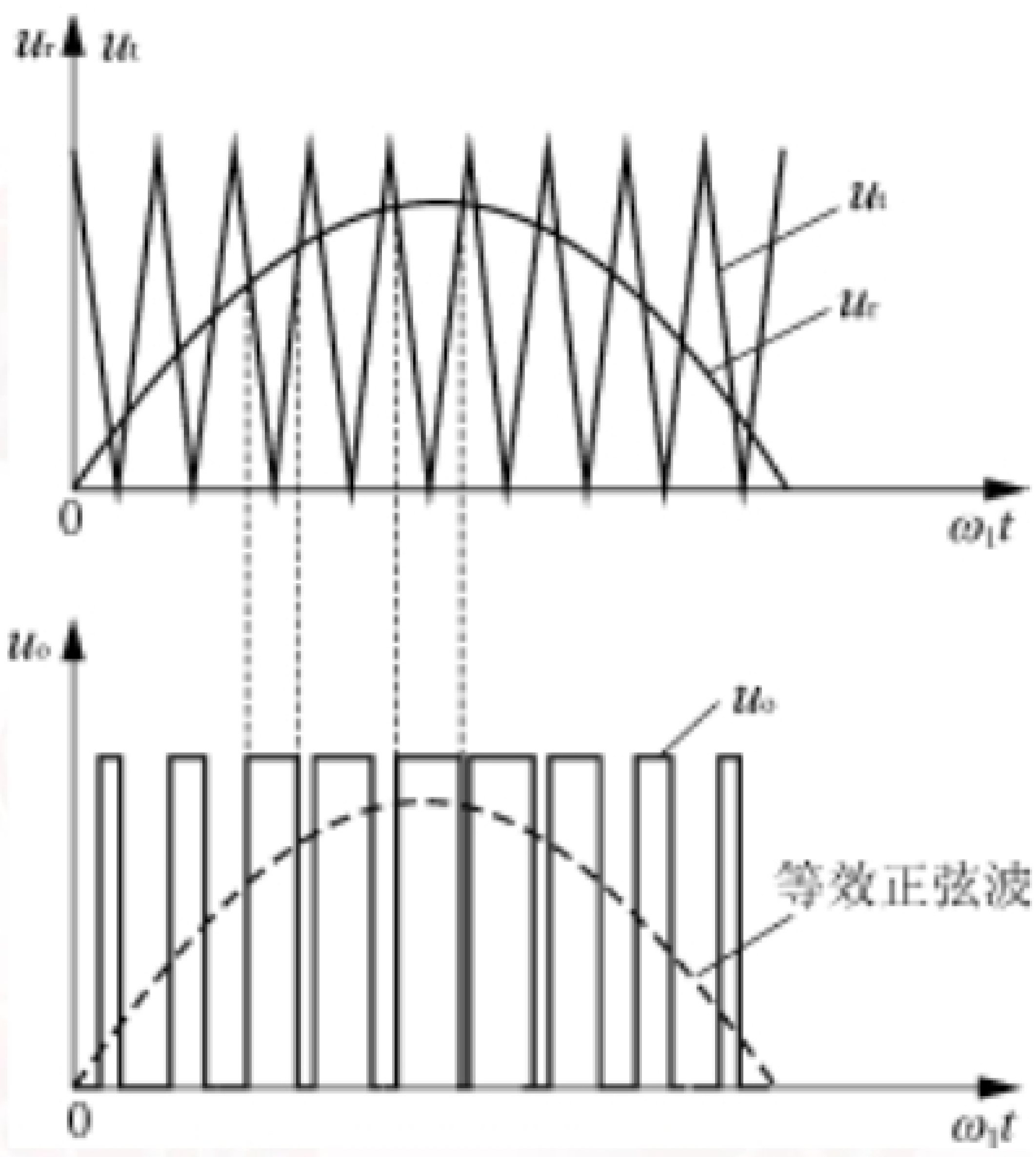
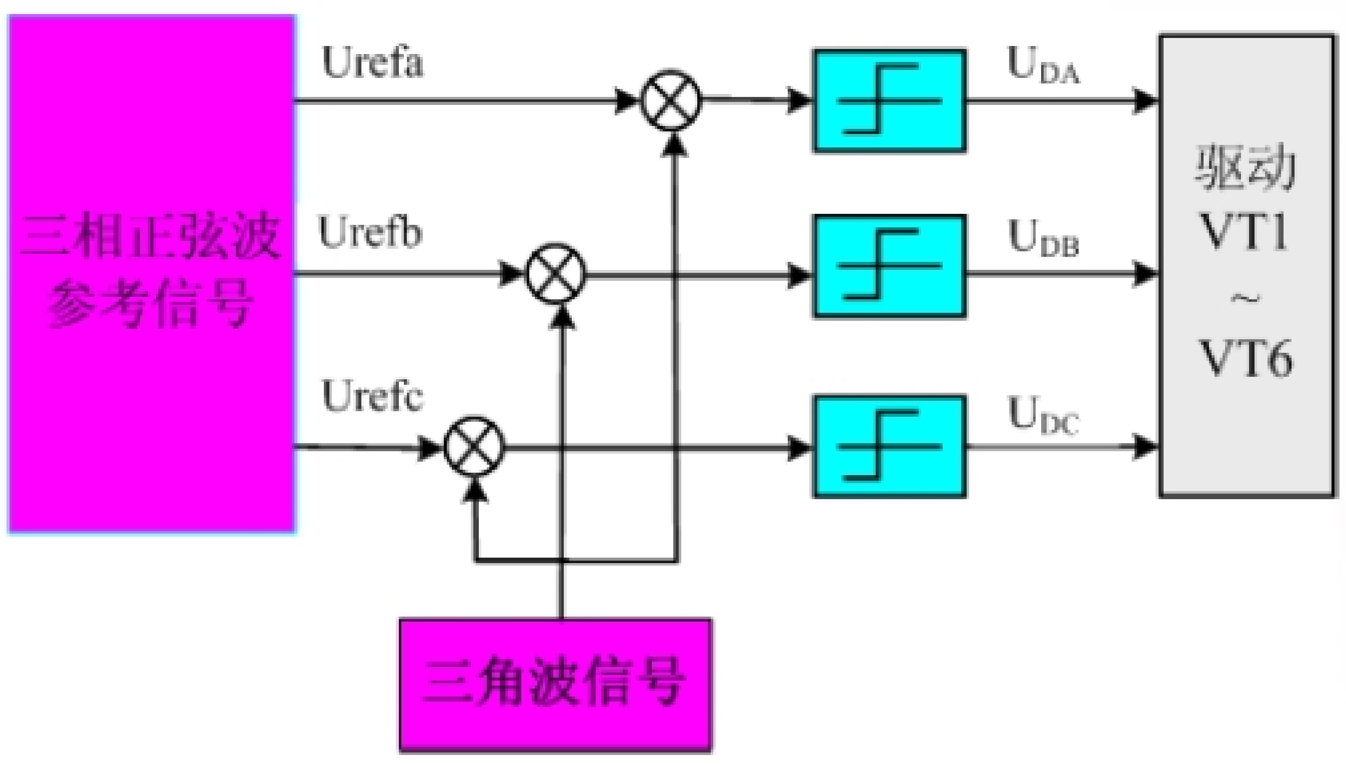
Contents

$$
\begin{cases}
U_A = U_m \sin(\omega t) \\
U_B = U_m \sin(\omega t - \frac{2}{3}\pi) \\
U_C = U_m \sin(\omega t + \frac{2}{3}\pi)
\end{cases}
$$



SPWM：着眼于生成三相对称正弦电压源



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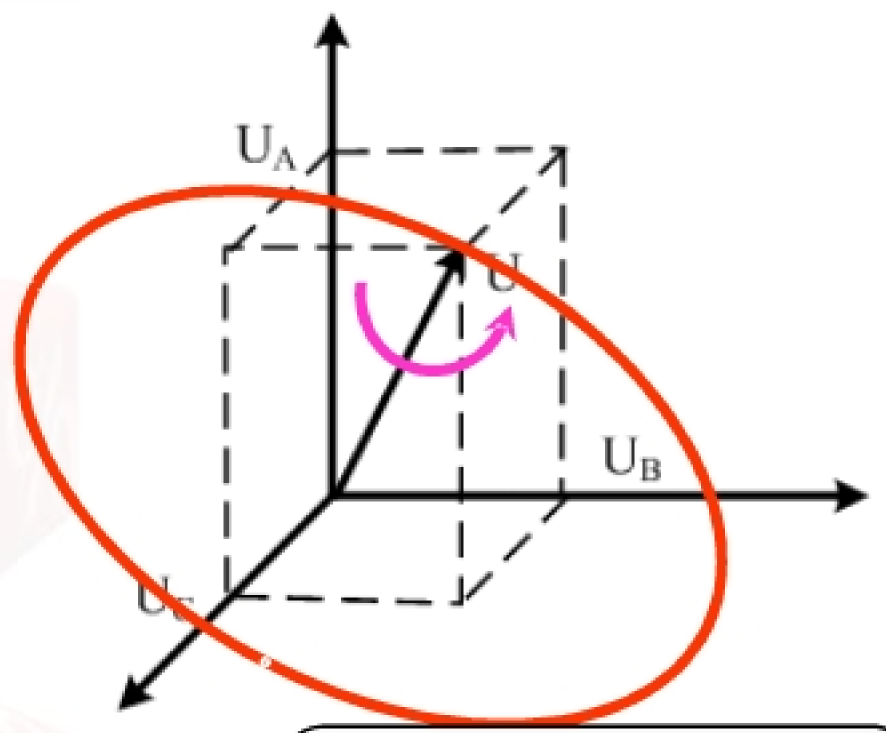


