k=G_2/(G_2+G_3)$ $A_2/(A_2+A_3)$

φ_3 $k\varphi_1$ $\mathrm{d}\varphi_3/\mathrm{d}t$ $k\mathrm{d}\varphi_1/\mathrm{d}t$

$$\frac{U_0}{U_i}=\frac{(N_2+k)}{N_1}$$





7-4

N_2

N_1

i_mN_1

7-2 A B

(2)

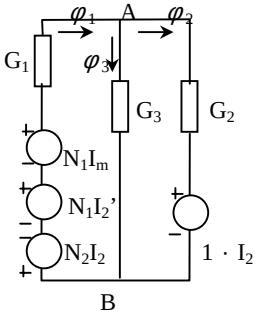
(7-4)

7-3

N_1i_m N_1I_2' N_2I_2

φ_1 U_i

1 I_2 φ_2 φ_3



7-3

$$L_2=\frac{\psi_F}{i}=\frac{(1-k)\phi}{Hl}=\frac{(1-k)BAk}{Hl}=(1-k)k\cdot\frac{\mu A}{l}$$ 7-5

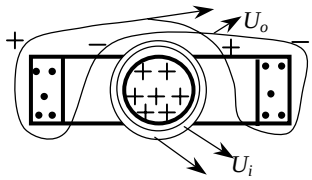
A A_2+A_3

l

$F=A_2/A$

k=0.5

(3)



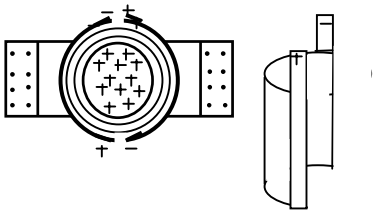
7-4 1 1

7-4

7-5

7-6

1



7-5

2A 3A

5A/2=2.5A 5

2.5A/5=0.5A 3A 2A

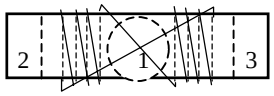
3/2/5=0.3A

E 1/2 1/2 7-1(b)

1/4 4 4

1 “ X ”

E



7-6

2 3 3

2 d φ_2/dt 3 1/3

1/4 2 3/4 3 2 1/4 3 3/4

100Hz

7.1.9

IR

R_{on}

IR

IR

7.1.10

1. 材料

10.3

2. 磁芯形状

R_{ac}

(GU P) PM RM PQ EE EC EP ETD RC UU UI EFD,EPC,LP

PQ (P) PQ EE EMI EMC 125W

EE EC ETD LP E

EC ETD EE 11
11 EE
5W 5kW EE
10kW

RM PM P E
EE RM

RM 30

PQ

LP EFD EPC

UU UI 1kW EE
EE

EMI
1

3 磁芯尺寸

1

$$AP = A_e A_W = \frac{P_O}{K\Delta B f_T}^{4/3} \quad cm^4 \qquad 7\text{-}6$$

P_o (W)

ΔB (T)

f_T (Hz)

K 0.014 0.017

420A/cm^2 40

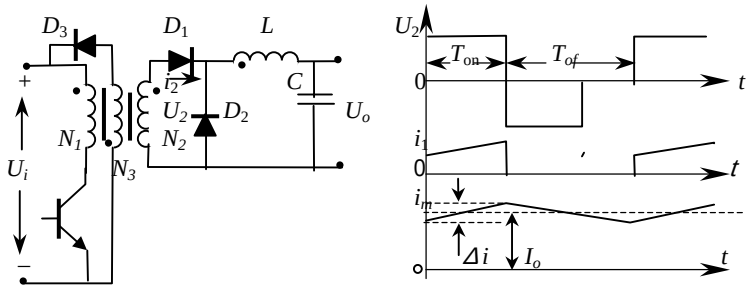
50kHz ΔB 100W/cm^3

f_T ΔB

2

η 80 0.4
4mm 4A/mm^2 50kHz
100 0.3T 0.2T

0.16T 50kHz 100 200mW/cm^3
ΔB ΔB/0.16



(a) (b) 0.5

7-7

7-7
ΔI=0.2I_o I_o

I_i= I_o/n

0.4

$$P_o = \eta P_i = \eta D U_{i\min} I_{dc} = 0.8 \times 0.4 U_{i\min} I_{dc} = 0.32 U_{i\min} I_{dc} \quad (7\text{-}7)$$

$$I = I_{dc}\sqrt{D} = I_{dc}\sqrt{0.4} = 0.632 I_{dc}$$

$I_{dc} = 1.58I$ (7-7)

$$P_o = 0.32 U_{i\,min} I_{dc} = 0.32 \times 1.58 U_{i\,min} I = 0.506 U_{i\,min} I \quad (7\text{-}8)$$

$$U_i = N_1 A_e \frac{\Delta B}{T_{on}} \quad (7\text{-}9)$$

U_i (V)
N_1
A_e (m^2) ΔB (T)
T_{on} s
$U_{i\min}$ f=1/ T, $\Delta B/T_{on\max}$= $B_{\max}$/0.4T 7-9 (7-8)

$$P_o = 0.506 U_{i\,min} I = \frac{0.506 I N_1 A_e B_{max} f}{0.4} = 1.265 N_1 B_{max} A_e f I_{rms} \quad (7\text{-}10)$$

1 A_W A_1 A_2
A_{1i}(cm^2) 0.4 A_1 A_2

$$A_1 = 0.2A_W = N_1 A_{1i} \qquad A_{1i} = \frac{0.2A_W}{N_1} \tag{7-11}$$

j A/cm^2

$$j = \frac{I}{A_{1i}} \qquad I = jA_{1i} = \frac{0.2jA_W}{N_1} \tag{7-12}$$

(7-12) (7-11), j =400A/cm^2

$$P_o = 1.265N_1 B_{max} A_e fI = 1.265N_1 B_{max} A_e f \times \frac{0.2jA_W}{N_1} \times 10^{-4}$$

$$= 1.012 fB_{max} A_e A_W \times 10^{-2} \tag{7-13}$$

$$AP = A_e A_w = \frac{99P_o}{fB_{max}} \tag{7-13a}$$

P_o W ;A_e A_W(cm^2) f(Hz) f 100mW/cm^3

7-13a P_o, (f)

10-15 B_{max}=0.16T $2\Delta B$/ 0.16

ΔB

η 0.8 D_{max}=0.4

× 2 0.8 $I_{dc} = 1.58I$

$$P_o = \eta DU_{i\min} I_{dc} = 1.01U_{i\min} I \tag{7-14}$$

0.4

(7-11)

$$A_1 = 0.2A_W = 2N_1 A_{1i} \qquad A_{1i} = \frac{0.1A_W}{N_1}$$ 7-15

(7-9)

$$U_{i\,min} = N_1 \frac{\Delta BA_e}{T_{on\,max}} = N_1 \frac{2B_{max} A_e}{0.4T} = 5N_1 fA_e B_{max} \tag{7-16}$$

7-12 ,

$$P_o = 1.01U_{i\,min} I = 5.05N_1 fA_e B_{max} \times j\frac{0.1A_W}{N_1} \times 10^6 \tag{7-17}$$

$$= 5.05jfA_e A_W B_{max} \times 10^5$$

A cm^2 j=400A/cm^2,

$$AP = A_e A_w \approx \frac{50P_o}{fB_{max}} \tag{7-17a}$$

(7-17) (7-13)

$2B_{\max}$

50kHz f

0.8 0.8T/2 η 80

0.4

$$I = I_{dc}\sqrt{0.8} = 0.894 I_{dc} \qquad I_{dc} = 1.12 I \tag{7-18}$$

$$P_o = \eta \cdot \frac{U_{i\min}}{2} \cdot I_{idc} D = 0.8 \times 0.8 \times 0.5 U_{i\min} \times 1.12 I = 0.358 U_{i\min} I \tag{7-19}$$

$$A_1 = 0.2 A_W = N_1 A_{1i} \qquad A_{1i} = \frac{0.2 A_W}{N_1} \tag{7-20}$$

$$I_{rms} = A_{1i} j = \frac{0.2 j A_W}{N_1} \tag{7-21}$$

U_1=U_i/2,

$$U_{i\,min} = 2 N_1 A_e \frac{\Delta B}{D_{max} T / 2} = 10 f N_1 A_e B_{max} \tag{7-22}$$

ΔB=2$B_{\max}$ $D_{\max}$=0.8

(7-21),(7-22) (7-19)

$$P_o = 0.358 U_{i\,min} I = 0.358 \times 10 f N_1 A_e B_{max} \times \frac{0.2 j A_W}{N_1}$$

$$= 0.716 f j A_e A_W B_{max} \times 10^6 \text{ (W)} \tag{7-23}$$

$$AP = A_e A_w \approx \frac{35 P_o}{f B_{max}} \tag{7-23a}$$

50kHz 4A/mm^2,$B_{\max}$=0.16T

10-16

10-15 10 16

100 200mW/cm^3 ΔB

ΔB/0.16T

7.2

例1

1

U_i 100 190V

5V,50A 250W

f_s 200kHz

2.5W;

40

2 D_{lim}, U_{imin} D_{max} U_iD

D_{lim} 0.47

D_{max} 0.42 5

U_iD: $U_{imin}D_{max}$ =42V

U_{imax} D_{lim} 89.3V

3 IR

U_o' 5.0+0.4=5.4V

4

$$n = \frac{N_1}{N_2} = \frac{U_i}{U_o'} = \frac{42}{5.4} = 7.8$$

8:1 7:1 15:2

5 200kHz 250W

Philips

3C90 7-8

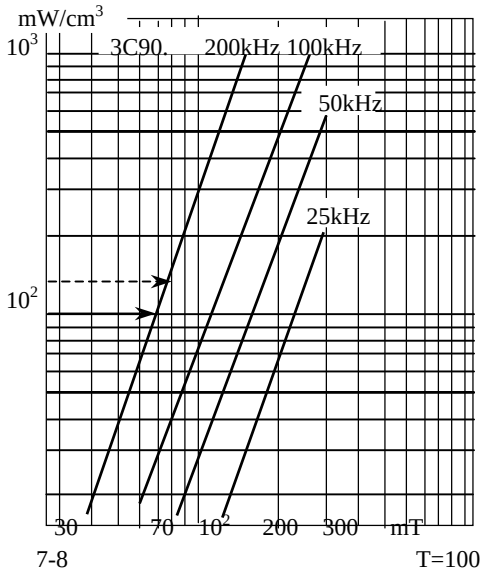
100mW/cm^3

0.068T (7-6)

$$AP = \left(\frac{250}{0.014 \times 0.068 \times 200 \times 10^3}\right)^{4/3} = 1.4\text{cm}^4$$

10-15

ETD34(AP=1.83cm^4) 7-9



AP 7-8 T=100

6

cm

A_e=0.97cm^2; V_e=7.64cm^3; l_e=7.9cm

,

A_W/ A_W'=1.89/1.23cm^2

b_W /b_W'=2.36/1.5cm

h_W /h_W'=0.775/0.6cm

l_{av} 5.8/6.1cm ETD 11mm, 25.6mm, 1.1mm

11 2 × 0.11=13.2mm π (1.32+25.6)

