7.10 The 101-m Siemens turbines in Table 7.5 come with either a 2300 or a 3000 kW generator. Using the approach based on Equation 7.63:

a. Find the energy (kWh/yr) each will deliver in an area with 5.7 m/s average wind speed.

b. Determine the optimum generator size for these winds. Check to be sure it does better than the standard size generators.

c. At what wind speed would the 3000 kW generator begin to outperform the 2300 kW generator? Check to see that the two generator outputs are the same at that wind speed.

Brand:	Siemens	Siemens
P_R (kW):	3000	2300
D (m):	101	101
Wind (m/s)	Power (kW)	Power (kW)
0	0	0
1	0	0
2	0	0
3	60	0
4	130	100
5	280	230
6	480	420
7	765	720
8	1175	1100
9	1650	1530
10	2200	2000
11	2700	2240
12	2900	2300
13	2970	2300
14	2990	2300
15	3000	2300
16	3000	2300
17	3000	2300
18	3000	2300
19	3000	2300
20	3000	2300
21	3000	2300
22	3000	2300
23	3000	2300
24	3000	2300
25	3000	2300

EQ 7.63: $CF = .087\bar{V} - \frac{P_R}{D^2}$ (RAYLEIGH WINDS)

$CF = \frac{\text{ENERGY DELIVERED}}{\text{ENERGY @ FULL POWER}}$

CF = CAPACITY FACTOR
$\bar{V}$ = AVG WIND SPEED
P_R = RATED POWER
D = ROTOR DIAMETER

a) 2300 kW:

$$CF = .087(5.7) - \frac{2300}{(101)^2}$$

$$= .4959 - .2245 = .2703$$

$$\Rightarrow .2703(2300)\,8760 = 5{,}466 \text{ MWh/YR}$$

$$CF = .087(5.7) - \frac{3000}{(101)^2} = .4959 - .294 = .2011$$

$$\Rightarrow .2011(3000)\,8760 = 5284.9 \text{ MWh/YR}$$

$\Rightarrow$ SMALLER GENERATOR MAY DELIVER MORE POWER.

b) EQN 7.65 COMPUTES MAX ENERGY

i.e. $$\frac{dE}{dP_R} = \frac{d\left[P_R \cdot 8760 \cdot CF\right]}{dP_R} = d\left[P_R \cdot 8760\left\{.087\bar{V} - \frac{P_R}{D^2}\right\}\right]$$

$$= 8760\left(.087\bar{V} - \frac{2P_R}{D^2}\right) = 0$$

$$\Rightarrow P_R = \frac{.087}{2}\bar{V}D^2$$

$$\Rightarrow P_R = \frac{.087}{2}(5.7)(101)^2 = 2529 \text{ kW}$$ ANS

$$2529(8760)\left(.087\bar{V} - \frac{2529}{(101)^2}\right) = 5493.8 \text{ MWh}$$ WHICH IS > THAN 2300/3000 kW GENERATORS.

c) AT WHAT SPEED DO THE GENERATORS HAVE EQUAL ENERGY

$P_1 = 3000 \qquad P_2 = 2300$

$$P_1\left(.087\bar{V} - \frac{P_1}{(101)^2}\right) = P_2\left(.087\bar{V} - \frac{P_2}{(101)^2}\right)$$

$$.087\bar{V}P_1 - \frac{P_1^2}{(101)^2} = .087\bar{V}P_2 - \frac{P_2^2}{(101)^2}$$

$$.087\bar{V}(P_1 - P_2) = \frac{(P_1^2 - P_2^2)}{(101)^2}$$

$$\bar{V} = \frac{(P_1^2 - P_2^2)}{(P_1 - P_2)(101)^2(.087)} = \frac{3000^2 - 2300^2}{(3000 - 2300)101^2(.087)}$$

$$= 5.971 \ \frac{M}{S}$$

CHECK:

$$P_1: \quad E = P_1 CF = 3000\left(.087(5.971) - \frac{3000}{(101)^2}\right)$$

$$= 3000(.5194 - .2294) = 676$$

MATCH.

$$P_2: \quad E = P_2 \cdot CF = 2300\left(.087(5.971) - \frac{2300}{(101)^2}\right)$$

$$= 2300(.5194 - \quad) = 676.04$$

✓

7.11 Consider the design of a home-built wind turbine using a 350-W permanent magnet DC motor used as a generator. The goal is to deliver 70 kWh in a 30-day month.

a. What capacity factor would be needed for the machine?

b. If the average wind speed is 5 m/s, and Rayleigh statistics apply, what should the rotor diameter be if the CF correlation of Equation 7.63 is used?

c. How fast would the wind have to blow to cause the turbine to put out its full 0.35 kW if the machine is 20% efficient at that point?