SVPWM：着眼于使形成的磁链轨迹跟踪由理想三相平衡正弦波电压源供电时所形成的基准磁链圆

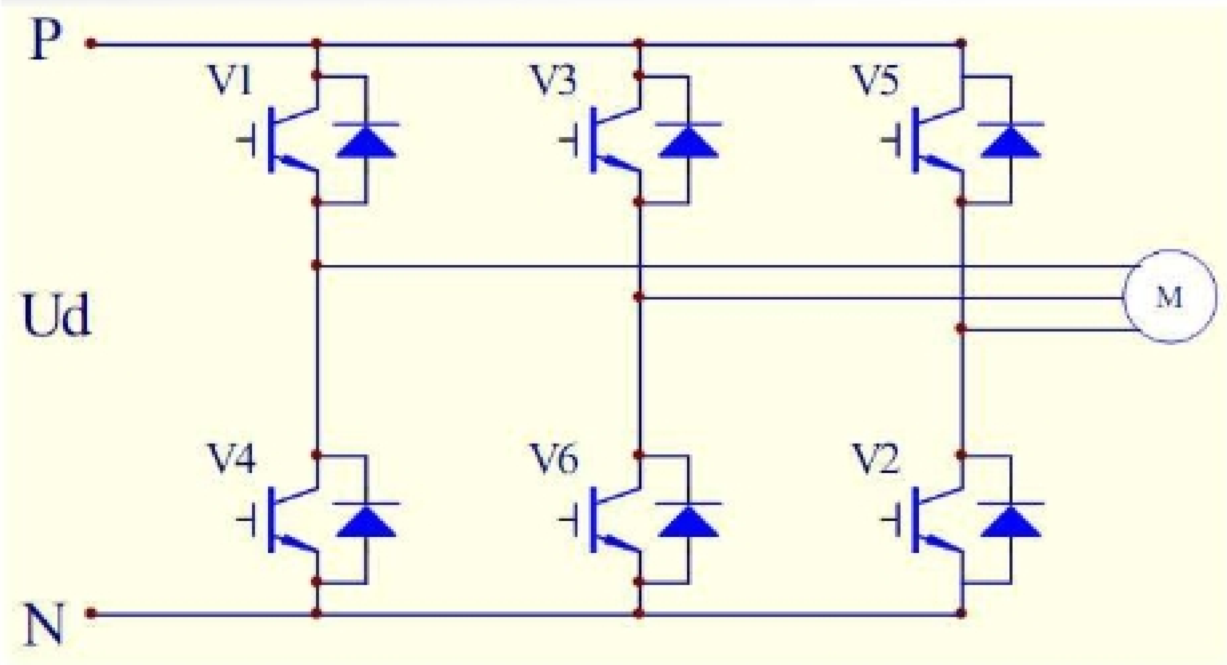
旋转向量

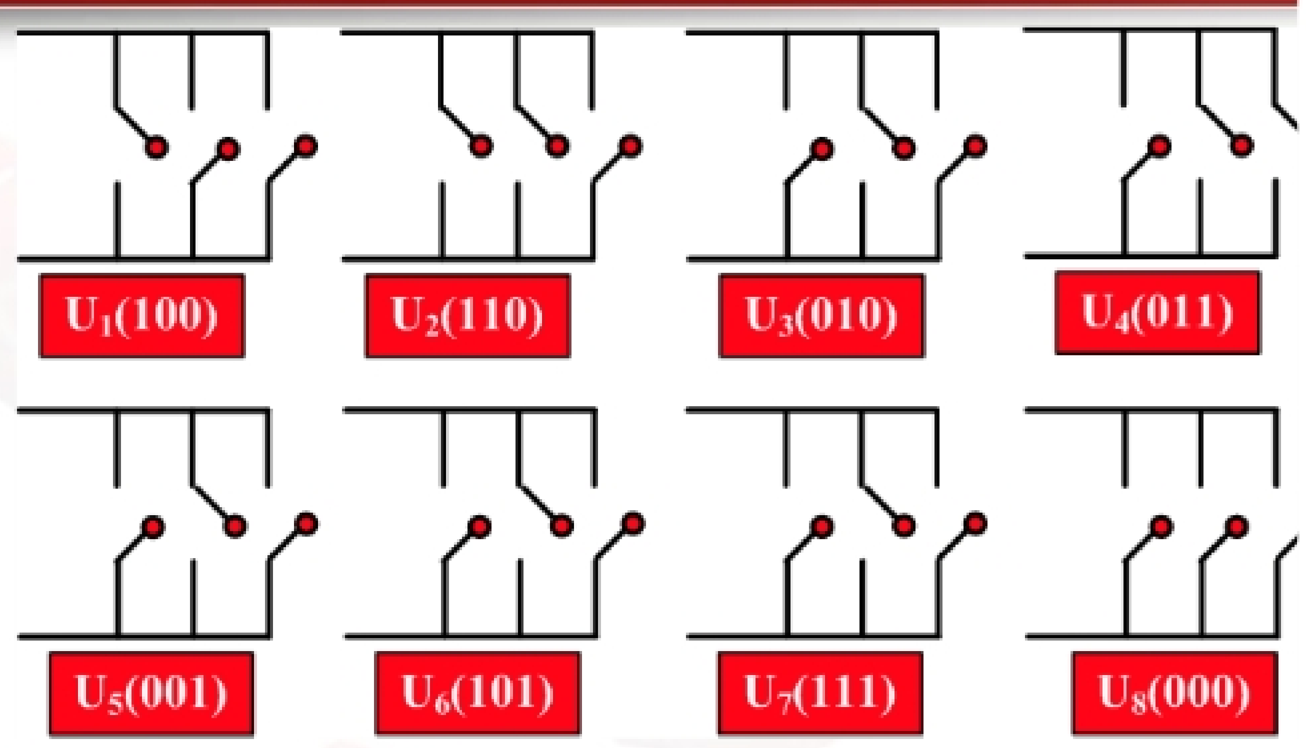
$$\vec{U} = \vec{U}_A + \vec{U}_B + \vec{U}_C = \sqrt{\frac{3}{2}} U_m (\sin \omega t, \sin \omega t - \frac{2}{3}\pi, \sin \omega t + \frac{2}{3}\pi)$$

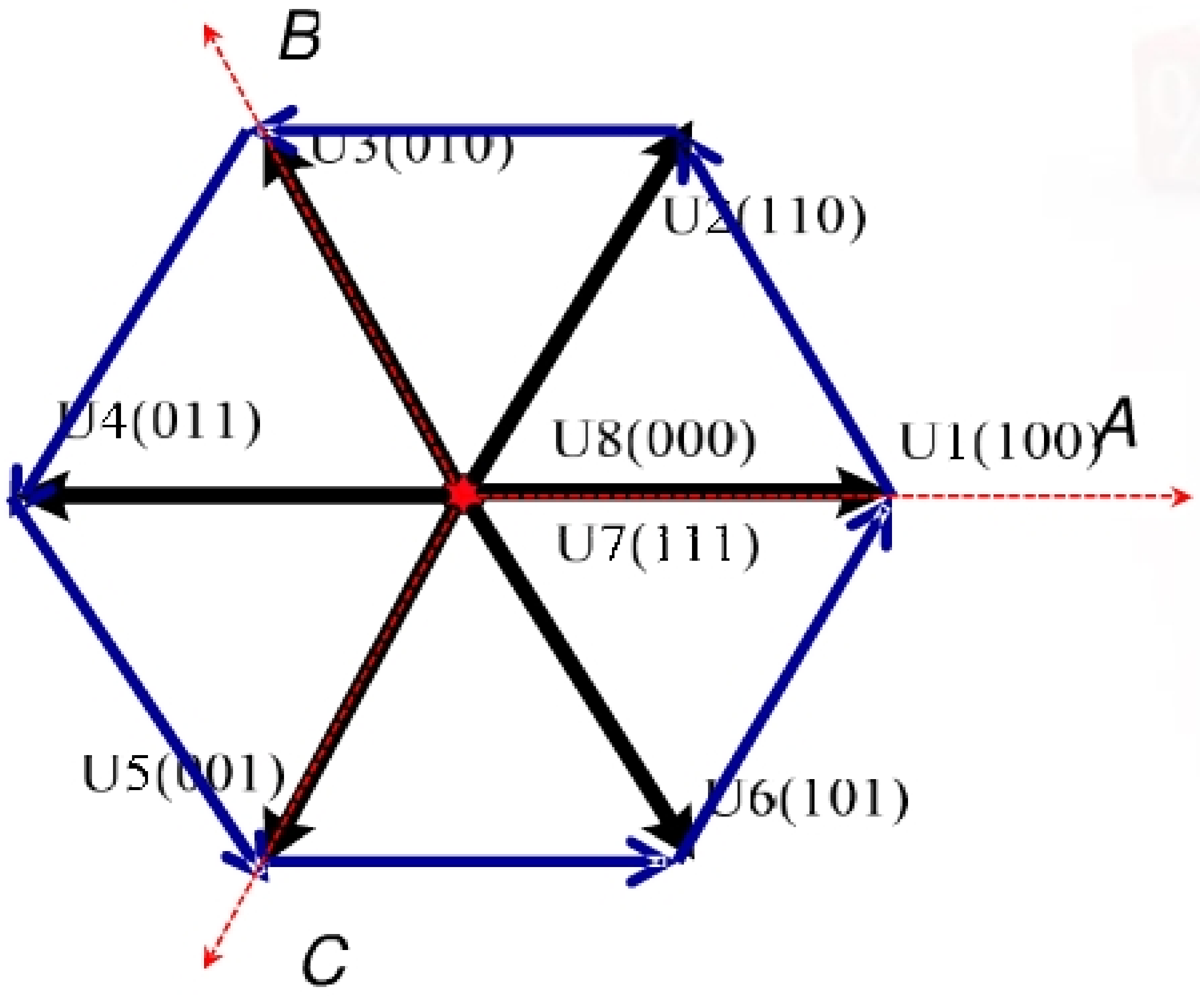
$$|\vec{U}| = \sqrt{U_A{}^2 + U_B{}^2 + U_C{}^2} = \sqrt{\frac{3}{2}} U_m$$