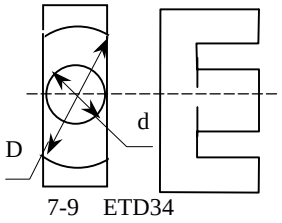
7 EC ETD

Magnetics

$$R_T = \frac{800}{22 \times A_W(cm^2)} = \frac{36}{189} = 19 \quad /W$$

ΔT

$$P_{\lim} = \Delta T / R_T = 40/19 = 2.1W < 2.5W$$



7-9 ETD34

1 2.5W 2.1W

P_{Clim}=1W,P_{Wlim}=1.1W 2.5W 40

8 ΔB

cm^3

$$P_{C\,lim} / V_e = 1/7.6 = 131mW/cm^3 (= kW/m^3)$$

3C90 (7-8) “

” ΔB:

7-8 131mW/cm^3→, 200kHz→0.08T 40

ΔB=2 × 800Gs=1600Gs=0.16T

Δ φ Δ$B \times A_e$

9

$$U_o' T_S = N_2 \Delta\phi$$

$$N_2 = \frac{U_o' T_S}{\Delta\phi} = \frac{5.4 \times 5 \times 10^{-6}}{0.16 \times 0.97 \times 10^{-4}} = 1.74$$

1 / 2

2 2

10 2

$$\Delta B = 0.16 \frac{1.74}{2} = 0.14(T)$$

7-8 0.14T/2 700Gs 110mW/cm^3

P_c=110 × 7.64=840mW=0.84W

11 D 4

N_1=15 7.5:1

U_iD $U_{imax}D_{lim}$

U_iD nU_O’=7.5 × 5.4=40.5V

ΔB_{lim}=0.14 × 89.3/40.5 0.31T <B_S

12

7-10

15

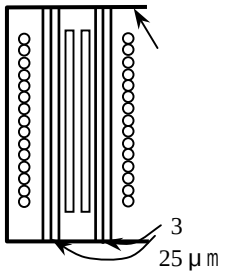
1 2 1

Δ

13 200kHz

$$\Delta = \frac{7.6}{\sqrt{f}} = \frac{7.6}{\sqrt{2\times10^5}} = 0.017cm$$

14 U_{inmin} D_{max} 11 6-22



7-10

$$I_{2dc} = 50A \cdot D_{max} = 50 \cdot 0.405 = 20.25A$$
$$I_{2ac} = I_{2dc}\sqrt{D(1-D)} = 24.5A$$
$$I_{1dc} = I_{2dc} / n = 20.25 / 7.5 = 2.7A$$
$$I_{1ac} = I_{2ac} / n = 24.5 / 7.5 = 3.27A$$

: 1.35A, 1.65A.

15:

A_{1i}=I_{1ac}'/j=1.65/4=0.39mm^2 1.3cm 15 ,
0.86mm 0.75mm, 0.442 6-12

$$H = 0.866d\sqrt{d / d'} = 0.866 \times 0.75 \times \sqrt{0.75 / 0.86} = 0.607mm$$

$$Q = \frac{H}{\Delta} = \frac{0.0607}{0.017} = 3.6$$

6-9 1 F_R=R_{ac}/R_{DC}=3.5 100 0.07mm
0.85mm,100 0.61mΩ/cm.

$$R_{dc} = \Omega / cm \cdot l_{cp} \cdot N_s = 0.00061 \cdot 6.1 \cdot 15 = 0.0558\Omega$$

$$I_{1dc}^2 R_{dc} = 1.35^2 \times 0.0558 = 0.1W$$ 0.2W

100 10×10 1 15
10 150 Q 1/10 Q =0.36 R_{ac}/R_{dc} 1.2
R_{ac} R_{dc} × 1.2=0.067Ω R_{ac} I^2=0.067 × 1.65^2=0.18W
0.36W 0.2W 0.56W
( )

16

2 1.3cm , 0.13cm
Δ
R_{ac}/R_{dc} R_{dc} R_{ac}
0.1cm.

Q H/Δ=0.13/0.017=7.6 6.9 Q 7.6 1
F_R=R_{ac}/R_{dc}=7.5

R_{dc}= ρ × × N_s/(bw'h)=2.3 × 10^{-6} × 6.1 × 2/(1.3 × 0.13)=166μΩ
P_{dc}=166μΩ × 20.25^2=0.068W
P_{ac}=7.5 × 166 × 10^{-6} × 24.5^2=0.75W

0.068W+0.75W=0.82W

0.82W+0.56W=1.38W

0.84W+1.38W=2.22W

2.5W 40 2.1W

1. Unitrode Magnetics Design Handbook Magnetics Design for Switching Power Supplies Lloyd H. Dixon
2. Swiching Power Supply Design Abraham I. Pressman Second Edition McGraw-Hill 1998
3. 1999
4. Philips Magnetic Components 1996 (Mannul)

第八章 电感和反激变压器设计

“ ”

8.1

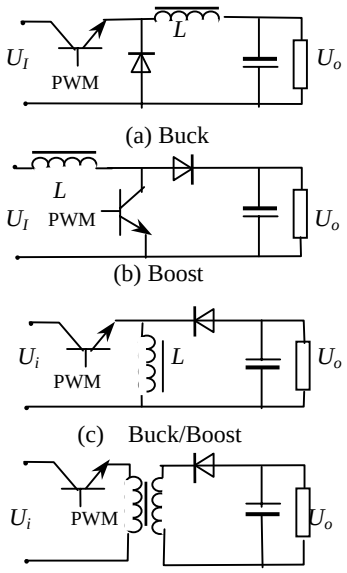
8-1

Buck Boost

Buck-Boost

EMI

8-2



7 8-1

8.1.1 Buck

Buck 8-1(a)

(8-2(b))

$$L \geq \frac{U_o T_{of}}{\Delta I} = \frac{U_o T_{of}}{2kI_o} = \frac{U_i D(1-D)}{2kfI_o} \qquad (8\text{-}1)$$

U_i (V)

D T_{on}/T

U_o DU_i (V)

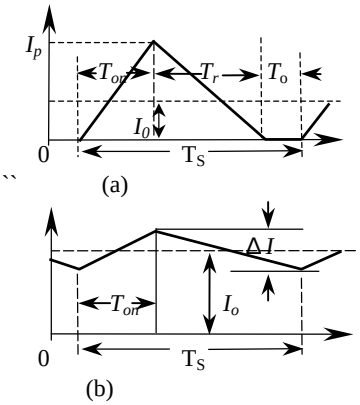
f=1/T Hz

I_o A

T_{on}, T_{of}=T- T_{on}

k= Δ I/2I_o

Δ I k L



8-2

L k 0.05~0.1

I_o 10A ΔI I_o 20 2A

U_i 0.58A((6-24) $\Delta I / \sqrt{12}$)

0.333A 100 I^2R R_{ac}/R_{dc} 300

6-9 300

DG3 0.05mm

40kHz Kool μ 100kHz

(8-2(a))

$$L \le \frac{U_o T_{of}}{\Delta I} = \frac{U_o T_{of}}{2 I_o} = \frac{U_i D(1-D)}{2 f I_o} \qquad 8\text{-}2$$

ΔI=2I_o (8-1) (8-2)

8-2

8.1.2 Boost Boost/Buck

8-1(b)(c) Boost Boost/Buck

$$L \ge \frac{U_i T_{on}}{\Delta I} = \frac{U_i D}{2kfI_i} \qquad (8\text{-}3)$$

I_i=I_o/ η (1-D) Boost Boost/Buck

η

8-2

Boost

$$L < \frac{U_i T_{on}}{\Delta I} = \frac{U_i T_{on}}{2 I_i} = \frac{U_i D(1-D)}{2 f I_o} \qquad 8\text{-}4$$

Boost APFC(Active Power Factor Correction)

Boost U_i

APFC Boost

Buck Boost (a) (b)

APFC Boost

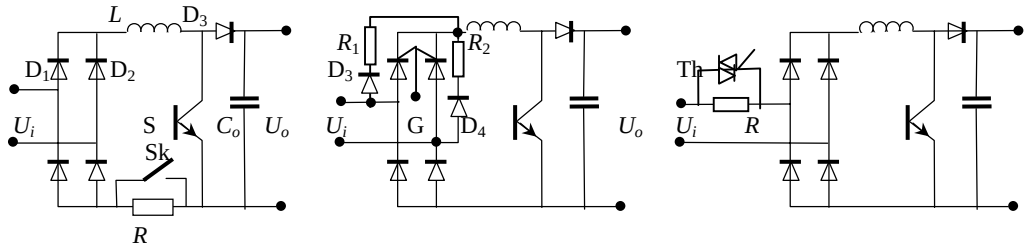
U_i U_o ΔI

ΔI

Boost APFC

Boost APFC

8-3



(a) (b) (c)

8-3 PFC

8-3 a R APFC

L R Sk

APFC

(b) (a) D_1 D_2

D_3 R_1 D_4 R_2 R_1 R_2 (a) R

R_1 R_2

(c) R Th R

LC Boost

NTC(Negative Temperature Coefficient) PTC(Positive Temperature Coefficient)

ESR PTC

PTC

8.1.3

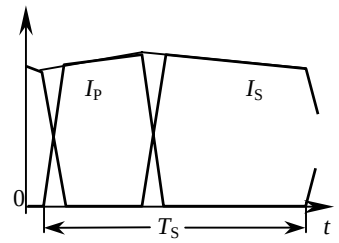
8-4

$$L_1 \geq \frac{U_i T_{on}}{\Delta I_1} = \frac{U_i D}{2kfI_1} = \frac{U_i D(1-D)}{2kfI_o} \cdot \frac{N_1}{N_2} \qquad (8\text{-}5)$$

$k = \Delta I_1/I_1 = \Delta I_2/I_2$

I_1 I_2

N_1 N_2



8-4

$$L_1 \leq \frac{(U_{i\min} D_{\max})^2 \eta}{2P_o f} \qquad 8\text{-}6$$

U_{imin} V

D_{max}

P_o W

f Hz

η 80%

8.1.4

8-5 3

1 n

$$U_{no} = \left(U_i - U_s\right)\frac{N_2}{N_1} - U_d \quad D \qquad (8\text{-}7)$$

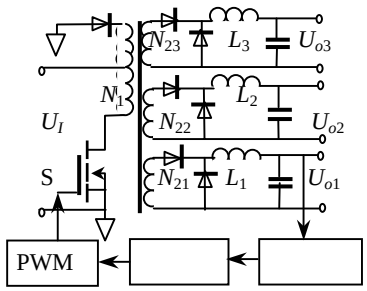
U_i

U_s

N_2

N_1

U_d



8-5

$D=T_{on}/T$

1V 10V

0.5V 1V

$$U_{no} = \left(U_i - 1\right)\frac{N_2}{N_1} - 0.5 \quad D = \left[U_2 - 0.5\right]D \qquad (8\text{-}7a)$$

(8-7a) U_2 1 U_{o1}

D

$$\frac{U_o}{U_i}=\frac{1}{1+I_o/\left(4I_{G\max}D^2\right)} \qquad (8\text{-}8)$$

