Homework Set #13 (ECE743)

The objective of this simulation is to gain an understanding of the variable frequency operation of induction machines. Perform the following:

1) Read the attached notes and write five page summary of your understanding of variable frequency operation.
2) Simulate the performance of the induction machine when it is supplied from a variable voltage and frequency power converter (See Matlab code in Appendix)

[redacted]

Simulation 2
Variable Frequency Operation

The objective of this simulation is to gain an understanding of the variable frequency operation of induction machines. Perform the following:

10 Read the attached notes and write five page summary of your understanding of variable frequency operation.

4) Simulate the performance of the induction machine of simulation 1 when it is supplied from a variable voltage and frequency power converter.

CHAPTER 1

Introduction

In this chapter, basics of the induction machine are introduced as much needed through this project. Details will not be introduced. Specifically, equivalent circuit will be given along with the torque equations of the induction machine. In addition to this, the problem definition will be given. Even though the simulations are not numbered as they given in the handout, results for all 6 question are included through the report.

1.1 Problem Definition

In this project the induction machine that was used for Simulation 2 is used. The variable-voltage and variable-frequency operations of the given induction machine is studied. For different conditions plots are produced and discussions are given for each working condition.

1.2 Introduction to Induction Machine

The control of dc motors requires providing a variable dc voltage which can be obtained from dc choppers or controlled rectifiers. Dc motors are relatively expensive and require more maintenance. However dc drives are used in many industrial

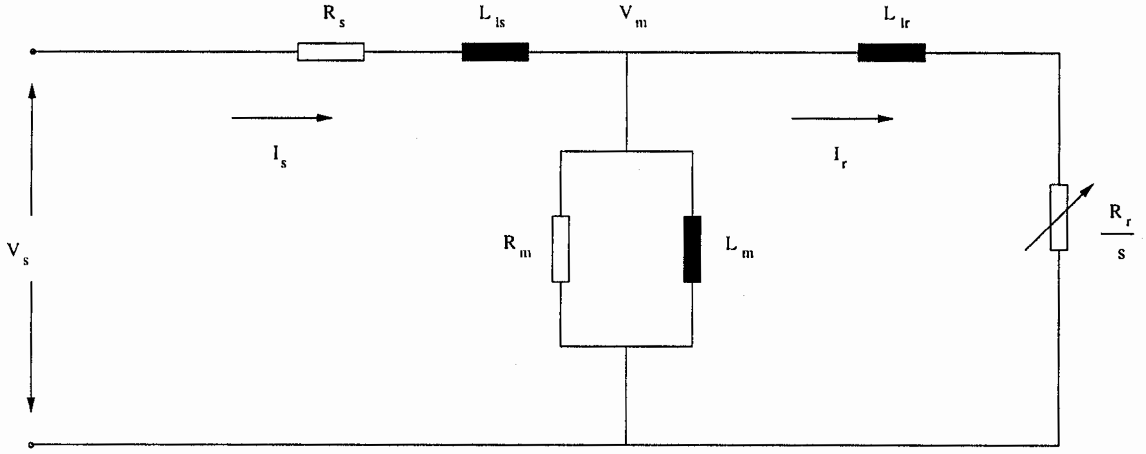

Figure 1.1: Per-phase equivalent circuit of induction motor.

applications. The ac motors on the other hand have a number of advantages; they are lightweight, inexpensive, and of a low maintanance compared to dc motors. They require control of frequency, voltage, and current for variable speed applications. The power converters, inverters and ac voltage controllers can control the frequency, voltage and current to meet the drive requirements. These power controllers, which are relatively complex and more expensive, require advanced feedback control techniques. However, the advantages of ac drives outweigh the disadvantages.

The induction machine is generally used in adjustable-speed ac drive systems. The stator windings are supplied with balanced three-phase ac voltage, that induces current in the short circuited rotor windings by induction. Per phase equivalent circuit of induction motor is given in Figure 1.1. Induction machine parameters that are used in Simulation 2 also, are $R_s = 0.4122\Omega$, $R_r' = 0.4976\Omega$, $X_{ls} = 1.1\Omega$, $X_{lr}' = 1.1\Omega$, $X_m(unsaturated) = 20.34\Omega$, $J = 0.11kg - m^2$ and $B = 0.01N - ms/rad$. Since for the following sections of the project, output torque of the machine is our main

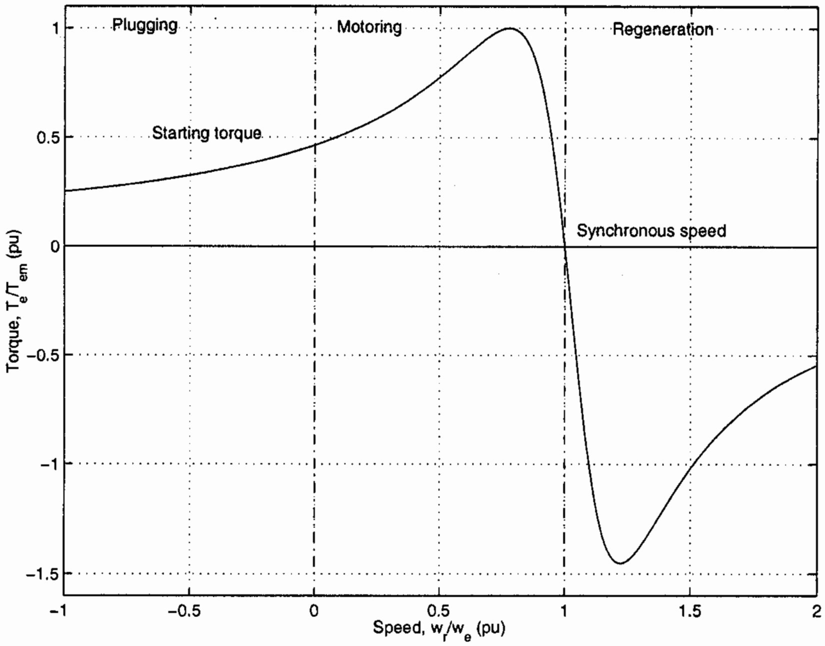

Figure 1.2: Torque-speed curve at constant voltage and frequency.

