1 Open circuit and short circuit test data of of a 150 MW, 13kV , 0.85 pf, 50 Hz synchronous generator is given by :

Open Circuit Test

| $I_f$ (A) | 200 | 450 | 600 | 850 | 1200 |
|---|---|---|---|---|---|
| $V_{oc}$ (L-L) (kV) | 4 | 8.7 | 10.8 | 13.3 | 15 |

Short Circuit Test

$I_f$ = 750 A $I_{sc}$ = 8000 A

I) Determine unsaturated synchronous reactance

II) Determine adjusted synchronous reactance. What is its pu value?

III) Determine short circuit ratio of the machine

Solution:

i) For $V_{oc}$ = 13 kV on the air gap line, $I_{sc}$ = 7000 A

$$\boldsymbol{X_s(unsaturated) = \frac{13 \times 10^3}{\sqrt{3} \times 7000} = 1.072\ \Omega}$$

ii) For Voc = 13kV on OCC, Isc = 8600 A

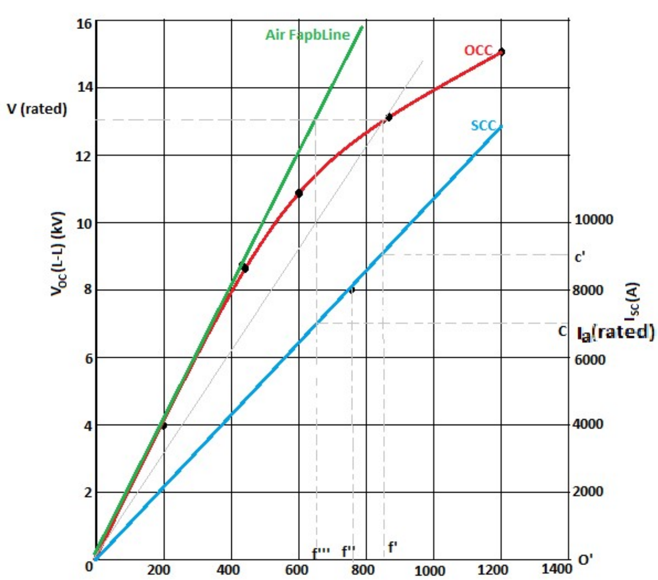
$$X_s(adjusted) = \frac{13 \times 10^3}{\sqrt{3} \times 8600} = 0.873\ \Omega$$

$$I_a\ (rated) = \frac{150 \times 10^6}{\sqrt{3} \times 13 \times 10^3 \times 0.85} = 7837\ A$$

$$Z_{base} = \frac{13 \times 10^3}{\sqrt{3} \times 7837} = 0.958\ \Omega$$

$$\boldsymbol{X_s(adjusted)pu = \frac{0.873}{0.958} = 0.911\ pu}$$

iii) Short Circuit Ratio (SCR) = $\frac{I_f\ required\ to\ produce\ rated\ voltage}{I_f\ required\ \ to\ produce\ rated\ current}$




$$\boldsymbol{SCR = \frac{of'}{of'''} = \frac{806.25}{734.7} = 1.09}$$

As SCC is linear $\frac{o'c}{of'''} = \frac{o'c'}{of'}$

$$\therefore \frac{of'}{of'''} = \frac{o'c'}{o'c}$$

$$\frac{of'}{of'''} = \frac{8600}{I_a(rated)} = \frac{V_{rated}}{V_{rated}} \times \frac{8600}{I_a(rated)}$$

$$= \frac{V_{rated}}{\sqrt{3} \times I_a(rated)} \times \frac{\sqrt{3} \times 8600}{V_{rated}}$$

$$= Z_{base} \times \frac{1}{X_{s(adjusted)}} = \frac{1}{X_{s(adjusted)pu}}$$

$$\therefore SCR = \frac{1}{0.911} = 1.09$$

2 A 6600 V, 1200kVA alternator has a reactance of 25% and is delivering full load at 0.8 pf lagging. It is connected to constant frequency bus-bar. If the steam supply is gradually increased, calculate:

I) At what output will the power factor become unity

II) The maximum load which it can supply without dropping out of synchronism and the corresponding power factor.

