Power System Analysis
供電=用電

Arthur R. Bergen
授課：侯中權 博士
(Prof. Chung-Chuan Hou)

鎖相回路(PLL: Phase Lock Loop)

1. 三相轉靜止座標(abc Reference Frame to Stationary Reference Frame)
2. 靜止座標轉同步座標(Stationary Reference Frame to Synchronous Reference Frame)
3. 靜止座標轉非同步座標(Stationary Reference Frame to Asynchronous Reference Frame)
4. 鎖相回路(PLL: Phase Lock Loop)
5. 平衡電壓驟降(Balanced voltage sag)
6. 不平衡電壓驟降(Unbalanced voltage sag)
7. 停電(Power Failure)
8. 相序錯誤(phase abc -> acb)
9. 帕克變換(Park Transformation)
10. 對稱分量(Symmetrical Components)
11. 馬達與發電機(Motor and Generator)

三相轉靜止座標(abc Reference Frame to Stationary Reference Frame)

$[v_{qs}\ \ v_{ds}] = [2/3\ \ -1/3\ \ -1/3;\ 0\ \ -1/\sqrt{3}\ \ 1/\sqrt{3}][v_a\ \ v_b\ \ v_c]$

$[v_a\ \ v_b\ \ v_c] = [1\ \ 0;\ -1/2\ \ -\sqrt{3}/2;\ -1/2\ \sqrt{3}/2][v_{qs}\ \ v_{ds}]$

3-phase 220V_{rms} (60Hz, line-to-line) , $\omega = 2\pi f = 120\pi = 377$ rad/sec.

$v_a + v_b + v_c = 0$, balanced system, ($v_a + v_b + v_c \neq 0$, unbalanced system)

$v_a = 180 \cos \omega t$, $v_b = 180 \cos (\omega t - 120^\circ)$, $v_c = 180 \cos (\omega t + 120^\circ)$,

abc Reference Frame to Stationary Reference Frame

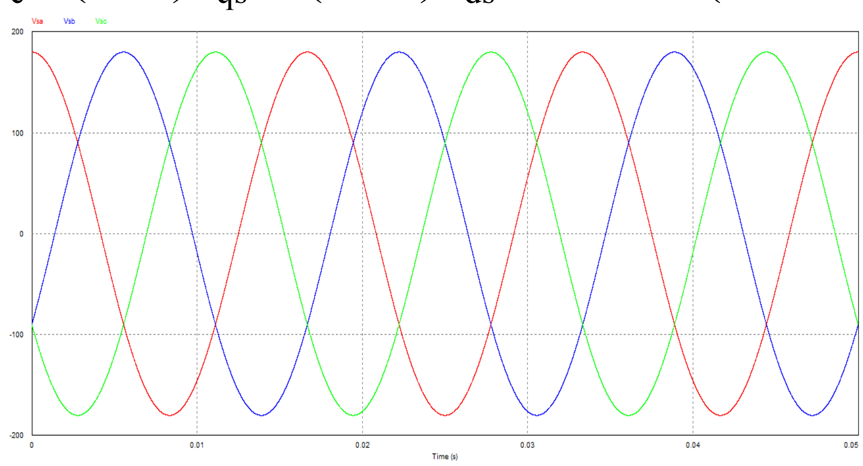
$v_{qs} = (2/3)v_a + (-1/3)v_b + (-1/3)v_c = (2/3)v_a + (1/3)v_a = v_a = 180 \cos \omega t$

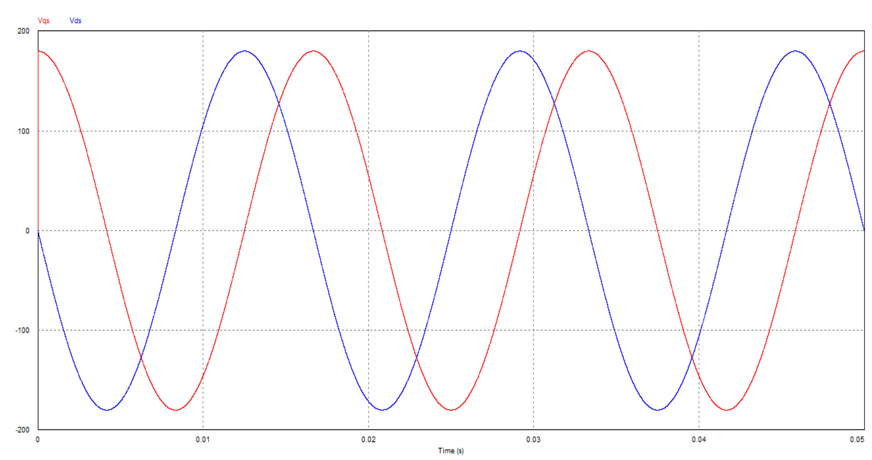
$v_{ds} = (-1/\sqrt{3})v_b + (1/\sqrt{3})v_c = (-1/\sqrt{3})[v_a + 2v_b] = -180 \sin \omega t$

Stationary Reference Frame to abc Reference Frame

$v_a = v_{qs}$, $v_b = (-1/2)v_{qs} + (-\sqrt{3}/2)v_{ds} = 180\cos(\omega t - 120^\circ)$,

$v_c = (-1/2)v_{qs} + (\sqrt{3}/2)v_{ds} = 180\cos(\omega t + 120^\circ)$





靜止座標轉同步座標(Stationary Reference Frame to Synchronous Reference Frame)

$[v_{qe} \ \ v_{de}] = [\cos \omega t \ \ -\sin \omega t; \sin \omega t \ \ \cos \omega t][v_{qs} \ \ v_{ds}]$

$[v_{qs} \ \ v_{ds}] = [\cos \omega t \ \ \sin \omega t; -\sin \omega t \ \ \cos \omega t][v_{qe} \ \ v_{de}]$

3-phase 220V_{rms} (60Hz, line-to-line) , $\omega = 2\pi f = 120\pi = 377$ rad/sec.

$v_{qs} = 180 \cos \omega t$, $v_{ds} = -180 \sin \omega t$,

Stationary Reference Frame to Synchronous Reference Frame

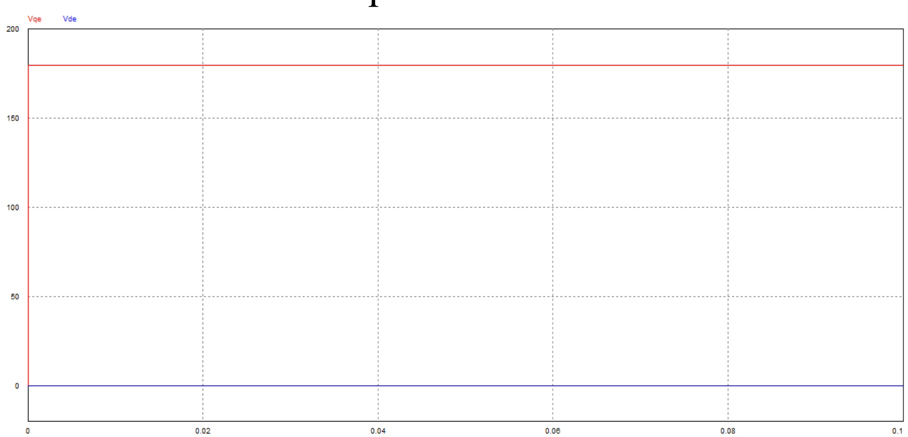
$v_{qe} = \cos \omega t \ v_{qs} - \sin \omega t \ v_{ds} = 180$

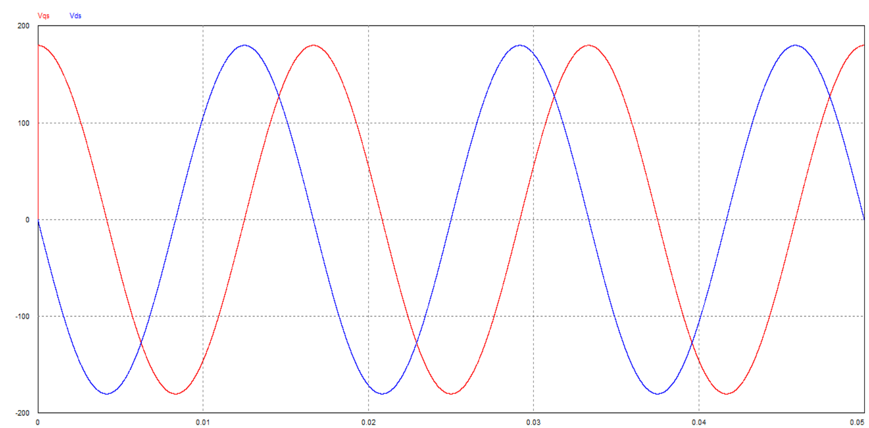
$v_{de} = \sin \omega t \ v_{qs} + \cos \omega t \ v_{ds} = 0$

Synchronous Reference Frame to Stationary Reference Frame

$v_{qs} = \cos \omega t \ v_{qe} + \sin \omega t \ v_{de} = 180 \cos \omega t$,

$v_{ds} = -\sin \omega t \ v_{qe} + \cos \omega t \ v_{de} = -180 \sin \omega t$





靜止座標轉非同步座標(Stationary Reference Frame to Asynchronous Reference Frame)($\omega_1 \neq \omega$, assume 59Hz, ω_1 =118π rad/sec.)