interest, it is sufficient to give these equations that can be written from equivalent circuit of the induction machine. The output torque is

$$T_e = 3\left(\frac{P}{2}\right)\frac{R_r}{Sw_e}\frac{V_s^2}{(R_s + R_r/S)^2 + w_e^2(L_{ls} + L_{lr})^2}. \tag{1.1}$$

In this equation, if the supply voltage and the frequency is held constant then, T_e can be found with respect to slip S as given in the Figure 1.2. In this figure, $0 \leq S \leq 1$ is the motoring region, $2 \geq S \geq 1$ is the breaking region, and $S \leq 0$ is the generating region. The slip frequency corresponding to the breakdown torque in motor region is

$$S_m = \frac{R_r}{\sqrt{(R_s^2 + w_e^2(L_{ls} + L_{lr})^2)}} \tag{1.2}$$

and the breakdown torque is

$$T_{em} = \frac{3P}{4w_e}\frac{V_s^2}{\sqrt{(R_s^2 + w_e^2(L_{ls} + L_{lr})^2 + R_s)}}. \tag{1.3}$$

From 1.2 that is the equation derived to calculate the maximum speed from the first derivative of the torque vs. slip, one can conclude that maximum slip is independent from the amplitude of the stator voltage. And it is inversely proportional to the stator frequency as well. From 1.3 one can conclude that T_{em} is proportional to the square of the stator voltage amplitude, and innerly proportional to the square of the stator frequency.

A further simplification of 1.1 can be made by neglecting the stator parameters R_s and L_{ls}. This assumption is not unreasonable since our induction machine is an integral-horsepower machine: $|R_s + jw_eL_s| = 1.1747\Omega \ll 20.34\Omega$ where $R_s = 0.4122\Omega$, $w_eL_{ls} = 1.1\Omega$, $w_eL_m = 20.34\Omega$ and if the speed is typically ebowe 10%, then the torque equation becomes

$$T_e = 3(\frac{P}{2})\frac{\Psi_m^2 w_{sl}}{R_r}$$

where

$$\Psi_m = \frac{V_s}{w_e} \tag{1.4}$$

and $R_r^2 \gg w_{sl}^2 L_{lr}^2$.

CHAPTER 2

Induction Machine Operating Conditions

In this chapter, the different working conditions of the induction machine whose parameters given above will be introduced by giving the plots of the machine for different cases. Specifically, first variable voltage operation will be discussed. Second, variable frequency operation will be discussed. For each case plots specified in the problem handout will be given. In addition, detailed discussions will be given for each plot.

2.1 Variable-Voltage Operation

A simple an economical method of speed control for an induction motor is to vary the stator voltage at constant frequency. The voltage at line frequency can be controlled by using phase-angle control of an inverter. Equation 1.1 indicates that the torque is proportional o the square of the stator supply voltage and a reduction in stator voltage will produce a reduction in speed. If terminal voltage is reduced to bV_s, then the developed torque becomes

$$T_e = 3\left(\frac{P}{2}\right)\frac{R_r}{Sw_e}\frac{(bV_s)^2}{(R_s + R_r/S)^2 + w_e^2(L_{ls} + L_{lr})^2} \tag{2.1}$$

where $b < 1$. The torque speed curves of the induction motor with variable voltage that are produced by changing b in Equation 2.1 is given in Figure 2.1. In this figure,

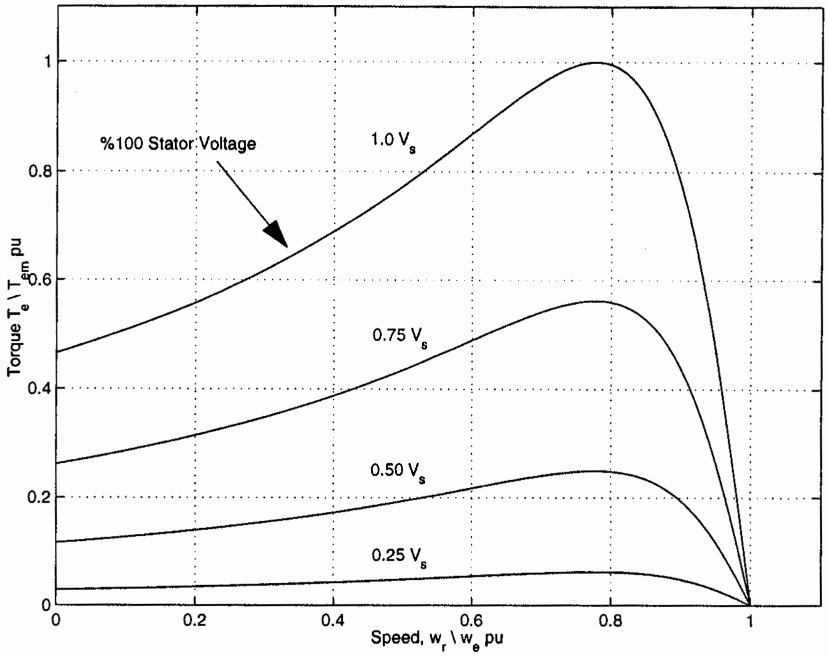

Figure 2.1: Torque-speed curves with variable stator voltage.

the torque-speed curves are plotted for different stator voltages, specifically stator voltage is changed from the rated value to $0.25V_s$. In the variable voltage constant frequency method of speed control, the developed torque per ampere of stator current is reduced as the stator voltage is reduced. That means the developed torque per ampere of stator current is reduced as the air gap flux is reduced. Therefore, for a constant load torque, the stator current increases as the speed is reduced, which results more copper loss and therefore a severe machine heating problem.

