Course:
ELEC ENG 3110 Electric Power Systems
ELEC ENG 7074 Electric Power Systems PG

(Semester 2, 2021)

Tutorial 1

(Due in person at the lecture at 16:10 on 4 August 2020)

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T1.1 Summarize your understanding of the concept of reactive power.

T1.2 Consider the a.c. system in Figure 1 in which the supply frequency is 50 Hz. The peak value of the voltage source is 113 kV. The source inductance is $L_s = 40\ \text{mH}$ and the load resistance and capacitance are respectively $R_L = 60\ \Omega$ and $C_L = 10\ \mu\text{F}$. Assume the system is operating in a sinusoidal steady-state.

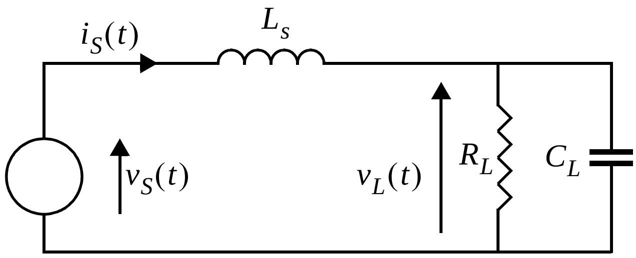

Figure 1: Circuit for Problem 1.2.

(a) Calculate the source impedance (in ohm).

(b) Calculate the admittance (in Siemens) of the load comprising the parallel combination of the load resistance and capacitance.

(c) Calculate the load impedance.

(d) Calculate the root mean square (RMS) of the current (in Amps) supplied by the source.

(e) Calculate the RMS load voltage (in kV).

(f) Calculate the average power consumed by the load (in MW).

(g) Calculate the reactive power supplied by the source (in MVAr).

(h) Calculate the reactive power consumed by the load (in MVAr).

(i) The load capacitance is replaced by an inductance $L_L = 1.0\ \text{H}$. Calculate the RMS load voltage, the reactive power (i) supplied by the source; and (ii) consumed by the load. How do the values compare with those calculated in (e), (g) and (h). Comment on the differences.

T1.3 Under steady-state conditions the real- and reactive-power consumed by loads are usually constant, independent of small variations in voltage. This means that we cannot represent the loads in an electric power network as resistors, inductors and capacitors. To begin to understand the implications of this consider the network in Figure 2 in which a generator supplies a constant power load through a transmission line represented by an inductance with reactance jX. The generator voltage magnitude is held constant by its voltage control system to $\hat{V}_S = V_S e^{j\theta_s}$. The complex load is $S_L = P_L + jQ_L$ is constant (i.e. independent of the load bus voltage, $\hat{V}_L = V_L e^{j\theta_L}$). [Note: in power systems it is common to refer to network 'nodes' as 'buses'].

(a) Attempt to formulate an equation, or set of equations, to calculate the load bus voltage. *Note that this is a challenging problem and your attempts to independently analyse this problem early in the course - and then return to it frequently - will be invaluable to developing your understanding of power systems.*

(b) In your attempt you might consider how the load current $\hat{I}$ is related to the load power and voltage and how you might apply Kirchoffs Laws to the solution of the load bus voltage.

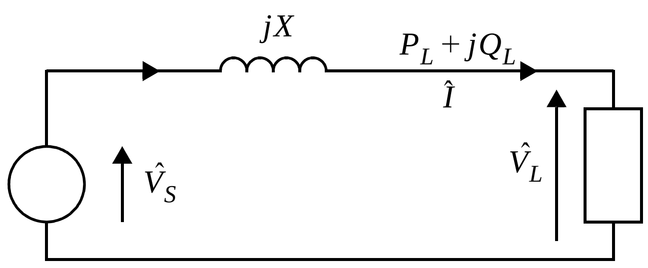

Figure 2: Power-system circuit for Problem 1.3.

T1.4 Figure 3 is the stylized system demand profile for one day.

(a) What is the maximum demand?

(b) What is the minimum demand?

(c) What is the total energy consumed during the day?