I_o

$I_{G\max}$ $U_2T/8L$ 0.5

D

1 (8-8) 1

D (8-7)

1

$(R_L=U_o/I_o)$

200 300

5V

1 2V

1V

U_{21}

U_{22} L_1 L_2

$$U_{o1}=DU_{21} \qquad (8\text{-}9a)$$

$$U_{o2}=DU_{22} \qquad (8\text{-}9b)$$

$U_{21}/U_{22}= N_{21}/N_{22}$ $U_{o1}< U_{o2}$ U_{22} U_{21} $U_{22}'=N_{21}$ U_{22}/N_{22}

$$U_{o2}'=DU_{22}'=U_{o1} \qquad 8\text{-}10$$

$$U_i-U_o=L\frac{\mathrm{d}i}{\mathrm{d}t}=L\frac{\Delta I}{T_{on}} \qquad 8\text{-}11$$

L_1 2 1 L'_2

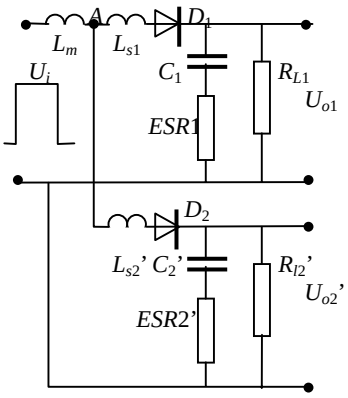
10 30 200 300

ESR

8-6 L_m ((8-11))
L_{s1} 1 L_{s2}’ 2 1

ESR

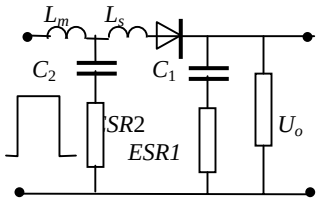
L_s ESR 2 1
L_{s2}’ ESR2’ 2 1
2 50V ESR
ESR1



8-6

L_{s2}’
200kHz

L_{s2}’< L_{s1}



8-7

C_1 C_2
8-7

2

10

8.2

,

8.3

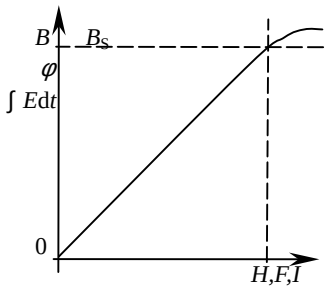
8.3.1

1-13

μ_e

a

b



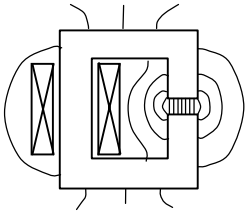
μ_e

μ_e 8-8

8-8

B_S

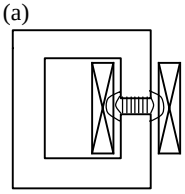
8-9a C



EMI

(a)

8-9b



E EE EC

ETD RM

(b)

8-9

8-9(b)

1/20

(3-12) (3-22)~(3-23)

7 8

8.3.2

Boost

1

2

3

EMI

8-9a b

8.3.3

$B+\Delta B$

ΔB

B_{r} H_{c}

H_{c} B_{r}

$$B = B_r - \frac{B_r}{H_C} H = B_r - \mu_0 \mu_d H$$

μ_{d} l_m μ_r

l_e A_e

$$H_c l_m = H l_m + H_c l_e = \frac{B l_m}{\mu_0 \mu_d} + \frac{B l_e}{\mu_0 \mu_r} = \frac{B l_e}{\mu_0 \mu_e}$$

$$\mu_e = \left(\frac{l_m}{l_c \mu_d} + \frac{1}{\mu_r} \right)^{-1}$$

$\mu_{\mathrm{e}} \approx \mu_{\mathrm{d}} l_{\mathrm{c}} / l_{\mathrm{m}}$

NI

$H_c l_m$

8.3.4

50kHz

Kool μ

B-H “ ”

PQ

EC ETD LP EE

EMI

8.3.5

(7-6)

B_{max}

$$AP = A_W A_c = \frac{LI_{Sp}}{B_{max}} \cdot \frac{I_{1L}}{K_1}^{4/3} \text{ cm}^4 \quad (8\text{-}12a)$$

ΔB

$$AP = A_W A_C = \frac{L\Delta I}{\Delta B_{max}} \cdot \frac{I_{FL}}{K_2}^{4/3} \text{ cm}^4 \quad (8\text{-}12b)$$

L H

I_{Sp} A

B_{max} T

ΔI A

ΔB_{max} T

I_{1L}

$$K_1, K_2 = J_{max} k_{1W} \times 10^{-4} \quad (8\text{-}13)$$

J_{max} A

k_{1w} /

10^{-4}

k_{1w} k_{1w}

A_W

k_w k_{1w}

K_1 K_2 k_{1w} 8-1

(8-12a) K_1

420A/cm^2

8-1

	k_{1w}	K_1	K_2
	0.7	0.03	0.021
	0.65	0.027	0.019
Buck/Boost	0.3	0.013	0.009
	0.2	0.0085	0.006

(8-12b)

297A/cm^2(420 × 0.707)　　K_2=0.707 × K_1

8-12

1/3

K

4/3

8-12b　　ΔB_{max}　　100mW/cm^3

100mW/cm^3(　　4-20)

“　　”

2

ΔB_{max}　　ΔB_{max}　　10^4　　T　　4-15

8-1　a　Buck　　(8-2b)

“　　”　　4-12

L　　N

A_e　　l　　δ

$$U_i - U_o = L\frac{\Delta I}{T_{on}} = N\frac{A\Delta B}{T_{on}} \qquad (8\text{-}14)$$

I_p

$$NI_p = H_c l + H_\delta \delta \qquad (8\text{-}15)$$

L=N^2 μ$_0$$A_e$/ δ

$$\Delta I = \frac{\delta \Delta B}{N\mu_0}$$

$$I_p = \frac{\delta B_p}{N\mu_0} \qquad (8\text{-}16)$$

k=Δ I/2I$_p$　　(8-16)

$$\frac{\Delta B}{B_p} = \frac{\Delta I}{I_p} = 2k \qquad (8\text{-}17)$$

I　I_G=ΔI/2

U_o=DU_i　　k　,　　I_G

k=0.05~0.1

(8-17)　　k=0.05　0.1　　250kHz

100mW/cm^3

$$\Delta B / 2k = B_p < B_S \qquad (8\text{-}18)$$

Boost　Buck/Boost

Kool μ

8.4

8.4.1

μ_r 3000 100000

μ_r 1 (3-50)

$$L = N^2 G_\delta = \frac{\mu_0 N^2 A_\delta}{\delta} \times 10^{-2} (H) \quad (8\text{-}19a)$$

cm A_δ- (cm^2)

8.4.2

μ_r 10 300

(3-51)

$$L = \alpha N^2 G = \alpha \frac{\mu_0 \mu_r N^2 A_e}{l_e} \times 10^{-2} \text{ (H)} \quad (8\text{-}19b)$$

cm α μ_r

8.4.3 A_L

μ_r A_e

mH/1000 nH/ A_L

A_L μH/1000 ,N

$L=N^2 A_L \times 10^{-6}$ (μH) (8-20)

(8-20)

δ

μ_e

8.5

8.5.1

(1) L I_L ΔI

I_{Sp},

Buck U_i Boost U_i Buck

(2)

(3)

I_{Sp} B_{max} B_S(100

0.3T 3000Gs) B H 4-12

(8-18)

$$\Delta B_{max} = 2kB_{max} \quad (8\text{-}21)$$

ΔB_{max} 2 4-20) “ ”

100mW/cm^3 ΔB_{max}

100mW/cm^3 , ΔB_{max} 5

I_{Sp} B_{max}

μ_r

100kHz

(4) 8-12a,8-12b

(5) 10.3.7 (6-16) (6-18) R_T

ΔB_{max}

(6) N (3) (5)

$$E = N\frac{\Delta\phi}{\Delta t} = NA_e\frac{\Delta B}{\Delta t}$$

$$E = L\frac{\Delta i}{\Delta t}$$

L μH,A_e cm^2

$$N = \frac{L\Delta I_{max}}{\Delta B_{max}A_e}\times 10^{-2} \qquad (8\text{-}22)$$

N N

N

N

L ΔI (8-22) N N 8-22 ΔB

ΔB

(7) δ N (8-19) (8-20)

δ A_e

(3-23) 3-23b A_g.

$$\delta = \mu_0 N^2\frac{A_g}{L}\times 10^4 \qquad (8\text{-}23a)$$

$$\delta = \mu_0 N^2\frac{A_e}{L}\left(1+\frac{\delta}{D_{cp}}\right)^2\times 10^4 \qquad (8\text{-}23b)$$

(L μH, cm)

δ $k_\delta = A_g/A_e$. (8-23) δ

δ 2 3

A_L :

$$\mu_e = \frac{Ll_e}{\mu_0 N^2 A_e}\times 10^{-4} \qquad (8\text{-}24)$$

(L μH, cm)

(8)

$$\rho_{cu} = 1.724\ 1+\frac{(T-20)}{234.5} \times 10^{-6}\ (\Omega \bullet\ \text{cm})$$

100

$$\rho_{cu} = 2.30\times 10^{-6}\ (\Omega \bullet\ \text{cm})$$

(cm)

$$R_{dc} = \frac{\rho_{cu} l}{A_{cu}}\ (\Omega) \qquad (8\text{-}25)$$

l Nl_{av} cm

l_{av}

A_{cu} cm^2

(9)

8.5.2 Buck

例1

5V 50A

(1)

(7.5:1)

13.35~25.33V

5V

I_o 50A

f 200kHz

0.405($U_{i\min}$)

0.213($U_{i\max}$)

ΔI 50A × 20%=10A

$I_{p\max}$ 65A

L 2.2 μ H $L=U_o'T_{of}/\Delta I=5.4\times 5\times 10^{6}\times 0.787/10=2.2\ \mu\text{H}$

2.5W

40

(2) 3C90(

)

(3) $B_{\max}$ 0.3T 3000

$B_{\max}$

$$\Delta B_{\max} = B_{\max}\frac{\Delta I_{\max}}{I_{p\max}} = 0.3\frac{10}{65} = 0.046\text{T}$$

2 0.023T 230 7.8 230

200kHz 4mW/cm^3 100mW/cm^3

$I_{p\max}$ Δ

B_{max}=0.046T.