Assuming a load, the points of intersection with the load line define the stable operating points. The range of speed control depends on the slip of the slip of the maximum torque, S_m.For a low slip motor, the speed range is very narrow. This type of speed control is not suitable for a constant torque load and is normally applied to

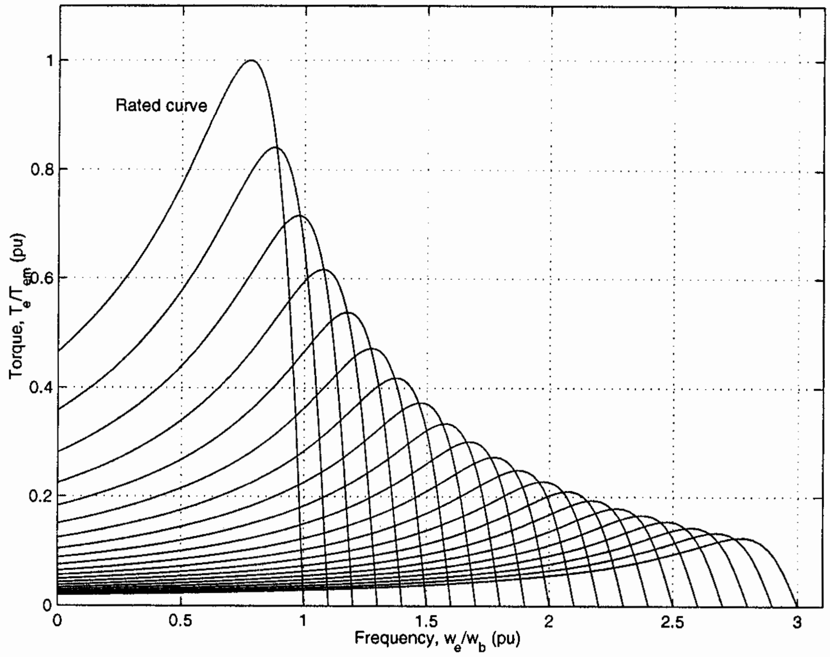

Figure 2.2: Torque-speed curves at variable frequency.

applications requiring low starting torque and a narrow range of speed at a relatively low slip.

2.2 Variable Frequency Operation

In this section variable frequency applications will be discussed by giving the torque-speed curves for different conditions. The torque and the speed of the induction motors can be controlled by changing the supply frequency. First assume the stator frequency is increased beyond the rated value, then torque-speed curves derived from 1.1 is given in Figure 2.2. Since the air gap flux and stator current decrease as frequency increases, the maximum developed torque decreases as well. When the

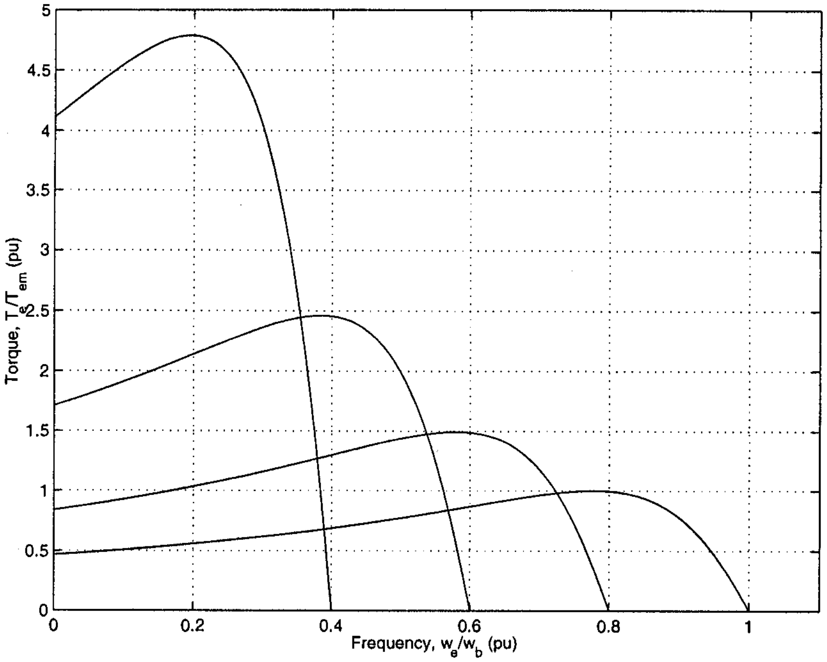

Figure 2.3: Torque-speed curves at variable frequency.

$T_{em}w_e^2$ is constant then the machine behaves like a dc series motor in variable frequency operation. The torque-speed curves are shown in Figure 2.2. The maximum torque as a function of slip can be given as

$$T_{em} = 3\left(\frac{P}{2}\right)\left(\frac{V_s^2}{w_e}\right)^2 \frac{w_{slm}R_r}{R_r^2 + w_{slm}^2 L_{lr}^2} \tag{2.2}$$

where $w_{slm} = R_r/L_{lr}$ is the slip frequency at maximum torque. Next, torque speed curves are given for different ranges of the $w_e p.u.$. First, $w_e p.u.$ is changed from 0 to 1, resulting torque-speed curve is given in Figure 2.3. Second, $w_e p.u.$ is changed from 0 to 1.5 and resulting torque-speed curve is given in Figure 2.4. Third, $w_e p.u.$ is changed from 0 to 2, and resulting torque-speed curve is given in Figure 2.5. Last, $w_e p.u.$ is changed from 0 to 3, resulting torque-speed curve is given in Figure 2.6.

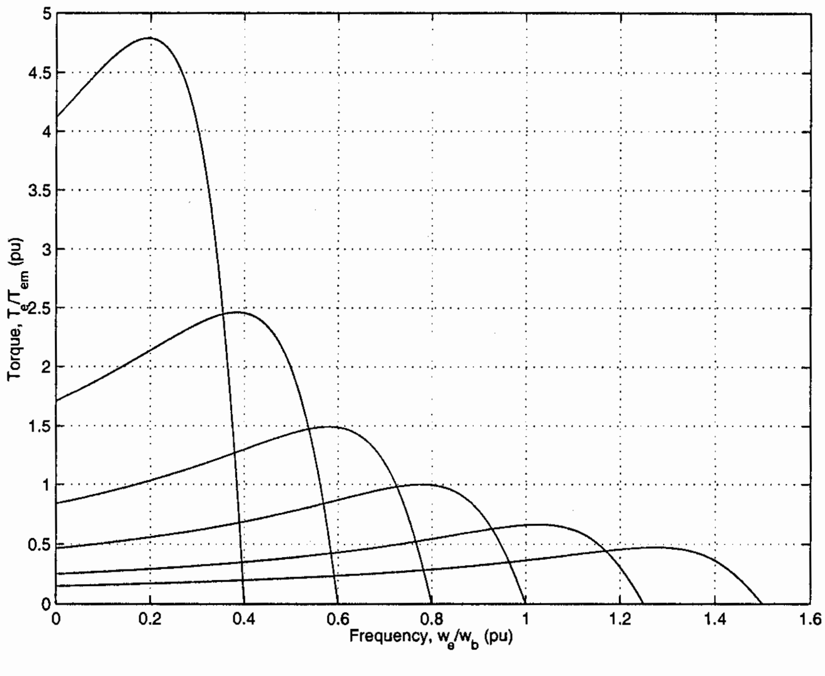

Figure 2.4: Torque-speed curves at variable frequency.