$[v_{qe} \;\; v_{de}] = [\cos \omega_1 t \;\; -\sin \omega_1 t; \sin \omega_1 t \;\; \cos \omega_1 t][v_{qs} \;\; v_{ds}]$

$[v_{qs} \;\; v_{ds}] = [\cos \omega_1 t \;\; \sin \omega_1 t; -\sin \omega_1 t \;\; \cos \omega_1 t][v_{qe} \;\; v_{de}]$

3-phase 220V_{rms} (60Hz, line-to-line) , $\omega = 2\pi f = 120\pi = 377$ rad/sec.

$v_{qs} = 180 \cos \omega t$, $v_{ds} = -180 \sin \omega t$,

Stationary Reference Frame to Asynchronous Reference Frame

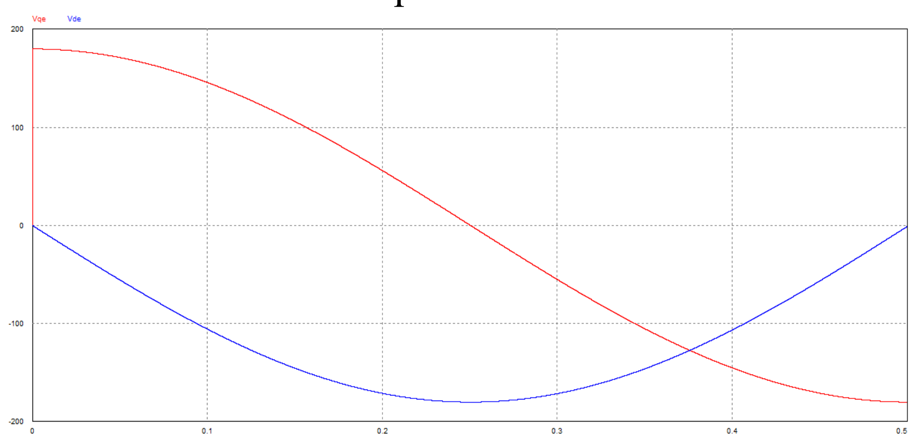
$v_{qe} = \cos \omega_1 t \; v_{qs} - \sin \omega_1 t \; v_{ds} = 180 \cos (\omega_1 - \omega)t \neq 180$

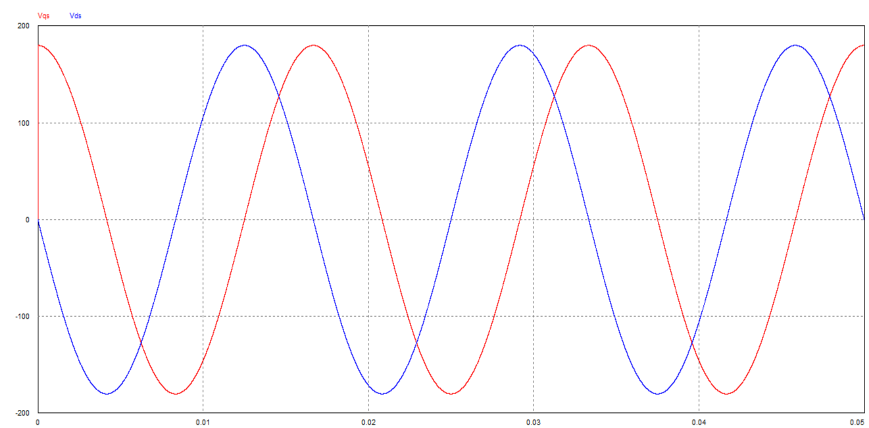
$v_{de} = \sin \omega_1 t \; v_{qs} + \cos \omega_1 t \; v_{ds} = 180 \sin (\omega_1 - \omega)t \neq 0$

Asynchronous Reference Frame to Stationary Reference Frame

$v_{qs} = \cos \omega_1 t \; v_{qe} + \sin \omega_1 t \; v_{de} = v_{qs} = 180 \cos \omega t$,

$v_{ds} = - \sin \omega_1 t \; v_{qe} + \cos \omega_1 t \; v_{de} = v_{ds} = -180 \sin \omega t$





鎖相回路(PLL: Phase Lock Loop)(ω_1 =314 rad/sec. ω_1 -> ω)

$[v_{qe} \;\; v_{de}] = [\cos \omega_1 t \;\; -\sin \omega_1 t; \sin \omega_1 t \;\; \cos \omega_1 t][v_{qs} \;\; v_{ds}]$

$[v_{qs} \;\; v_{ds}] = [\cos \omega_1 t \;\; \sin \omega_1 t; -\sin \omega_1 t \;\; \cos \omega_1 t][v_{qe} \;\; v_{de}]$

3-phase 220V_{rms} (60Hz, line-to-line) , $\omega = 2\pi f = 120\pi = 377$ rad/sec.

$v_{qs} = 180 \cos \omega t$, $v_{ds} = -180 \sin \omega t$,

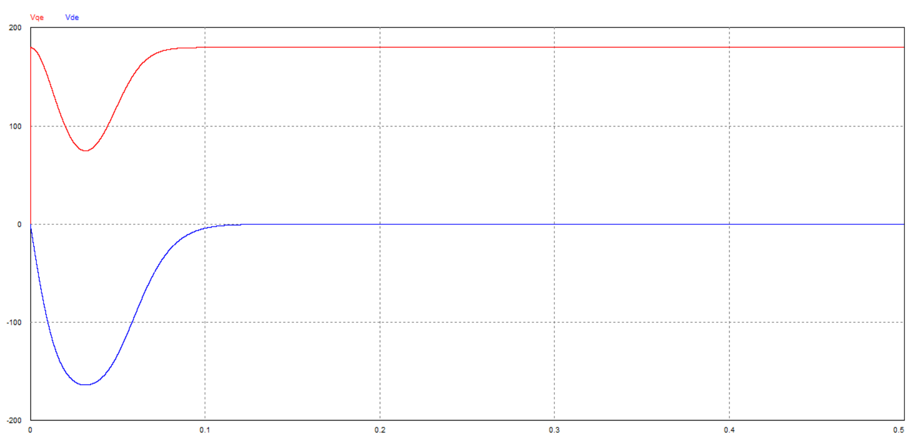
Stationary Reference Frame to Asynchronous Reference Frame

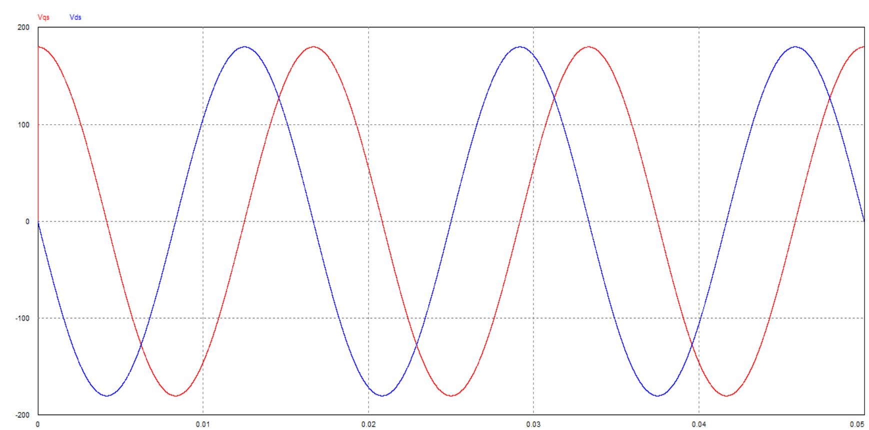
$v_{qe} = \cos \omega_1 t \; v_{qs} - \sin \omega_1 t \; v_{ds} = 180 \cos (\omega_1 - \omega)t \neq 180$

