Tutorial 3

Note: As is the usual convention, *rms* value of ac voltages are specified in the questions.

1. A wind turbine-generator system consists of a wind turbine whose characteristic for certain wind speed is shown in the figure. The turbine is coupled to a four-pole, 50 Hz squirrel cage induction generator through a gearbox. The power rating of the turbine and the generator are compatible. If the induction generator is connected to a 50 Hz AC grid, it is found that maximum power is extracted at this wind speed. The approximate gear ratio of the gearbox is

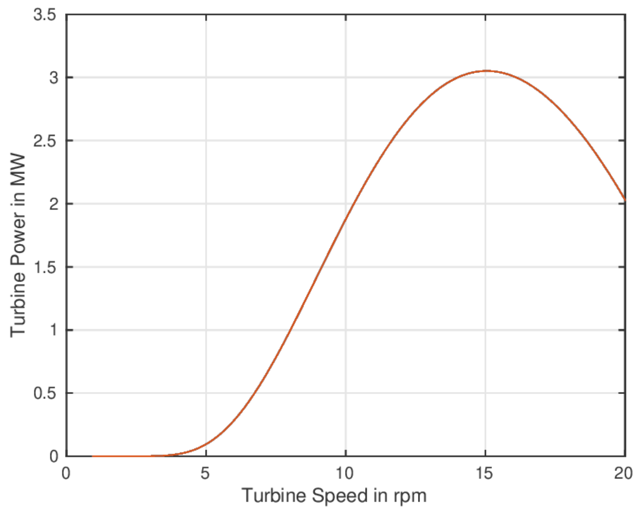


Figure 1: Wind power versus turbine speed for a particular wind speed

(a) 1:20 (b) 1:80 (c) 1:100 (d) 1:150

2. In the wind-turbine squirrel-cage induction generator (SCIG) configuration shown in the figure below, what is the role of the soft-starter and capacitor bank/reactive power compensator? Why is a gear necessary?

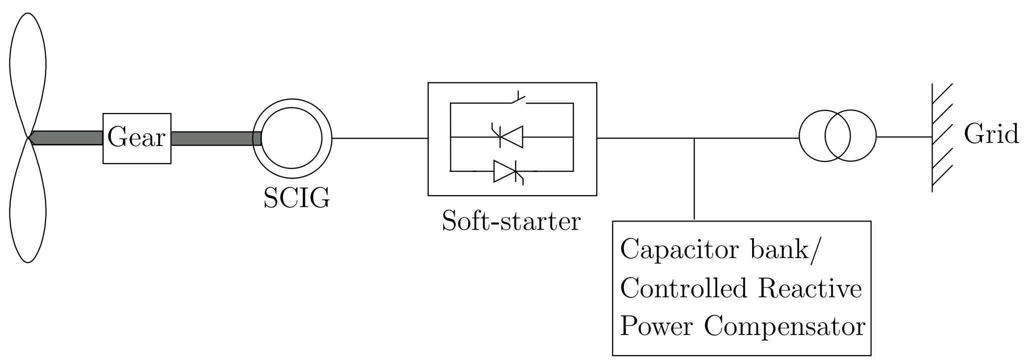
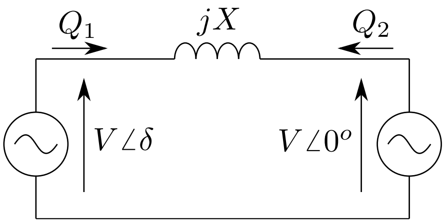


Figure 2: Type I Wind Turbine-Generator System

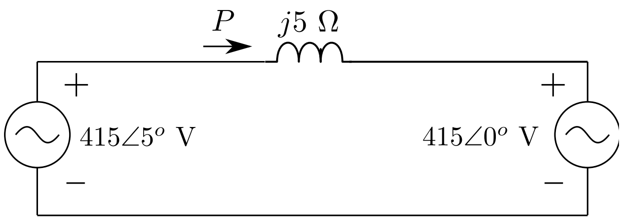
3. For the system shown in the figure, which of the following relationships is true? Note that the voltage *magnitudes* at both ends are equal. Q_1 and Q_2 denote the reactive power injected at the two ends, as shown below.



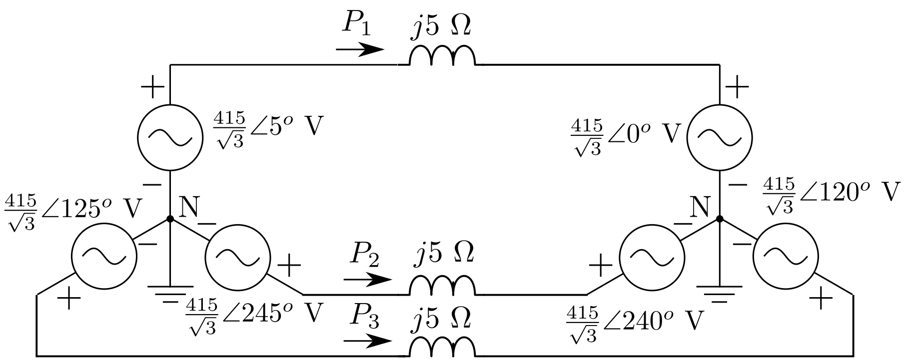
(a) $Q_1 = Q_2$ (b) $Q_1 = -Q_2$ (c) $Q_1 < Q_2$ (d) $Q_1 > Q_2$

4. In the previous question, which of the relationships will be true if $\delta = 0$ and sending end voltage magnitude (left hand side) is greater that the receiving end voltage magnitude (right hand side)?