Solutions:

i) $V_{ph} = \frac{6600}{\sqrt{3}} = 3810\,V;\qquad I_1 = \frac{1200\times10^3}{\sqrt{3}\times6600} = 105\,A$

$$Z_{base} = \frac{3810}{105} = 36.28\,\Omega\,;\qquad \mathrm{X_s} = 0.25\times36.28 = 9.07\,\Omega$$

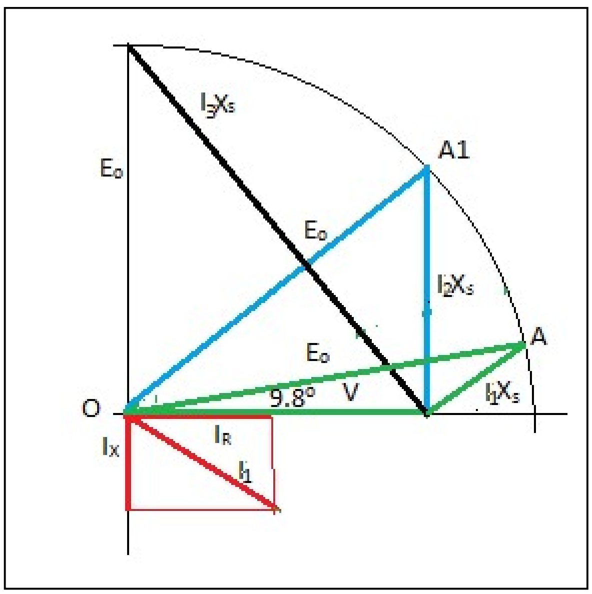
$$p.f. is\ 0.8\ \therefore\ active\ component\ of\ current\ I_{1R} = 105\times0.8 = 84\,A$$

$$and\ \ reactive\ component\ of\ current\ I_{1x} = 105\times0.6 = 63\,A$$

$$E_o = V_{ph} + j\,I_1\times(0.8-0.6j)\times X_s$$

$$= 3810 + j\,105\times(0.8-0.6j)\times9.07$$

$$= 3810 + j\,761.88 + 571.41 = 4447.15\,\angle9.8^o\ V$$




$$Excitation\ is\ constant\ \therefore for\ p.f.$$

$$= 1.0\ the\ tip\ of\ E_o\ must\ be\ A1$$

$$\therefore\ I_2X_s = \sqrt{(E_o{}^2 - V_{ph}{}^2)}$$

$$= \sqrt{(4447.15^2 - 3810^2)} = 2293.4\,V$$

$$\therefore\ I_2 = 252.8\,A$$

$$\therefore\ \boldsymbol{P_{out} = \sqrt{3}\times6600\times252.8\,W = 2890\,kW}$$

ii) For maximum power angle = 90°

$$I_3X_s = \sqrt{(E_o{}^2 + V_{ph}{}^2)}$$

$$= \sqrt{(4447.15^2 + 3810^2)} = 5856\,V$$

$$\therefore\ I_3 = 645.6\,A$$

$$let\ \ active\ component\ of\ current\ I_{3R}\ \ and\ reactive\ component\ \ I_{3X}$$

$$\therefore\ I_{3R}X_s = 4447.15\,V\ \ \ and\ \ I_{3X}X_s = 3810\,V$$

$$\therefore\ \ I_{3R} = 290.3\,A\ \ \ and\ \ I_{3X} = 420\,A$$

$$\therefore\ \boldsymbol{\cos\varphi = \cos\left(\tan^{-1}\frac{420}{490}\right) = 0.759\ lead\ \ \ and\ \varphi = 40.58^o\ lead}$$

$$\therefore\ \boldsymbol{P_{max} = \sqrt{3}\times6600\times645.6\times0.759\,W = 5601.57\,kW}$$

3. A 3 phase 11 kV, 10MW, star connected synchronous generator has a synchronous impedance of 0.6+J 10 Ω /ph . if excitation is such that the open circuit voltage is 12kV, determine:

i) maximum output of the generator

ii) current and p.f. at maximum output

Solution:

i) $P_{max}/ph = \frac{E_f V_t}{X_s}$

$$E_f = \frac{12000}{\sqrt{3}} = 6928\,V \quad V_t = \frac{11000}{\sqrt{3}} = 6351\,V \quad X_s = 10\Omega$$

$$\therefore P_{max}/ph = \frac{6928 \times 6351}{10} = 4400\,kW/ph$$

$$\therefore \boldsymbol{P_{max} = 13200\,kW = 13.2\,MW}$$

$$ii)\ I_{max}X_s = \sqrt{({E_f}^2 + {V_t}^2)} = \sqrt{(6928^2 + 6351^2)} = 9398.5\,V$$

$$\therefore I_{max} = \frac{I_{max}X_s}{X_s} = \frac{9398.5}{10} = \boldsymbol{939.8\,A} \ \ and\ \ p.f. = \frac{E_f}{I_{max}X_s} = \frac{6928}{9398.5} = \boldsymbol{0.737\ lead}$$