$v_{de} = \sin \omega_1 t \; v_{qs} + \cos \omega_1 t \; v_{ds} = 180 \sin (\omega_1 - \omega)t \neq 0$

Error=(0 - v_{de}), ωp= Pgain*Error, ωi = ωi+Igain*error, $\omega_1 = \omega_1 + \omega p + \omega i$

PLL: Phase Lock Loop ω_1 -> ω





平衡電壓驟降(Balanced voltage sag)(with PLL)

$[v_{qs}\ \ v_{ds}] = [2/3\ \ -1/3\ \ -1/3;\ 0\ \ -1/\sqrt{3}\ \ 1/\sqrt{3}][v_a\ \ v_b\ \ v_c]$

$[v_{qe}\ \ v_{de}] = [\cos \omega t\ \ -\sin \omega t;\ \sin \omega t\ \ \cos \omega t][v_{qs}\ \ v_{ds}]$

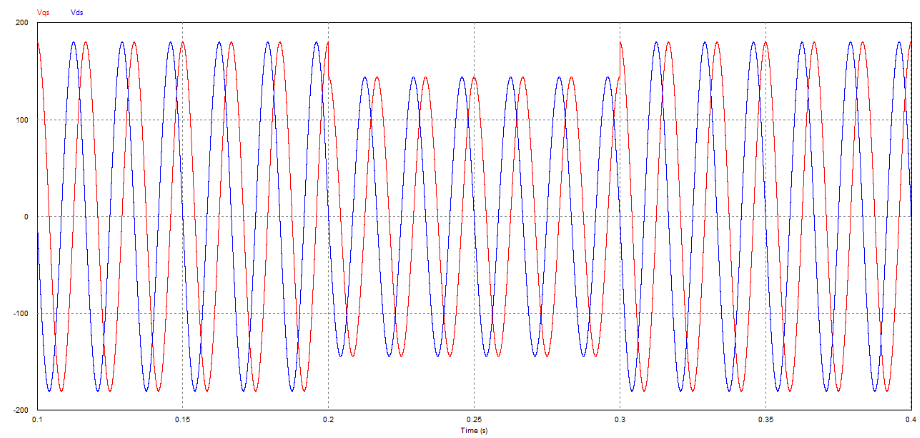
3-phase $220V_{rms}$ (60Hz, line-to-line) , $\omega = 2\pi f = 120\pi = 377$ rad/sec.

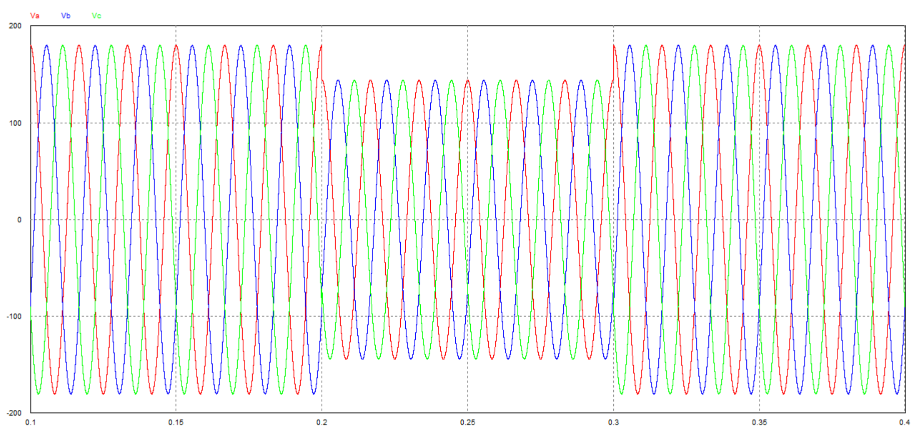
Balanced voltage sag at t = 0.2~0.3, 0.8* $220V_{rms}$, (180V*0.8)

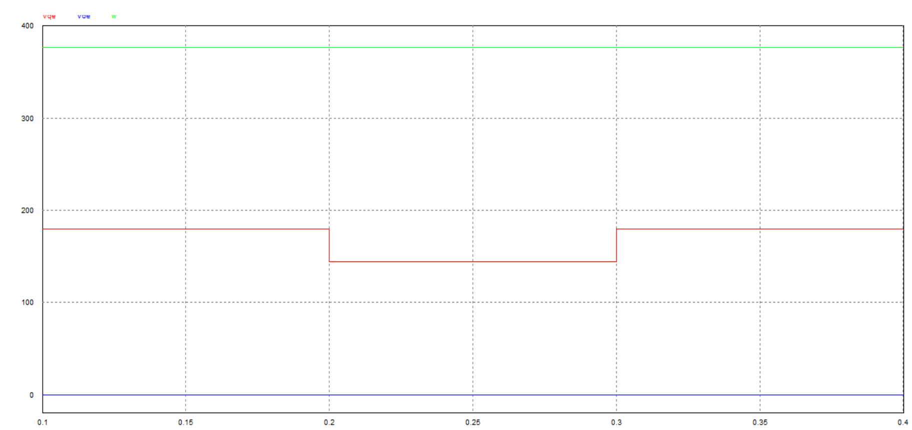
$v_a = 180 \cos \omega t$,

$v_b = 180 \cos (\omega t-120^\circ)$,

$v_c = 180 \cos (\omega t+120^\circ)$,







不平衡電壓驟降1(Unbalanced voltage sag)(with PLL)

$[v_{qs}\ \ v_{ds}] = [2/3\ \ -1/3\ \ -1/3;\ 0\ \ -1/\sqrt{3}\ \ 1/\sqrt{3}][v_a\ \ v_b\ \ v_c]$

$[v_{qe}\ \ v_{de}] = [\cos \omega t\ \ -\sin \omega t;\ \sin \omega t\ \ \cos \omega t][v_{qs}\ \ v_{ds}]$

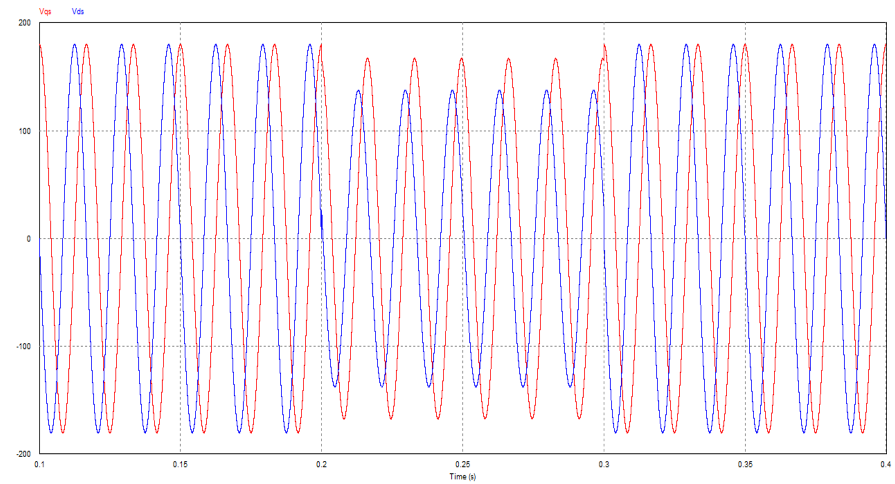
3-phase 220V_{rms} (60Hz, line-to-line) , $\omega = 2\pi f = 120\pi = 377$ rad/sec.