d. If the TSR is assumed to be 4, what gear ratio would be needed to match the rotor speed to the generator if the generator needs to turn at 600 rpm to deliver its rated 350 W?

a) $CF = \frac{\text{ENERGY DELIVERED / HR}}{\text{ENERGY @ FULL POWER}} = \frac{[70{,}000/720]\ \text{HR/MON}}{350}$

$= .278 \Rightarrow 27.8\%$ ANS.

b) EQN 7.63: $CF = (.087)(\bar{V}) - \frac{P_R}{D^2}$

$.278 - (.087)(5) = \frac{-.350}{D^2}$

$D^2 = \frac{+.350}{(-.278 + .435)}$

$D = 1.49\,m$ ANS.

c) $P_R = \eta \frac{1}{2} \rho A v^3$

$\eta = 20\%$

$A = \left(\frac{D}{2}\right)^2 \pi = \left(\frac{1.49}{2}\right)^2 \pi = 1.743\,m^2$

$v^3 = \frac{2P_R}{\eta \rho A}$

$= \frac{2(350)}{.2(1.225)(1.743)} = 1220.7$

$v = \sqrt[3]{\frac{350}{.214}} = 11.78\,m/s$ ← WIND SPEED ANS

d) $TSR = 4$

$\frac{\text{TIP SPEED}}{\text{WINDSPEED}} = 4$

$\Rightarrow$ TIP SPEED $= 4$ (WIND SPEED)

$= 4(11.78\,m/s) = 47.12\,m/s$

TIP SWEEP CIRCUMFERENCE $= 2\pi R = \pi(1.49) = 4.68$

$\frac{47.12\,m/s}{4.68} \Rightarrow 10.066\,Hz \Rightarrow \left(10.066\,\frac{REV}{S}\right)\left(\frac{60\,S}{M}\right)$

$= 604.$ REV/MIN ANS.

d) (CONT)

$$\text{GEAR RATIO} = \frac{\text{GENERATOR RPM}}{\text{ROTOR RPM}} = \frac{600}{604} \approx 1 \Rightarrow \underline{1:1} \text{ ANS}$$

GEAR RATIO

7.12 Consider the perspective of a landowner being offered the following three choices by a wind developer. Compare the options.

a. A flat \$20,000/yr per turbine

b. 0.5¢ for each kWh generated

c. \$500/yr per acre (4047 m^2/acre) of array (turbine corner to turbine corner) plus \$100/yr per acre of buffer zone.

The proposal is for thirty 1.6-MW, 80-m turbines with 3D (side-by-side) and 10D (row-to-row) spacing plus a 5D buffer zone. Winds are modeled with Rayleigh assumptions at an average wind speed of 7 m/s. Wind-farm losses (wake loss, interconnects, blade bugs) are estimated at 15%.

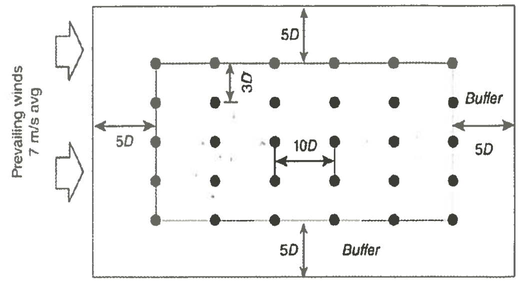


Figure P7.12

a) $30 \cdot \$20k = \$600k/\text{yr}$

b) USING EQN 7.64:

PER TURBINE: ANNUAL ENERGY (kWh/yr) $= 8760 \cdot P_R(\text{kW}) \left\{ .087\,\bar{V}(\text{m/s}) - \dfrac{P_R(\text{kW})}{[D(\text{m})]^2} \right\}$ — CF, EQN 7.63

$= 8760\,(1600)\left\{ .087(7) - \dfrac{1600}{(80)^2} \right\}\{1 - .15\}$

$= 4276 \ \text{MWh/yr}$

$\$ = 30 \cdot 4276 \ \frac{\text{MWh}}{\text{y}} \cdot .005\$$

$= \$641,550/\text{yr}$

c) COMPUTE THE WINDFARM AREA

ARRAY $= 50D \cdot 12D = 600\,D^2 = 600(80^2)$

$= 3,840,000 \ m^2$

ACRES $= \dfrac{3840,000\,m^2}{4047\ m^2/\text{ACRE}} = 948.5$ ACR

BUFFER $= 60D \cdot 22D -$ ARRAY

$= (60 \times 22)D^2 - 3,840,000$

$= 8,448,000 - 3,840,000 = 4,608,000$

c)(CONT) $\text{ACRE} = \dfrac{4{,}608{,}000}{4047} = 1138.\text{ACRE}$

$\$ = (918.5)\left(\$500\ \dfrac{\text{ACRE}}{\text{YR}}\right) + (1138)\left(\$100\ \dfrac{\text{ACRE}}{\text{YR}}\right)$