幅值

位于过O点的平面







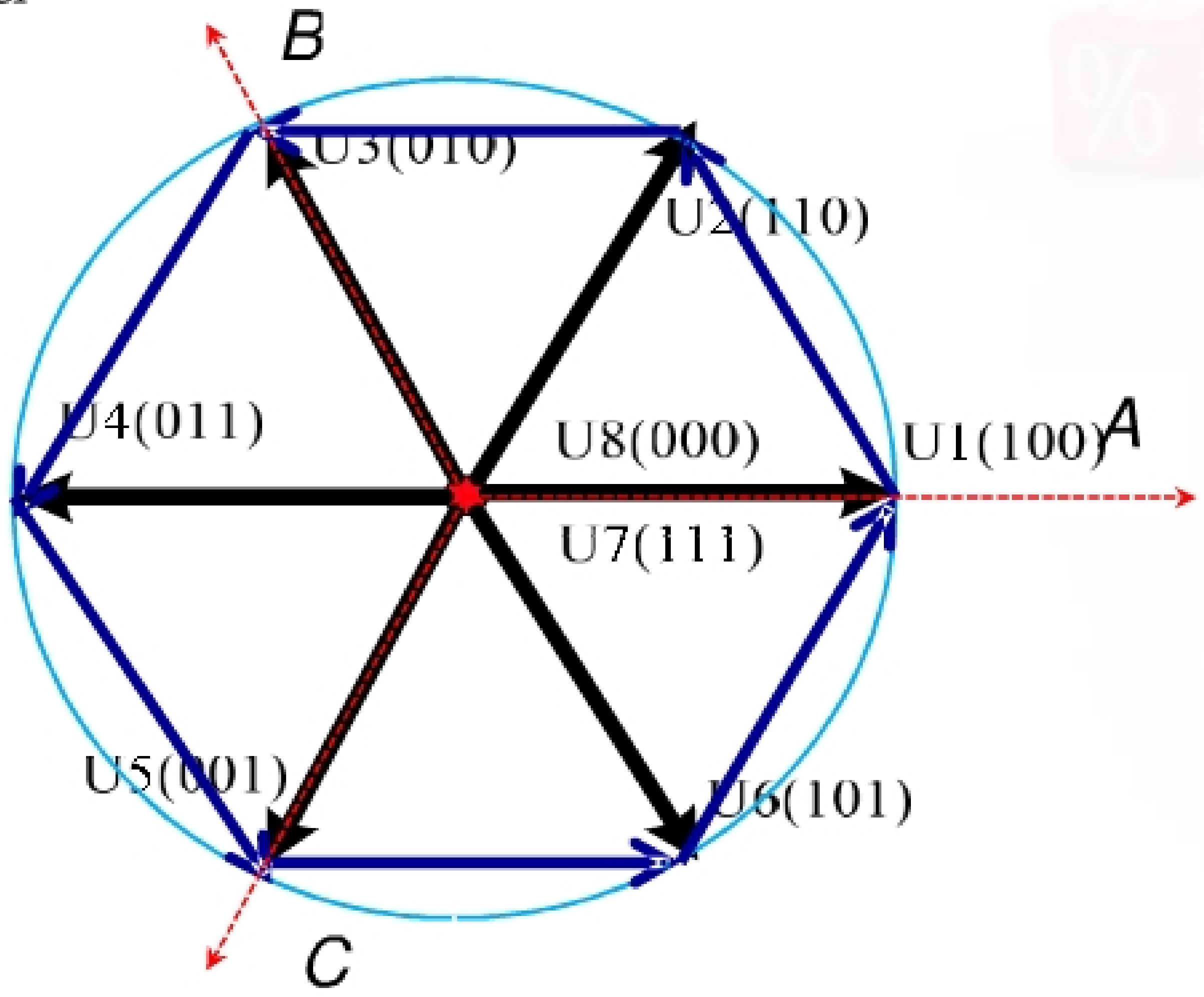
U1~U6:有效电压矢量

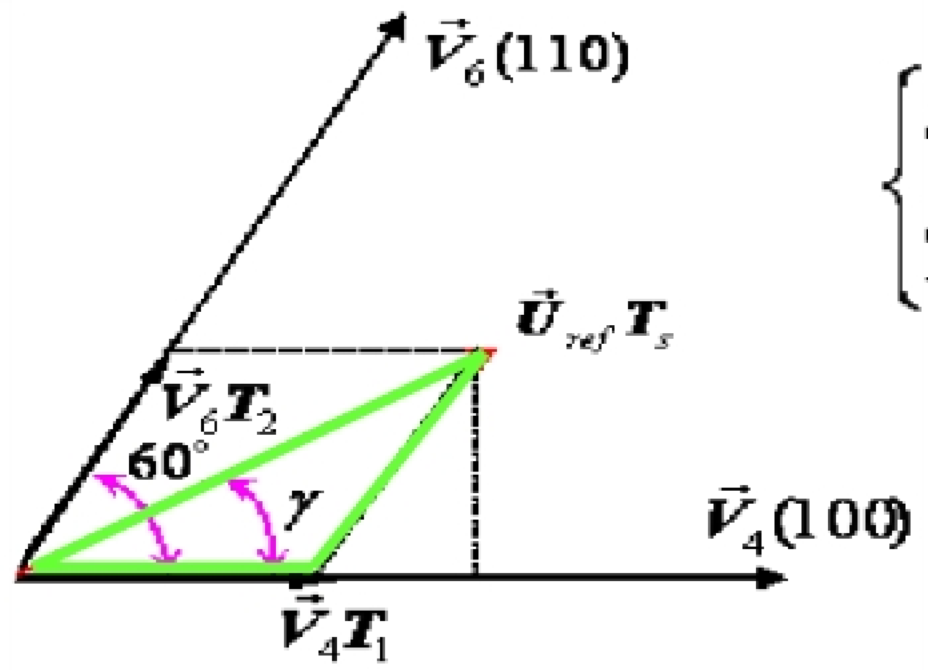
U7~U8:零矢量

转矩、转速波动，运行特性恶化：步进磁场，每T/6跳变一次 → *形成更多电压和磁链空间矢量* → *细分电压矢量作用时间，电压矢量重新组合* → *形成正多边形磁链轨迹，逼近圆形基准磁链*

SVPWM的基本原理:

在每一个采样周期内利用若干个基本电压矢量合成任意给定的参考电压矢量 U_{ref}



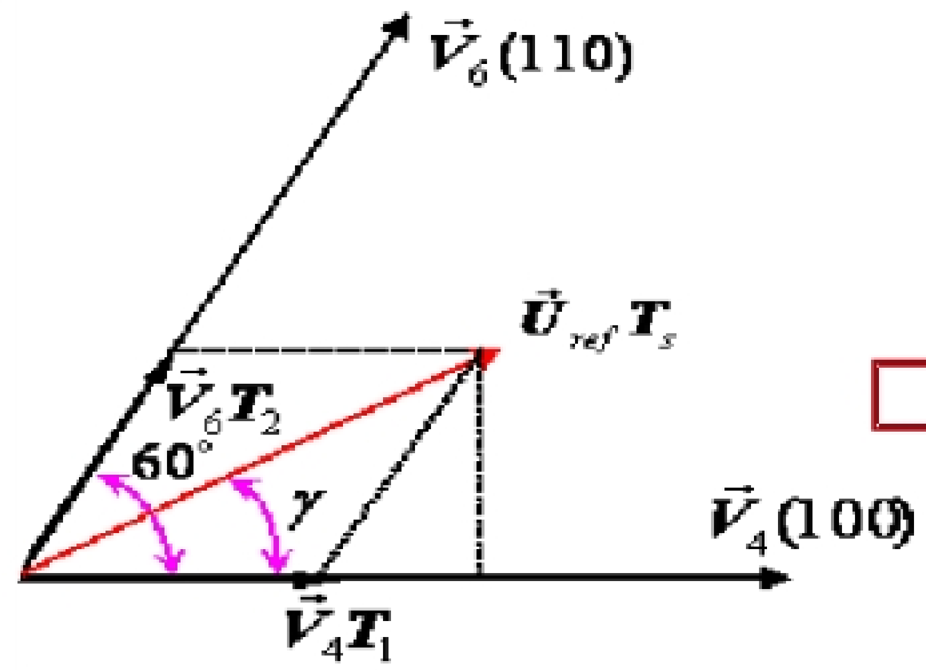


$$\begin{cases}\vec{U}_{ref}T_S = \vec{V}_4 T_1 + \vec{V}_6 T_2 \\ T_0 = T_s - T_1 - T_2\end{cases}$$

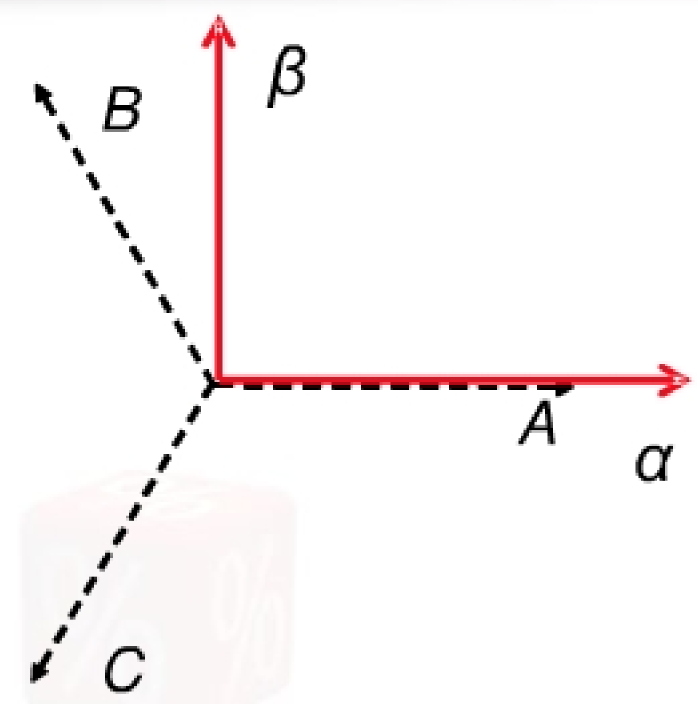
$$\frac{|U_{ref}|}{\sin\frac{2\pi}{3}} = \frac{\left|\frac{T_2}{T_S}V_6\right|}{\sin\gamma} = \frac{\left|\frac{T_1}{T_S}V_4\right|}{\sin(\frac{\pi}{3}-\gamma)}$$

$$\Rightarrow \begin{cases}T_1 = \sqrt{3}T_S\dfrac{|U_{ref}|}{V_{dc}}\sin(\dfrac{\pi}{3}-\gamma) \\ T_2 = \sqrt{3}T_S\dfrac{|U_{ref}|}{V_{dc}}\sin\gamma\end{cases}$$