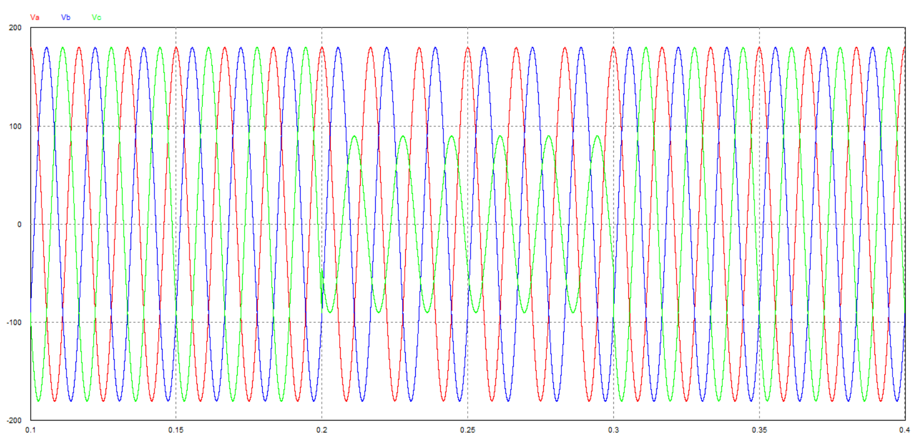
Unbalanced voltage sag at t = 0.2~0.3, $|v_c|$ =180V*0.5

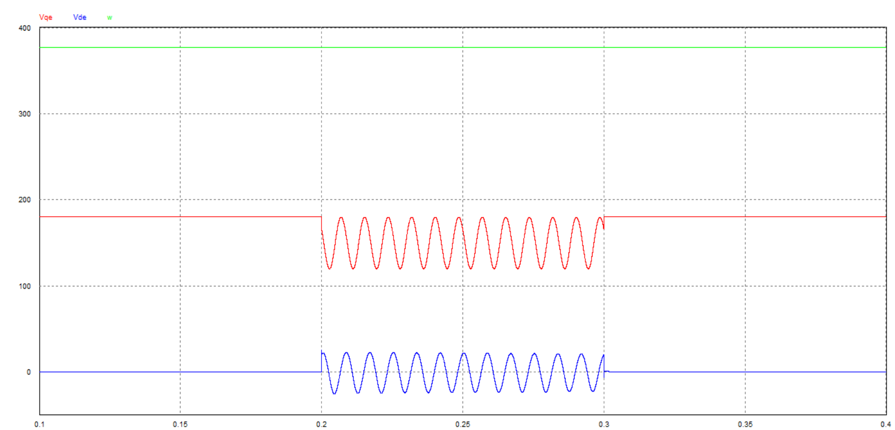
$v_a = 180 \cos \omega t$,

$v_b = 180 \cos (\omega t - 120^\circ)$,

$v_c = 180 \cos (\omega t + 120^\circ)$,(180*0.5)







不平衡電壓驟降2(Unbalanced voltage sag)(with PLL)

$[v_{qs}\ \ v_{ds}] = [2/3\ \ -1/3\ \ -1/3;\ 0\ \ -1/\sqrt{3}\ \ 1/\sqrt{3}][v_a\ \ v_b\ \ v_c]$

$[v_{qe}\ \ v_{de}] = [\cos\omega t\ \ -\sin\omega t;\ \sin\omega t\ \ \cos\omega t][v_{qs}\ \ v_{ds}]$

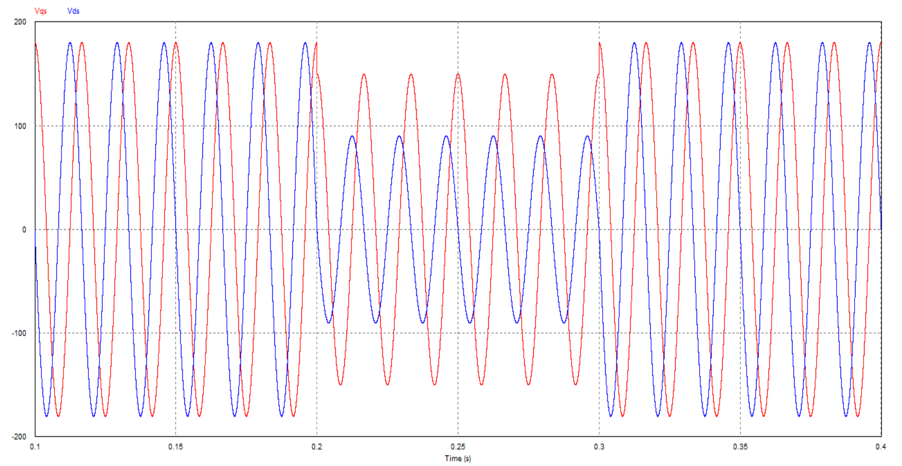
3-phase 220V_{rms} (60Hz, line-to-line) , $\omega = 2\pi f = 120\pi = 377$ rad/sec.

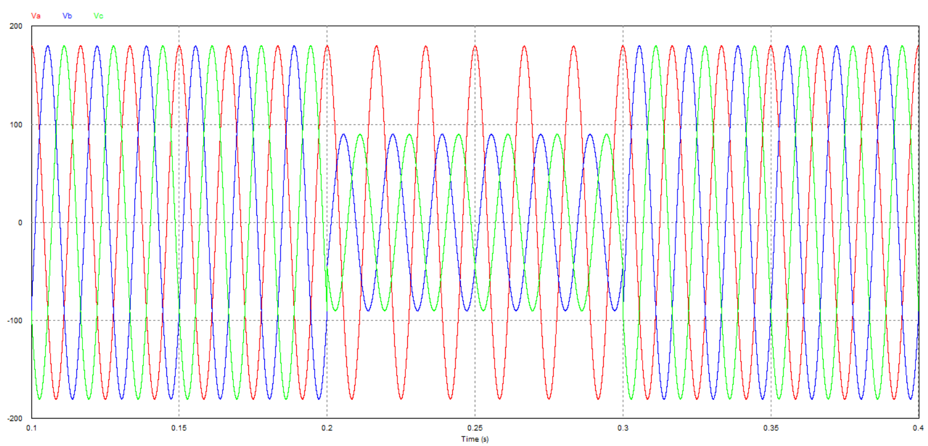
Unbalanced voltage sag at t = 0.2~0.3, $|v_b|$ =180V*0.5 , $|v_c|$ =180V*0.5

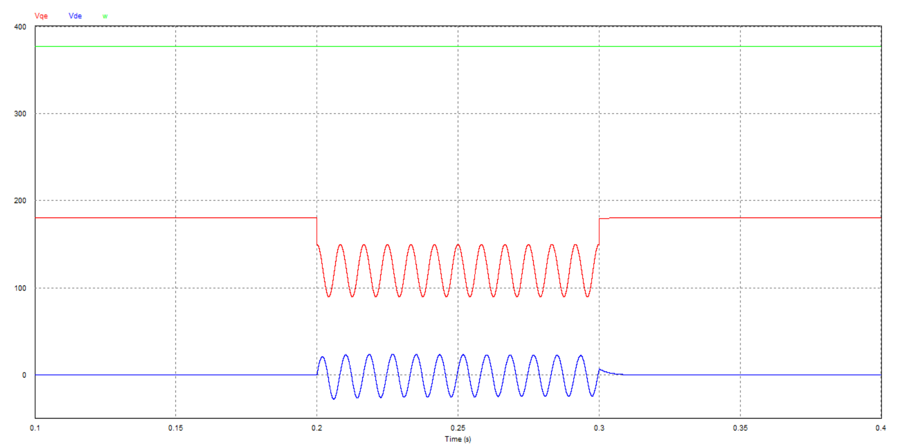
$v_a = 180 \cos\omega t$,

$v_b = 180 \cos(\omega t - 120^\circ)$,(180*0.5)

$v_c = 180 \cos(\omega t + 120^\circ)$,(180*0.5)







不平衡電壓驟降3(Unbalanced voltage sag)(with PLL)

$[v_{qs}\ \ v_{ds}] = [2/3\ \ -1/3\ \ -1/3;\ 0\ \ -1/\sqrt{3}\ \ 1/\sqrt{3}][v_a\ \ v_b\ \ v_c]$

$[v_{qe}\ \ v_{de}] = [\cos \omega t\ \ -\sin \omega t;\ \sin \omega t\ \ \cos \omega t][v_{qs}\ \ v_{ds}]$

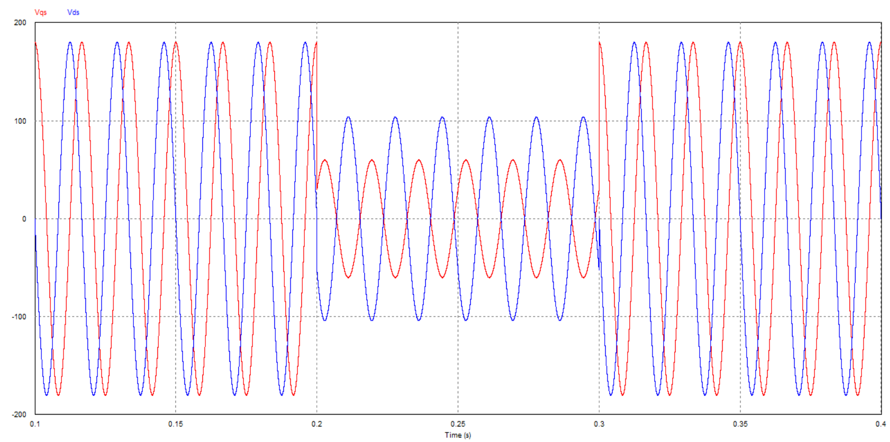
3-phase 220V_{rms} (60Hz, line-to-line) , $\omega = 2\pi f = 120\pi = 377$ rad/sec.