(d) What is the average demand?

(e) Construct the demand-duration curve for this day.

(f) For what percentage of the day is the load at or above 1,900 MW?

(g) For what proportion of the day is the load at or above 900 MW?

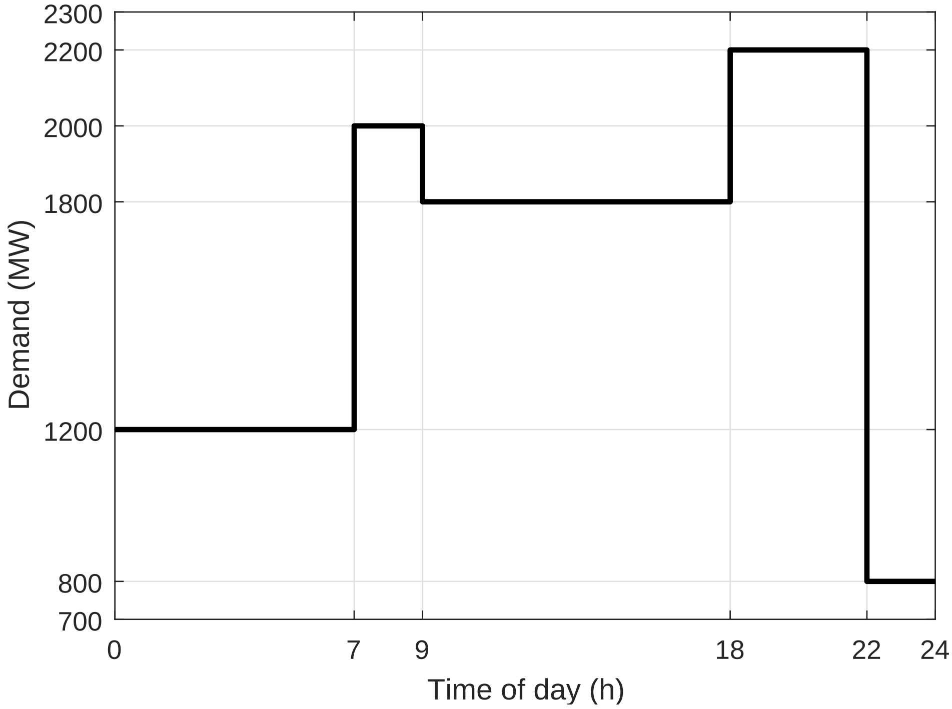

Figure 3: Problem 1.4 – Demand Profile.

T1.5 A household is equipped with a rooftop solar PV source and has a connection to the grid as depicted by the circuit diagram in Figure 4.

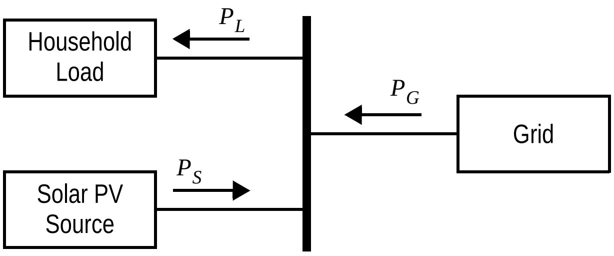

Figure 4: Problem 1.5 – Household power supply.
(Note: Arrows are drawn in the positive direction for the corresponding variables.)

Figure 5 is the stylized plot of the household load (P_L) and solar PV generation (P_S) for one day.

(a) Construct a plot of the power supplied to the household by the grid (P_G).

(b) What is the maximum power consumed by the household from the grid?

(c) What is the maximum power supplied by the household to the grid?

(d) How much energy is consumed by the household during the day?

(e) How much of the energy consumed by the household is supplied from the solar PV source?

(f) By what factor would the capacity of the solar PV source need to be increased such that the total solar PV energy produced is equal to the energy consumed by the household?