(4) Philips

B_{max} 0.3T K_1=0.03 8-12a

$$AP = \frac{LI_{sp}}{B_{max}} \cdot \frac{I_{FL}}{K} = \frac{2.2\times10^{-6}\times65\times50}{0.3\times0.03} = 0.74\text{cm}^4$$

ETD34 A_eA_w=1.21cm^4( )

: 34mm ETD34 7-9

A_e 0.97cm^2

V_e 7.64cm^3

l_e 7.9cm

D_{cp} 1.08cm

A_W 1.23cm^2

b_W 1.50cm

h_W 0.60cm

l_{av} 6.10cm

(5) R_T 19 /W

ΔT

P_{lim}= $\Delta T/R_T$:=40/19=2.1W

2.5W 2.1W 4mW/cm^3(3)

P_C=mW/cm^3 × V_e=4 × 7.64=30mW

2W

(6) 8-22

$$N = \frac{L\Delta I_{max}}{\Delta B_{max} A_e}\times10^{-2}$$

(L μH, cm)

$$N = \frac{2.2\times10}{0.046\times0.97}\times10^{-2} = 4.93 \rightarrow 5$$

(7) 8-23b

$$\delta = \mu_0 N^2 \frac{A_e}{L}\left(1+\frac{\delta}{D_{cp}}\right)^2 \times10^4$$

(L μH, cm)

$$\delta = 4\pi\times10^{-7}\times5^2\cdot\frac{0.97}{2.2}\left(1+\frac{\delta}{1.08}\right)^2\times10^4 = 0.192cm$$

(8) 4 b_W=2.1cm, h_W=0.6cm 6

5 5 2.0cm 0.05mm

450A/cm^2, 50A 0.111cm^2

0.0555cm 5 0.005cm 0.3cm

0.1cm 0.525cm 0.2cm^2

6.1cm 30.5cm

$$R_{dc} = \rho\frac{l}{A} = 2.3\times10^{-6}\times\frac{30.5}{0.2} = 0.35\,\text{m}\Omega$$

$P_{dc}=50^2\times0.00035$ 0.89W

6.4.1 200kHz 0.017cm

0.1cm, Q=0.1/0.017=5.9 Dowell 6.9 Q=6 5 R_{ac}/R_{dc} 100 R_{ac}=0.035 Ω

(6.24b) $\Delta I/\sqrt{12}$ ΔI=10A,

$$I=10/\sqrt{12}=2.9\text{A}$$

$$P_{ac}=I^2R=2.9^2\cdot0.035=0.29\text{W}$$

P_W=0.89+0.29=1.18W

(9) 30mW 1.21W 2.1W

250A/cm^2 ETD34 65

ETD

8.5.3

1. 占空度和匝比

( )

8-10 8-11

D

$$n=\frac{U_i}{U_o'}\frac{D}{1-D};\rightarrow D=\frac{nU_o'}{U_i+nU_o'} \quad (8\text{-}26)$$

U_o’

U_i U_o

D 0.5 n

0.5 n

2. 线圈电流参数的计算

8-10 6.5.2 ( )

8-10

$$I_{dc}=D\frac{(I_p+I_{\min})}{2}=DI_a \quad (8\text{-}27)$$

$I_{min}=I_p-\Delta I$;

$D=T_{on}/T$

8-27 $I_{\min}$=0

(6-22)

$$I=\sqrt{D\left(I_a^2+(\Delta I)^2/12\right)} \quad (8\text{-}28)$$

6-22a

$$I=\sqrt{DI_a^2}=I_a\sqrt{D} \quad (8\text{-}28\text{a})$$

8-28

$$I=\sqrt{\frac{D}{3}I_p^2}=0.577I_p\sqrt{D} \qquad \text{(8-28b)}$$

, (6-22b)

$$I_{ac}=\sqrt{I^2-I_{dc}^2} \qquad \text{(8-29)}$$

3. 连续工作模式

8-10

U_i U_i

U_i

U_i

4. 连续模式电感设计举例

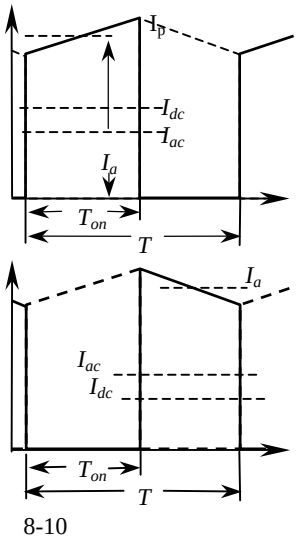
例2

(1)

U_i 28 ± 4V

U_o 5V

I_o 10A



8-10

f_s 100kHz

D 28V 0.5

ΔI 5A( ),32V

I_{sp} 25A( )

L 6.8μH(D=0.5, ΔI=5A)

2.0W

40

(2)

(8.26) U_i =28V 0.5

$$n=\frac{U_i}{U_o^{'}}\cdot\frac{D}{1-D}=\frac{28}{5+0.6}\cdot\frac{0.5}{1-0.5}=5$$

U_i U_i D

$$D_{24}=\frac{nU_o^{'}}{U_i+nU_o^{'}}=\frac{5(5+0.6)}{24+5(5+0.6)}=0.538$$

$$1-D_{24}=0.462$$

(3) Philips 3C90 100 0.32T

(4)

$B_{\max}$ 0.3T(3000) ,B

$B_{\max}$ B H $\Delta B_{\max}$ 32V

$$\Delta B_{\max} = B_{\max}\frac{\Delta I}{I_{Sp}} = 0.3\frac{5}{25} = 0.06\text{T}$$

2 0.03T 300 3C90 300

100kHz 2.6mW/cm^3 100mW/cm^3

I_{Sp} 25A $B_{\max}$ ΔI=5A $\Delta B_{\max}$ 0.06T

(5) (8-12)

B_{max}=0.3T, K_1=0.085

$$AP = \frac{LI_{sp}}{B_{max}} \cdot \frac{I_{1L}}{K_1}^{4/3} = \frac{6.8\times10^{-6}\times25\times10}{0.3\times0.0085}^{4/3} = 0.58\ \text{cm}^4$$

EE- ETD34. :

A_e 0.97cm^2

V_e 7.64cm^3

l_e 7.9cm

D_c 1.08cm

A_w 1.23cm^2

b_w 1.50cm

h_w 0.60cm

l_{av} 6.10cm

(6) R_T R_T 19 /W

ΔT

P_{lim}= ΔT( )/R_T=40/19=2.1W

2W 2W

P_C=p × V_e=2.6 × 7.64=20mW

(7) (8-22) (L μH; cm)

$$N_2 = \frac{L\Delta I}{\Delta B_{max}A_e}\times10^{-2} = \frac{6.8\times5}{0.06\times0.97}\times10^{-2} = 5.84 \to 6$$

$$N_1 = N_2 \times n = 6\times5 = 30$$

(8) (8-23b) (L μH; cm)

$$\delta = \mu_0 N^2 \frac{A_e}{L}(1+\frac{\delta}{D_{cp}})^2\times10^4$$

$$= 4\pi\times10^{-7}\times5^2\frac{0.97}{6.8}(1+\frac{\delta}{1.08})\times10^4 = 0.08cm$$

(9)

(5) b_w=2.10cm h_w=0.60cm 0.3cm.

2.1 2 × 0.3=1.5cm

-U_o=24V,1-D_{24}=0.462 (8-28a 8-28b 8-29)

I_o=10A

$$I_{2a}=\frac{I_o}{1-D_{24}}=\frac{10}{0.462}=21.65A$$

$$I_2=\sqrt{(1-D_{24})I_{2a}^2}=14.7A$$

$$I_{2ac}=\sqrt{I_2^2-I_o^2}=10.77A$$

6 6 1.5cm 0.015cm 0.015 × 1.5=0.0225cm^2

650A/cm^2 6

0.005cm 0.12cm 6.1cm 36.6cm

$$R_{dc}=\rho\frac{l}{A}=2.3\times\frac{36.6}{0.0225}=0.0037\ \Omega$$

100kHz Δ 0.024cm 0.015cm Q=0.015/0.024=0.625 6-9 Dowell Q=0.625 6 R_{ac}/R_{dc} 1.6

$$R_{ac}=R_{dc}\times1.6=0.0037\Omega\times1.6=0.0059\Omega$$

-U_i=24V D=0.538 8-28 8-28a (8-28b) (8-29

I_{1a} I_{2a}/n=21.65/5=4.33A

I_{dc} $D\ I_{1a}$=0.538 × 4.33=2.33A

I_1 $\sqrt{D\cdot I_{1a}^2}=3.18A$

I_{1ac} $\sqrt{I_{rms}^2-I_{1dc}^2}=2.16A$

I_{1sp} 25/n=5A

3 0.127cm 3 10 10 3

3 × 0.127=0.381cm

150 0.0081cm 0.081mm 0.046Ω/cm

150 100 0.00031Ω/cm 30 30 × 6.1cm=138cm

R_{dc}=0.00031 × 183=0.0567Ω

150 12 12 12 150

30 3 12

0.081mm S 120 10 12 0.081mm

0.0125cm

6.4.1

$$0.83d\sqrt{\frac{d}{S}}=0.83\times0.0081\sqrt{\frac{0.0081}{0.0125}}=0.054cm$$

6-9

Q=0.0054cm/Δ=0.0054/0.024=0.225

36 R_{ac}/R_{dc}=1.6,

R_{ac}= R_{dc} × 1.6=0.0567 × 1.6 0.090Ω

(10)

$P_{2dc}=I_o^2R_{dc}=10^2\times0.0037=0.37W$

$P_{2ac}=I_{2ac}^2R_{ac}=10.77^2\times0.0059=0.68W$

$P_2=0.37+0.68=1.05W$

Q

$R_{dc}=0.0567\Omega$

$P_{1dc}=I_{1dc}^2R_{dc}=2^2\times0.0567=0.225W$

$R_{ac}=0.09\Omega$

$P_{1ac}=I_{1ac}^2R_{ac}=2.16^2\times0.09=0.42W$

$P_1=0.025+0.42=0.645W$

$P_w=1.05+0.645=1.695W$

20mW 1.71W 2W

0.02cm 0.12+0.381+0.02=0.521cm 0.6cm

6.8μH 170μH($L_1=n^2L_2$).