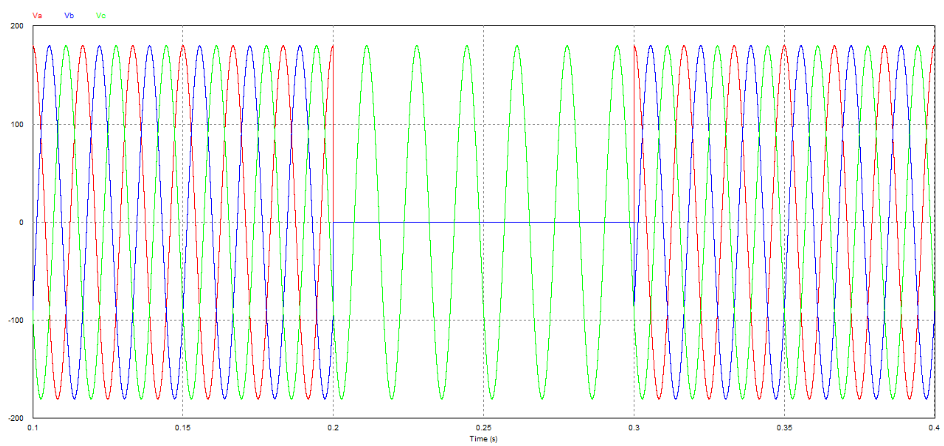
Unbalanced voltage sag at t = 0.2~0.3, $|v_a| = 0$, $|v_b| = 0$

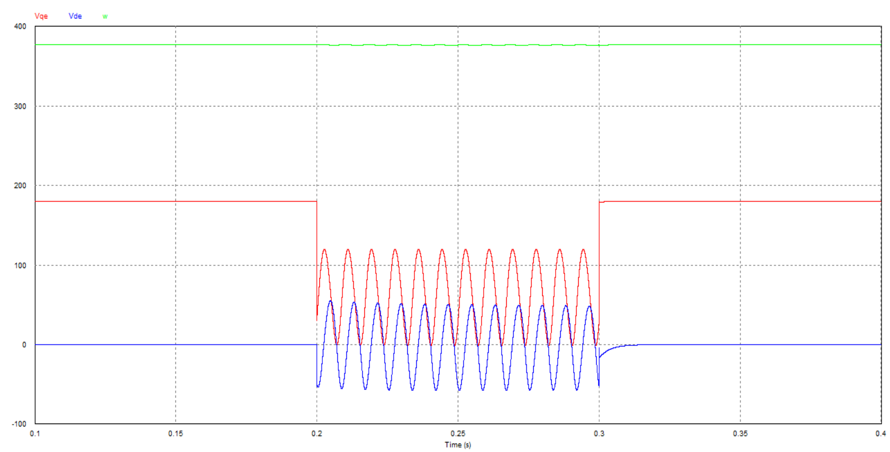
$v_a = 180 \cos \omega t$, $v_a = 0$

$v_b = 180 \cos (\omega t - 120^\circ)$, $v_b = 0$

$v_c = 180 \cos (\omega t + 120^\circ)$,







停電(Power Failure)(PLL is fail and fixed at 377 rad/sec.)

$[v_{qs}\ \ v_{ds}] = [2/3\ \ -1/3\ \ -1/3;\ 0\ \ -1/\sqrt{3}\ \ 1/\sqrt{3}][v_a\ \ v_b\ \ v_c]$

$[v_{qe}\ \ v_{de}] = [\cos\omega t\ \ -\sin\omega t;\ \sin\omega t\ \ \cos\omega t][v_{qs}\ \ v_{ds}]$

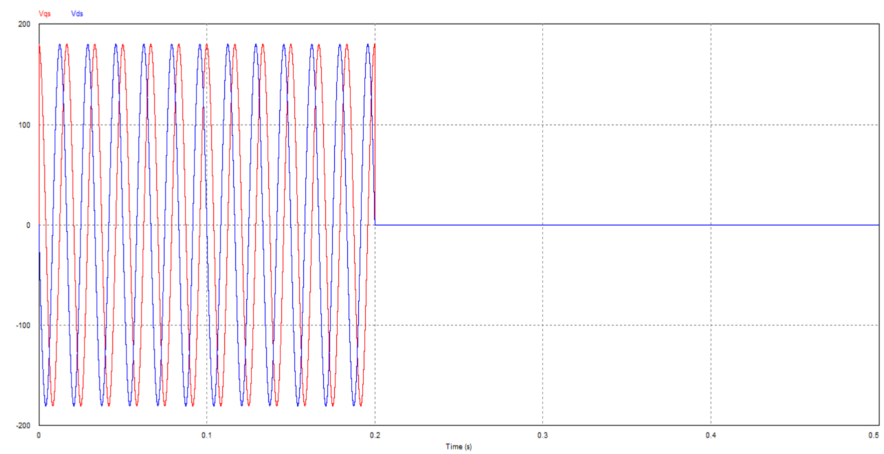
3-phase 220V_{rms} (60Hz, line-to-line) , $\omega = 2\pi f = 120\pi = 377$ rad/sec.

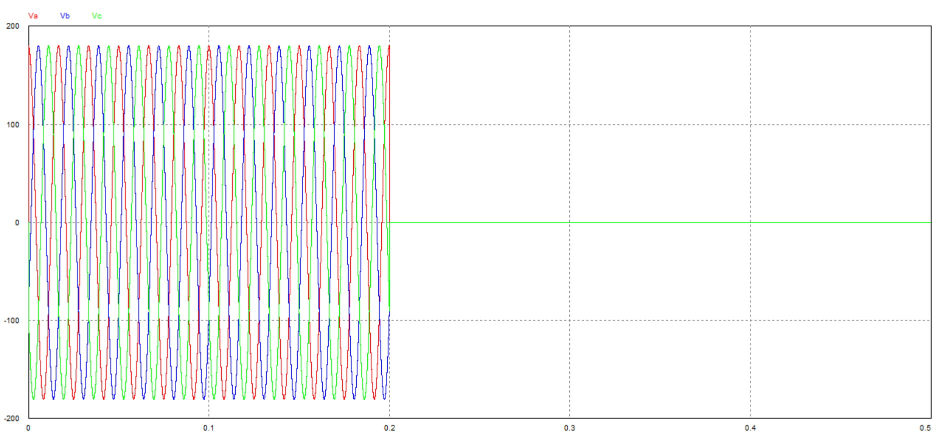
Unbalanced voltage sag at t = 0.2~0.5, $|v_a| = 0$, $|v_b| = 0$, $|v_c| = 0$

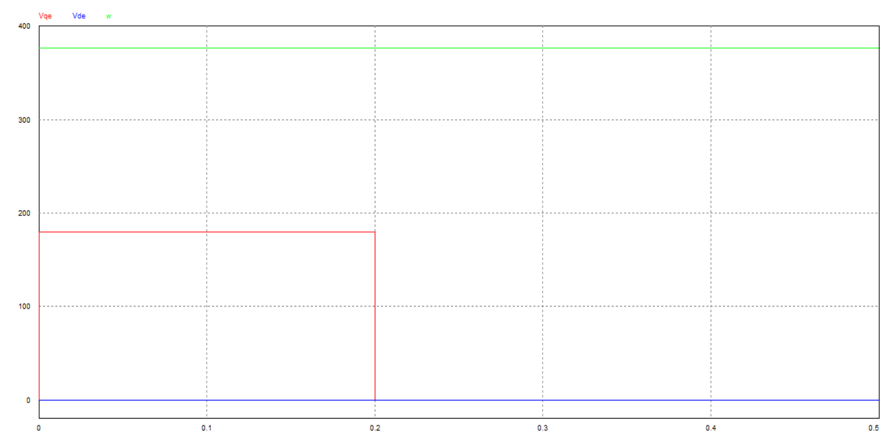
$v_a = 180\cos\omega t$, $v_a = 0$

$v_b = 180\cos(\omega t - 120^\circ)$, $v_b = 0$

$v_c = 180\cos(\omega t + 120^\circ)$, $v_c = 0$







相序錯誤(phase abc -> acb)(PLL is fail)

$[v_{qs}\ \ v_{ds}] = [2/3\ \ -1/3\ \ -1/3;\ 0\ \ -1/\sqrt{3}\ \ 1/\sqrt{3}][v_a\ \ v_b\ \ v_c]$