5. Calculate the active power (P) and reactive power (Q) in the 415 V single phase circuit shown in Figure 3a.
   Also calculate active powers (P_1, P_2 and P_3) in the 415 V three phase circuit[1] shown in Figure 3b. What will be the total active power (P_1 + P_2 + P_3) in the three phase circuit? Compare it to P. Repeat the same exercise for the corresponding sending end reactive powers.



(a) Single line diagram



(b) Three-phase circuit representation

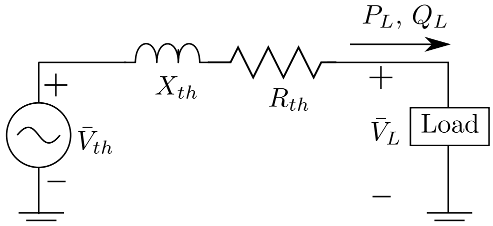
Figure 3: Schematic for Problem 5

[1] The voltage refers to the line-line rms value, as is the usual convention in three-phase circuits

6. Consider the single phase circuit shown below. The voltage source $\bar{V}_{th}$ is given by $240\angle 0$ V and R_{th} and X_{th} are $0.1\ \Omega$ and $j0.2\ \Omega$ respectively. The load power characteristics are given as follows:

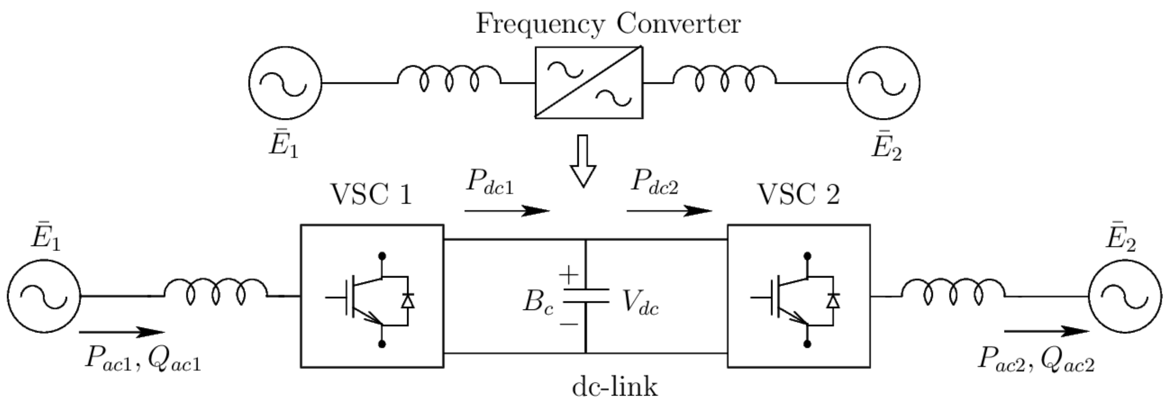
$$P_L = 8\left(1 + k_{pv}\frac{V_L - 235}{235}\right)\ \text{kW}, \quad Q_L = 6\left(1 + k_{qv}\frac{V_L - 235}{235}\right)\ \text{kVAr}$$

where V_L is the magnitude of the load terminal voltage (in V), P_L and Q_L are defined in absorption sense, k_{pv} and k_{qv} are defined in kVA/V. Calculate the steady state voltage $\bar{V}_L$, P_L and Q_L when
(a) $k_{pv} = 0$, $k_{qv} = 0$,
(b) $k_{pv} = 2$, $k_{qv} = 2$,
(c) $k_{pv} = 0.1$, $k_{qv} = 0.5$.



Hint: It may be convenient to solve this numerically.

7. A frequency converter is made up of back-to-back connected three-phase voltage source converters, as shown in the figure. If the converters are assumed to be lossless then under steady-state which of the following statements is/are FALSE:



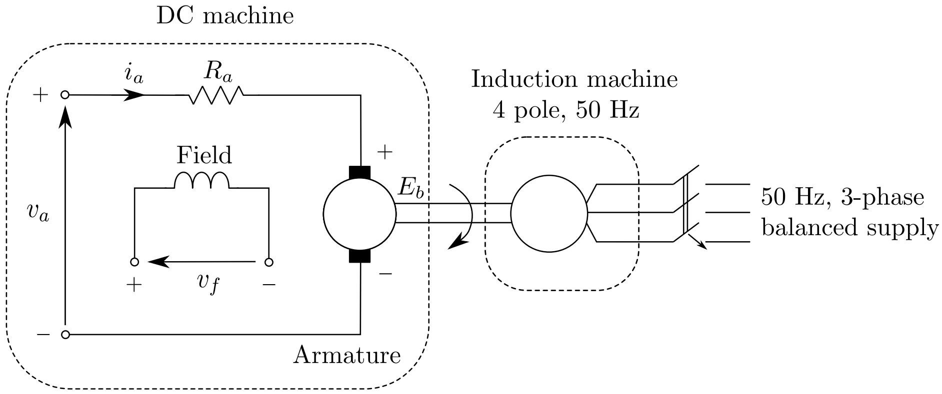
(A) $P_{ac1} = P_{dc1}$ and $P_{ac2} = P_{dc2}$