4. The effective resistance of a 3 phase star connected 650 Hz 2200 V alternator is 0.5 Ω /ph . On short circuit a field current of 40 A gives the full load current of 200A. An emf(L-L) of 1100 V is produced on open circuit with the same excitation. Determine synchronous impedance. Hence compute power angle and regulation at 0.8 lagging pf.

Solution:

$$Z_s = \frac{E_f(L-L)}{\sqrt{3}\,I} = \frac{1100}{\sqrt{3}\times 200} = 3.18\ \Omega$$

$$\therefore X_s = \sqrt{{Z_s}^2 - {r_a}^2} = \sqrt{3.18^2 - 0.5^2} = 3.14\ \Omega$$

$$\mathrm{V_t} = \frac{2200}{\sqrt{3}} = 1270\ \mathrm{V}$$

$$\mathrm{E_f} = \mathrm{V_t} + \mathrm{I}(\mathrm{r_a} + \mathrm{jX_s})$$

$$= 1270 + 200(0.8 - j0.6)(0.5 + j3.14) = 1726 + j442 = 1782\angle 14.4^o$$

$$\therefore \text{power angle}\ \ \delta = 14.4^o$$

$$\text{regulation} = \frac{1782-1270}{1270} \times 100\% = \mathbf{40.3\%}$$

5. A 2000kVA 11 kV 3 ph star connected alternator has a resistance of 0.3 Ω/ph and reactance of 5 Ω/ph. It delivers full load current at 0.8 lagging p.f at normal voltage. Compute the terminal voltage for the same excitation and load at 0.8 leading p.f.

Solution;

$$V_t = \frac{11000}{\sqrt{3}} = 6351\,V \quad and\ I = \frac{2000 \times 10^3}{\sqrt{3} \times 11000} = 105\,A$$

$$E_f = V_t + I(r_a + jX_s) = 6351 + 105\,(.8 - j.6)(.3 + j5)$$

$$\therefore E_f = 6703.2\angle 3.43^o$$

$$\therefore for\ leadin\ p.f.\ E_f = V_t + I(.8 + j.6)(r_a + jX_s)$$

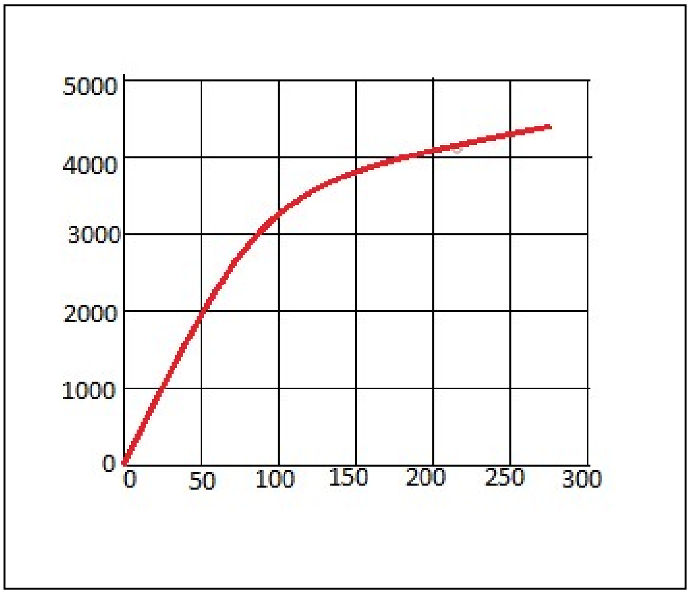
$$\therefore E_f = V_t + 105(.8 + j.6)(.3 + j5)$$

$$E_f = V_t - 289.8 + j438.9$$

$$\therefore {E_f}^2 = (V_t - 289.8)^2 + 438.9^2$$

$$\boldsymbol{V_t/ph = 6978.6\,V \quad and\ V_t(L-L) = 11776\,V}$$

6. A 3 phase 2 pole 2000 kVA, 6600 V, 3000 rpm turbo alternator, has 60 armature slots with 4 conductors per slot and its effective resistance and leakage reactance are 0.1 Ω and 2 Ω per phase respectively. There are 10 rotor slots per pole with angular pitch of slots equal to 10° and 20 conductors per slot. The open circuit characteristics are given by fig. 1. Determine regulation at full load 0.8 pf lagging.