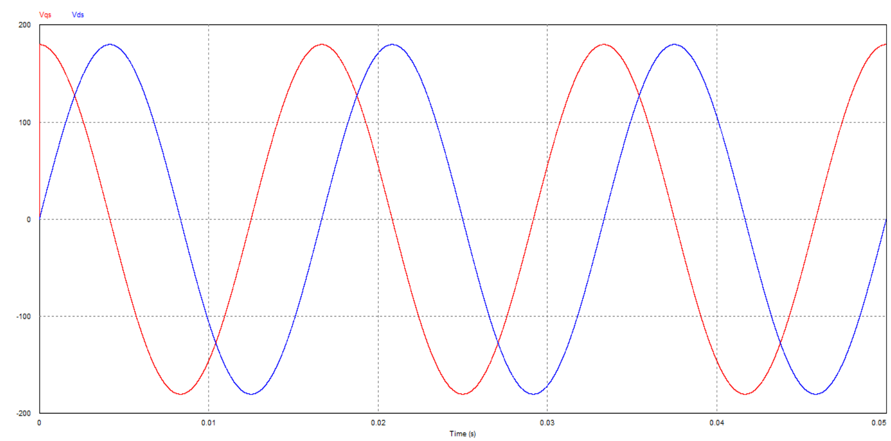
$[v_{qe}\ \ v_{de}] = [\cos\omega t\ \ -\sin\omega t;\ \sin\omega t\ \ \cos\omega t][v_{qs}\ \ v_{ds}]$

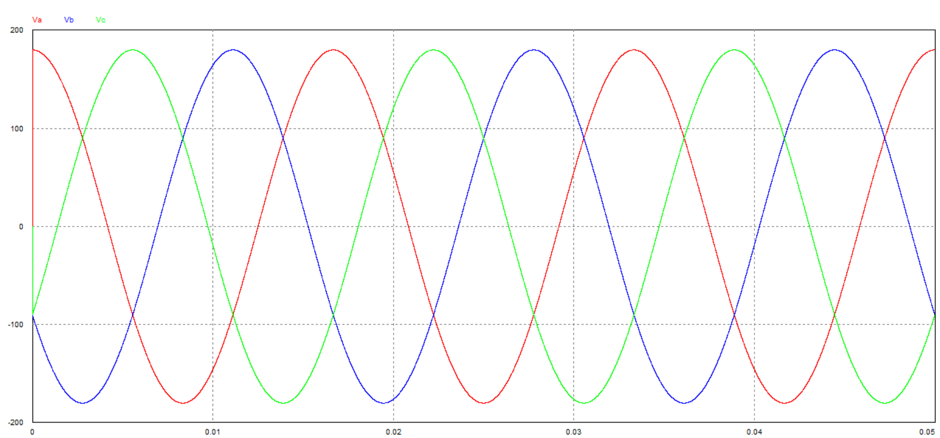
3-phase 220V_{rms} (60Hz, line-to-line) , $\omega = 2\pi f = 120\pi = 377$ rad/sec.

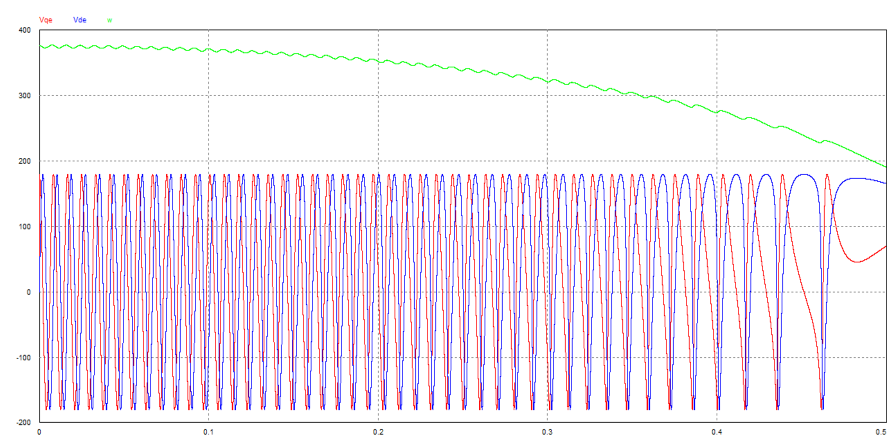
$v_a = 180\cos\omega t$,

$v_c = 180\cos(\omega t - 120^\circ)$,

$v_b = 180\cos(\omega t + 120^\circ)$,







帕克變換(Park Transformation) $\theta = \omega t$, $[v_0\ v_d\ v_q] = P[v_a\ v_b\ v_c]$

$[v_{qs}\ \ v_{ds}] = [2/3\ \ -1/3\ \ -1/3;\ 0\ \ -1/\sqrt{3}\ \ 1/\sqrt{3}][v_a\ \ v_b\ \ v_c]$

$[v_{qe}\ \ v_{de}] = [\cos\theta\ \ -\sin\theta;\ \sin\theta\ \ \cos\theta][v_{qs}\ \ v_{ds}]$

$[v_{qe}\ v_{de}] = (2/3)\ [\cos\theta\ \cos(\theta-2\pi/3)\ \cos(\theta+2\pi/3);\ \sin\theta\ \sin(\theta-2\pi/3)\ \ \sin(\theta+2\pi/3)]\ [v_a\ \ v_b\ \ v_c]$

$v_0 = (1/3)(v_a + v_b + v_c)$, $v_0 = (1/\sqrt{3})(v_a + v_b + v_c)$

$$[v_0\ \ v_d\ \ v_q] = (2/3)^{0.5} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2}; \\ \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta+2\pi/3)\ ; \\ \sin\theta & \sin(\theta - 2\pi/3) & \sin(\theta+2\pi/3) \end{bmatrix} [v_a\ \ v_b\ \ v_c]$$

$$P^{-1} = P^T = (2/3)^{0.5} \begin{bmatrix} 1/\sqrt{2} & \cos\theta & \sin\theta; \\ 1/\sqrt{2} & \cos(\theta - 2\pi/3) & \sin(\theta - 2\pi/3); \\ 1/\sqrt{2} & \cos(\theta+2\pi/3) & \sin(\theta+2\pi/3) \end{bmatrix}$$

To simplify the equations and in some important cases obtain linear time-invariant equations, we use a Park transformation (also called a Blondel transformation, or 0dq transformation to rotor coordinates) of the stator abc quantities. We transform abc voltages, current, and flux linkages.

對稱分量(Symmetrical Components)

Represent V_a, V_b, and V_c in terms of nine symmetrical components , zero sequence set ($V^0_a = V^0_b = V^0_c$), positive (abc) sequence set, and negative (acb) sequence set. ($V^0_a, V^+_a, V^-_a, V^0_b, V^+_b, V^-_b, V^0_c, V^+_c, V^-_c$)

$V_a = V^0_a + V^+_a + V^-_a$, $V_b = V^0_b + V^+_b + V^-_b$, $V_c = V^0_c + V^+_c + V^-_c$,

Define $\alpha = e^{j2\pi/3} = 1\angle 120^\circ$, $\alpha^2 = e^{j4\pi/3} = 1\angle 240^\circ = 1\angle -120^\circ$, $\alpha^* = \alpha^2$, $1+\alpha+\alpha^2 = 0$

$[V_a\ V_b\ V_c] = A[V^0_a\ V^+_a\ V^-_a]$, $A = [1\ 1\ 1; 1\ \alpha^2\ \alpha; 1\ \alpha\ \alpha^2]$

A is symmetrical components transformation matrix.