5μH 50pF

7-4

R_{ac}/R_{dc} 1 0.35W

1.71W 1.36W

5．断续工作模式

8-2

t_{on} t_R t_0(8-11(b))

I_p t_{on} t_R t_0 t_0 (8-11(a))

$LI_{1p}^2/2$

$P_o=I_oU_o$ f L U_o $LI_{1p}^2/2$ U_i

I_{1p}

1.5 1 2

3:

(1)

U_i 28±4V

U_o 5V

I_o 10A

I_s 12A

f 100kHz

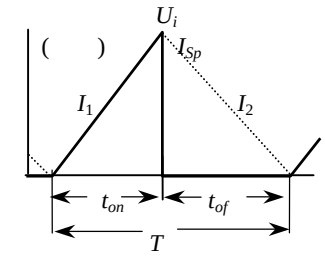
D 24V, 0.5

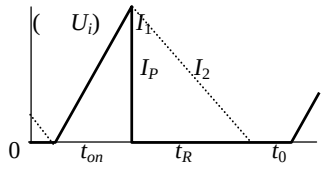
I_{2p} 45A( )

L_2 0.62μH(D=0.5, ΔI=45A)

2.0W

ΔT 40





8-11

(2)

U_i(24V) U_o' 5.6V 0.5

$$n = \frac{U_i}{U_o} \cdot \frac{D}{1-D} = \frac{24}{5.6} \cdot \frac{0.5}{1-0.5} = 4.28 \rightarrow 4$$

n 4:1 5:1

(a) 4:1

(b)

(c)

0.5

$$D_{24} = \frac{U_o \cdot n}{U_i + U_o \cdot n} = \frac{5.6 \times 4}{24 + 5.6 \times 4} = 0.483$$

$$1 - D_{24} = 0.517$$

$$I_{2dc} = I_{2p} \frac{1-D_{24}}{2}$$

$$I_{2p} = \frac{2I_{2dc}}{1-D_{24}} = 12\frac{2}{0.517} = 46.4\text{A}$$

11.6A 46.4A/n

46.4A

$$L = U_o \frac{\Delta t}{\Delta i} = U_o \frac{T \cdot (1-D_{24})}{\Delta i} = 5.6\frac{10 \cdot 0.517}{46.4} = 0.624\ \mu\text{H}$$

U_i

(3) P

(4) B_{max}=0.3T(3000Gs)

ΔI I_p, ΔB

B_p ΔB_{max} B_{max}

P 100mW/cm^3 100kHz

1100Gs 2 2200Gs,

0.22T B_{max} ΔB_{max} B_{max} 0.22T B_{max} 0.22T

$\Delta I=I_{2p}$=46.4A

(5) EE ETD

(8-12) ΔB_{max} 0.22T K_2=0.006 0.31cm^4 ETD24

AP=0.37cm^4( )

A_e=0.56cm^2

V_e=3.48cm^3

l_e=6.19cm

D=0.85cm

,

A_w/A_W'=1.02/0.86cm^2

b_w/b_W'=2.07/1.72cm

h_w/h_W'=0.50/0.38cm

l_{av}=4.63cm

(6) R_T 28 /W

ΔT

$P_{lim}=\Delta T/R_T$=40/28=1.42W

2W 1.42W

$P_C=p' \times V_e$=100mW × 3.48=350mW p' 3C90

(7)

$$N_2 = \frac{L\Delta I_{max}}{\Delta B_{max} A_e} \times 10^{-2} = \frac{0.63 \cdot 46}{0.22 \cdot 0.56} \times 10^{-2} = 2.35 \rightarrow 2$$

$$N_1 = N_2 \times n = 2 \times 4 = 8$$

N_2 2.35 2

$$\Delta B_{\max} = 0.22 \frac{2.35}{2} = 0.258\text{T}$$

2 0.13T(1300Gs)

160mW/cm^3 V_e=3.48 560mW

N_2 3

(8)

$$\delta = \mu_0 N^2 \frac{A_e}{L} (1 + \frac{\delta}{D_{cp}}) \times 10^4$$

$$\delta = 4\pi \times 2^2 \frac{0.56}{0.62} (1 + \frac{\delta}{0.95}) \times 10^4 = 0.05\text{cm}$$

(L μH; cm)

(9)

(5) b_w=1.72cm h_w=0.38cm 0.3cm

1.72cm-2 × 0.3cm=1.12cm

U_i=24V 1 D_{24}=0.517

I_o=12A

I_{2sp}=46.4A

$$I_2 = \sqrt{\frac{1 - D_{24}}{3} I_{2p}^2} = \sqrt{\frac{0.517}{3} 46.4^2} = 19.2\text{A}$$

$$I_{2ac} = \sqrt{I_2^2 - I_o^2} = 15\text{A}$$

450A/cm^2, 19.2A/450=0.043cm^2 2.36mm

1.12cm, 0.038cm 2 2 2 0.005cm 0.081cm

4.6cm 9.2cm

$$R_{dc} = \rho \frac{l}{A} = 2.3\times10^{-6} \frac{9.2}{0.043} = 0.00049\ \Omega$$

100kHz Δ 0.024cm 0.38cm,Q=0.038/0.024=1.6, Dowell Q=1.6 2 $R_{ac}/R_{dc} \approx 2.5$

$$R_{ac} = R_{dc} \times 2.5 = 0.00049 \times 2.5 = 1.22m\Omega$$

8-12 1 Q=1.6 1 $R_{ac}/R_{dc} \approx 1.5$

$$R_{ac} = R_{dc} \times 1.5 = 0.00049 \times 1.5 = 0.74m\Omega$$

U_i=24V D_{24}=0.483

$$I_{1p} = I_{2p} / n = 46.4 / 4 = 11.6A$$

$$I_{1dc} = I_{1p} \times \frac{D}{2} = \frac{11.6 \times 0.483}{2} = 2.8A$$

$$I_1 = I_{1p} \times \sqrt{\frac{D}{3}} = 11.6 \times \sqrt{\frac{0.483}{3}} = 4.65A$$

$$I_{1ac} = \sqrt{I_2^2 - I_o^2} = 3.71A$$

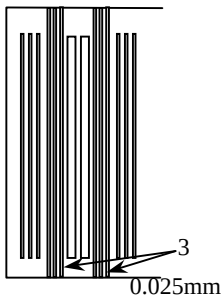
450A/cm^2 4.65/450=0.01cm^2 d=0.93mm 0.009cm 1.12cm 8 8 0.005cm 8 × (0.009+0.005)=0.112cm 4.6cm 36.8cm

$$R_{dc} = \rho \frac{l}{A} = 2.3\times10^{-6} \frac{4.6}{0.01} = 8.5\ \mathrm{m}\Omega$$

100kHz Δ=0.24 8 0.009mm Q=0.009/0.24 0.375 6-9 R_{ac}/R_{dc}=1.2

$$R_{ac} = R_{dc} \times 1.2 = 8.5 \times 1.2 = 10.2\ \ \mathrm{m}\Omega$$

4 Q=0.375 6-9 R_{ac}/R_{dc}=1.0



8-12

R_{ac} R_{dc} 0.0085Ω

(10)

R_{dc} 0.49mΩ

P_{2dc}=12^2 × 0.00049=0.07W

R_{ac}=0.74mΩ :

P_{2ac}=I_{Sac}^{2} × R_{ac}=15^2 × 0.00074=0.17W

P_2=0.07+0.17=0.24W

R_{dc}=8.5mΩ :

P_{1dc}=I_{1dc}^{2} × R_{1dc}=2.8^2 × 0.0085=0.067W

(R_{ac}=0.0085Ω) :

P_{2ac}=I_{1ac}^{2} × R_{1ac}=3.71^2 × 0.0085=0.12W

P_1=0.07+0.12=0.19W

P_w=0.23+0.19=0.42W.

P_T=P_w+P_C=0.42+0.56=0.98W

1.42W

ΔT=R_T × P_T=28 × 0.98=27

0.02cm 0.04+0.081+0.112=0.233cm 0.38cm

0.08 μ H 8-12 50pF

6-11

1. Unitrode Magnetics Design Handbook Magnetics Design for Switching Power Supplies Lloyd H. Dixon
2. Swiching Power Supply Design Abraham I. Pressman Second Edition McGraw-Hill 1998
3. 1998
4. Philips Magnetic Components 1996 (Mannul)

第九章 特殊磁性元件

9.1

APFC

LEM

LEM

1

100

9.1.1

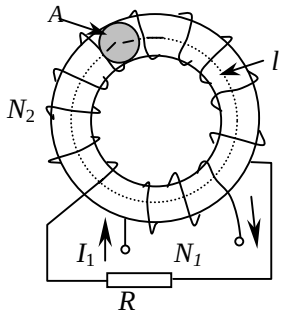
1．基本原理

N_1 ，

N_2 R，

9-1

I_1 I_2



$$i_1 N_1 - i_2 N_2 = Hl \qquad (9\text{-}1)$$

H

l

i_1 i_2 9-1

I_2’

$$I_2' = \frac{N_2}{N_1} I_2 \qquad (9\text{-}2)$$

$$\dot{F}_1 = \dot{F}_2 + \dot{F}_m \qquad (9\text{-}3)$$

$\dot{F}_m$ 9-2

$\dot{F}_m = 0$ ，

$$\dot{F}_1 = \dot{F}_2 \qquad (9\text{-}4)$$

I_2

$$e_2 = I_2(R + R_{cu}) = 4.44 fBAN_2 \qquad 9\text{-}5$$

R_{cu}— Ω

f— Hz

B— T

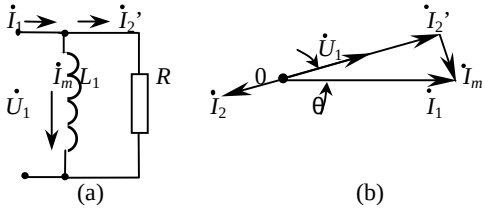
A— m^2

B—R

,

$$\theta = \arctan\frac{R}{\omega L_1} \qquad (9\text{-}6)$$

$R'=(R+R_{cu})\,N_1^2\,/\,N_2^2$—



9-2 (a) (b)

$$L_1 = N_1^2\mu_0\mu_a\frac{A}{l} \qquad (9\text{-}7)$$

μ a $L_2 = N_2^2 L_1 / N_1^2$ $R' = N_1^2\left(R_{cu}+R\right)/N_2^2$ (9-6)

$$\theta = \arctan\frac{(R+R_{cu})}{\omega L_2} \qquad (9\text{-}8)$$

( )

$$\gamma = \frac{I_1 - I_1\cos\theta}{I_1} = 1-\cos\theta \qquad (9\text{-}9)$$

cos θ , θ ,

$$\cos\theta = 1-\frac{\theta^2}{2!}+\frac{\theta^4}{4!}-\frac{\theta^6}{6!}\cdots\approx 1-\frac{\theta^2}{2}$$

9-9

$$\gamma = 1-\cos\theta = \frac{\theta^2}{2} \qquad 9\text{-}9a$$

(9-8),(9-9)

L_2 u_2 R I_2

L_2

.