We can notice from Eq. 1.4 that at the rated voltage and rated frequency, the flux will be the rated value.

If the voltage is maintained fixed at its rated value while the frequency is reduced below its rated value, the flux, and breakdown and standstill torque will increase. At low frequency the reactances will decrease and the motor current may be too high. This would cause saturation of the air gap flux, Ψ_m given in 1.4. This mode of operation is shown in Figure 2.3. If the frequency is increased above its rated value, the flux and torque would decrease. The typical torque-speed characteristics are shown in Figures 2.4, 2.5 and 2.6 for various values of multiples of rated synchronous angular frequency, w_e.

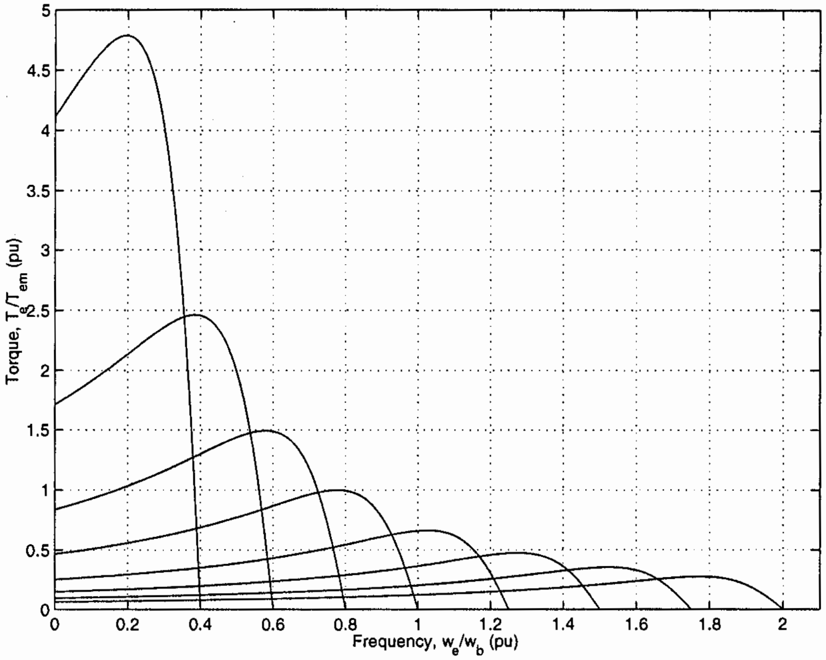

Figure 2.5: Torque-speed curves at variable frequency.

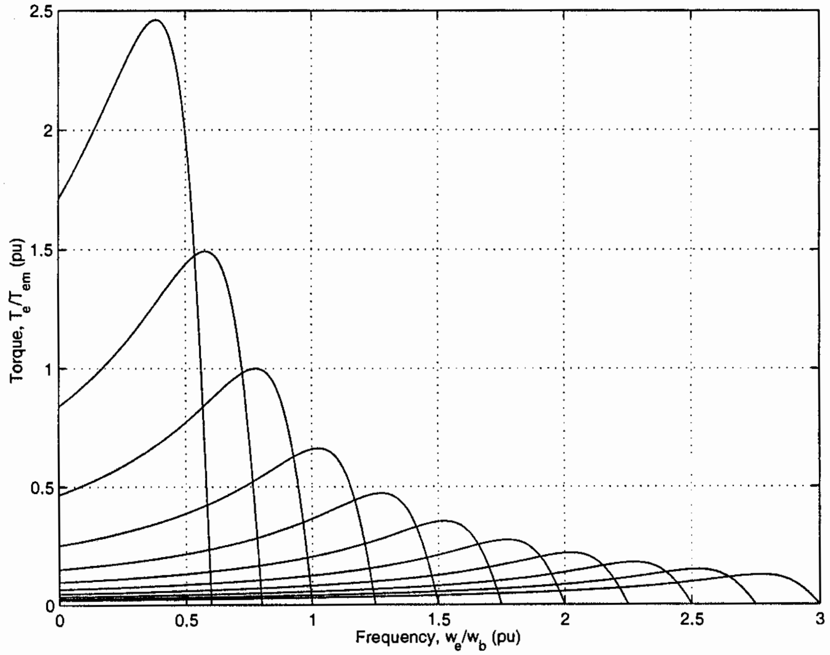

Figure 2.6: Torque-speed curves at variable frequency.

Assume that one would like to decrease the supply frequency at rated voltage, then as a result the air gap flux will saturate, causing excessive stator current. Therefore, to be able to maintain constant air gap flux, stator voltage should be boosted by $\psi = \frac{V_s}{w_e}$ the amount corresponding reduction of ~~stator voltage~~ frequency. for the region below the base ? frequency. For situation torque-speed curves are produced and given in Figure 2.7 where the V_s/w_e ratio is maintained constant. The maximum torque given by eq 2.2 is approximately valid except the low-frequency region where the air gap flux can not be maintained at its rated value because of voltage drop over the stator impedance. Therefore, in this region stator voltage should be boosted to compensate the drop and produce the maximum torque. Next the same torque-speed curves are produced for different frequency regions. Specifically, in Figure 2.8, the curves are produced from 0 to $0.85 p.u.$ and in Figure 2.9, the curves are produced from 0 to $0.5 p.u.$. Since in the region where $T_e = constant$, the motor is operated at a constant air gap flux, the torque sensitivity per ampere of stator current is high, allowing fast transient response of the drive system. In variable-voltage variable-frequency drive system, the machine usually has a low slip characteristic, giving improved efficiency. Even though the machine has a low starting torque for base-frequency operation, it can always be started at maximum torque, as presented in Figure 2.7.