$A^{-1} = (1/3)\ [1\ 1\ 1;\ 1\ \alpha\ \alpha^2;\ 1\ \alpha^2\ \alpha]$, $[V^0_a\ V^+_a\ V^-_a] = A^{-1}\ [V_a\ V_b\ V_c]$,

Balanced Positive Sequence $V_a = 1\angle 0^\circ$, $V_b = 1\angle -120^\circ$, $V_c = 1\angle 120^\circ$,

$[V^0_a\ V^+_a\ V^-_a] = A^{-1}\ [V_a\ V_b\ V_c] = [0\ \ 1\angle 0^\circ\ \ \ 0]$

Balanced Negative Sequence $V_a = 1\angle 0^\circ$, $V_b = 1\angle 120^\circ$, $V_c = 1\angle -120^\circ$,

$[V^0_a\ V^+_a\ V^-_a] = A^{-1}\ [V_a\ V_b\ V_c] = [0\ \ 0\ \ 1\angle 0^\circ\ ]$

Ex13.1 Finding Symmetrical Components ($\theta = \omega t$)

$V_a = 1\angle 0^\circ$, $V_b = 1\angle -90^\circ$, $V_c = 2\angle 135^\circ$,

Define $\alpha = e^{j2\pi/3} = 1\angle 120^\circ$, $\alpha^2 = e^{j4\pi/3} = 1\angle 240^\circ = 1\angle -120^\circ$

$A^{-1} = (1/3)\,[1\ 1\ 1;\ 1\ \alpha\ \alpha^2;\ 1\ \alpha^2\ \alpha]$, $[V^0_a\ V^+_a\ V^-_a] = A^{-1}\,[V_a\ V_b\ V_c]$,

$[V^0_a\ V^+_a\ V^-_a] = [0.195\angle 135^\circ\quad 1.311\angle 15^\circ\quad 0.494\angle -105^\circ]$

$V^0_a = 0.195\angle 135^\circ = 0.195\cos(\omega t + 135^\circ)$

Zero Sequence: $V^0_a = V^0_b = V^0_c = 0.195\angle 135^\circ$

$V^+_a = 1.311\angle 15^\circ = 1.311\cos(\omega t + 15^\circ)$

Positive Sequence: $1.311\angle 15^\circ$, $1.311\angle(15^\circ - 120^\circ)$, $1.311\angle(15^\circ + 120^\circ)$

$V^-_a = 0.494\angle -105^\circ = 0.494\cos(\omega t - 105^\circ)$

Negative Sequence: $0.494\angle -105^\circ$, $0.494\angle(-105^\circ + 120^\circ)$, $0.494\angle(-105^\circ - 120^\circ)$

$V_a = 1\angle 0^\circ = V^0_a + V^+_a + V^-_a = 0.195\angle 135^\circ + 1.311\angle 15^\circ + 0.494\angle -105^\circ$

$V_b = 1\angle -90^\circ = V^0_b + V^+_b + V^-_b = V^0_a + \alpha^2 V^+_a + \alpha V^-_a$

$= 0.195\angle 135^\circ + 1.311\angle(15^\circ - 120^\circ) + 0.494\angle(-105^\circ + 120^\circ)$

$V_c = 2\angle 135^\circ = V^0_c + V^+_c + V^-_c = V^0_a + \alpha V^+_a + \alpha^2 V^-_a$

Ex13.1 $V_a = 1\angle 0^\circ$, $V_b = 1\angle -90^\circ$, $V_c = 2\angle 135^\circ$, (PLL is fail)

$[v_{qs}\ \ v_{ds}] = [2/3\ \ -1/3\ \ -1/3;\ 0\ \ -1/\sqrt{3}\ \ 1/\sqrt{3}][v_a\ \ v_b\ \ v_c]$

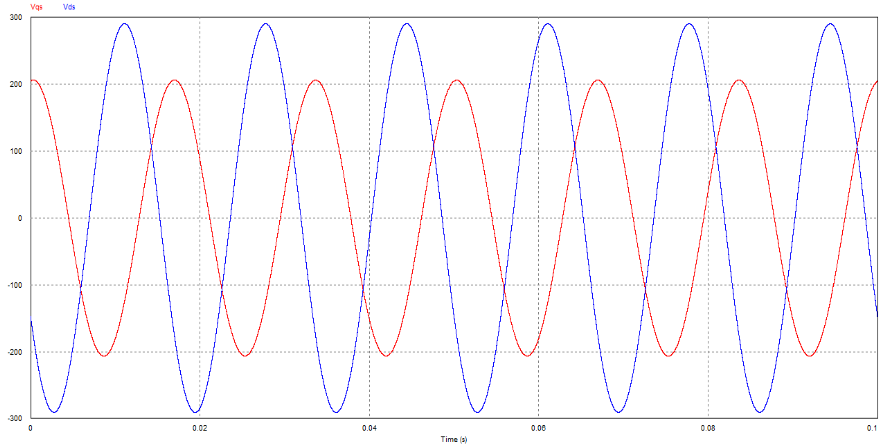
$[v_{qe}\ \ v_{de}] = [\cos \omega t\ \ -\sin \omega t;\ \sin \omega t\ \ \cos \omega t][v_{qs}\ \ v_{ds}]$

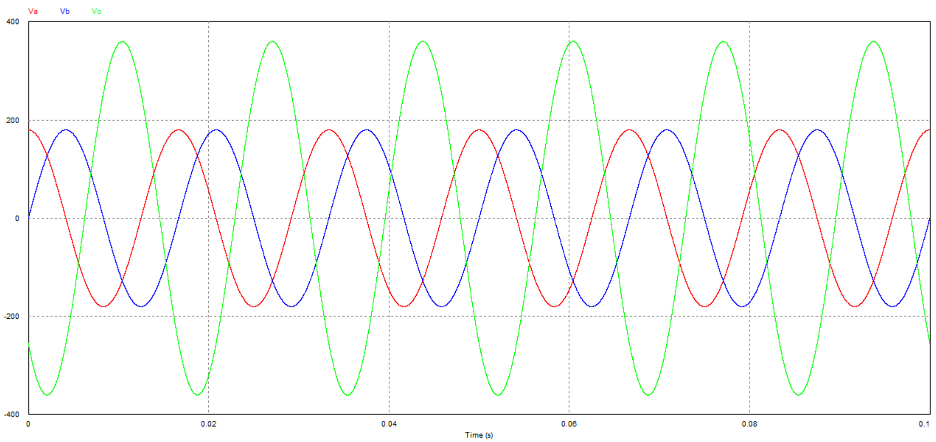
3-phase 220V_{rms} (60Hz, line-to-line) , $\omega = 2\pi f = 120\pi = 377$ rad/sec.