$= \$588{,}112$ PER YEAR

THUS MOST \$ PRODUCED BY OPTION (b) WHICH REIMBURSES BASED UPON kWhr PRODUCED ⇒ BUT MOST RISKY BECAUSE IT DEPENDS ON WIND a) TURBINE AVAILABILITY, MARKET DEMAND

2ND BEST OPTION IS FLAT RATE PER TURBINE

3RD BEST OPTION IS PER ACRE RATE.

7.13 The 2013 "low wind" turbine pricing in Table 7.6 uses a 1.62 MW turbine with an installed cost of $2025/kW with a 100-m rotor diameter.

a. At a site with 6 m/s Rayleigh winds at 50-m, estimate the energy this turbine would deliver at a hub height of 100 m assuming the usual 1/7th wind-shear factor. Assume 15% losses.

b. Assuming a nominal 9% financing charge with a 20-year term along with annual O&M costs of $60/kW, find the levelized cost of electricity. Does it agree with Figure 7.48?

Characteristics	2002	2009	2013 Turbine Pricing	
Technology Type	Standard	Standard	Standard	Low Wind
Rated power (MW)	1.5	1.5	1.62	1.62
Hub height (m)	65	80	80	100
Rotor diameter (m)	70.5	77	82.5	100
Installed capital cost ($/kW)	1300	2150	1600	2025
Operating cost ($/kW/yr)	60	60	60	60
Losses (%)	15	15	15	15
Financing (nominal) (%)	9	9	9	9

Table 7.6

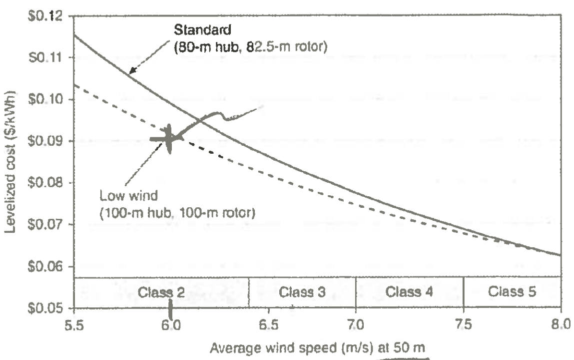


Fig. 7.48

a) COMPUTE HEIGHT ADJUSTED WINDSPEED

$$V = V_0 \left(\frac{H}{H_0}\right)^{\alpha} = 6\left(\frac{100}{50}\right)^{1/7} = 6.624 \text{ m/s}$$

$\alpha \equiv$ WIND SHEAR FACTOR $= \frac{1}{7}$

$H_0 = 50$ m ; $H = 100$ m

EQN 7.63:

$$CF = \frac{\text{ENERGY DELIVERED}}{\text{ENERGY @ FULL POWER}}$$

$$= .087(\bar{V}) - \frac{P_R}{D^2} = .087(6.624) - \frac{1620}{(100)^2} = .4143$$

($\bar{V}$ in M/S, P_R in KW, D in M)

$$E = CF(1 - \text{LOSSES})(8760) \cdot P_R = .4143(1-.15)(8760)(1{,}620)$$

(8760 HRS/YR; P_R RATED PWR kW)

$$= 4.997 \times 10^6 \text{ kWh/yr}$$ EXPECTED ENERGY DELIVERED PER YEAR

b) USING EQN 6.14 $

$A \triangleq$ ANNUAL PAYMENTS $= CRF(i,n) \cdot \$P$

A = ANNUAL PAYMENT ($/YR)
P($) = PRINCIPLE
n = # YEARS
i = INTEREST RATE

CRF = CAPITAL RECOVERY FACTOR

$$CRF(i,n) = \frac{i(1+i)^n}{(1+i)^n - 1} = \frac{.09(1+.09)^{20}}{(1+.09)^{20} - 1}$$

$$= .1095$$

$$A = .1095 \cdot 2025(\$/kW) \cdot 1{,}620 \text{ kW} = \$359{,}367K$$

LCOE (LEVELIZED COST OF ENERGY) = $\frac{\text{(ANNUAL FIXED COST + ANNUAL VARIABLE \$)}}{\text{ANNUAL OUTPUT.}}$

OPERATING COST (\$ KW/YR) = $\$60/_{KW} \cdot 1620 = \$97,200$

$$LCOE = \frac{\$359,367 + 97,200}{4.997 \times 10^6} = .0914 \ \$/_{KWhr}$$

THIS LCOE **DOES AGREE** w/ FIG 7.48 (@ 6 m/s, 50 m)

ANS.