2.2.1 Computation of the rated flux for the rated voltage and rated load by adjusting slip

For the computation of the rated flux for the rated voltage and rated load current by adjusting the slip, flux equation is found by using the approximate equivalent circuit given in Figure 2.10. The equivalent circuit given in Figure 1.1 can be simplified to that of Figure 2.10, where the core loss resistor R_m has been dropped out. In

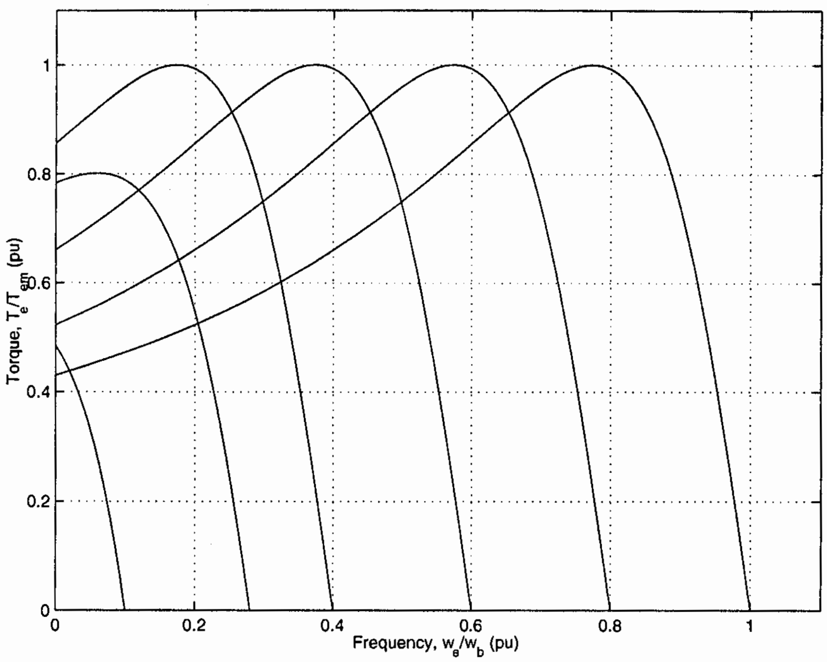

Figure 2.7: Torque-speed curves at constant volts/hertz.

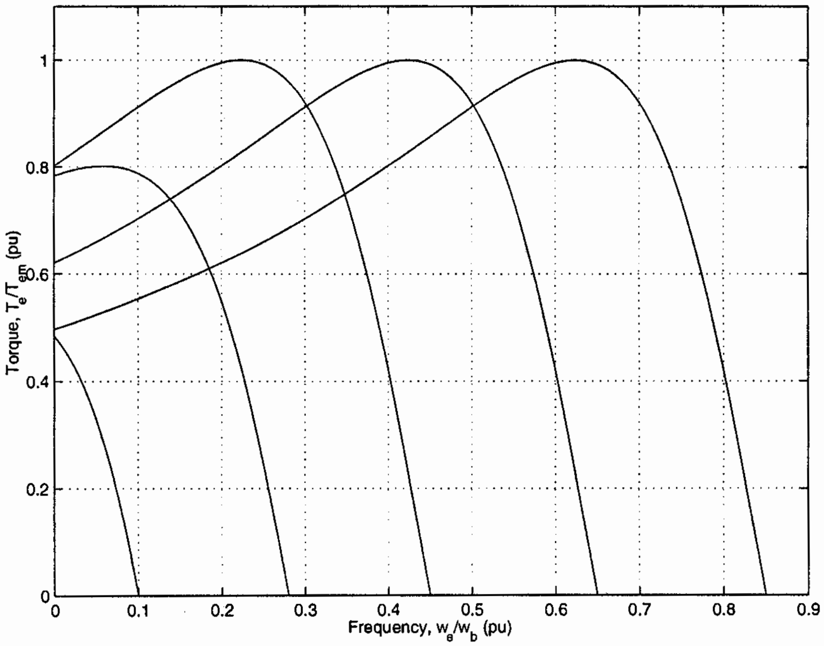

Figure 2.8: Torque-speed curves at constant volts/hertz.

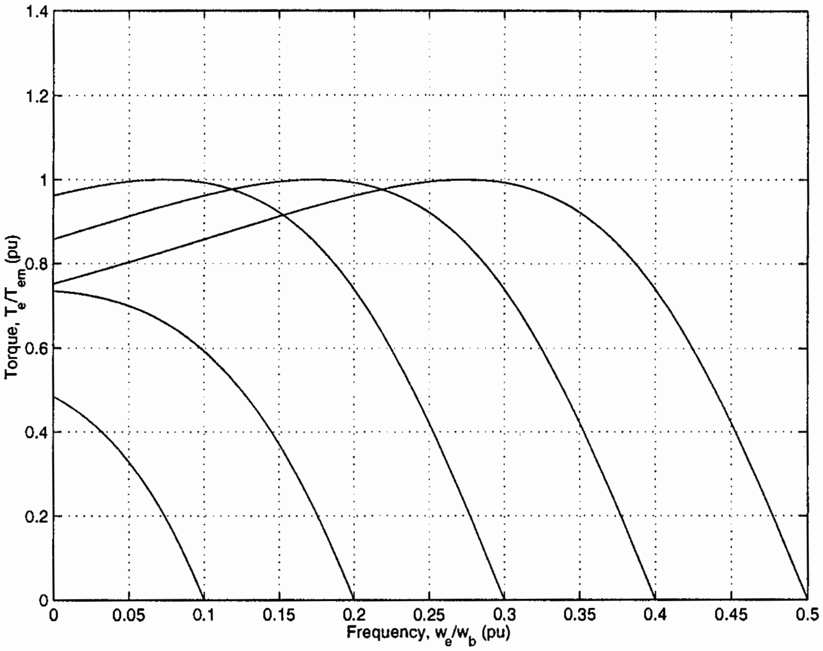

Figure 2.9: Torque-speed curves at constant volts/hertz.