(B) $P_{dc1} = P_{dc2}$

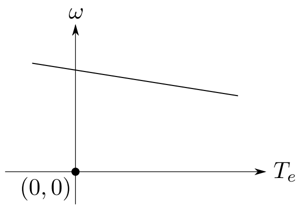
(C) Q_{ac1} and Q_{ac2} are independently controllable

(D) P_{ac1} and P_{ac2} are independently controllable

8. The rotor of the separately excited DC machine is mechanically coupled to the rotor of a 50 Hz, three-phase, 4-pole induction machine, as shown in Figure (a). The steady state speed-torque characteristic of the DC motor (motor convention) for a fixed v_a and v_f is given in Figure (b).
The DC machine is energized first, and the machines are found to rotate at 1600 rpm. Subsequently, the induction machine is connected to a 50 Hz, three-phase balanced AC source with the phase sequence being consistent with the direction of rotation. v_a and v_f are not changed.



(a) A DC machine coupled to an induction machine



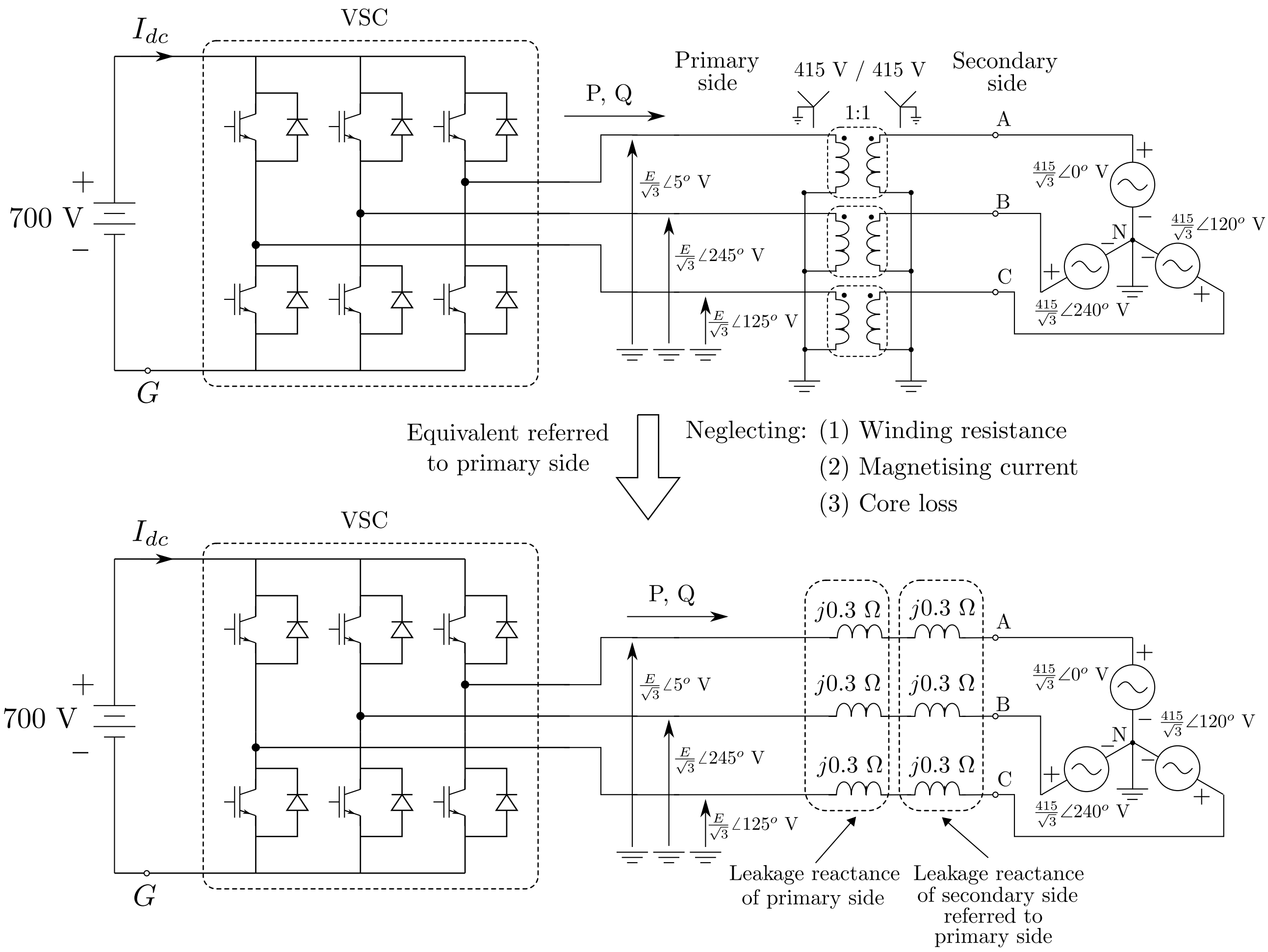
(b) Speed-torque characteristic of the DC machine

(a) Will the induction machine operating in generating or motoring mode?