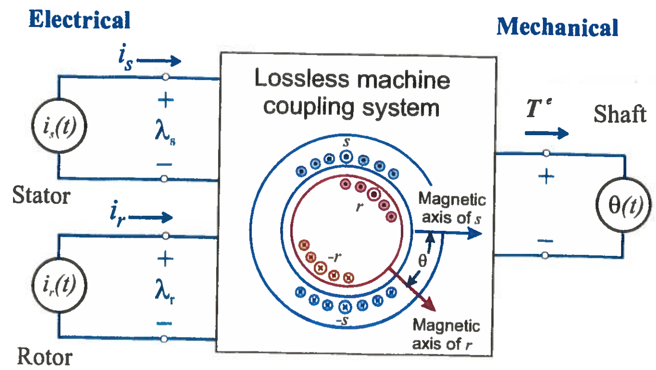


Figure 1: 3-Terminal EM Conversion System

1. Explain induction machine power flows using the 3-terminal electromechanical conversion diagram (Fig. 1), the machine conditions for average power conversion, and the induction machine torque speed curve (Fig. 2). Explain how Faraday's Law applies to induction machine operation. Note: machine includes generator, motor, and brake operation.

CONDITIONS FOR NON-ZERO AVERAGE POWER FLOW : $\omega_m = \pm \omega_s \pm \omega_r$

IN AN INDUCTION MACHINE $\omega_r \neq 0$; $\omega_r \neq \omega_s$

$\omega_r < 0$; $\frac{\omega_s - \omega_r}{\omega_s} > 1$ (SLIP)

$\omega_r > 0$; $\frac{\omega_s - \omega_r}{\omega_s} < 1$

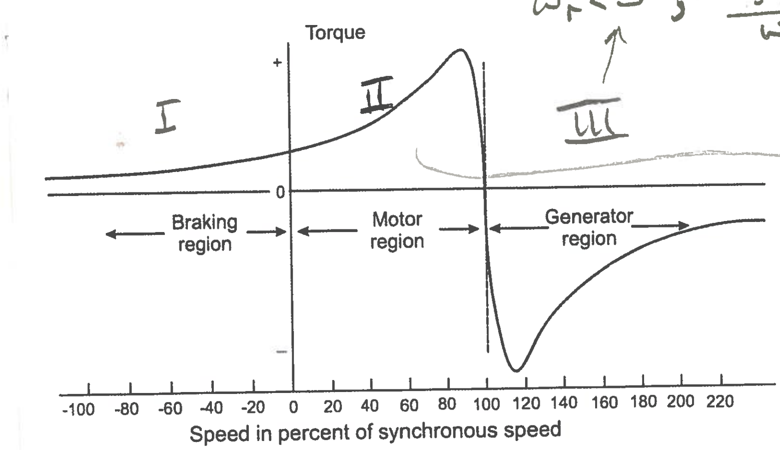


Figure 2: Induction Machine Torque Speed Curve

NOTES:
- FARADAY'S LAW : $V = \frac{d\lambda}{dt} = \frac{d(Li)}{dt}$; L CHANGES W/ TIME AS ROTOR MOVES
- ASSUMING 3ϕ INPUTS ; MOTOR WINDINGS ARE ROTATED IN SPACE 120° ; PHASE CURRENT INPUTS ARE SINUSOIDAL & SHIFTED IN TIME BY 120° (i.e. 120° PHASE SHIFT)
- THIS PRODUCES A <u>UNIFORM</u> <u>ROTATING</u> <u>MAGNETIC</u> <u>FIELD</u> ON THE STATOR THAT ROTATES AROUND THE MACHINE AXIS AT <u>ω_s</u>

MOTOR REGION (II ON FIG 2.)

- ROTOR REVOLVES IN SAME DIRECTION AS THE MAGNETIC FIELD ROTATION (PRODUCED BY SOURCE/LINE CURRENTS)
- SLIP : $s = \frac{W_s - W_r}{W_s}$; $0 < s < 1$ $(W_r < W_s)$

(SLIP IS THE NORMALIZED DIFFERENCE BETWEEN ROTATING MAGNETIC FIELD AND THE VOLTAGE FREQUENCY INDUCED ON THE ROTOR (FARADAY'S LAW)