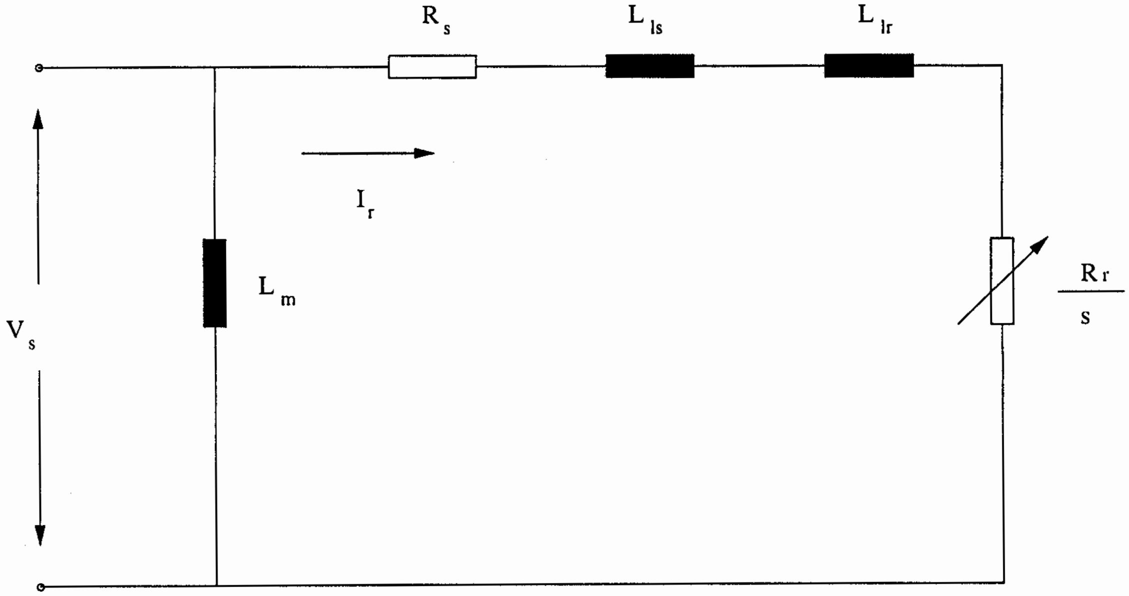

Figure 2.10: Approximate equivalent circuit.

addition to that since for our induction machine, $|R_s + jw_eL_s| = 1.1747\Omega \ll 20.34\Omega$ where $R_s = 0.4122\Omega$,$w_eL_{ls} = 1.1\Omega$,$w_eL_m = 20.34\Omega$, the magnetizing inductance L_m has been transferred to the input. From the Figure 2.10 the rotor current I_r can be found as

$$I_r = \frac{V_s}{\sqrt{(R_s + R_r/S)^2 + w_e^2(L_{ls} + L_{lr})^2}}$$

and the impedance is

$$Z_{eq} = w_eL_m//(R_s + R_r/S) + jw_e(L_{ls} + L_{lr}),$$

and

$$|\frac{1}{Z_{eq}}| = \sqrt{\frac{(R_s + R_r/S)^2 + w_e^2(L_{ls} + L_{lr} + L_m)^2}{w_e^4L_m^2(L_{ls} + L_{lr})^2 + w_e^2L_m^2(R_s + R_r/S)^2}}.$$

I_s can be found as

$$|I_s| = \frac{|V_s|}{|Z_{eq}|}$$

and I_m can be found as

$$I_m = I_s - I_r.$$

Therefore Ψ_m is

$$\Psi_m = L_mI_m.$$

The simulation results for the rated load are given in table 2.2.1.

Torque-speed characteristics of the induction machine for the rated stator voltage, frequency, rated load torque is given in Figure 2.11. In 2.2.1, for different stator voltage and frequency values and for the rated load, rotor angular speed, w_r, stator I_s, rotor I_r and magnetizing I_m currents are given. Using magnetizing current rated flux Ψ_m is calculated.

Since w_e between 0 p.u. and 1 p.u. V_s/w_e is kept constant and air gap flux is almost constant , $\Psi_m = 0.5Weber$. On the other hand in the region where w_e

V_s	w_e	w_r	slip %	I_s	I_r	I_m	Φ_m
34.5	37.69	36.85	5.26	11.6	2.3	9.2	0.50
46	75.39	73.31	2.76	11.6	2.5	9.1	0.49
69	113.09	112.03	2.13	11.7	2.9	8.8	0.48
92	150.79	147.59	1.70	11.8	3.1	8.7	0.47
115	188.49	185.29	1.44	11.8	3.3	8.5	0.46
138	226.19	220.92	1.28	11.9	3.5	8.4	0.45
161	263.89	260.52	1.16	12.0	3.7	8.3	0.44
184	301.59	298.10	1.07	12.1	3.9	8.2	0.44
207	339.29	335.67	1.00	12.2	4.1	8.1	0.43
230	376.99	373.22	0.90	12.2	4.1	8.0	0.43
230	414.69	410.38	1.04	11.5	4.7	6.8	0.36
230	452.38	447.00	1.19	11.2	5.4	5.7	0.31
230	490.08	483.45	1.35	11.5	6.1	4.9	0.26
230	520.78	482.92	1.46	10.9	6.6	4.3	0.23
230	565.48	519.10	1.64	11.1	7.4	3.7	0.20
230	659.73	644.90	2.25	12.8	10.0	2.8	0.15
230	753.98	642.33	2.64	14.0	11.6	2.4	0.13
230	848.23	-9.280	101.2	50.6	45.7	4.9	0.26

Table 2.1: Simulation results for the rated flux for different stator voltages

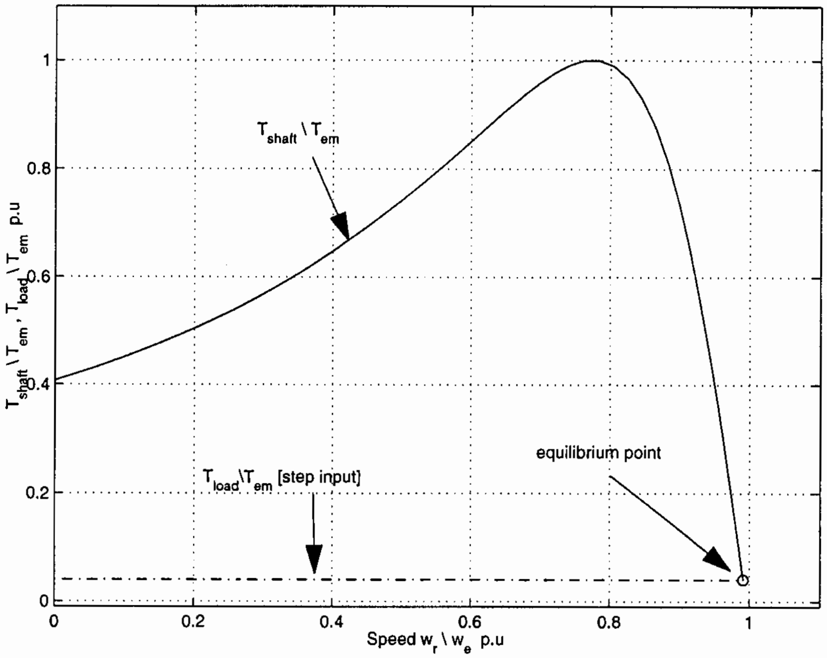

Figure 2.11: Torque-speed curves for the rated flux.