(b) Will the dc machine operating in generating or motoring mode?

(c) The overall speed in steady state will be
(A) >1600 rpm,
(B) <1500 rpm,
(C) between 1500 rpm and 1600 rpm.

9. A lossless three-phase voltage source converter (VSC) is connected to a power system, as shown in the figure. The VSC converter is switched in such a way that the lower order harmonics in the output voltage are negligible. The leakage reactances of the transformer (referred to the primary side) are indicated in the figure. This reactance behaves like a filter and ensures that the ac side current is practically sinusoidal at the fundamental frequency. In steady-state reactive power (Q) supplied by the inverter is 1.092 kVAr. The dc voltage of the converter is maintained at 700 V by a battery. Compute the following quantities:



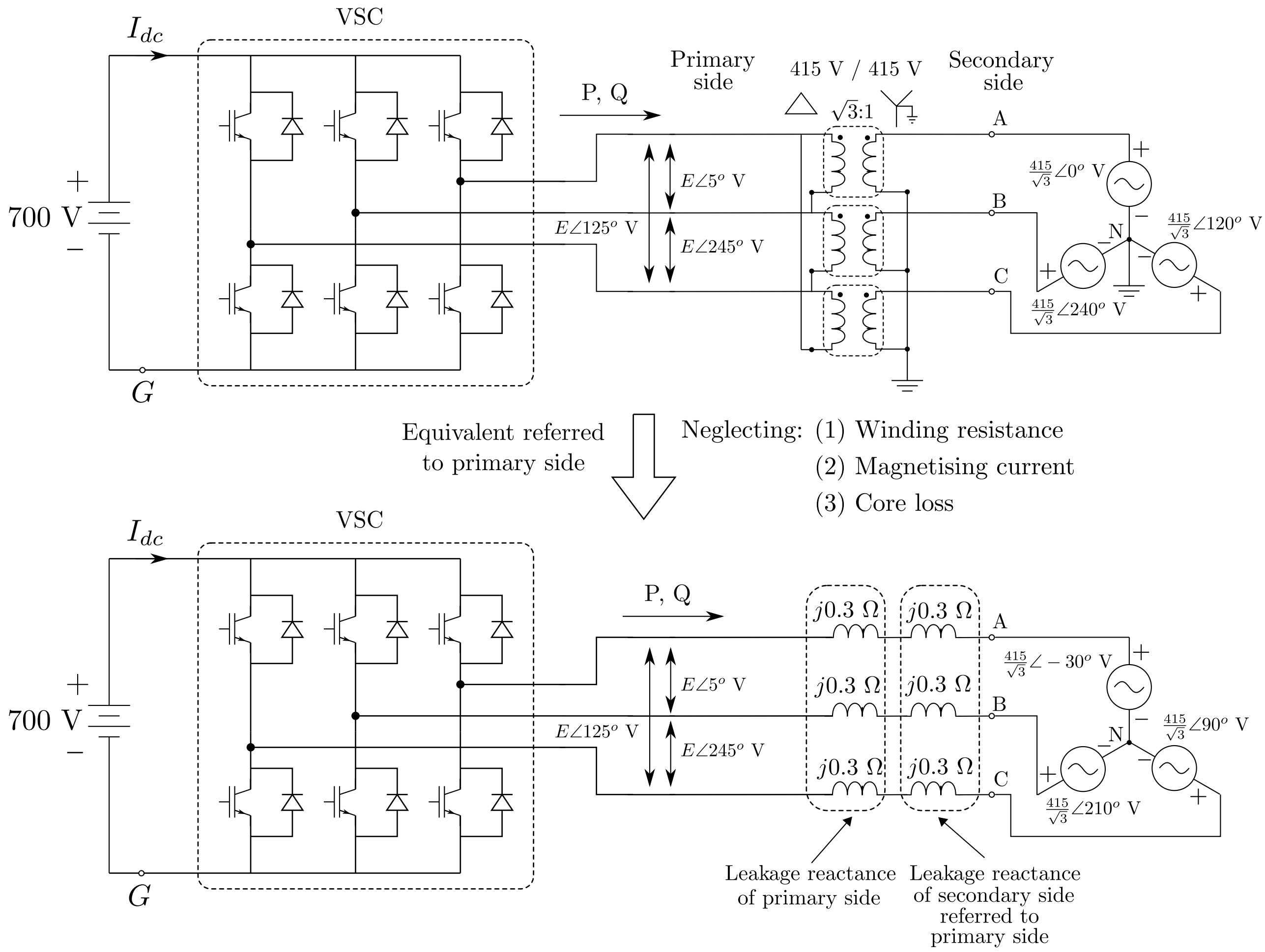
(a) steady-state line to line rms value of the fundamental component of inverter output voltage E = ___________ V

(b) active power supplied by the inverter P = ___________ W

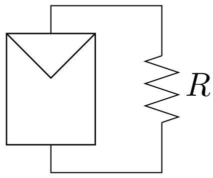
(c) Average dc side current (I_{dc}) = ___________ A

(d) Can the point G shown in the figure be grounded?