2．交流电流互感器设计

$f(\omega)$ I_1

U_2 γ

. R_{cu},

, (9-8)

$$\theta \approx \frac{R}{\omega L_2}$$

$R=U_2/I_2=u_2N_2/I_1N_1$ $L_2=\mu_0\mu_a N_2^2 A/l= N_2^2 A_L$

$$\theta \approx \frac{U_2}{\omega I_1 N_1 N_2 A_L} \qquad (9\text{-}10)$$

$A_L=\mu_0\mu_a A/l$— $N_1=1$, (9-9a)

$$N_2 A_L = \frac{U_2}{\omega I_1 \theta} = \frac{U_2}{\omega I_1 \sqrt{2\gamma}} \qquad (9\text{-}10a)$$

γ δ

N_2 500

50Hz 0.35mm 400Hz 0.1mm

10kHz μ

μ μ_a

μ_i μ_i μ_a

N_2 (9-10a) A_L A_L

$$A_L = \mu_0 \mu_i \frac{A_e}{l_e} \qquad (9\text{-}11)$$

l_e— (m)

A_e— (m^2)

N_2 ,

$$R = \frac{U_2 N_2}{I_1 N_1} = \frac{U_2 N_2}{I_1} \qquad (9\text{-}12)$$

γ=1% θ 8^o(0.14)

3．讨论

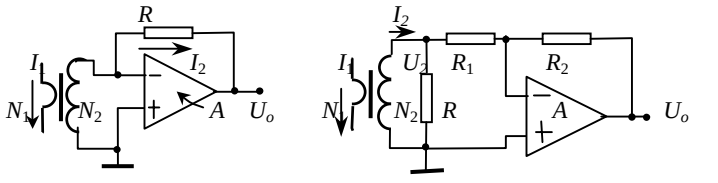
(1) (I_m)

I_2N_2 N_1I_1

ΔB

(2) (9-10) U_2

9-3 9-3(a) U_2



I_2,

$U_o=I_2R=I_1N_1R\ /N_2$

(a) (b) 9-3(a) A

9-3

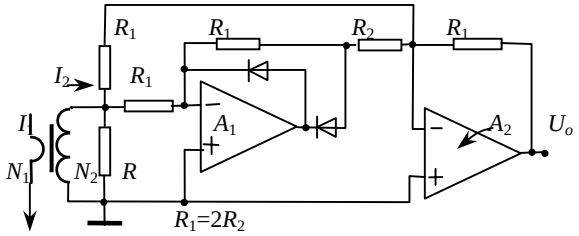
9-3(b) R

$R_1>>R$, R_1 R , $U_o=-U_2R_2/R_1$

1V U_2 ,

(9-4)

(3) (9-10)



9-4

(4)

,

B

$$P = I_1 U_1 \cos\theta \approx \frac{I_1^2 (R + R_{cu})}{N_2^2} \qquad (9\text{-}13)$$

(5)

U_2 9-12

9.1.2

(

9-5(a)) (9-5(b))

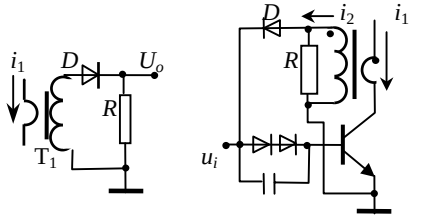
1. 原理

(9-6)

(T_{on})

B_r

9-7



(a) (b)

9-5

9-5(b) R L_2

$T_{of}>4L_2/R$.

,

$$e_2 T_{on} = = V_{DB} T_r \qquad (9\text{-}14)$$

e_2— i_2

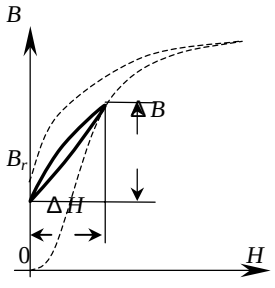
T_{on}—

V_{DB}—

T_r—

$$i_1 - i_m = i_2 N_2 \qquad (9\text{-}15)$$

i_m—



9-6

$$i_2 = i_1 / N_2$$

R

$$u_2 = i_2 R = i_1 R / N_2$$

i_1

2. 直流脉冲互感器的设计

$$e_2 = N_2 A_e \frac{\mathrm{d}B}{\mathrm{d}t} \qquad (9\text{-}16)$$

(9-7)

$$e_2 T_{on} = N_2 A_e \Delta B \qquad (9\text{-}17)$$

μ_Δ $i_m N_1 = H l_e$

$$i_m = \frac{e_2 l_e T_{on}}{\mu_\Delta \mu_0 N_2 N_1 A_e} \qquad (9\text{-}18)$$

N_1=1

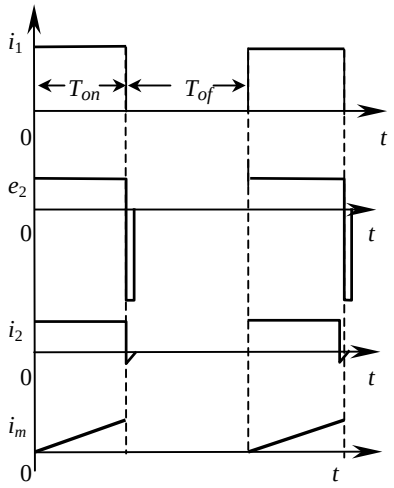
$$i_m = \frac{e_2 T_{on}}{N_2 A_L} \qquad (9\text{-}18a)$$

l_e(m) A_e(m^2)

μ_Δ

A_L—

(9-15)



9-7

$$\gamma = \frac{i_m}{i_1} = \frac{e_2 T_{on}}{i_1 N_2 A_L} \qquad (9\text{-}19)$$

$$N_2 A_L = \frac{i_m}{i_1 \gamma} = \frac{e_2 T_{on}}{i_1 \gamma} \qquad (9\text{-}19)$$

γ

β

1 $N_2 < \beta$

$$A_L = \frac{e_2 T_{on}}{\gamma i_1 N_2} \qquad (9\text{-}20)$$

例 1：直流脉冲互感器设计举例

9-5(a) 22A 50kHz 0.36

1V γ=0.2%

：

50kHz 3C85 T_{on}=0.36 × 10^{-3}/50=7.2μS, $e_2=u_2+U_{Df}$=1+0.7=1.7V 2V

(9.19)

$$N_2 A_L = \frac{e_2 T_{on}}{i_1 \gamma} = \frac{2 \times 7.2 \times 10^{-6}}{22 \times 2 \times 10^{-3}} = 322\mu\,\mathrm{H}$$

N_2A_L=322μH A_L

A_L 3C85

TN19/15 10-11 A_e=61.2mm^2 A_L=3.5μH D=19.5mm d=9.8mm h=15.5mm

l_{av}=60mm

$$N_2 = 322 / 3.5 = 92$$

N_2=100

$$I_2 \approx i_1 / N_2 = 22 / 100 = 0.22A$$

$$R = u_2 / I_2 = 1 / 0.22 = 4.545\Omega$$

4.7Ω/0.5W.

$$R_w = \frac{e_2 - U_2}{I_2} = \frac{2 - 1.7}{0.22} \approx 1.4\ \Omega$$

$$r = \frac{R_w}{N_2 l_{av}} = \frac{1.4}{100 \times 6} = 0.00233\ \Omega/\text{m}$$

10-2 0.33mm 0.39mm 0.232 Ω. A_{cu}=0.0855mm^2 $I_{2rms} / A_{cu} = 1.54\text{A/mm}^2$ (

)

:

A_{cu}=N_2 × 0.0855=8.55mm^2

$$k = \frac{A_{cu}}{A_w} = \frac{8.55 \times 4}{\pi \times 9.8^2} = 0.113 < 0.3$$

A_W— ( )

$$R_{cu} = l_{cp} \times N_2 \times r = 0.06 \times 100 \times 0.232 = 1.392\ \Omega < 1.4\Omega$$

$$e_2 = u_2 + U_{DF} + I_2 R_{cu} = 1 + 0.7 + 0.22 \times 1.392 = 2.0067\ \text{V}$$

$$i_m = \frac{e_2 T_{on}}{N_2 A_L} = \frac{2.0067 \times 7.2 \times 10^{-6}}{100 \times 3.5 \times 10^{-6}} = 0.0413\ \text{A}$$

$$\gamma = \frac{i_m}{i_1} = \frac{0.0413}{22} = 0.187\% < 0.2\%$$

$$\Delta B = \frac{e_2 T_{on}}{N_2 A_e} = \frac{2.0067 \times 7.2 \times 10^{-6}}{100 \times 61.2 \times 10^{-6}} = 0.00236\text{T} = 23.6\ \text{Gs}$$

μ_i

μ_Δ μ_Δ<μ_I

$$P = (R + R_{cu}) I_{2rms}^2 = (4.7 + 1.224) \times 0.132^2 = 0.1W$$

例 2 比例驱动互感器设计举例

9-5(b) 33kHz 0.3 16A

β=10 0.05(5%)

$\beta_{\min}$=10 N_2=5<$\beta_{\min}$

U_{BE}

$$u_2 = 3 \times 0.8 + 1 = 3.4V$$

$$T_{on} = D / f = 9\mu \text{ S}$$

$$A_L = \frac{e_2 T_{on}}{\gamma i_1 N_2} = \frac{3.4 \times 9 \times 10^{-6}}{0.05 \times 16 \times 5} = 7.65\mu \text{ H}$$

A_L

f=33kHz LP3 4 R18 × 10 × 8 A_e=32mm^2

A_L 2.16μH

$$L_2 = N_2^2 A_L = 5^2 (2.16 \times 4) = 216\mu \text{ H}$$

$$\Delta B = \frac{u_2 T_{on}}{N_2 A} = \frac{3.4 \times 0.3 \times 30 \times 10^{-6}}{5 \times 32 \times 4 \times 10^{-6}} = 0.048T = 480Gs$$

$$i_m = \frac{u_2 T_{on}}{N_2 A_L} = \frac{3.4 \times 9 \times 10^{-6}}{4 \times 2.16 \times 5 \times 10^{-6}} = 0.708A$$

$$\gamma = \frac{i_m}{i_1} = \frac{0.708}{16} = 4.4\%$$

.

3.2A 1.75A j=5A/mm^2

0.35mm^2 33kHz 0.41mm 0.67mm

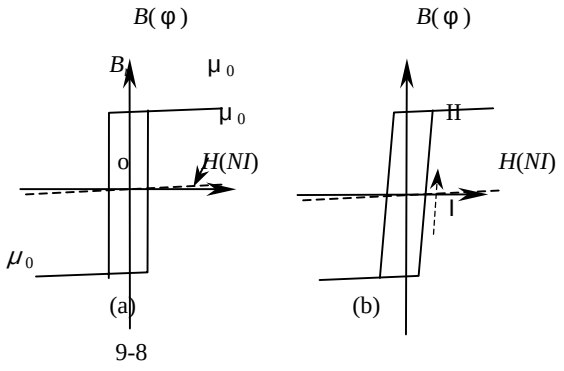
5 0.2m R_{cu}=0.2 × 0.05=0.01Ω 3.2 × 0.01=0.032V u_2 1

9.2

9.2.1

9-8(a)

1



9-8

9-8(b)

“ I ” “ II ” μ

(4-2)

μ_0

9.2.2

5.4.1

t_b

9-9 a U_{o1} ,U_{o2}

U_{22} V

$D_{on}=T_{on}/T$

$f=1/T$ (Hz)

I_o A

1.

(t_b) (t_{on})

$-B_s$ $+B_s$ ψ

$$\psi = \frac{U_{22}D_{on}}{f} = N\phi_c = 2NB_sA_c \text{ (Wb)} \quad (9\text{-}21)$$

B_s T

A_c m^2

2.