需要进行三角函数的求解，耗费大量计算时间



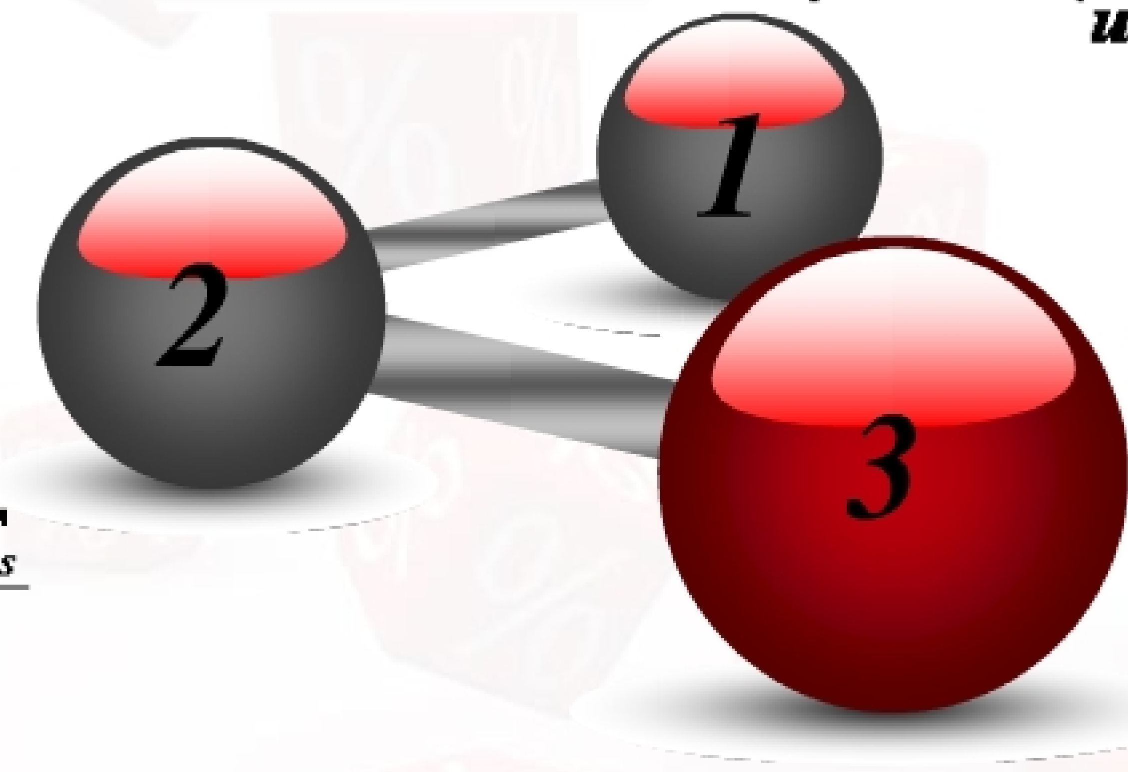
$$T(0)=\frac{2}{3}\begin{bmatrix}1 & -\frac{1}{2} & -\frac{1}{2}\\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}\end{bmatrix}$$



$$\begin{cases}\vec{U}_{ref}T_S=\vec{V}_4T_1+\vec{V}_6T_2\\ T_0=T_s-T_1-T_2\end{cases}\Rightarrow\begin{cases}\vec{u}_{ref\alpha}T_S=T_1\vec{V}_4+T_2\vec{V}_6\cos 60^\circ\\ \vec{u}_{ref\beta}T_S=T_2\vec{V}_6\sin 60^\circ\end{cases}\Rightarrow\begin{cases}T_1=\frac{1}{2}(\sqrt{3}u_{ref\alpha}-u_{ref\beta})\frac{\sqrt{3}T_s}{V_{dc}}\\ T_2=u_{ref\beta}\frac{\sqrt{3}T_s}{V_{dc}}\end{cases}$$

$$T_0 = T - T_1 - T_2$$

常规实现方法



扇区确定

$$|\boldsymbol{u}_{ref}| = \sqrt{\boldsymbol{u}_{ref\alpha}^2 + \boldsymbol{u}_{ref\beta}^2}$$

$$\gamma = \tan^{-1}\left(\frac{\boldsymbol{u}_{ref\beta}}{\boldsymbol{u}_{ref\alpha}}\right)$$

电压矢量作用时间确定

$$\begin{cases} T_1 = \dfrac{1}{2}(\sqrt{3}\boldsymbol{u}_{ref\alpha} - \boldsymbol{u}_{ref\beta})\dfrac{\sqrt{3}T_s}{V_{dc}} \\ T_2 = \boldsymbol{u}_{ref\beta}\dfrac{\sqrt{3}T_s}{V_{dc}} \end{cases}$$

$$T_0 = T - T_1 - T_2$$

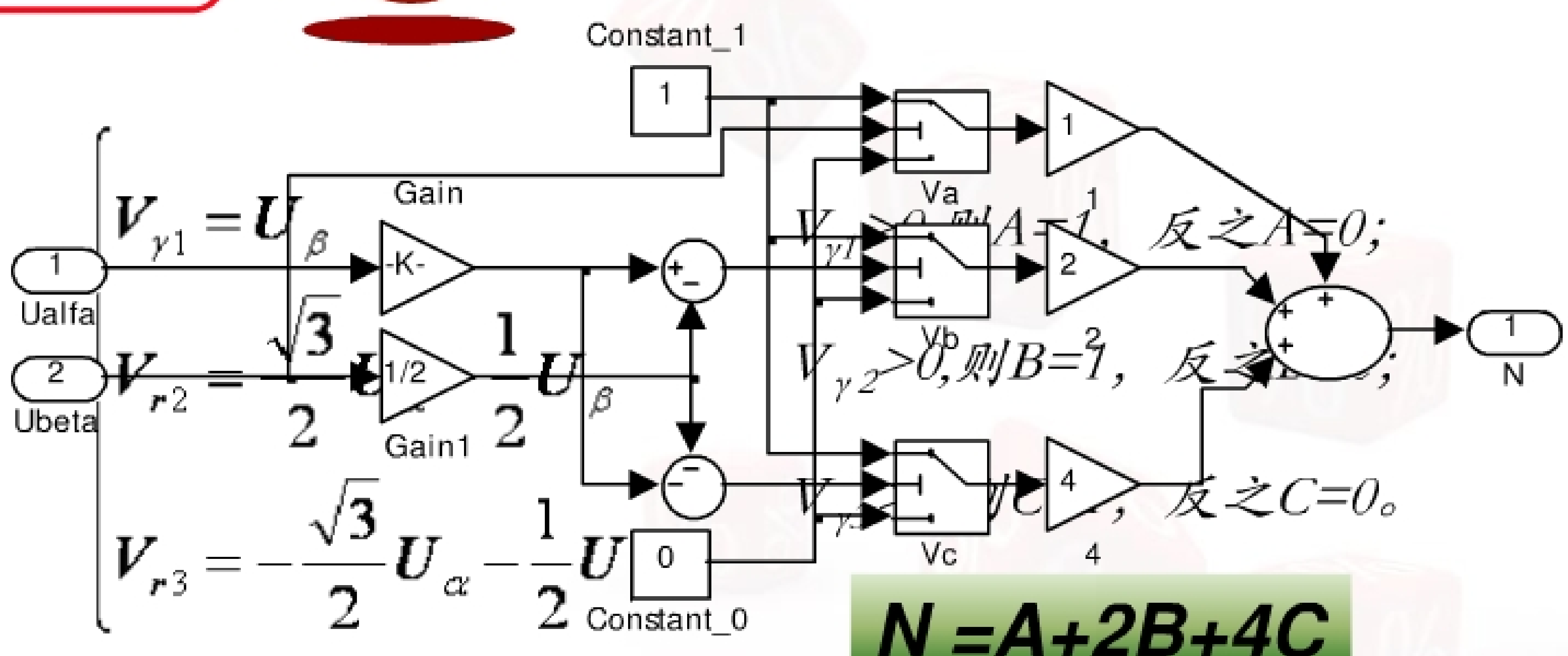
形成开关信号，控制变换器

现实考虑

1. 易于计算机实现
2. 挖掘SVPWM优势

数字实现方式

扇区确定



$$\begin{cases} V_{\gamma 1} = U_\beta \\ V_{r2} = \frac{\sqrt{3}}{2}U_\alpha - \frac{1}{2}U_\beta \\ V_{r3} = -\frac{\sqrt{3}}{2}U_\alpha - \frac{1}{2}U_\beta \end{cases}$$

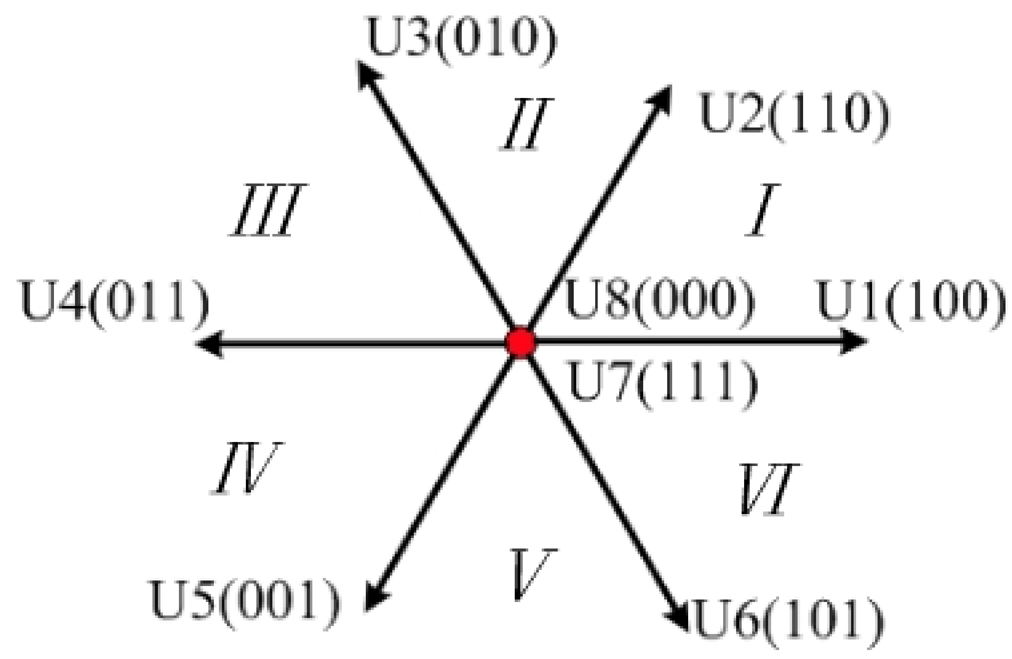
$V_{\gamma 1}>0$,则A=1，反之A=0；

$V_{\gamma 2}>0$,则B=1，反之B=0；

$V_{\gamma 3}>0$,则C=1，反之C=0。

N =A+2B+4C

当N=3时，U_{ref}位于第Ⅰ扇区；
当N=1时，U_{ref}位于第Ⅱ扇区；
当N=5时，U_{ref}位于第Ⅲ扇区；
当N=4时，U_{ref}位于第Ⅳ扇区；
当N=6时，U_{ref}位于第Ⅴ扇区；
当N=2时，U_{ref}位于第Ⅵ扇区。