$$V_t = \frac{6600}{\sqrt{3}} = 3816\,V$$

$$I = \frac{2000\times10^3}{\sqrt{3}\times6.6\times10^3} = 175\text{ A}$$

$$E_r = V_t + I\times(0.8 - j\,0.6)(r_a + jX_{al})$$

$$= 3810 + 175\times(0.8 - j\,0.6)(0.1 + j2)$$

$$= 4034 + j269.5 = 4043\,\angle 3.8^o\ V$$

$$from\ OCC\ F_r = 215\ A$$

$$F_a = \frac{3}{2}\times\frac{4}{\pi}\frac{N_{ph}\sqrt{2}I}{P}k_w k_p$$

$$N_{ph} = \frac{60\times4}{2\times3} = 40$$

$$slot\ per\ ploe\ per\ phase\ q = \frac{60}{2\times3} = 10$$

$$for\ full\ pitch\ coil\ phase\ spread\ \sigma = 60^o$$

$$slot\ pitch\ \gamma = \frac{60^o}{10} = 6^o$$

$$k_w = \frac{\sin\frac{q\gamma}{2}}{q\sin\frac{\gamma}{2}} = \frac{\sin\frac{10\times6^o}{2}}{10\ \sin\frac{6^o}{2}} = \frac{\sin 30^o}{10\times\sin 3^0} = 0.955\ and\ k_p = 1.0$$

$\therefore F_a = \frac{3}{2}\times\frac{4\sqrt{2}}{\pi}\frac{40\times175}{2}0.955\times1$ =9027.9 AT/pole

For the field slot/pole =10 and conductor/slot =20

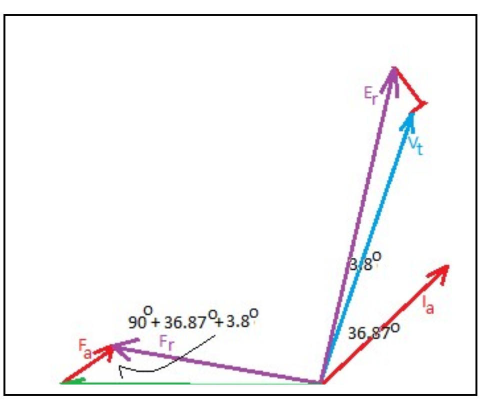
$$\therefore\ N_f = \frac{10\times20}{2} = 100\ and\ \ k_{wf} = \frac{\sin\frac{10\times10}{2}}{10\times\sin\frac{10}{2}} = 0.879$$

$$\therefore for\ any\ field\ current\ I_f\ ,\ \ F_f = \frac{4}{\pi}N_f I_f k_{wf} k_{pf} = \frac{4}{\pi}\times100\times0.879 I_f = 111.9 I_f$$

$$\therefore equivalent\ field\ amp.for\ F_a = \frac{F_a\ AT/pole}{111.9} = \frac{9027.9}{111.9} = 80.7\ A$$

$$\alpha = 90^o + 36.87^o + 3.8^o = 130.7^o$$

$$\bar{F_f} = \bar{F_r} - \bar{F_a}$$




$$\therefore |F_f| = \sqrt{{F_r}^2 + {F_a}^2 - 2F_r F_a cos130.7^o}$$

$$= \sqrt{215^2 + 80.7^2 - 2\times215\times80.7\times cos130.7^o}$$

$$F_f = 274.5\ A \quad \therefore\ \ E_f = 4500\ V/ph$$

$$\therefore regulation = \frac{4500 - 3810}{3810}\times100\% = \mathbf{18.1}\ \%$$

7. The full load torque angle of a synchronous motor at rated voltage and frequency is 30°. The motor resistance is negligible. How will the torque angle be affected by the following changes?

i) the load torque and terminal voltage remaining constant, the excitation and frequency are raised by 10%

ii) the load power and terminal voltage remaining constant, the excitation and frequency are reduced by 10%

iii) the load torque and excitation remaining constant, the terminal voltage and frequency are raised by 10%

iv) the load power and excitation remaining constant, the terminal voltage and frequency are reduced by 10%

Solution:

i) load torque is $= \frac{1}{\omega_s}\frac{E_f \times V_t}{X_s}\sin\delta$ is constant and terminal voltage $V_t$ is constant.