9-21

$$A_w = \frac{I_oN}{\sqrt{D}\,jk_w} \quad (9\text{-}22)$$

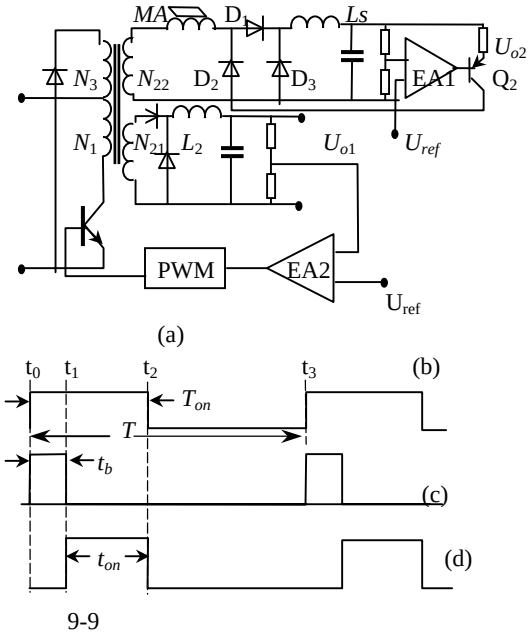
I_o

N

D

k_w 0.4

j 5 7A/mm^2



9-9

$$\phi_cA_w \geq \frac{\psi \times I_o}{\sqrt{D}k_wj} \text{ (Wb} \cdot \text{mm}^2\text{)} \quad (9\text{-}23)$$

φ_c (Wb);

A_w

9-23 $\varphi_c A_w$, 10-21 10-22 $\varphi_c A_w$

φ_c

$$AP = A_e A_w \geq \frac{U_{22} T_{on} I_o}{2\sqrt{2} B_s j k_w k_c}$$

U_{22} V

B_s T

k_c

$T_{on}=D/f$ s

3.

N

$$N = \frac{\psi}{\phi_c} = \frac{U_{22} T_{on}}{B_s A_e k_c} \qquad (9\text{-}24)$$

N

4.

I_o j

$$d = 2\sqrt{\frac{I_o}{\sqrt{2}\pi j}} \text{ (mm)} \qquad (9\text{-}25)$$

A_w φ_c

a) (

)

b)

c)

3

9-9 5V/20A 15V/5A

U_{22}=51V, D_{on} 0.4— 15V

f=150kHz I_o=5A

(1)

9-21

$$\psi = \frac{U_{22} D_{on}}{f} = \frac{51 \times 0.4}{150 \times 10^3} = 0.136 \times 10^{-5} \text{VS} = 136 \ \mu\text{Wb}$$

2)

j=6A/mm^2, 9-23

$$\phi_c A_w \geq \frac{\psi \times I_o}{k_w j} = \frac{136 \times 10^{-6} \times 5}{0.4 \times 6} \approx 2.83 \times 10^{-4} \text{Wb} \cdot \text{mm}^2 = 283 \ \mu\text{Wbmm}^2$$

TOSHIBA 10-21 MS14 × 8 × 4.5W

(3)

MS14 × 8 × 4.5W φ_c

$\phi_c = 11.14 \ \mu\text{Wb}$

9-24

$$N = \frac{\psi}{\phi_c} = \frac{136 \times 10^{-6}}{11.14 \times 10^{-6}} \approx 12.2 \rightarrow 13$$

(4)

9-25

$$d = 2\sqrt{\frac{I_o}{\pi j\sqrt{D}}} = 2\sqrt{\frac{5}{\pi \times 6\sqrt{0.4}}} \approx 1.3\text{mm}$$

100×0.13mm　　MS14 × 8 × 4.5W

1.6mm　　13　1　　150kHz

$$\Delta = \frac{7.6}{\sqrt{f}} = \frac{7.6}{\sqrt{150 \times 10^3}} = 0.02cm = 0.2\text{mm}$$

$l_{in} = \pi d = \pi \times 8 = 25\text{mm} > 13 \times 1.6 = 20.8\text{mm}$,　　10　　$10 \times 13 = 130$

$$Q = \frac{0.83 \times 0.13 \times \sqrt{0.84}}{0.2} = 0.49 \qquad F_l = \frac{0.13 \times 10 \times 13}{\pi(d - 1.6)} = 0.84$$

6-9　　$F_R \approx 1$

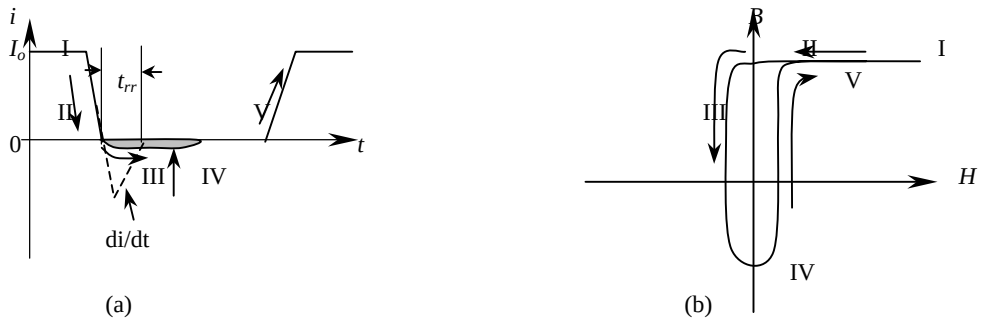
9.2.3

1．尖峰抑制磁珠

1

D　　d　　h

9-10



9-10

I_o　　(a)　“ I ”　　(b)　“ I ”

μ_0

I_o　　(a)　“ II ”　　“ II ”

B_r

(a)

t_{rr}

(a)　　“ III ”

“ III ”　　d*i*/d*t*

(a) “ IV ”

(b) “ IV ”

(a) “ V ”

“ V ”

“ I ” “ V ”

2

$$\phi_c = 2B_s A_e \geq \pi U_r t_{rr} \quad \text{Wb} \qquad 9\text{-}26$$

φ_c Wb

U_r V

t_{rr} s .

9-26 9-26

2 噪声抑制器

$$\phi_c A_w \geq U_r \times I_o \times t_{rr} \times 1.5(\text{Wb}\cdot\text{mm}^2) \qquad 9\text{-}27$$

φ_c Wb

A_w (mm^2)

U_r (V) ,

t_{rr} (s)

(9-27)

$$d \geq 1.5\sqrt{I_o} \qquad (9\text{-}28)$$

N

$$N \geq \frac{U_c \times 3 \times t_{rr}}{\phi_c} \qquad (9\text{-}29)$$

例 4

U_o=12V, t_{rr}=35nS

D=0.3

9-26

$$\phi_c \geq U_c t_{rr} = \frac{12 \times 35 \times 10^{-9}}{0.3} = 1.4 \times 10^{-6} = 1.4\ \mu\text{Wb}$$

10 24 AB3×2×6W φ_c 1.8μWb>1.4μWb

例 5

U_o=24V t_{rr}=60nS 0.3

2A

1

9-27

$$\phi_c A_w \geq U_c \times I_o \times t_{rr} \times 1.5 = \frac{24 \times 2 \times 60 \times 10^{-9} \times 1.5}{0.3}$$

$$= 1.44 \times 10^{-5} \left(\text{Wb} \cdot \text{mm}^2 \right)$$

14.4 μ Wb · mm^2

10.5.4 SA7 × 6 × 4.5

2

9-28

$$d \geq 0.5 \times \sqrt{2} \geq 0.7mm$$

0.7mm .

(3) N

SA7 × 6 × 4.5 $\phi_c = 1.8.2 \times 10^{-6} Wb$, (9-29)

$$N \geq \frac{U_c \times 3 \times t_{rr}}{\phi_c} = \frac{24 \times 3 \times 60 \times 10^{-9}}{0.3 \times 1.82 \times 10^{-6}} \geq 7.9$$

8 SA7 × 6 × 4.5, 0.7mm 8

1. Amorphous Magnetic Parts Toshiba 1997
2. Swiching Power Supply Design Abraham I. Pressman Second Edition McGraw-Hill 1998
3. Philips Magnetic Components 1996 (Mannul)
4. 1991

第十章 基础资料

10.1

CGS

SI CGS

10-1

表 10-1 电磁单位制和转换

	- - (MKS)	- - (CGS)	MKS→CGS
			10^2
			10^3
t			1
δ	/ ²	/ ²	10^{-2}
F	(· / ²)	(· / ²)	10^5
	·	(·)	10^7
P	(/)	/	10^7
V			
L	(Ω/)		
R			
B	/ ²		10^4
H	/ (10^2 /)	( )	$4\pi\times10^{-3}(4\pi\times10^{-1})$
F	·	·	$4\pi\times10^{-1}$
ϕ	(·)	( )	10^8
μ_r			1
μ_0	/ ·		$10^7/4\pi$
μ	/ ·		$10^7/4\pi$
R_m	/	· /	$4\pi\times10^{-9}$
G_m	/ (Ω/)	/(·)	$10^9/4\pi$

:

1Wb=10^8Mx ( )

1Gs=10^{-4}T=10^{-4}Wb · m^2=10^{-8}Wb/cm^2 ( )

1Max=10^{-8}Gs × cm^2.

$1\text{A/m}=10^{-2}\text{A/cm}=0.4\pi\times10^{-2}\text{Oe}$

1A/cm=0.4π Oe

$$\mu = \frac{\text{Wb/m}^2}{\text{A/m}} = \frac{\text{V}\cdot\text{s}}{\text{A}\cdot\text{m}} = \frac{\Omega\cdot\text{s}}{\text{m}} = \text{H/m}\ (\quad /\quad)$$

$$\mu_0 = 4\pi\times10^{-7}\text{H/m} = 0.4\pi\times10^{-8}\text{H/cm}$$

$$= \frac{1\text{Wb}}{1\text{A}} = \frac{1\text{V}\cdot1\text{s}}{1\text{A}} = \Omega\cdot\text{s} = \text{H}(\qquad =\quad)$$

10.2

10.2.1

QZ-2 QA-2 QY-2 QHN QA-2 0.31mm QZ-2
130 QY-2 220 QQ-2 10-2
10-3 10-4 QA-2
6 10 370±10

10-2 QQ-2

mm	mm	mm^2	Ω/m(20℃)	mm	mm	mm^2	Ω/m(20℃)
0.06	0.09	0.00288	6.18	0.63	0.70	0.312	0.056
0.07	0.10	0.0038	4.54	0.67	0.75	0.353	0.0496
0.08	0.11	0.005	3.48	0.69	0.77	0.374	0.047
0.09	0.12	0.0064	2.75	0.71	0.79	0.396	0.0441
0.10	0.13	0.0079	2.23	0.75	0.84	0.442	0.0396
0.11	0.14	0.0095	1.84	0.77	0.86	0.466	0.0377
0.12	0.15	0.0113	1.55	0.80	0.89	0.503	0.0348
0.13	0.16	0.0133	1.32	0.83	0.92	0.541	0.0324
0.14	0.17	0.0154	1.14	0.85	0.94	0.5675	0.0308
0.15	0.19	0.0177	0.988	0.90	0.99	0.636	0.0275
0.16	0.20	0.0201	0.876	0.93	1.02	0.679	0.0258
0.17	0.21	0.0227	0.77	0.95	1.04	0.709	0.0247
0.18	0.22	0.0256	0.686	1.00	1.11	0.785	0.0223
0.19	0.23	0.0284	0.616	1.06	1.17	0.882	0.0198
0.20	0.24	0.0315	0.557	1.12	1.23	0.985	0.0178
0.21	0.25	0.0347	0.506	1.18	1.29	1.094	0.016
0.23	0.28	0.0415	0.423	1.25	1.36	1.227	0.0145
0.25	0.30	0.0492	0.356	1.30	1.41	1.327	0.0132
0.27	0.32	0.0573	0.306	1.35	1.46	1.431	0.0123
0.28	0.33	0.0616	0.284	1.40	1.51	1.539	0.0114
0.29	0.34	0.066	0.265	1.45	1.56	1.651	0.0106
0.31	0.36	0.0755	0.232	1.50	1.61	1.767	0.00989
0.33	0.39	0.0855	0.205	1.56	1.67	1.911	0.00918
0.35	0.41	0.0965	0.182	1.60	1.72	2.01	0.0087
0.38	0.44	0.114	0.155	1.70	1.82	2.27	0.0077
0.40	0.46	0.1257	0.133	1.80	1.92	2.545	0.00687
0.42	0.48	0.138	0.127	1.90	2.02	2.835	0.00617
0.45	0.51	0.159	0.11	2.00	2.12	3.14	0.00557
0.47	0.53	0.1735	0.101	2.12	2.24	3.53	0.00495
0.50	0.56	0.1963	0.089	2.24	2.36	3.94	0.00444
0.53	0.60	0.221	0.0793	2.36	2.48	4.37	0.004
0.56	0.63	0.2463	0.071	2.50	2.62	4.91	0.00356
0.60	0.67	0.283	0.0618				

$$A_{cu} = \frac{\pi}{4} d^2$$

d

1000 $R = \rho_{20^\circ} \frac{1000(\mathrm{m})}{A_{cu}(\mathrm{m}^2)}$

ρ_{20° $1.724 \times 10^{-6}\,\Omega\,\mathrm{cm}$ 20 .