开关矢量时间确定

$$U_{ref\beta}\frac{\sqrt{3}T_s}{V_{dc}} \qquad \frac{1}{2}(\pm\sqrt{3}u_{ref\alpha}+u_{ref\beta})\frac{\sqrt{3}T_s}{V_{dc}}$$

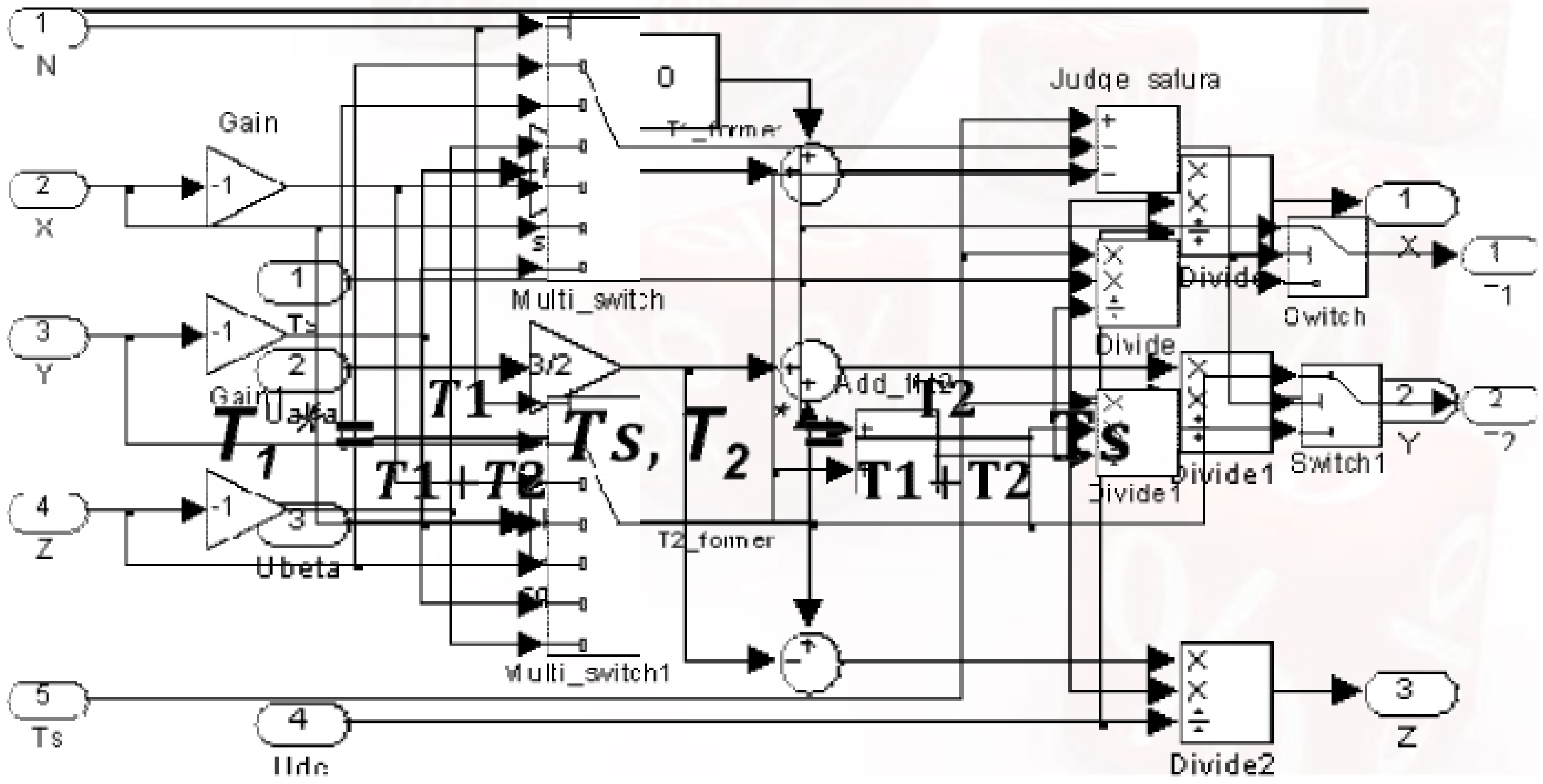
$$\begin{cases} X=\dfrac{\sqrt{3}T_S}{V_{dc}}U_\beta \\ Y=\dfrac{\sqrt{3}T_S}{2V_{dc}}(\sqrt{3}U_\alpha+U_\beta) \\ Z=\dfrac{\sqrt{3}T_S}{2V_{dc}}(-\sqrt{3}U_\alpha+U_\beta) \end{cases}$$