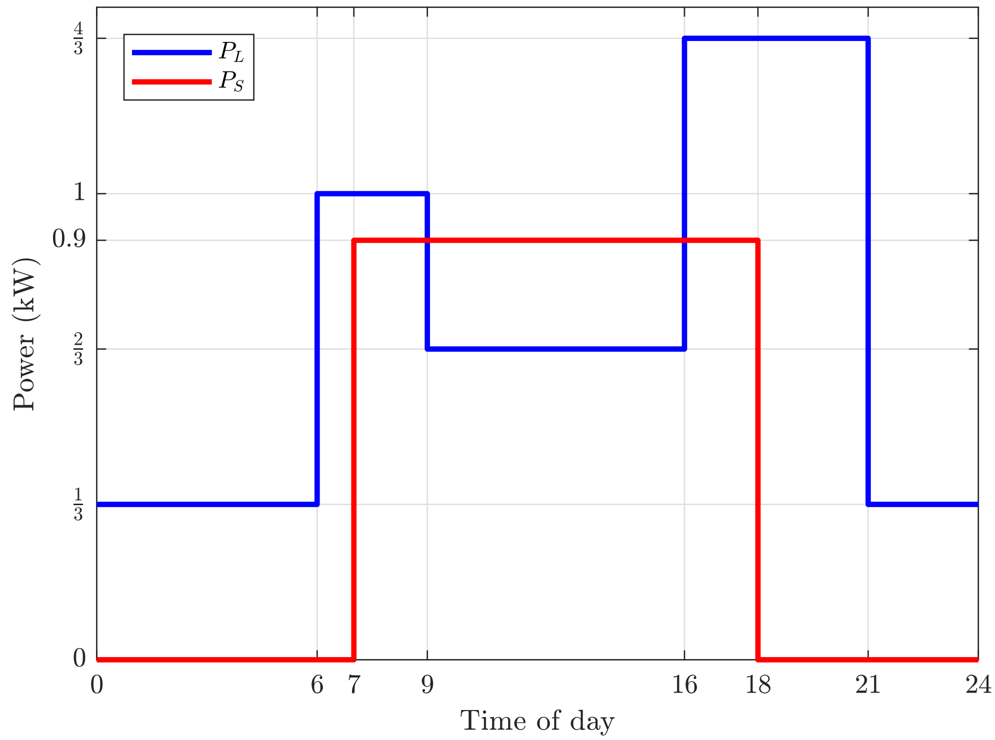

Figure 5: Problem 1.5 – Household demand and solar PV generation profile for one day.

(g) Suppose the household installs a battery as shown in Figure 6. The battery has an energy capacity of 5 kWh and rated continuous power capacity of 2.5 kW for both charging and discharging. Suppose that the battery is fully charged at 0 hours. The battery power output is assumed to be continuously controllable within its power range from +2.5 kW (rated discharge power) to -2.5 kW (rated charging power). Show by means of time-series plots how you would control the battery power output P_B and stored energy E_B so as to minimize the energy that the household consumes from the grid.

(h) Based on your answer to (g):

(i) How much energy is consumed by the household from the grid?

(ii) What is the maximum power consumed by the household from the grid?

(iii) Can you suggest how your battery control strategy could be changed to also minimize the power consumed from the grid?

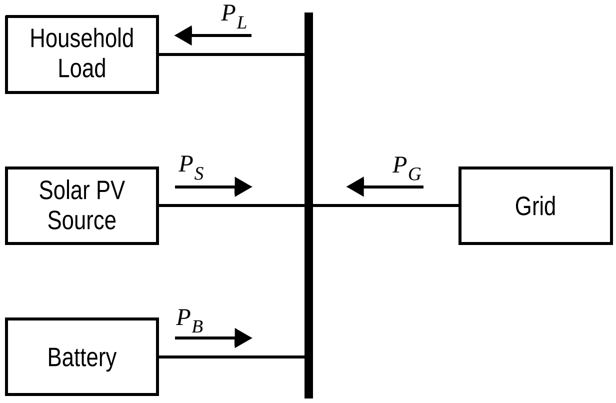

Figure 6: Problem 1.5 – Household power supply augmented with a battery.
(Note: Arrows are drawn in the positive direction for the corresponding variables.)