New excitation is $1.1E_f$, new synchronous speed is $1.1\omega_s$ and synchronous impedance is $1.1X_s$

$$\therefore \frac{1}{\omega_s}\frac{E_f \times V_t}{X_s}\sin\delta = \frac{1}{1.1\omega_s}\frac{1.1E_f \times V_t}{1.1X_s}\sin\delta_1 \qquad \therefore \sin\delta \times 1.1 = \sin\delta_1$$

$$\sin\delta_1 = 1.1 \times \sin 30^o = 0.55 \qquad \therefore \boldsymbol{\delta_1 = 33.36^o}$$

ii) load power is $= \frac{E_f \times V_t}{X_s}\sin\delta$ is constant and terminal voltage $V_t$ is constant.

New excitation is $0.9E_f$, new synchronous speed is $0.9\omega_s$ and synchronous impedance is $0.9X_s$

$$\therefore \frac{E_f \times V_t}{X_s}\sin\delta = \frac{0.9E_f \times V_t}{0.9X_s}\sin\delta_1 \qquad \therefore \sin\delta = \sin\delta_1 \qquad \therefore \boldsymbol{\delta_1 = 30^o}$$

iii) load torque is $= \frac{1}{\omega_s}\frac{E_f \times V_t}{X_s}\sin\delta$ is constant and excitation $E_f$ is constant.

New terminal voltage is $1.1V_t$, new synchronous speed is $1.1\omega_s$ and synchronous impedance is $1.1X_s$

$$\therefore \frac{1}{\omega_s}\frac{E_f \times V_t}{X_s}\sin\delta = \frac{1}{1.1\omega_s}\frac{E_f \times 1.1V_t}{1.1X_s}\sin\delta_1 \qquad \therefore \sin\delta \times 1.1 = \sin\delta_1$$

$$\sin\delta_1 = 1.1 \times \sin 30^o = 0.55 \qquad \therefore \boldsymbol{\delta_1 = 33.36^o}$$

iv) load power is $= \frac{E_f \times V_t}{X_s}\sin\delta$ is constant and excitation $E_f$ is constant.

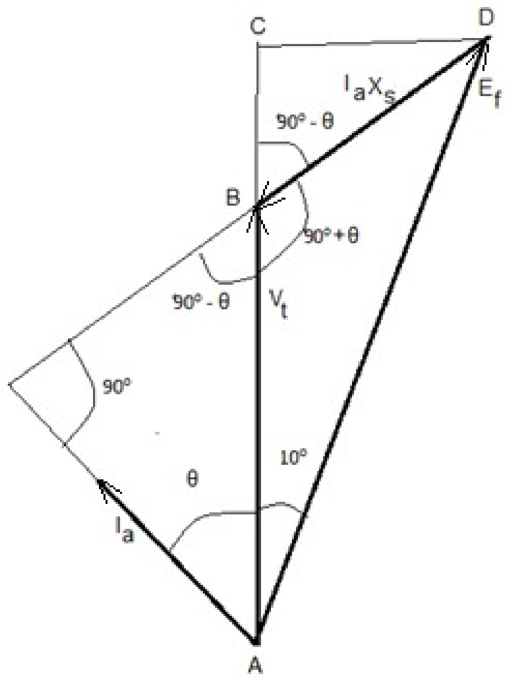
New terminal voltage is $0.9V_t$, new synchronous speed is $0.9\omega_s$ and synchronous impedance is $0.9X_s$

$$\therefore \frac{E_f \times V_t}{X_s}\sin\delta = \frac{E_f \times 0.9V_t}{0.9X_s}\sin\delta_1 \qquad \therefore \sin\delta = \sin\delta_1$$

$$\therefore \boldsymbol{\delta_1 = 30^o}$$

8. A 1000kVA 3 phase 11 kV star connected synchronous motor has negligible resistance and synchronous reactance 0f 35 ohm per phase.