表 I 矢量作用时间分配

扇区	I	II	III	IV	V	VI
N	3	1	5	4	6	2
T1	−Z	Z	X	−X	−Y	Y
T2	X	Y	−Y	Z	−Z	−X

DANGER

$T_1+T_2>T_s$ **!!**



$$T_1=\frac{T1}{T1+T2}Ts,\quad T_2=\frac{T2}{T1+T2}Ts$$

3 确定电压矢量及其作用时刻

N	1	2	3	4	5	6
矢量所在扇区	Ⅱ	Ⅵ	Ⅰ	Ⅳ	Ⅲ	Ⅴ

原则：使每一次的开关切换只涉及一个开关，降低开关频率

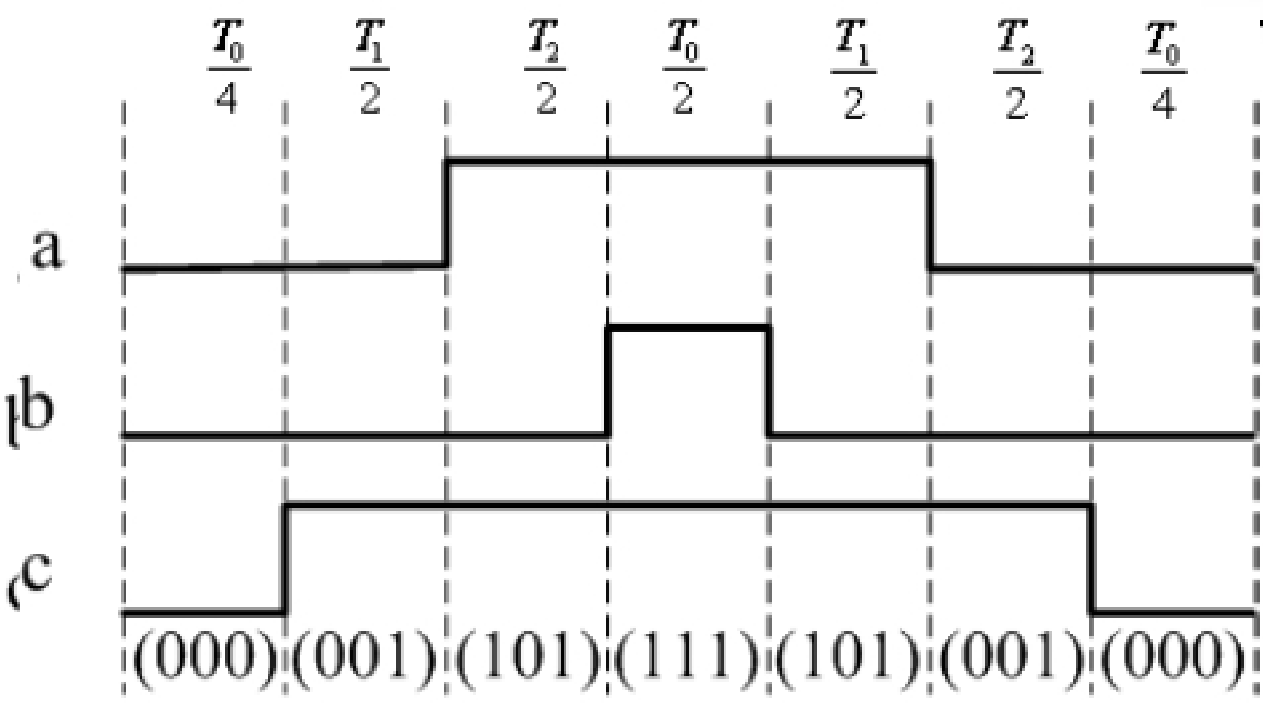
七段空间矢量合成方式

均以零矢量(000)开始和结束，中间用零矢量（111）,其余时间有效矢量合理安排

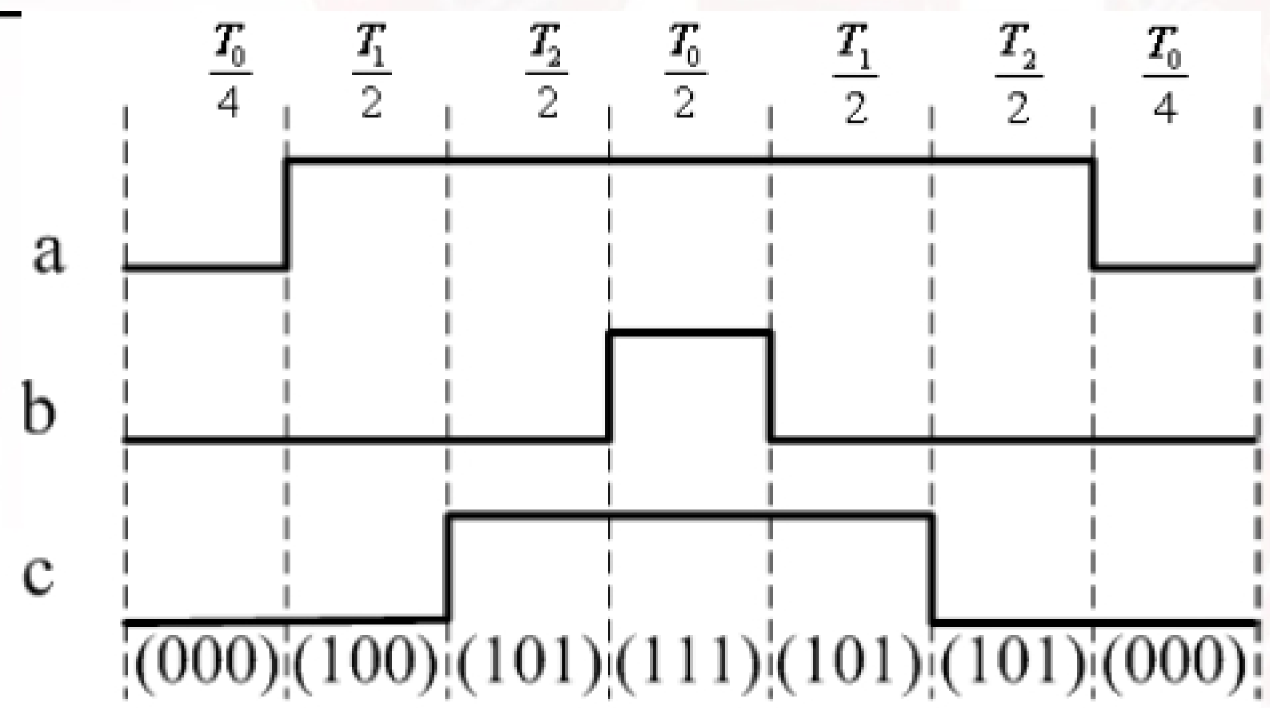
T_S

零矢量(000)	矢量A	矢量B	零矢量(111)	矢量B	矢量A	零矢量(000)

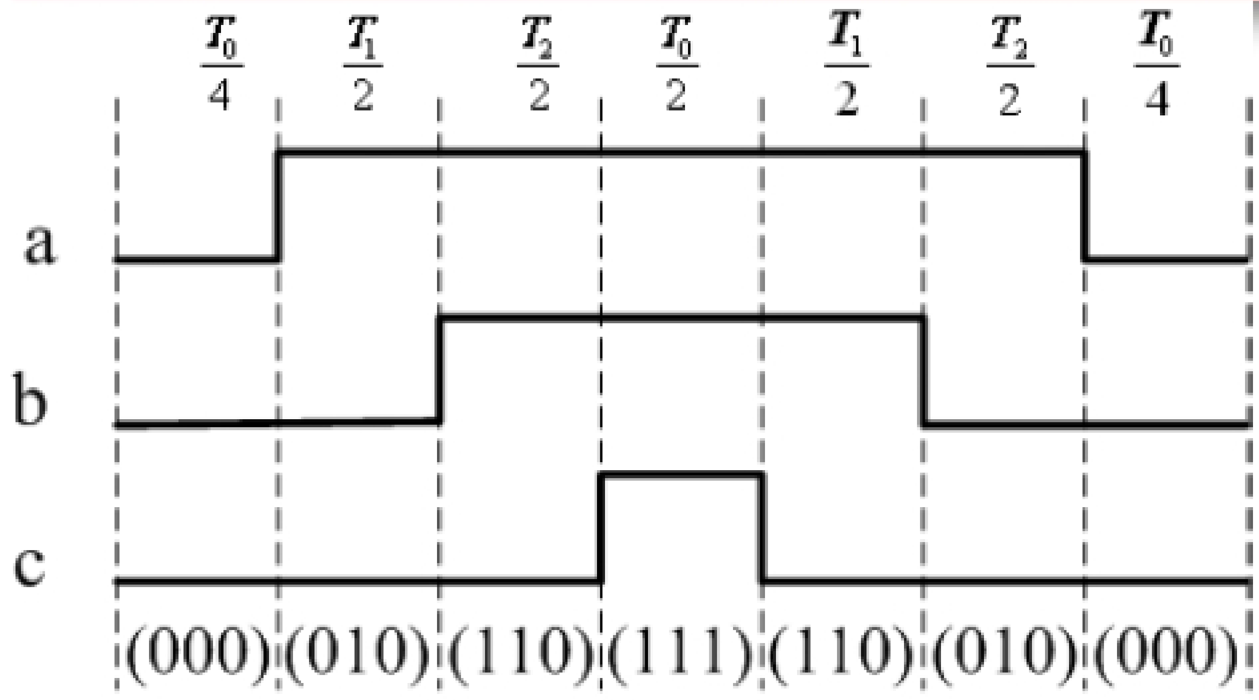
作用时间 / 扇区	T0/4 零矢量	T1/2 第一矢量	T2/2 第二矢量	T0/2 零矢量	T2/2 第二矢量	T1/2 第一矢量	T0/4 零矢量
I	000	100	110	111	110	100	000
II	000	010	110	111	110	010	000
III	000	010	011	111	011	010	000
IV	000	001	011	111	011	001	000
V	000	001	101	111	101	001	000
VI	000	100	101	111	101	100	000



Section V

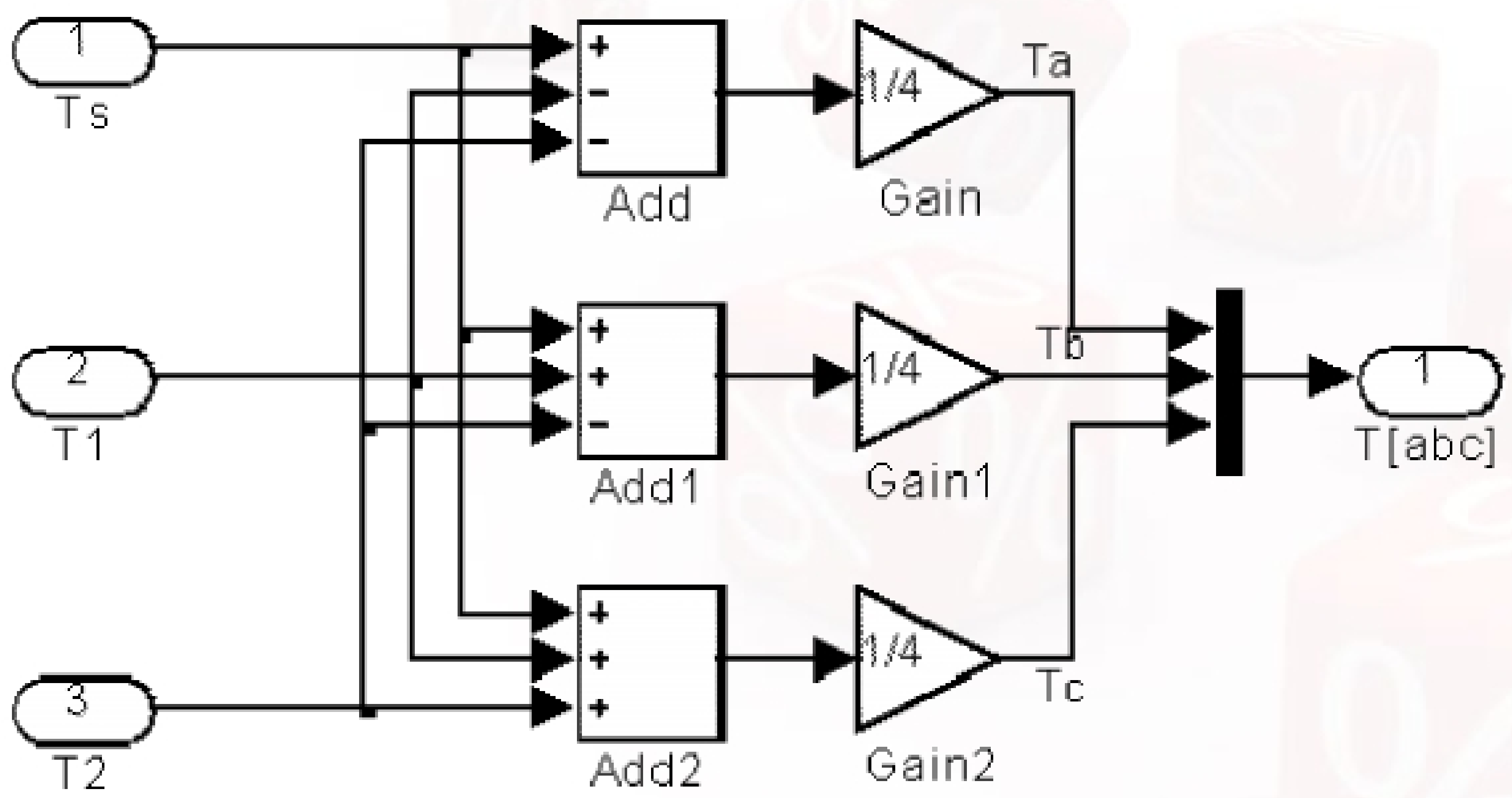


Section VI



$$
\begin{cases}
Ta = (T_S - T_1 - T_2)/4 \\
Tb = Ta + T_1/2 = (T_S + T_1 - T_2)/4 \\
Tc = Tb + T_2/2 = (T_S + T_1 + T_2)/4
\end{cases}
$$