- POSITIVE TORQUE ⇒ POWER OUT OF MECHANICAL TERMINAL
- $W_M = W_s - W_r$; $W_s, W_m, W_r > 0$
- MAGNETIC FIELD (W_s) ROTATES SLIGHTLY FASTER THAN THE ROTOR IS SPINNING (W_M), SO THE ROTOR WINDING ALWAYS SEES A CHANGING MAGNETIC FIELD.
  ⇒ ∴ BY FARADAY'S LAW, VOLTAGES ARE INDUCED ON THE ROTOR WINDINGS w/ SPEED W_r
- POWER INTO THE ELECTRICAL TERMINALS

GENERATOR REGION (III ON FIG 2)

- THE INDUCTION MACHINE OPERATES AS A GENERATOR, IF THE STATOR TERMINALS ARE CONNECTED TO A CONSTANT-FREQUENCY VOLTAGE SOURCE (W_s) AND THE ROTOR IS DRIVEN <u>ABOVE</u> SYNCHRONOUS SPEED BY A MECHANICAL SOURCE.
- $W_M > W_s$
- SLIP : $s = \frac{W_s - W_r}{W_s}$ SUCH THAT $s < 0$ $W_r > W_s$
- NEGATIVE TORQUE ⇒ POWER INTO MECHANICAL TERMINAL
-

BRAKING REGION (I ON FIG 2)

- TO OBTAIN PHYSICAL OPERATION W/ S > 1, THE MOTOR MUST BE DRIVEN BACKWARD — AGAINST THE ROTATION OF THE MAGNETIC FIELD PRODUCED BY THE LINE CURRENT — BY A SOURCE CAPABLE OF COUNTERACTING THE INTERNAL TORQUE T. THE CHIEF PRACTICAL USEFULNESS IS BRINGING MOTORS TO A QUICK STOP.

☆ • INTERCHANGING 2 STATOR LEADS ON A 3Φ MOTOR CHANGES MAGNETIC FIELD ROTATION DIRECTION. →

- THE MOTOR COMES TO A STOP UNDER TORQUE T <u>AND</u> IS DISCONNECTED BEFORE IT STARTS ROTATING IN THE OPPOSITE DIRECTION.

☆ • THIS MODE <u>IS</u> <u>NOT</u> USED IN STEADY STATE. ⇒ ONLY IN TRANSIENT CONDITION OF BRAKING SPINNING MACHINE. — REMOVING ENERGY IN THE SPINNING ROTOR

2. Explain synchronous machine power flows using the 3-terminal electromechanical conversion diagram (Fig. 1), the machine conditions for average power conversion, and the induction machine torque speed curve (Fig. 2). Note: machine includes generator and motor operation.

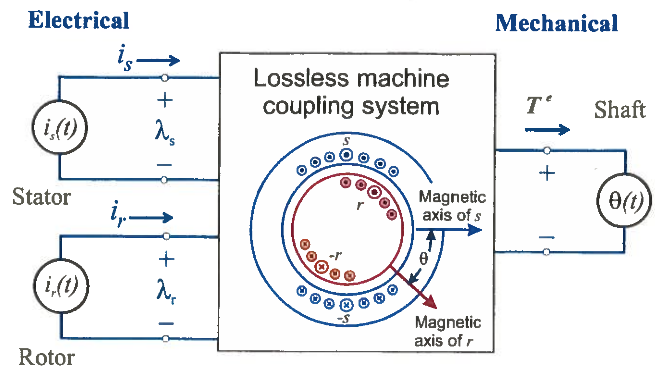
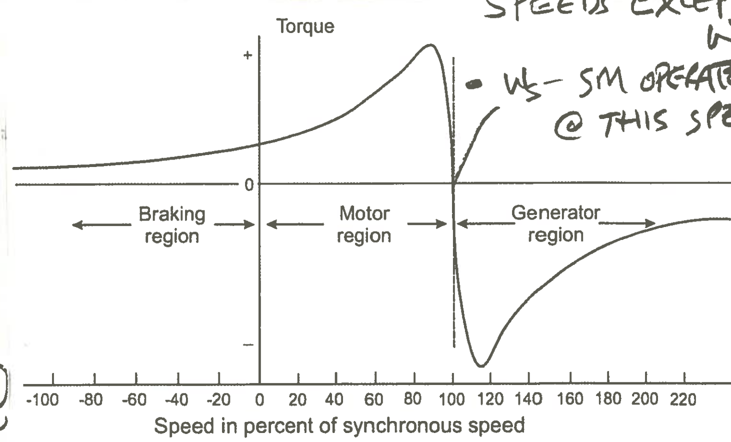


Figure 1: 3-Terminal EM Conversion System

- INDUCTION MACHINE OPERATES AT ALL SPEEDS EXCEPT ω_s



- ω_s – SM OPERATES @ THIS SPEED

Figure 2: Induction Machine Torque Speed Curve

- GENERAL CONDITION FOR NON-ZERO AVERAGE POWER CONVERSION:

$$\omega_m = \pm\omega_s \pm \omega_r$$

- IN A SYNCHRONOUS MACHINE (SM)

$$\omega_r = 0$$

A DC CURRENT IS APPLIED TO THE ROTOR WINDING.