changes from 1 p.u. to 2 p.u. Ψ_m is decreased since it is inversely proportional to the stator angular frequency therefore this region is called flux weakening region. However according to our machine parameters and to the load torque, generated torque is less than the load torque for $w_e \geq 2.2$ p.u. that is given in the last row of the table. From the results, given above, the plot of V_sp.u versus w_ep.u where

$$1 \leq w_e p.u \leq 3p.u.$$

given in Figure 2.13.

In the region where $0 \leq w_e \leq 1$ p.u. V_s/f_s ratio is kept constant. Therefore T_{em} given in 1.3 is kept at its maximum value and constant. In this region keeping V_s/f_s ratio constant infinite number of characteristics can be generated. From $w_e = 0$ to $w_e \leq 1$ p.u. breakdown torque may be used as a standstill torque, and as increasing

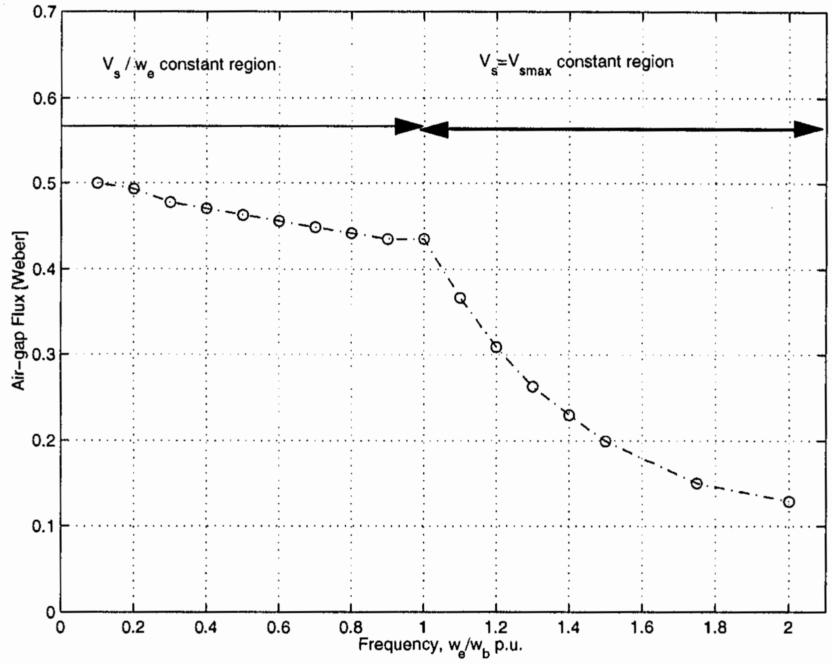

Figure 2.12: Air gap flux speed curve for $V_s/w_e = constant$ and $V_s = rated$.

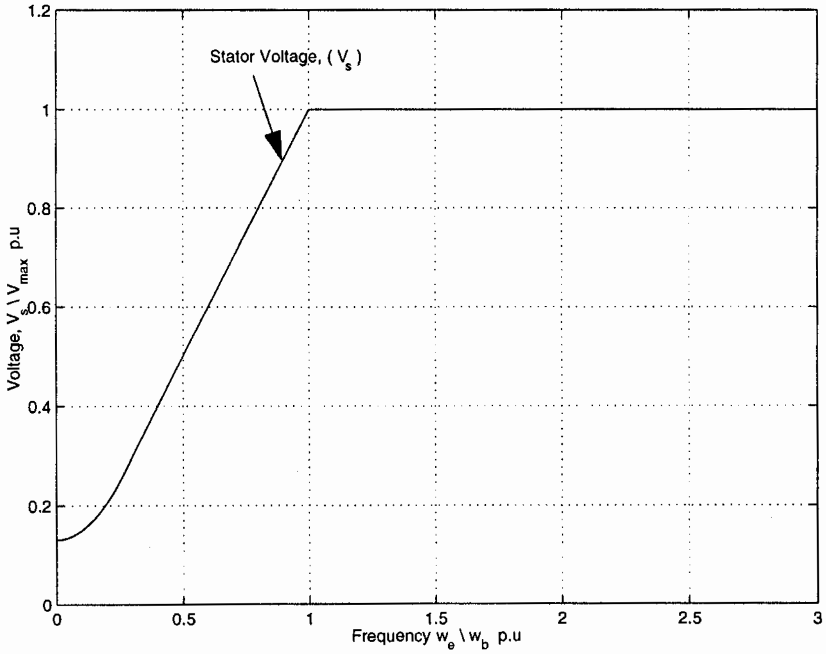

Figure 2.13: Voltage-frequency relation of induction motor.