Section Ⅰ



4 开关矢量时间确定

控制脉冲最终控制开关管，故需实现：

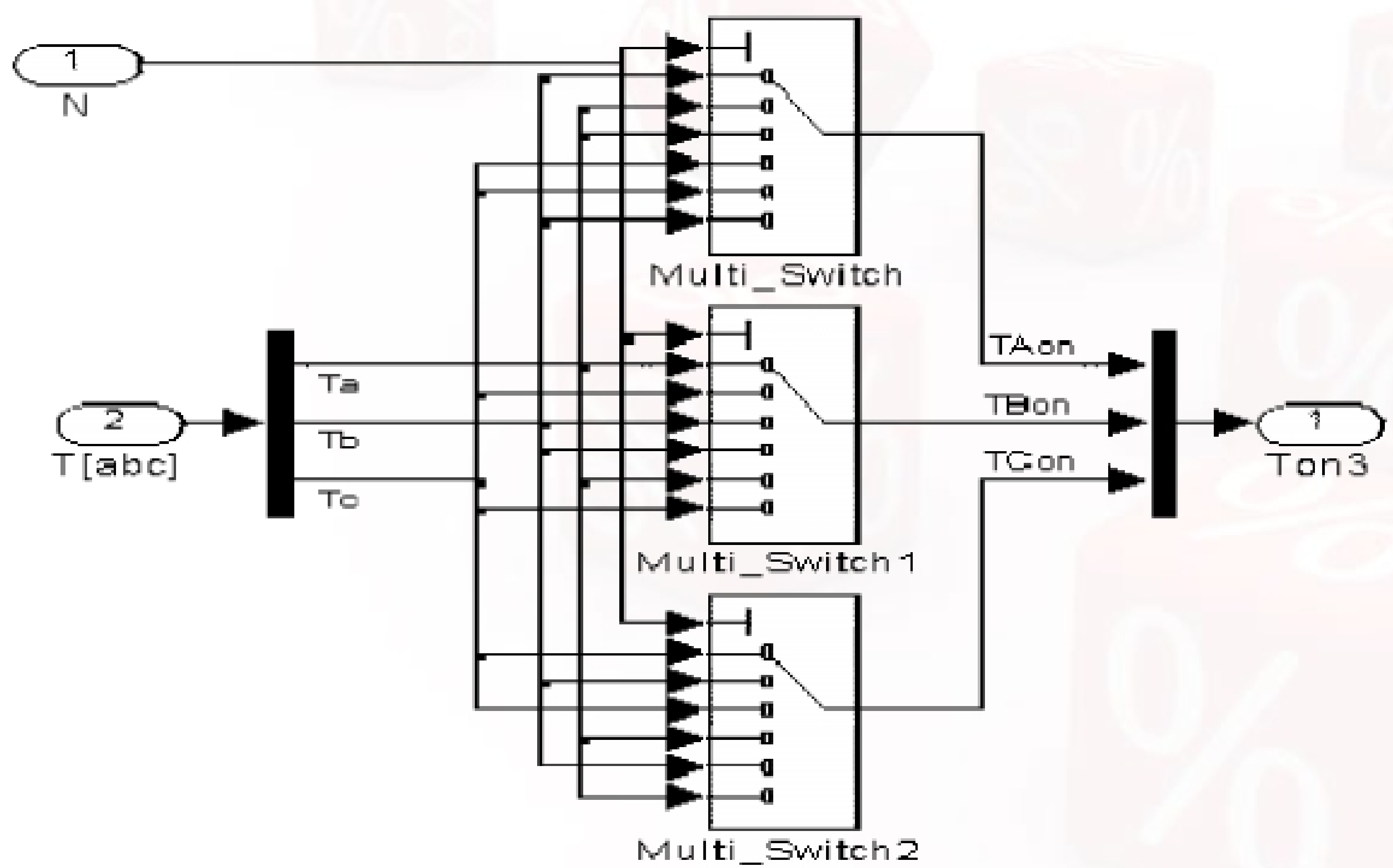
电压矢量切换时刻

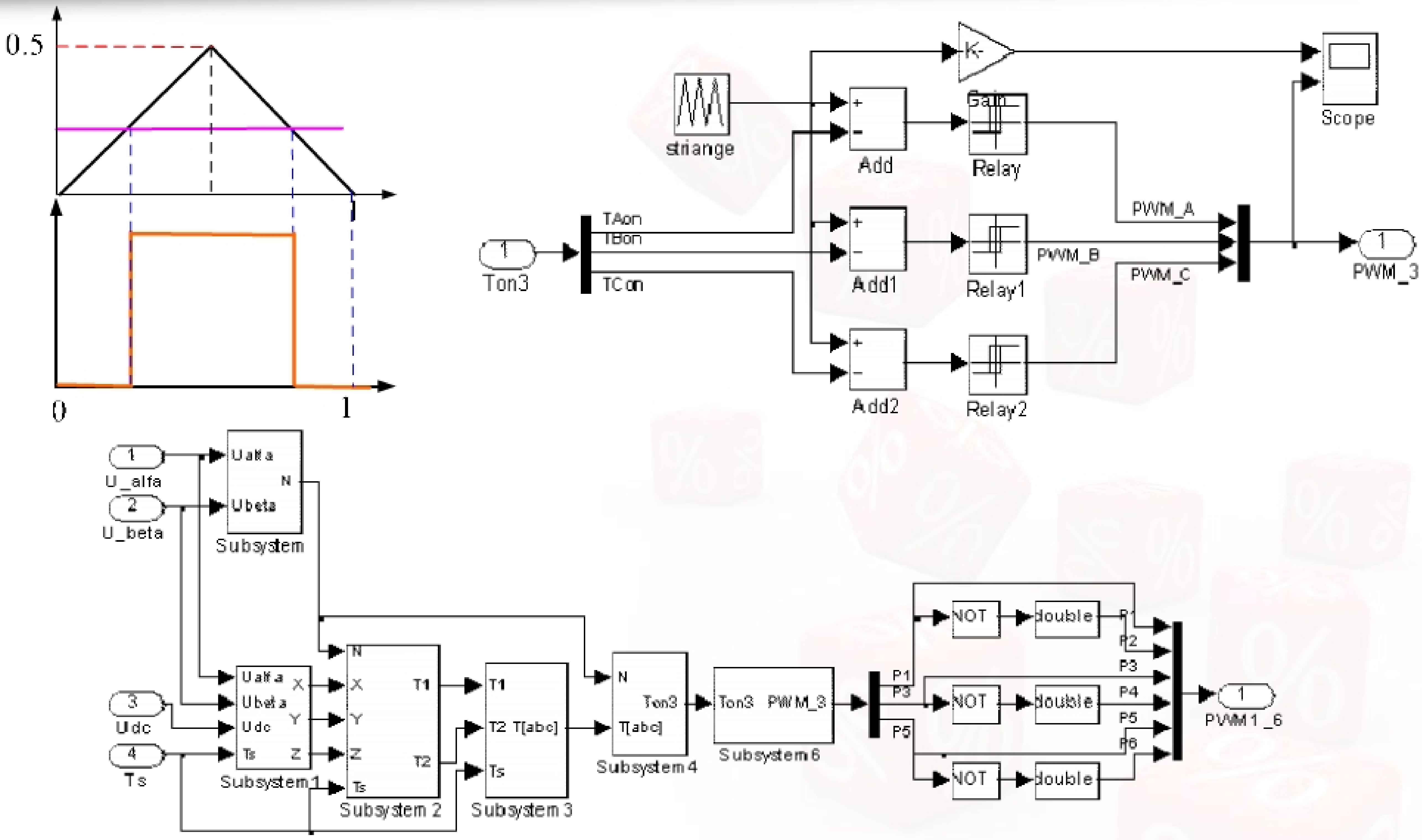
↓

各相开关切换时刻

扇区	Ⅰ	Ⅱ	Ⅲ	Ⅳ	Ⅴ	Ⅵ
N	3	1	5	4	6	2
Tcm1	Ta	Tb	Tc	Tc	Tb	Ta
Tcm2	Tb	Ta	Ta	Tb	Tc	Tc
Tcm3	Tc	Tc	Tb	Ta	Ta	Tb

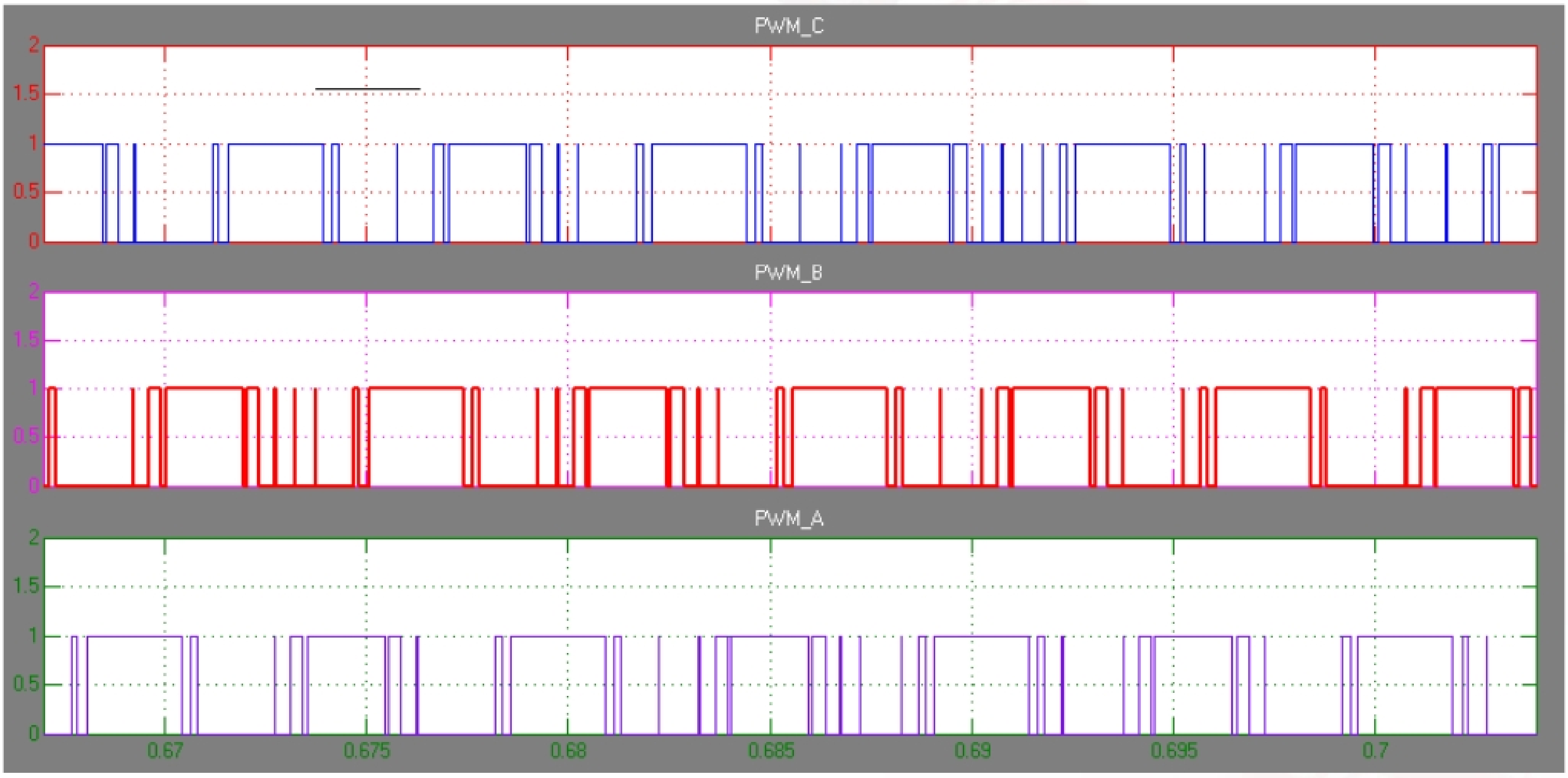
Ta,Tb,Tc分别为先作用电压矢量、次作用电压矢量、零矢量(111)的作用时刻