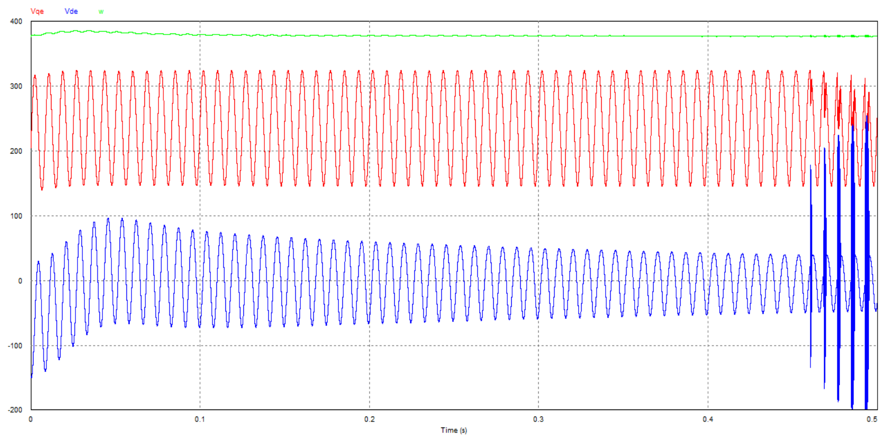
$v_a = 180 \cos \omega t$,

$v_b = 180 \cos (\omega t - 90^\circ)$,

$v_c = 2*180 \cos (\omega t + 135^\circ)$,





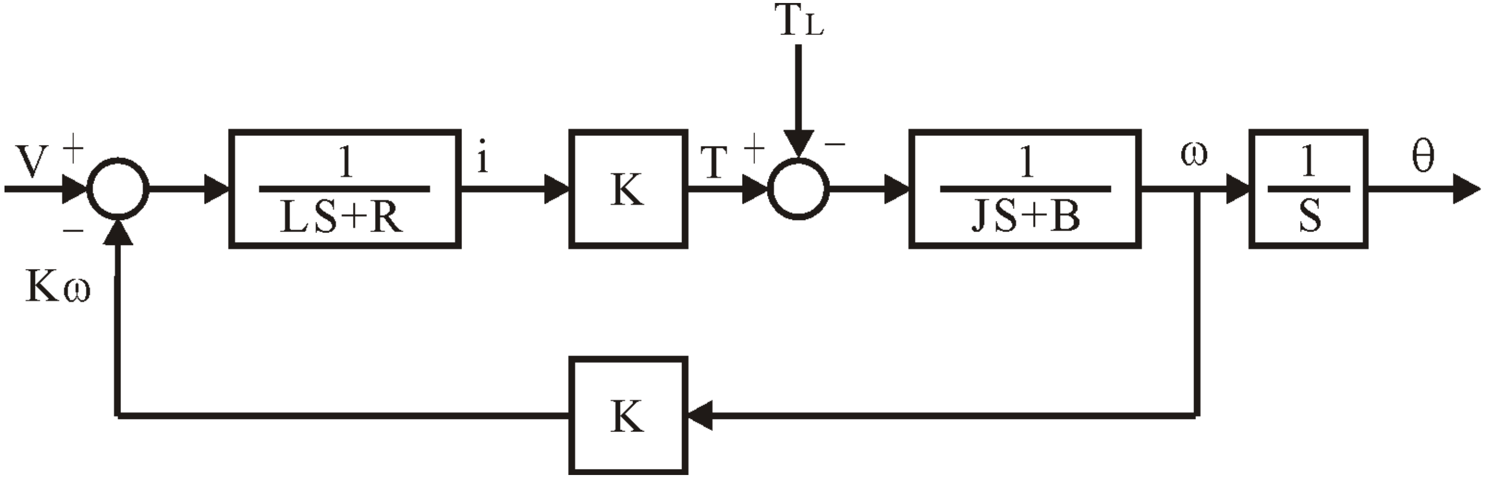


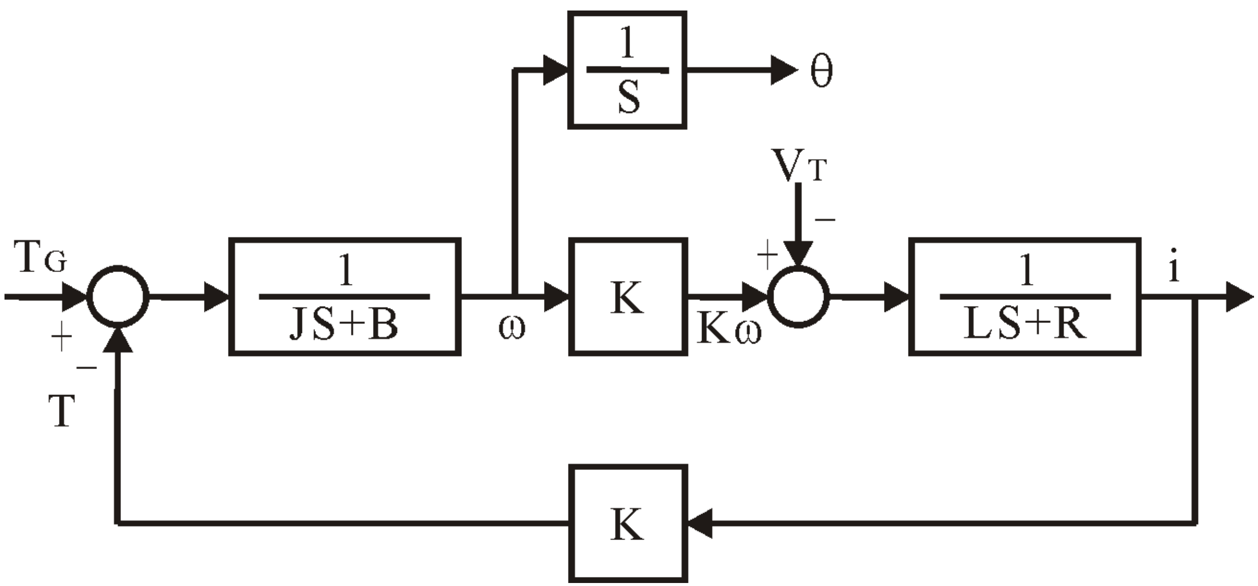
馬達與發電機(Motor and generator)

$V = L\,di/dt + iR + K\omega = (LS+R)i + K\omega$; $K\omega = V_T + L\,di/dt + iR = V_T + (LS+R)i$

Induced Torque: $T = Ki$; Induced Voltage: $K\omega$

$T - T_L = J\,d\omega/dt + B\omega = (JS+B)\omega$; $T_G - T = J\,d\omega/dt + B\omega = (JS+B)\omega$



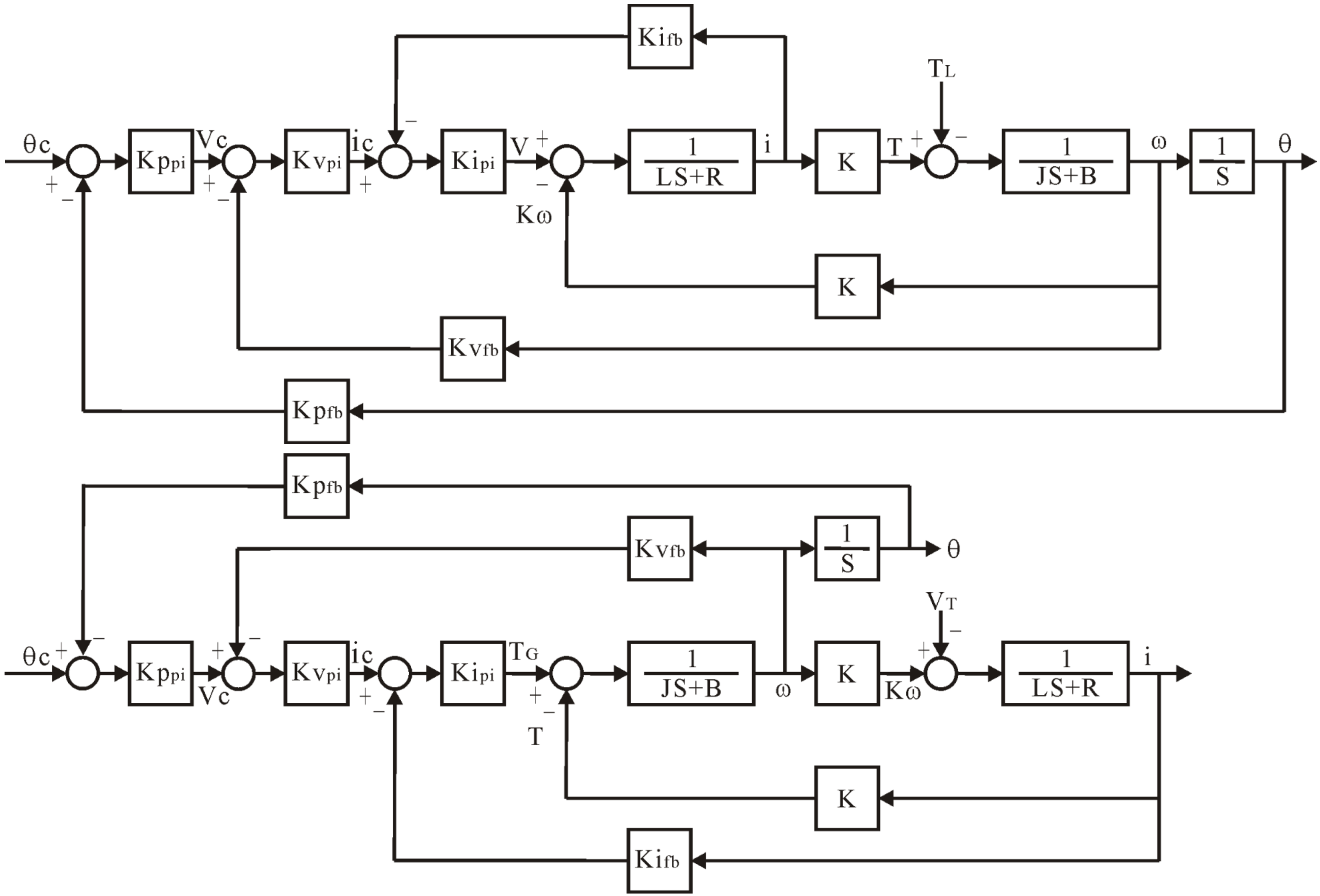


馬達與發電機控制(Control of motor and generator)

$V = L\,di/dt + iR + K\omega = (LS+R)i + K\omega$; $K\omega = V_T + L\,di/dt + iR = V_T + (LS+R)i$

Torque equation: $T = Ki$; Induced Voltage: $K\omega$

$T - T_L = J\,d\omega/dt + B\omega = (JS+B)\omega$; $T_G - T = J\,d\omega/dt + B\omega = (JS+B)\omega$



重疊定理(Superposition Principle)

The superposition principle states that the voltage across (or current through) an element in a linear circuit is the algebraic sum of the voltage across (or current through) that element due to each independent source acting alone.

We consider one independent source at a time while all other independent sources are turned off. This implies that we replace every voltage source by 0V (or a short circuit), and every current source by 0A (or an open circuit). This way we obtain a simpler and more manageable circuit.

Dependent sources are left intact because they are controlled by circuit variables.

Step1: Turn off all independent sources except one source. Find the output (voltage or current) due to that active source using the Kirchhoff's Voltage and Current Laws (KVL and KCL).

Step2: Repeat step 1 for each of the other independent sources.

Step3: Find the total contribution by adding algebraically all the contributions due to the independent sources.