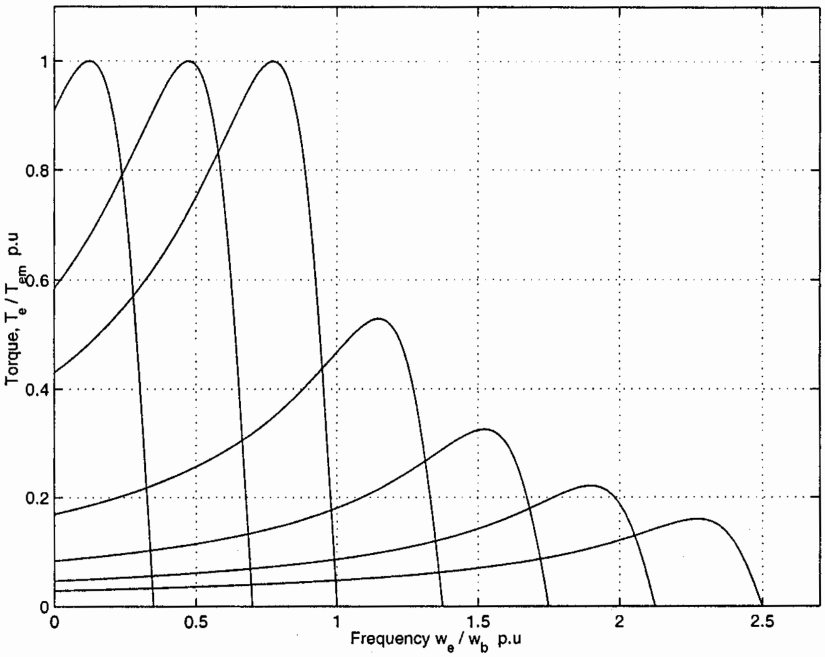

Figure 2.14: Torque-speed curves with variable-voltage, variable-frequency power supply.

the frequency the system can be accelerated. Reference to Figure 2.14 shows the high starting torque possible with a low-frequency source. With a low frequency start, the rotor inductive reactance is low; hence the induced rotor current are much closer in phase to voltage, so giving high torque with high power factor, and consequently minimum starting current amplitude. In the region where $1 \leq w_e \leq 2.5$ p.u. the frequency is increased above its rated value, the stator voltage amplitude is kept constant at its base value, therefore V_s/f_s can not be kept constant anymore. In this region, air gap flux is inversely proportional to the frequency and it decreases from its rated value. Induction machine speed is higher then its rated value, torque and flux are lower their rated value. And also the maximum torque is inversely proportional to frequency squared. In this type of control, the motor is said to be operated in a field-weakening mode. For higher torque demand this region is not suitable.

The torque-speed characteristics of induction motors depend on the type of the control. It may be necessary to vary the voltage and frequency to meet the torque speed requirements as shown in Figure 2.15. In the low frequency region, the air gap flux is reduced by the stator impedance drop. Therefore, in this region stator has to be compensated by an additional voltage boost so as to produce maximum torque. In the second region, V_s/f_s is maintained constant by adjusting stator voltage change according to the frequency change. And also air gap flux and breakdown torque are kept at their rated value. In the third region stator voltage amplitude can not be increased along with the frequency increase because stator windings are designed for the rated voltage value and applying over voltage at steady state operation is going to damage the windings. The breakdown torque decreases inversely proportional to

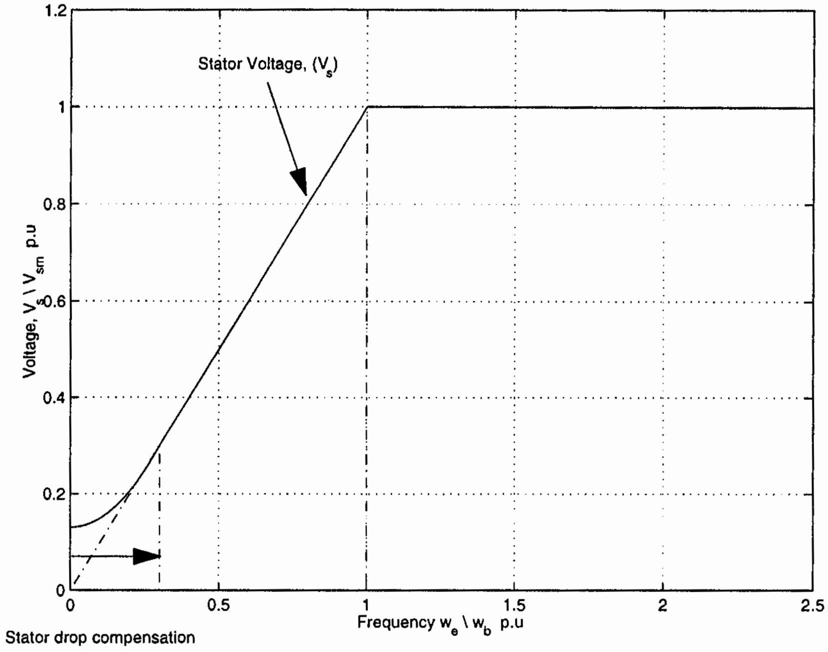

Figure 2.15: Voltage-frequency relation of induction motor.

the square of frequency and flux decreases inversely proportional to frequency as well.

2.3 APPENDIX

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% MATLAB file for torque-speed curves with variable stator voltage %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear;

rs=0.4122;
rr=0.4976;
Lls=1.1/377;
Llr=1.1/377;
Lm=20.34/377;
p = 2;
fe = 60;
we = 2*pi*fe;
V = 230;
P = 5*746;

for i = 1:-0.25:0.25
   Vs = V*i;
   ind = 1;
   for k = 0:0.01:1
      s = 1-k;
      wre(ind) = k;
```

```
      Te(ind) = 3*rr*s*Vs^2/(we*((s*rs+rr)^2+(s*we*(Lls+Llr))^2));
      ind = ind + 1;
   end
   if i == 1
      Tem = max(Te);
   end

   plot(wre,Te/Tem)
   hold on
end

grid


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% MATLAB file for torque-speed curves with volt-hertz control      %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear;

rs=0.4122;
rr=0.4976;
Lls=1.1/377;
Llr=1.1/377;
```

```
Lm=20.34/377;

p = 2;

fe = 60;

wef = 2*pi*fe;

V = 230;

P = 5*746;


ind = 1;

for s = 0:0.01:1

   Te(ind) = 3*rr*s*(230)^2/(wef*((s*rs+rr)^2+(s*wef*(Lls+Llr))^2));

   wre(ind) = (1-s)*1;

   ind = ind + 1;

end

Tem = max(Te);


for W = 0.25:0.25:2.5

  ind = 1;

  we = wef*W;

  if W <= 1

    m = 230*W;

  else

    m = 230;

  end
```

```
  for s = 0:0.01:1
     Te(ind) = 3*rr*s*(m)^2/(we*((s*rs+rr)^2+(s*we*(Lls+Llr))^2));
     wre(ind) = (1-s)*W;
     ind = ind + 1;
  end
  plot(wre,Te/Tem)
  hold on
end
grid
```