SVPWM调制波产生总图

三相变换器上开关管的控制信号



Comparisons

传统PWM技术一般通过将三角载波和调制函数波比较获得相应脉冲波形

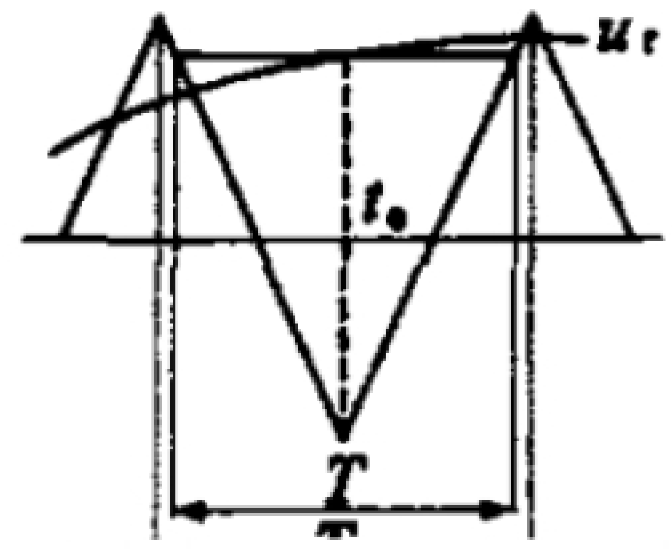
$$u_A = a\times\begin{cases}\cos(\omega t-30^\circ) & 0\le\omega t<60^\circ\\ \sqrt{3}\cos\omega t & 60^\circ\le\omega t<120^\circ\\ -\cos(\omega t-150^\circ) & 120^\circ\le\omega t<180^\circ\\ -\cos(\omega t-210^\circ) & 180^\circ\le\omega t<240^\circ\\ \sqrt{3}\cos\omega t & 240^\circ\le\omega t<300^\circ\\ \cos(\omega t+30^\circ) & 300^\circ\le\omega t<360^\circ\end{cases}$$

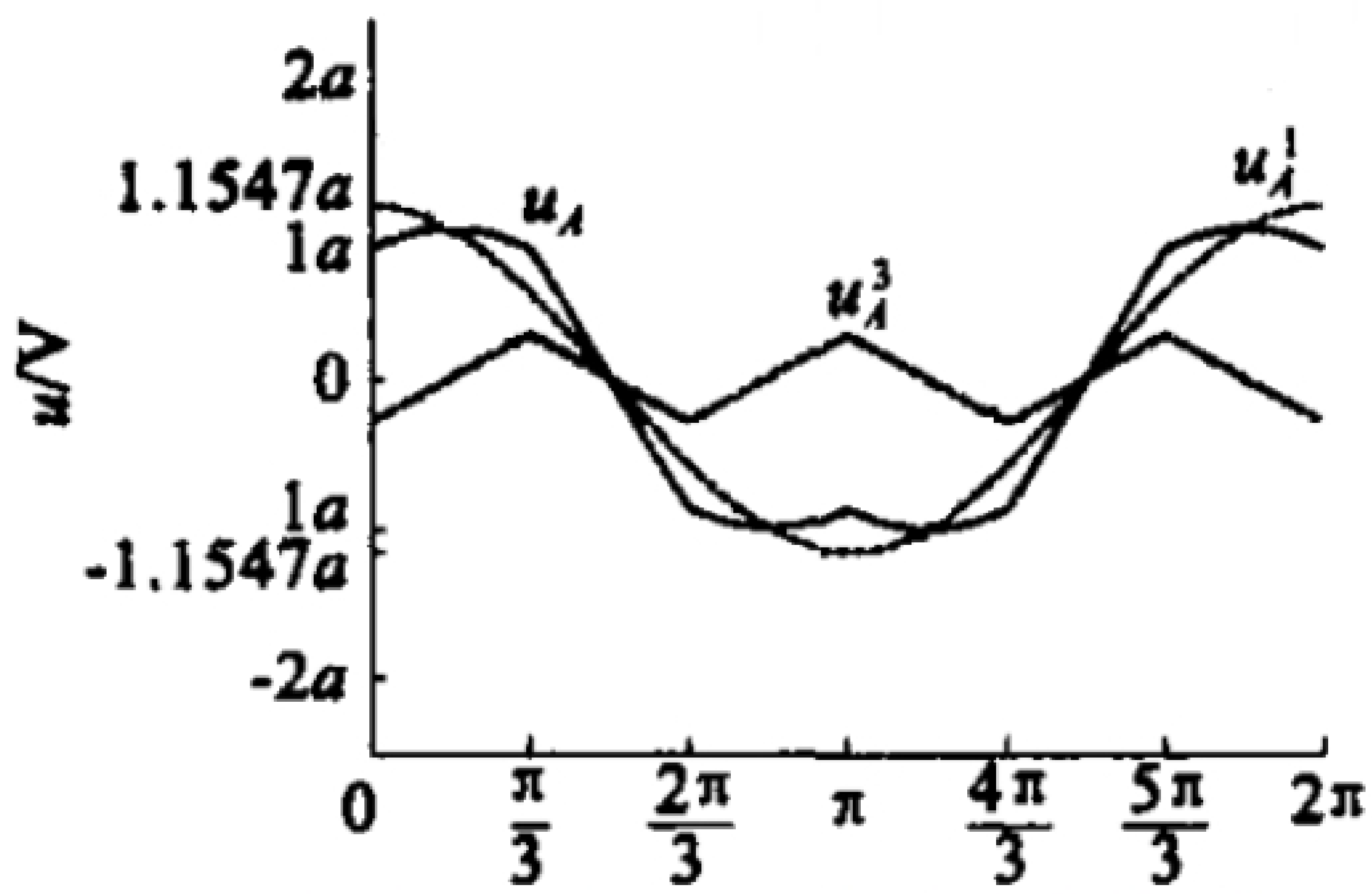
$$u_A(t)=u_B(t-120^\circ)=u_C(t+120^\circ)$$

$$u_{AB}=u_A-u_B=2a\cos(\omega t+30^\circ)$$

调制函数与其基波相差为一三倍频率的三角波，故输出相电压不为正弦波

SVPWM的调制函数又该是什么样呢?





Comparisons

SPWM

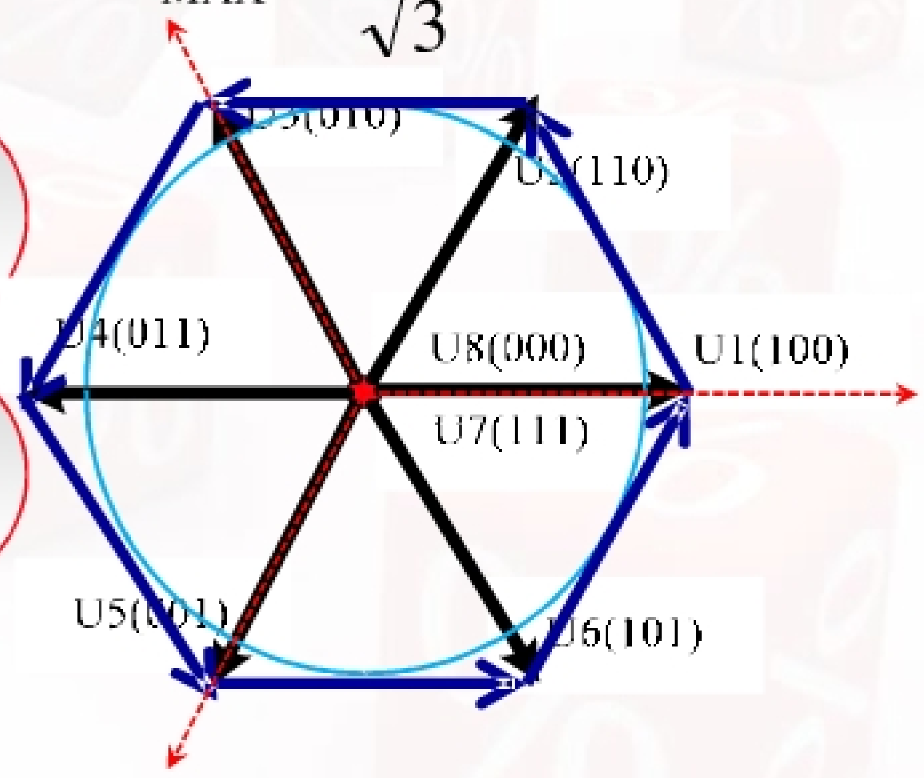
$u(t)=\sqrt{3}M\sin\omega t$ + 零序分量 → 规则采样

SVPWM

$$u_{AB}=u_A-u_B=2a\cos(\omega t+30^\circ)$$

$$M=\frac{2a}{\sqrt{3}}=\frac{2|U_{ref}|}{V_{DC}}\qquad |U_{ref}|\le\frac{V_{DC}}{\sqrt{3}}$$

$$M\le 1 \quad\Longleftrightarrow\quad M_{\mathrm{MAX}}=\frac{2}{\sqrt{3}}\approx 1.1547$$



优点

1. 提高直流电压利用率
2. 动静态性能提高，转矩脉动小