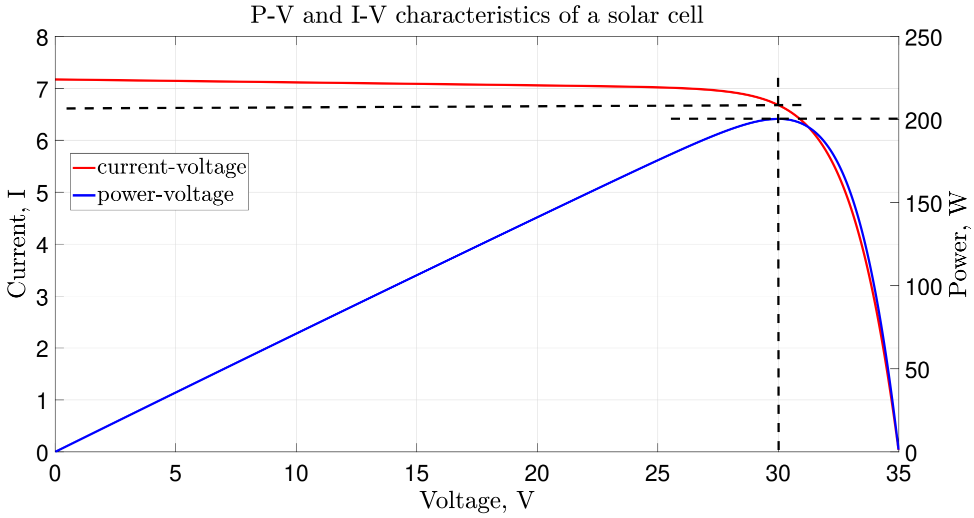
10. If the (star-grounded)-(star-grounded) configuration of the transformer is replaced by a delta-(star-grounded) configuration without changing the line to line voltage ratio, as shown in the figure below, answer the same questions as given in the previous question.



11. A solar module is connected to a resistive load, as shown in figure (a). The I-V characteristic and P-V characteristic of the solar cell is shown in figure (b). What should value of the load resistance R be (approx.) so that the solar cell operates at maximum power point?



(a) Circuit schematic



(b) P-V and I-V characteristics of a solar cell

12. The solar module described in the previous section is connected to a lossless DC-DC boost converter (instead of a resistor). The output of the converter is then connected to a lossless three-phase VSC in order to inject power into the AC grid, as shown in Figure 6.

    The total three-phase reactive power supplied by the converter (Q) = 37.5 VAr, the grid voltage = 200∠0 V as shown in the figure and V_{dc} is maintained at 70 V.