THEREFORE $\omega_m = \omega_s$ IN BOTH MOTOR & GENERATOR MODES.

- ASSUMING BALANCED 3ϕ WINDINGS AND 3 APPLIED CURRENTS SHIFTED IN TIME BY 1/3 CYCLE (120°), THE MAGNETIC FIELD IN THE GAP ROTATES @ ω_s w/ CONSTANT MAGNITUDE.

- IN STEADY STATE, MOTOR OPERATION 3ϕ POWER IS APPLIED TO THE THE ELECTRICAL TERMINALS

MECHANICAL POWER IS OUTPUT THROUGH THE MECHANICAL TERMINALS

IN STEADY STATE GENERATOR OPERATION, MECHANICAL POWER IS APPLIED TO THE MECHANICAL TERMINALS

THE ROTATION OF THE STEADY MAGNETIC FIELD PRODUCED BY THE DC CURRENT ON THE ROTOR INDUCES (FARADAY'S LAW) VOLTAGES ON THE 3ϕ ELECTRICAL TERMINALS

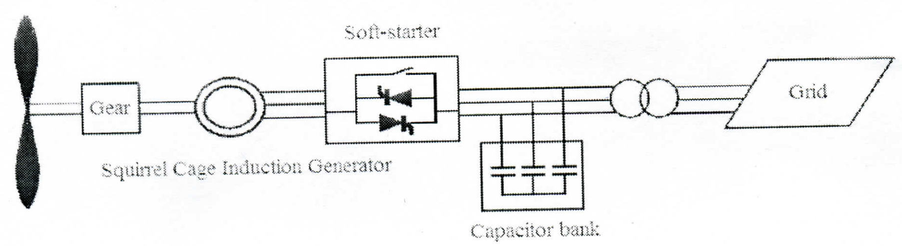
w/ $\omega_s = \omega_m$

POWER FLOWS OUT THE ELECTRICAL TERMINALS

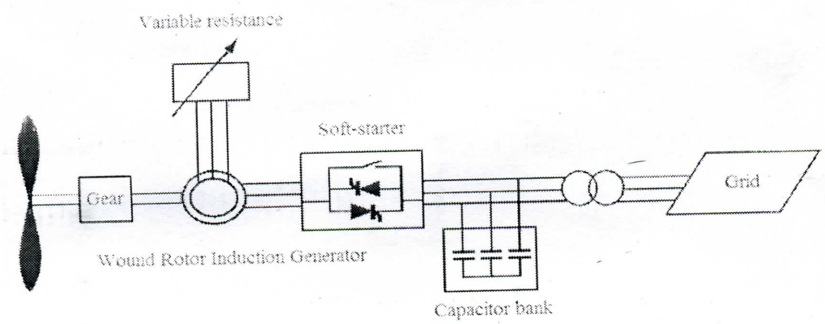
NOTE: THE SM OPERATES AT THE ONLY FREQUENCY THAT THE INDUCTION MOTOR DOES NOT OPERATE.

3. Describe the wind power source conditions and required power conditioning system components for using induction and synchronous generators to convert wind power into electrical power for the IEEE Wind Energy Conversions System types 1 thru 4.

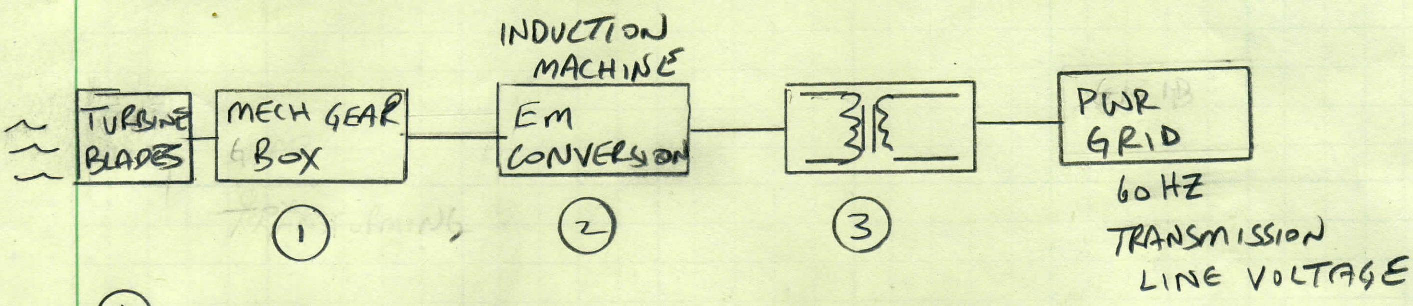
Type 1



Type 2



TYPES 1 & 2 ARE VERY SIMILAR



① CHANGE MECHANICAL SPEED OF SHAFT
- CONNECTED TO TURBINE BLADES TO A MORE EFFECTIVE MECHANICAL SPEED (ELECTRICAL FREQ >> MECHANICAL FREQ)
- FIXED GEAR RATIO