I) what is the excitation emf of the motor if the power angle is 10° and the motor takes rated current at a) lagging pf and b) leading pf . what is the mechanical power developed and the power factor .




rated current $I_a = \frac{1000\times10^3}{\sqrt{3}\times11\times10^3} = 52.5\ A$

$$V_t = \frac{11\times10^3}{\sqrt{3}} = 6351\ V$$

CD= $I_aX_s\cos\theta = E_f \sin 10^o$

or $52.5\times35 \cos\theta = 0.1736\ E_f$

or $1837.5 \cos\theta = 0.1736\ E_f$

or $\cos\theta = (0.1736/1837.5)\ E_f = .000095E_f$

AC=AB+BC=$V_t + I_aX_s\sin\theta = E_f\cos 10^o$

or $6351+1837.5\sin\theta = 0.9848E_f$

or $\sin\theta = 0.0005359\ E_f - 3.51$

$$\sin^2\theta + \cos^2\theta = 1$$

$$\left(\frac{0.1736}{1837.5}\right)^2 \mathrm{Ef}^2 + \left((0.9848/1837.5)\ \mathrm{Ef} - (6351/1837.5)\right)^2 = 1$$

$$(0.1736)^2\mathrm{Ef}^2 + (0.9848\ \mathrm{Ef} - 6351)^2 = 1837.5^2$$

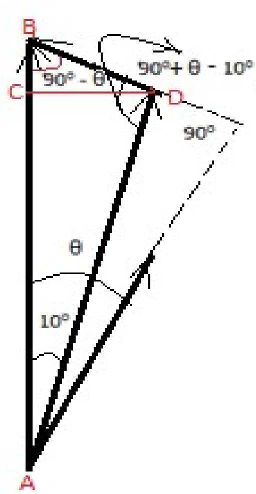
$$0.0301{E_f}^2 + .9698{E_f}^2 - 12508E_f + 40335201 = 3376406$$

$${E_f}^2 - 12508E_f + 36958795 = 0$$

$$E_f = \frac{12508 \mp \sqrt{12508^2 - 4\times36958795}}{2} = \frac{12508 \mp \sqrt{8614885}}{2}$$

$$= \frac{12508 \mp 2935}{2} = 7721\ \ or\ 4684$$

**Excitation 7.72 kV for leading pf.**




For leading pf. $\cos\theta = (0.1736/1837.5)\ E_f = (0.1736/1837.5)\ 7721$

**=0.7294 lead**

Power = $3\times\frac{7721\times6351}{35}\sin 10 = \mathbf{729.86kW}$

**Excitation 4.68 kV for lagging pf.**

For leading pf. $\cos\theta = (0.1736/1837.5)\ E_f = (0.1736/1837.5)\ 4684$

**=0.4225 lag**

Power = $3\times\frac{4684\times6351}{35}\sin 10 = \mathbf{422.7kW}$

**From phasor for lagging pf:**

$$CD= I_a X_s \cos \theta = E_f \sin 10^o$$

$$\text{or} \quad 52.5\times 35 \cos \theta = 0.1736\ E_f$$

$$\text{or} \quad 1837.5 \cos \theta = 0.1736\ E_f$$

$$\text{or} \quad \cos \theta = (0.1736/1837.5)\ E_f = .000095 E_f$$

$$AC=AB-BC=V_t - I_a X_s \sin \theta = E_f \cos 10^o$$

$$\text{or } 6351-1837.5\sin\theta = 0.9848 E_f$$

$$\text{or } \sin\theta = 3.51-0.0005359\ E_f$$

$$\sin^2 \theta + \cos^2 \theta = 1$$

$$\left(\frac{0.1736}{1837.5}\right)^2 \mathrm{Ef}^2 + \left((6351/1837.5) - (0.9848/1837.5)\ \mathrm{Ef}\right)^2 = 1$$

$$(0.1736)^2 \mathrm{Ef}^2 + (6351 - 0.9848\ \mathrm{Ef})^2 = 1837.5^2$$

$$0.0301 E_f{}^2 + .9698 E_f{}^2 - 12508 E_f + 40335201 = 3376406$$