T1.6 The transmission system in Figure 7 supplies a distribution network through two parallel circuits. Note that the two transmission lines and the HV sides of the transformers are connected to a common busbar. This network is currently rated to provide N-1 reliability for a maximum demand of at least 100 MW. (Note: For simplicity in the following analysis we neglect the reduction in power transmission limits due to the need to also transmit reactive power.)

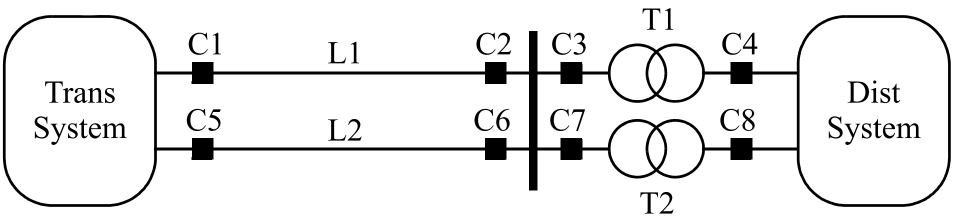

Figure 7: Problem 1.6 – Transmission system supply to a distribution network.

(a) What is the minimum required power rating of transmission lines L1 & L2 and transformers T1 & T2 to achieve this N-1 reliability standard.

Due to the adoption of dynamic line rating technology it is anticipated that L1 & L2 will each achieve a rating of at least 120 MW. The transformers T1 & T2 are each rated at 105 MW.

(b) The annual demand duration curve projected for five years hence is shown in Figure 8. Explain whether or not the transmission system will comply with the N-1 reliability standard in five years time.

(c) Commencing in five years time for how many hours during the year is there a risk that the total load will not be able to be supplied?

(d) For which line and/or transformer outages will it be possible to supply the projected maximum demand?

(e) If L1 is out-of-service when the projected demand is at its maximum value how much load would need to be disconnected to ensure that all equipment operates within its rated values. (You can assume that the circuit breakers (C1, ..., C6) and the busbar are not limiting.)

(f) Repeat the previous question for transformer T2 being out-of-service.

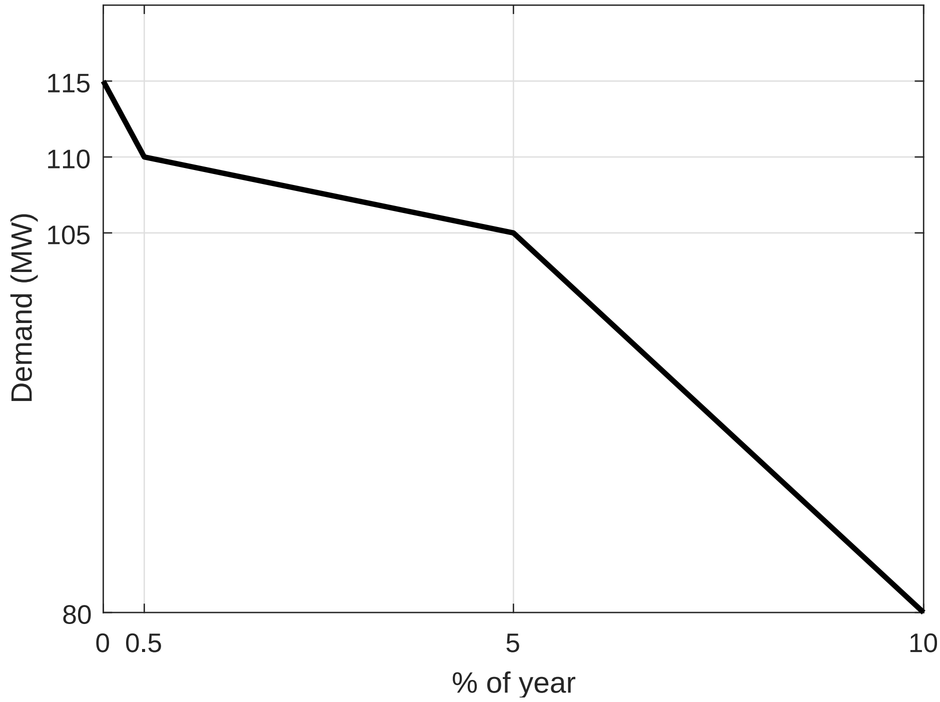

Figure 8: Problem 1.6 – Annual Demand Duration Curve for Year 5.