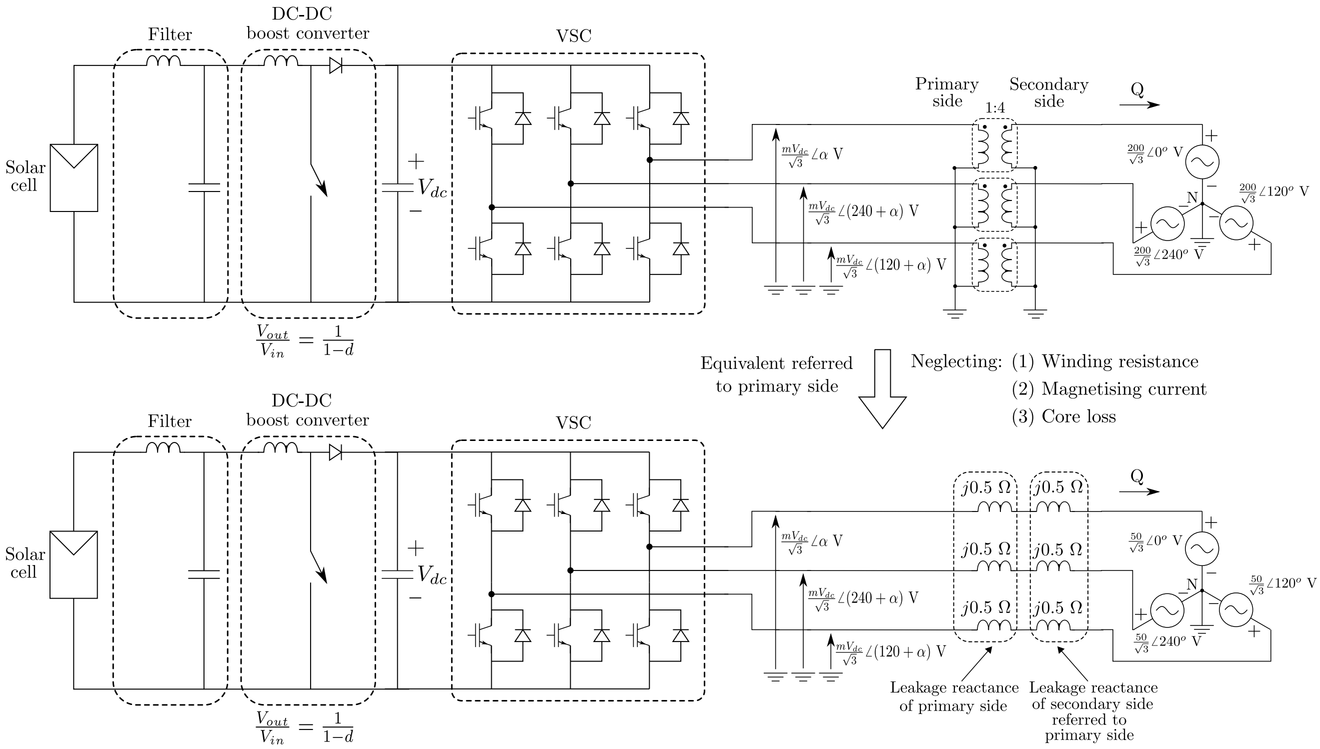


Figure 6: Schematic of Problem 12

If the solar module is to operate at the maximum power point, then calculate

(a) Duty ratio (d) of DC-DC boost converter = ______,

The relation between the average input and output voltage of the DC-DC boost converter and the duty ratio is indicated in the figure.

(b) Modulation index (m) = ______,

Note that the modulation index relates the dc voltage (V_{dc}) to the fundamental frequency component of the line to line rms voltage on the ac side. It can be varied by changing the switching pattern of the converter (PWM).

(c) Phase angle (α) = ______

Note that the phase angle can be varied by shifting (advancing or delaying) the switching instants.

13. A cylindrical rotor (non-salient) synchronous generator is modelled as a voltage source (E_{fd}) behind a reactance X_s. Note that the voltage E_{fd} is directly proportional to the field voltage and the speed. The angle δ is dependent on the position of the rotor relative to the resultant rotating magnetic field seen by the stator windings. The generator is connected to the grid (which is represented by a three-phase voltage source having a magnitude V_b) as shown in Figure 7.

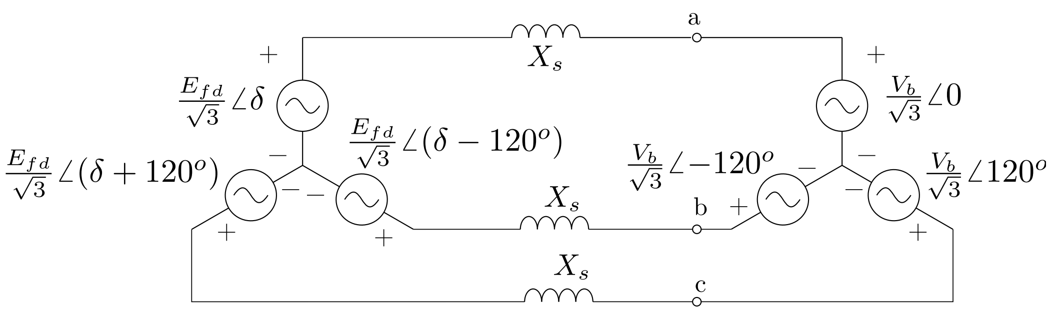


Figure 7: Synchronous generator connected to voltage source

(a) If the initial steady state value of δ is less than 90^o, what impact will a small increase in prime mover power have on

i. the steady state electrical power output of the generator?

ii. the steady state value of δ?

Note: Assume here that E_{fd}, V_b and the grid frequency are unchanged. Also note that in steady state, the generator electrical speed equals to the grid frequency. The expression for three phase electrical power (in steady state) equals $P_e = \frac{E_{fd}V_b}{X_s}\sin\delta$.

(b) If the prime-mover power is not changed, but E_{fd} is changed by *a small amount* by changing the field voltage, then show that in steady state the change in the reactive power injected by the generator into the grid is given by the following expression:

$$\Delta Q = \frac{V_b}{X_s \cos\delta_o}\Delta E_{fd}$$

where δ_o is the initial steady state angle and ΔE_{fd} denotes the (small) change in E_{fd}.

14. If the synchronous generator of the previous section is connected to a three-phase balance resistive load as shown in Figure 11. Assuming it is initially in steady state, what impact will an increase in the prime mover power have on

    (a) the steady state speed of the generator?

    (b) the steady state electrical power output of the generator?

    (c) steady state E_{fd}? Assume that the field voltage is constant.