T

$$\rho = \rho_{20}\ 1+\frac{T-20}{234.5}$$

10-3

	Q	0.05 2.50	JB658-75	A
	QZ	0.06 2.50	GB1193-74	B
	QA	0.06 0.31	JB2079-77	E
	QQ	0.06 2.50	GB1313-77	E
	QY	0.06 2.50	JB2080-77	C
	QHN	0.1 0.50	Q/YX8004-64	E
	QAN	0.1 0.50	-	E
	QZY	0.06 2.50	-	F
	SQZ	0.06 2.50	JB661-75	A
	SBEC	0.53 6.00	GB1342-77	B
	SBECB		GB1342-77	B
	QZSBC	0.53 2.50	GB1342-77	B
	ASEBR	0.07,0.1,0.15,0.2mm^2	—	Y
	AF—250	0.07,0.1,0.15,0.2mm^2	JB1141-70	C
	TR	0.3,0.5,1.0,1.5,2.0mm^2	JB647-77	—
	TRJ—2	0.1,0.15,0.2,0.3,0.5mm^2	Q/JBD97-66	—
	QGV			—
	JBF	0.06—1.5mm^2	JB1138—76	—

10-4

(mm)	(V)	
	QZ-2,QQ-2,QA-2,QY-2	QHN
0.06 0.90	600	—
0.10 0.14	900	700
0.15 0.23	1200	800
0.25 0.31	1500	1200
0.33 0.50	1800	1200
0.53 0.71	2400	—
0.75 0.95	3000	—
1.00 1.50	3600	—
1.60 2.50	4200	—

10.2.2

10-5

4.5A/mm^2

AWG

$$D_x = \frac{2.54}{\pi}10^{-AWG/10}\ \text{cm}$$

$$D_x^{'} = D_x + 0.028\sqrt{D_x}\ \text{cm}$$

$$A_X = \pi D_x^2 / 4\ \ \text{cm}^2$$

$r_x = \rho / A_x$ Ω/m

1 $\rightarrow 7.85 \times 10^{-7}$

1 $\rightarrow 5.07 \times 10^{6}\text{cm}^2 = 5.07 \times 10^{-4}\text{mm}^2$

500 /A $\rightarrow 3.944\text{A/mm}^2$

1 1000

10-5

AGW	mm	mm^2	mm	mm^2	Ω/m 20	Ω/m 100	A $j=4.5\text{A/mm}^2$
10	2.59	5.2620	2.73	5.8572	0.0033	0.0044	23.679
11	2.31	4.1729	2.44	4.7638	0.0041	0.0055	18.778
12	2.05	3.3092	2.18	3.7309	0.0052	0.0070	14.892
13	1.83	2.6243	1.95	2.9793	0.0066	0.0088	11.809
14	1.63	2.0811	1.74	2.3800	0.0083	0.0111	9.365
15	1.45	1.6504	1.56	1.9021	0.0104	0.0140	7.427
16	1.29	1.3088	1.39	1.5207	0.0132	0.0176	5.890
17	1.15	1.0379	1.24	1.2164	0.0166	0.0222	4.671
18	1.02	0.8231	1.11	0.9735	0.0209	0.0280	3.704
19	0.91	0.6527	1.00	0.7794	0.0264	0.0353	2.937
20	0.81	0.5176	0.89	0.6244	0.0333	0.0445	2.329
21	0.72	0.4105	0.80	0.5004	0.0420	0.0561	1.847
22	0.64	0.3255	0.71	0.4013	0.0530	0.0708	1.465
23	0.57	0.2582	0.64	0.3221	0.0668	0.0892	1.162
24	0.51	0.2047	0.57	0.2586	0.0842	0.1125	0.921
25	0.45	0.1624	0.51	0.2078	0.1062	0.1419	0.731
26	0.40	0.1287	0.46	0.1671	0.1339	0.1789	0.579
27	0.36	0.1021	0.41	0.1344	0.1689	0.2256	0.459
28	0.32	0.0810	0.37	0.1083	0.2129	0.2845	0.364
29	0.29	0.0624	0.33	0.0872	0.2685	0.3587	0.289
30	0.25	0.0509	0.30	0.0704	0.3385	0.4523	0.229
31	0.23	0.0404	0.27	0.0568	0.4269	0.5704	0.182
32	0.20	0.0320	0.24	0.0459	0.5384	0.7192	0.144
33	0.18	0.0254	0.22	0.0371	0.6789	0.9070	0.114
34	0.16	0.0201	0.20	0.0300	0.8560	1.1437	0.091
35	0.14	0.0160	0.18	0.0243	1.0795	1.4422	0.072
36	0.13	0.0127	0.16	0.0197	1.3612	1.8186	0.057
37	0.11	0.0100	0.14	0.0160	1.7165	2.2932	0.045
38	0.10	0.0080	0.13	0.0130	2.1644	2.8917	0.036
39	0.09	0.0063	0.12	0.0106	2.7293	3.6464	0.028
40	0.08	0.0050	0.10	0.0086	3.4427	4.5981	0.023
41	0.07	0.0040	0.09	0.0070	4.3399	5.7982	0.018

10.2.3 GB 2059-89

T2M T2Y 0.05 0.08 0.1 0.15 0.20 0.25 0.30

mm

10-6

10-6 (GB2059-89)

	mm

	mm			
		≤ 200	200 300	
>0.09~0.20	±0.015	±0.010	±0.020	±0.015
>0.20~0.35	±0.020	±0.015	±0.025	±0.020
>0.35~0.45	±0.025	±0.020	±0.030	±0.025
>0.45~0.70	±0.030	±0.025	±0.035	±0.030
>0.70~1.10	±0.040	±0.030	±0.050	±0.040
>1.10~1.50	±0.045	±0.035	±0.055	±0.045
>1.50~2.00	±0.060	±0.050	±0.080	±0.060

10.3

10.3.1

10^6 10^{12} μ Ω · cm Hz

μ_i ,

PHILIPS <100kHz 3C81 3C90 3C91 3C94 3C96 <400kHz 3C90 3C94 3C96 200kHz 1MHz 3F3 3F4 3F35 1~3MHz 3F4 4F1 >3MHz 4F1 <500kHz 2P… 3C30 3C90;<1MHz 3C90 3F3 3F35

10-7

10.3.2

E ETD EC RM PQ EFD EI EFD LP .

FERROXCUBE-PHILIPS E EP EQ ER IIC Integrated inductance component IIC PCB

10-1 E 10-8

10-2 ETD 10-9 EC

10-3 P 10-10

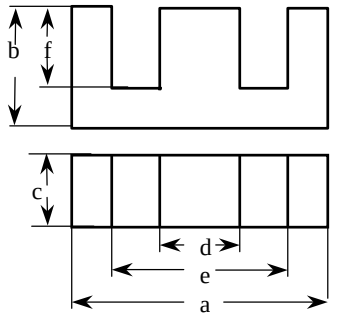
10-4 10-11

10-5 RM 10-6 EDF

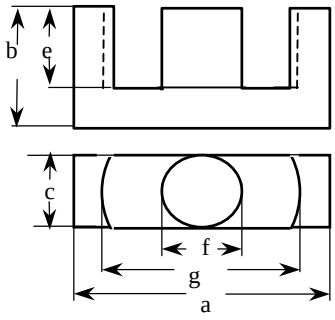
10-7

	μ_i							
	$\times 10^{-6}$H/m	G/Oe	f_1(MHz)	$tg\delta_1/\mu_i \times 1/0.4\pi$	f_2(MHz)	$tg\delta_2/\mu_i \times 1/0.4\pi$	$\alpha_{\mu i}/\mu_I$ (20 55)	$\times 0.16\pi^2 \times 10^6$
R20	25	20	4	250	75	1000	0 30	
R60	75	60	2	80	25	850	0 35	
RK1	125	100	1.5	70	15	200	0 5	
RK4	500	400	0.05	10	1.5	60	0 5	
R1K	1250	1000			0.5	35	0 3	0.05(10kHz)
R6K	7500	6000	0.002	5			0 2	
R10K	12500	10000	0.002	3			±1	

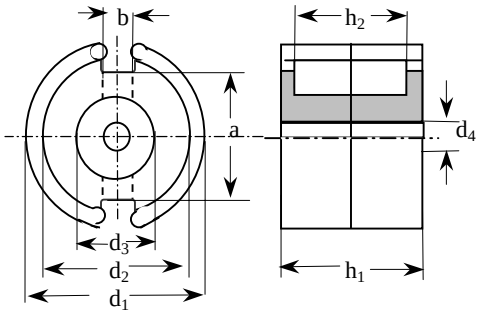
	D.F $\times$ $1/0.4\pi$ (-5 40)	H_C		B_S		T_C	ρ	d
		A/m	Oe	Wb/m^2	Gs		$\mu\Omega \cdot cm$	g/cm^3
R20		1200	15	0.22	2200	350	10^{12}	4.0
R60		320	4	0.32	3200	300	10^{11}	4.2
RK1	20	240	3	0.30	3000	250	10^{11}	4.3
RK4		80	1	0.32	3200	180	10^9	4.5
R1K		10	0.2	0.31	3100	150	10^8	4.8
R6K	2	8	0.1	0.34	3400	100	10^6	4.8
R10K	0.5	4	0.05	0.34	3400	85	10^6	4.9



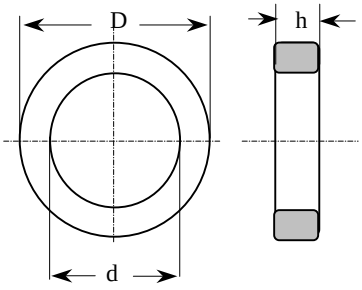
10-1 EE



10-2 ETD



10-3 P



10-4