T1.7 What are the primary objectives when operating a power system?

T1.8 Consider the circuit in Figure 9 which represents one phase of an open-circuit 500 kV (rms, phase-phase) transmission line of length 300 km. The transmission line is energized at the sending end with a balanced 50 Hz three-phase supply with phase-neutral voltage of $\hat{V}_S = 1.05 \times \dfrac{500}{\sqrt{3}}$ kV. The line inductance and capacitance are respectively $L = 0.2586$ H and $C = 4.137$ uF

(a) Calculate the current (A) supplied by the source.

(b) Calculate the real (MW) and reactive power (MVAr) supplied by the source.

(c) Calculate the voltage $\hat{V}_R$ (kV) at the open circuit receiving end of the transmission line.

(d) To lower the voltage of long lightly loaded EHV transmission lines it is common to connect reactors. Recalculate the quantities in (a) to (c) above with the reactor switch S closed. The inductance of the reactor L_R consumes 100 MVAr when the applied voltage is $500/\sqrt{3}$ kV.

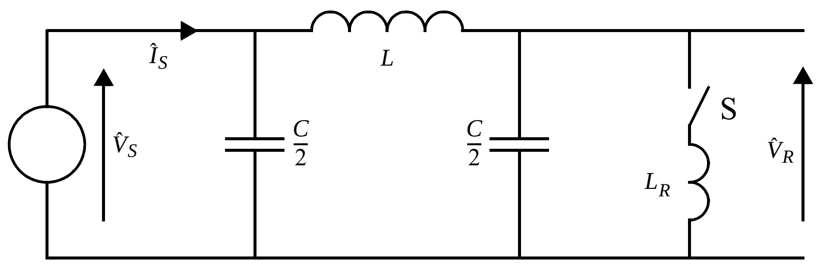

Figure 9: Figure 1.8 – Equivalent circuit model of one phase of an open-circuit 500 kV transmission line.

T1.9 The simple RL circuit in Figure 10 is of considerable practical interest in the analysis of short-circuits in power systems. We will return to it later in the course.

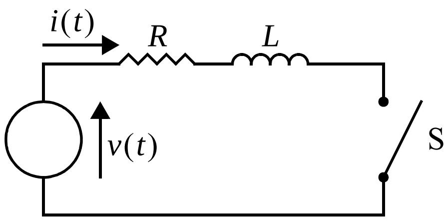

Figure 10: RL Circuit for Problem 1.9

The sinusoidal source voltage is $v(t) = \sqrt{2}V\cos(2\pi f_0 t + \alpha)$ and the switch S is initially open and closes at t = 0+. The objective is to calculate the general solution for the current flow $i(t)$ in this circuit: $i(t) = i_T(t) + i_S(t)$ where $i_S(t)$ is the forced response due to the sinusoidal source voltage and $i_T(t)$ is the transient solution.

(a) Derive the forced response, $i_S(t)$. [Hint: this corresponds to current under sinusoidal steady-state conditions and can be determined by transforming the problem into the phasor domain.]

(b) Derive the transient solution, $i_T(t)$, which you will be able to resolve to a single unknown constant which is to be determined by the initial conditions.

(c) Based on (a) and (b) and the fact that at t = 0+ the current is zero derive the general solution for the current.

(d) How long does it take for the transient component of the current to decay to 2% of its initial value? How could this time be reduced?

(e) If $V = 158.8\,\text{kV}$, $f_0 = 50\,\text{Hz}$, $R = 0.8\Omega$, $L = 0.25\,\text{H}$ produce a single plot in Matlab showing the current response for $\alpha = 90°$, $45°$ and $0°$.