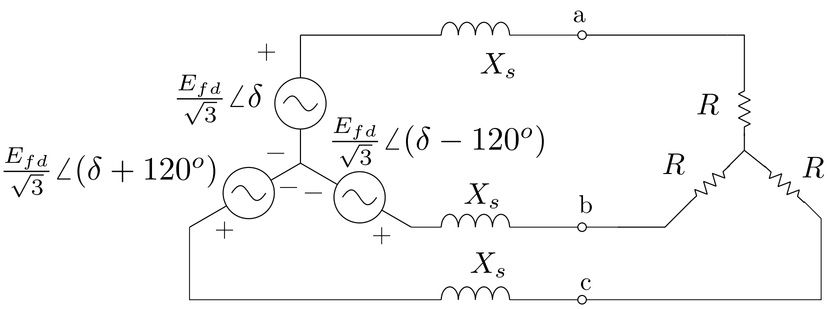


Figure 8: Synchronous generator connected to resistive bank

15. The characteristics of a wind turbine are shown in the figure below (y axis is the turbine speed) at the minimum blade pitch angle. The wind turbine power and speed ratings are also indicated on the figure. The turbine, generator and power electronic system have compatible speed and power ratings. The turbine has blade-pitch control to avoid over-speed, while the generator torque-speed characteristic is power electronically controlled. If the wind speed is 9 m/s, then it is most appropriate that the wind-turbine should be made to operate at the

    (a) Rated Speed

    (b) Rated Power

    (c) Maximum Power Point at that speed.

    What is the answer to this question if the wind speed is (a) 11 m/s and (b) 15 m/s? In each case, state whether it is necessary to invoke blade-pitch control.

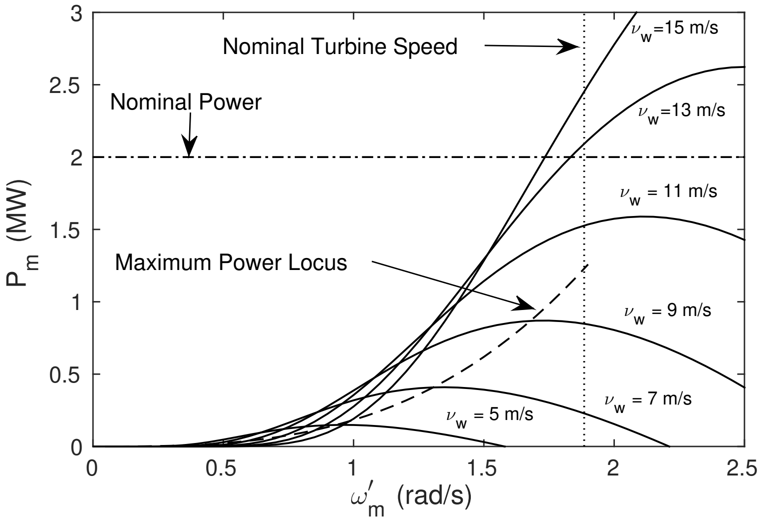


Figure 9: Wind turbine characteristics

16. A three-phase synchronous generator is used in the configuration shown in the figure below. The wind turbine characteristic is shown in Fig. 9. The field voltage of the generator is controlled so that the dc link voltage V_{dc} is regulated at 3.75 kV. The VSC is controlled so that it extracts maximum power from the wind. The reactive power output at the terminal of the VSC is maintained at zero. Compute m and α for the VSC.