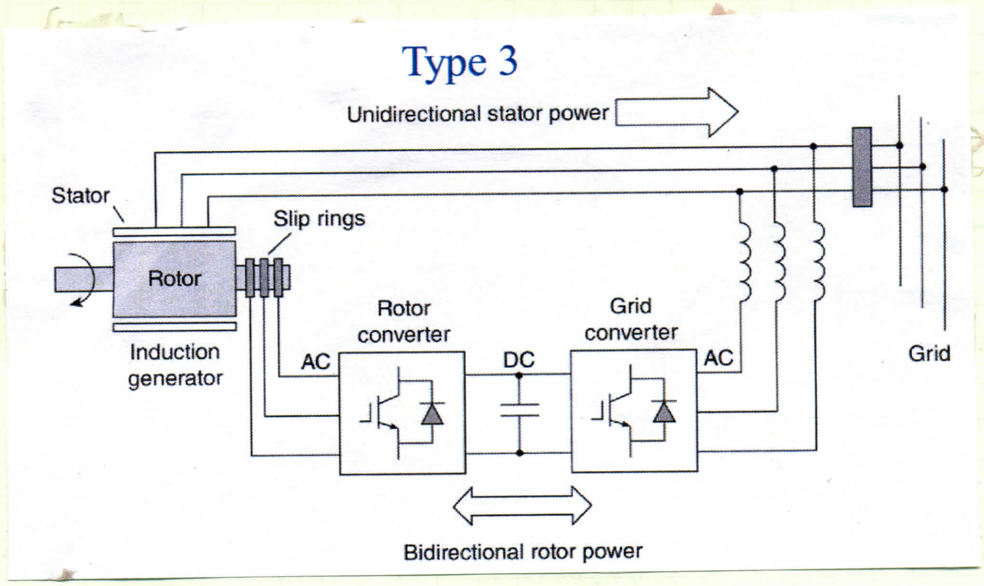
② ELECTROMECHANICAL ENERGY CONVERSION DEVICE
MECH PWR IN → ELECT POWER OUT.

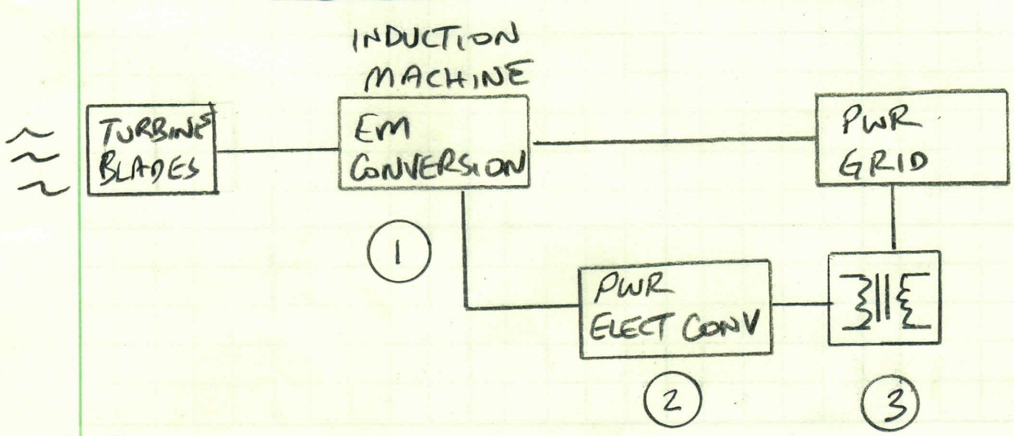
③ TRANSFORMER STEPS VOLTAGE UP (TYPICALLY) TO MATCH POWER GRID

TYPE 1 USES A FIXED RESISTANCE SQUIRREL CAGE INDUCTION GENERATOR, HOWEVER, THE FIXED RESISTANCE SEVERELY LIMITS THE RANGE OF WIND SPEEDS RESULTING IN "PRODUCTIVE" E-M POWER CONVERSION

TYPE 2 USES A WOUND ROTOR INDUCTION GENERATOR. THIS ENABLES SWITCHING WINDINGS IN/OUT OF THE ROTOR CIRCUIT – ENABLING STEP RESISTANCE CHANGES THAT EXPANDS THE RANGE OF WIND SPEEDS THAT RESULT IN "PRODUCTIVE" E-M POWER CONVERSION → (BUT STILL LESS THAN DESIRED)

FIXED MECHANICAL GEAR RATIO LIMITS WECS ADJUSTMENTS TO OPTIMIZE EM POWER CONVERSION





TYPE 3.