From your plot what is the maximum / minimum current in each case? Can you explain the physical reason for your observation?

T1.10 The regulation of frequency within very tight tolerances is of critical importance. Regulation of power system frequency is closely related to the regulation of the rotor-speed of synchronous machines. The regulation of rotor-speed depends on balancing the mechanical power developed by the turbine and the electrical power supplied by the machine. A much simplified model of the speed-control system (usually called a 'speed-governor' or 'governor') of a synchronous system is shown in Figure 11.

(a) With the governor control loop open (i.e. switch SG open) what is the final steady-state deviation of the rotor-speed from synchronous-speed (i.e. $\Delta\omega$) due to a step-change in the load of $\Delta P_L = p$.

 (i) If $p > 0$ (i.e. an increase in load) does the rotor-speed increase or decrease?

 (ii) Does $2H$, the inertia constant, affect the final rotor-speed deviation?

(b) Repeat (a) with the governor in-service (i.e. with the switch SG closed). Additionally,

 (i) Do the fuel control or turbine time-constants affect the final rotor-speed deviation?

 (ii) How does the value of the 'speed-droop' setting, R, affect the final rotor-speed deviation?

In Figure 11 all quantities are the deviation of the variable from their initial steady-state values. Thus, all variables (i.e. Δx) are initially zero. The model is a per-unitized representation of the system. Rotor-angle dynamics are neglected on the basis that rotor-angle oscillations decay much more rapidly than do the rotor-speed variations that occur due to governor response. The model represents (i) the fuel control system as a first order system with time-constant T_g; (ii) the turbine as a first order system with time-constant T_t; and (iii) rotor-dynamics by the rotational acceleration equation in which $2H$ is the per-unit rotational-inertia constant and D is the per-unit damping constant representing speed-dependence of loads as well as windage and friction effects within the generating systems.

- $\Delta\omega$ is the perturbation in rotor-speed (equivalently system frequency)
- ΔP_m is the perturbation in the mechanical power developed by the turbine
- ΔP_L is the perturbation in the electrical demand
- $\Delta P_a = \Delta P_m - \Delta P_L$ is the acceleration power

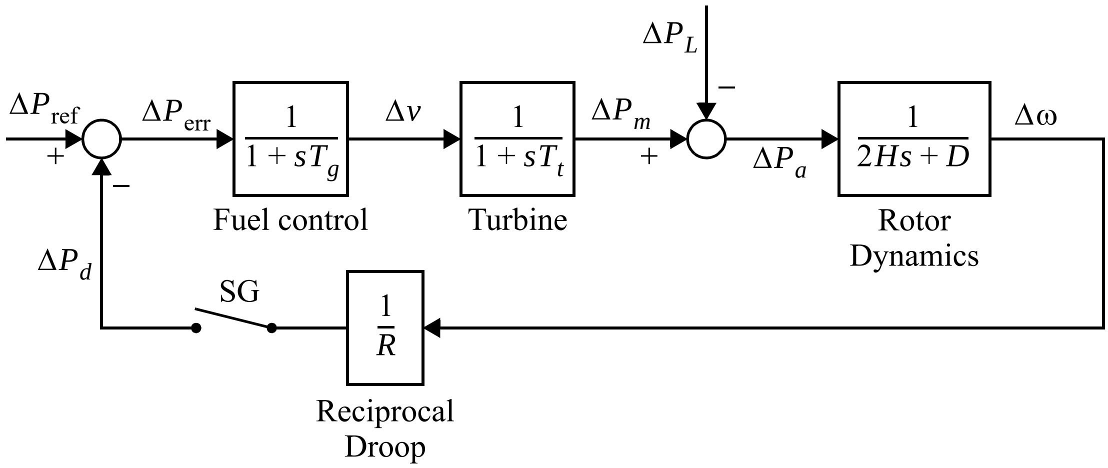

Figure 11: Simplified synchronous-generator speed-governing system for conceptual analysis.