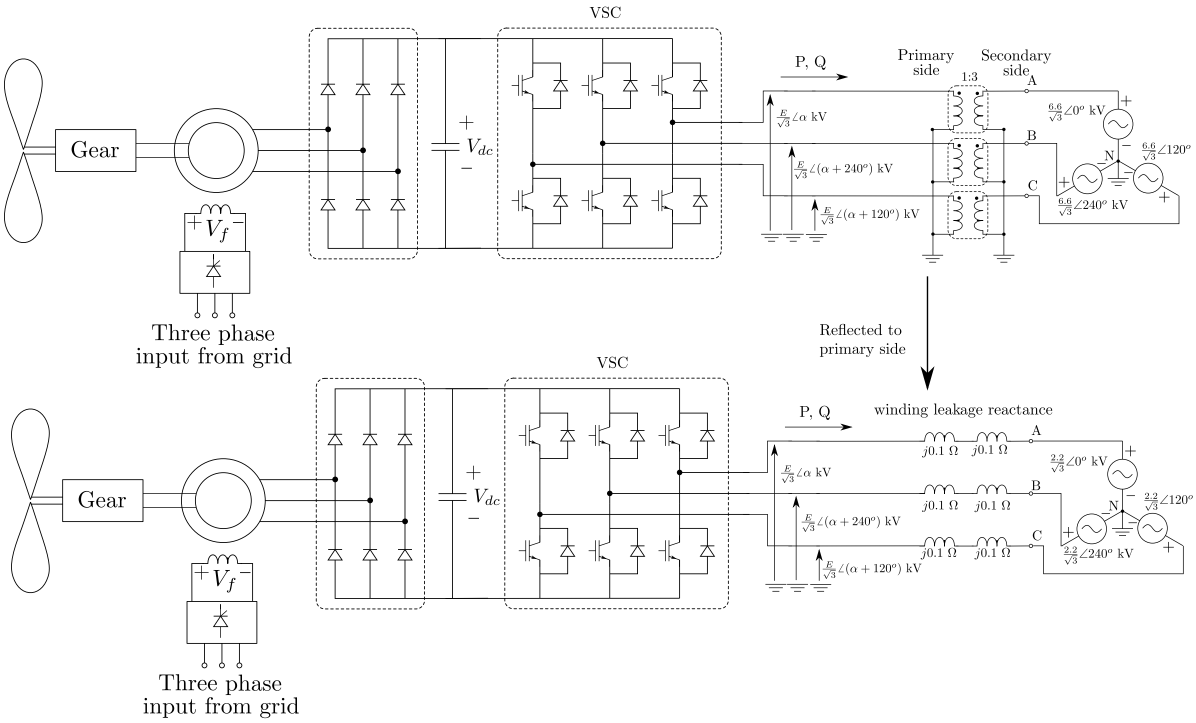


Figure 10: Schematic of the wind-generator system

- If $E = mV_{dc}$, then what will be the value of m and α for wind speed of 9 m/s ?

17. The power electronic configuration in the wind-turbine generator system of the previous question is changed to the one shown below. The field voltage of the synchronous generator is controlled such that the dc link voltage V_{dc} is maintained at 8.5 kV. If the wind speed is 9 m/s, then

    (a) compute the firing delay angle of the three-phase LCC bridge to extract maximum power.

    (b) determine P and Q assuming that the converters are lossless.

    The speed-torque characteristics of the wind turbine is given in Fig. 9.

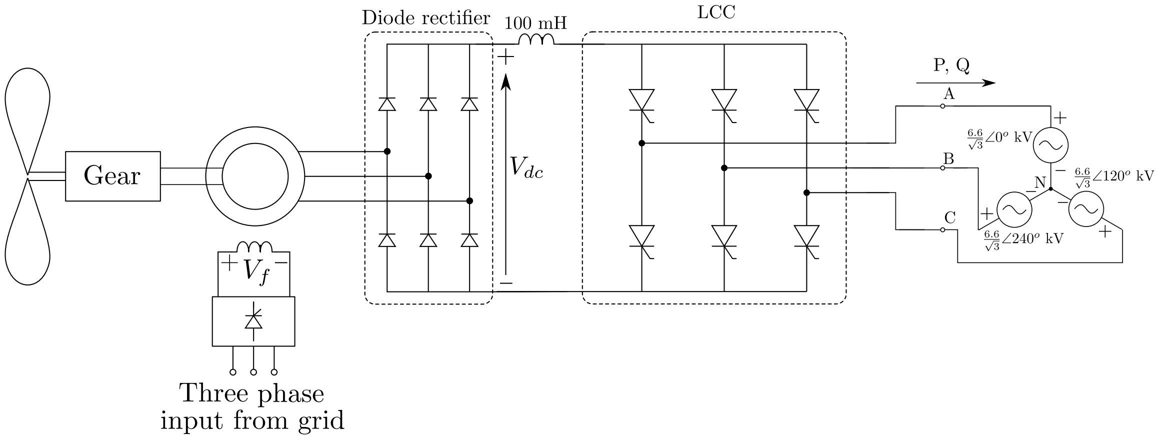


Figure 11: Schematic of the wind-generator system

Note: The expressions of an LCC bridge converter are given below for a firing angle delay α with reference to Figure 12.

$$v_{dc} = \frac{3\sqrt{2}}{\pi} V \cos\alpha$$
$$P = v_{dc} i_{dc}, \quad Q = P \tan\phi$$

where α is the angle by which fundamental line current lags the line to neutral source voltage.

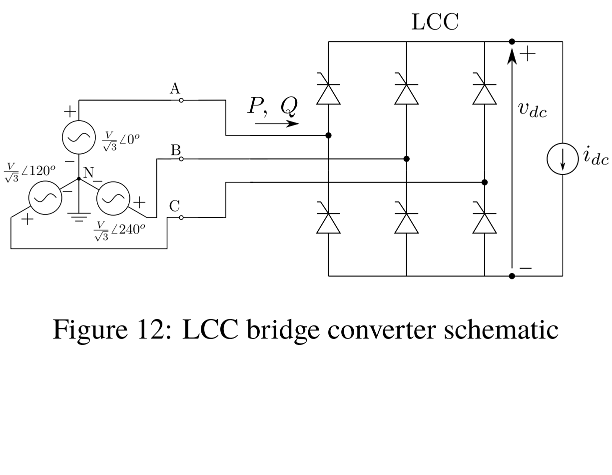


Figure 12: LCC bridge converter schematic

18. A three-terminal AC-DC system is shown in the figure below. VSC 1 regulates the dc voltage V_{dc1} at 500 kV, while VSC 2 and VSC 3 draw power equal to 500 MW and 400 MW respectively. The transmission lines are represented by an equivalent π model. If the ripples in V_{dc1} are neglected, find V_{dc2} and V_{dc3}.