(1) EM ENERGY CONVERSION DEVICE (INDUCTION GEN)

MECH POWER IN - ELECT POWER OUT.

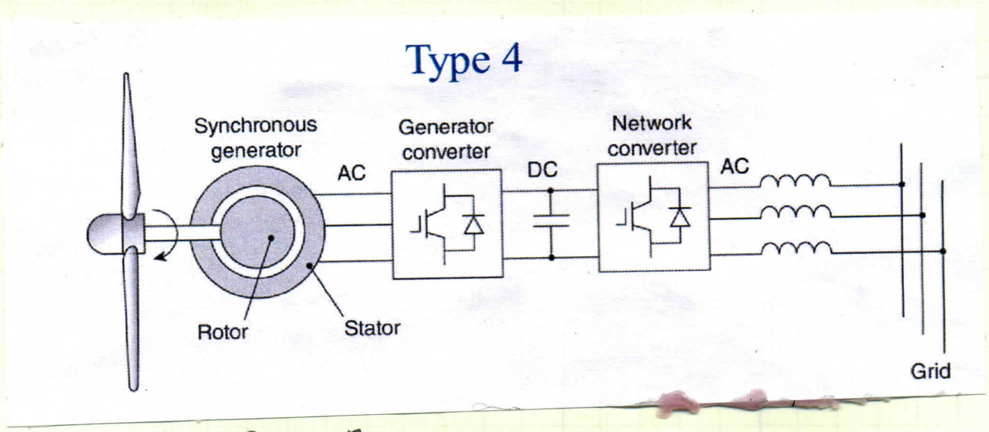
$\omega_M = \pm \omega_M \pm \omega_s$

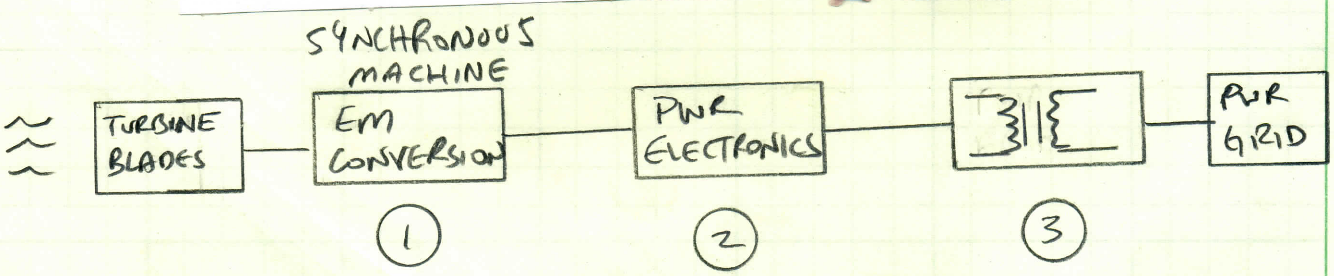
(2) • POWER ELECTRONICS PACKAGE REPLACES THE MECH GEAR BOX IN TYPES 1 & 2. POWER ELECTRONICS ADJUST FREQUENCIES TO ROTOR WINDING TO PRODUCE 60 HZ OUTPUT FREQ.

• MUCH GREATER EM CONVERSION OPTIONS AVAILABLE TO OPTIMIZE EM POWER CONVERSION

$\omega_m = \pm \omega_s \pm \omega_r$ STILL HOLDS → BUT MORE FLEXIBILITY FOR CONTROL

(3) TRANSFORMER STEPS GRID VOLTAGE DOWN TO LEVELS SUITABLE FOR POWER ELECTRONICS





(1) EM CONVERSION IN SYNCH GENERATOR ($\omega_R = 0$)

POWER ELECTRONICS PACKAGE DECOUPLES GEN ELECT. FREQ FROM GRID FREQ.

(2) LIKE TYPE 3, TYPE 4 PWR ELECTRONICS PACKAGE REPLACES MECH GEAR BOX.

ADDITIONALLY PWR ELECTRONICS PACKAGE DECOUPLES ELECT POWER FROM E-M CONVERSION DEVICE FROM POWER GRID → DC VOLTAGE HAS FREQ = 0 !

(3) TRANSFORMER STEPS POWER ELECTRONICS OUTPUT VOLTAGE UP TO GRID VOLTAGE.