1 INTRODUCTION TO ELECTRIC DRIVE SYSTEMS

Spurred by advances in power electronics, adjustable-speed electric drives now offer great opportunities in a plethora of applications: pumps and compressors to save energy, precision motion control in automated factories, and wind-electric systems to generate electricity, to name a few. A recent example is the commercialization of hybrid-electric vehicles [1]. Figure 1.1 shows the photograph of a hybrid arrangement in which the outputs of the internal-combustion (IC) engine and the electric drive are mechanically added in parallel to drive the wheels. Compared to vehicles powered solely by gasoline, these hybrids reduce fuel consumption by more than 50 percent and emit far fewer pollutants.

1.1 HISTORY

Electric machines have now been in existence for over a century. All of us are familiar with the basic function of electric motors: to drive mechanical loads by converting electrical energy. In the absence of any control, electric motors operate at essentially a constant speed. For example, when the compressor-motor in a refrigerator turns on, it runs at a constant speed.

FIGURE 1.1 Photograph of a hybrid-electric vehicle.

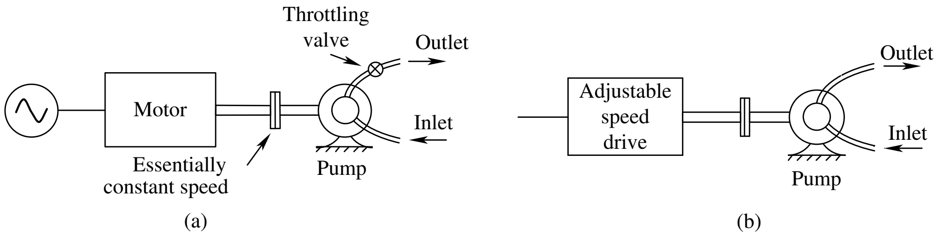

FIGURE 1.2 Traditional and ASD-based flow control systems.

Traditionally, motors were operated uncontrolled, running at constant speeds, even in applications where efficient control over their speed could be very advantageous. For example, consider the process industry (like oil refineries and chemical factories) where the flow rates of gases and fluids often need to be controlled. As Figure 1.2a illustrates, in a pump driven at a constant speed, a throttling valve controls the flow rate. Mechanisms such as throttling valves are generally more complicated to implement in automated processes and waste large amounts of energy. In the process industry today, electronically controlled adjustable-speed drives (ASDs), shown in Figure 1.2b, control the pump speed to match the flow requirement. Systems with adjustable-speed drives are much easier to automate, and offer much higher energy efficiency and lower maintenance than the traditional systems with throttling valves.

These improvements are not limited to the process industry. Electric drives for speed and position control are increasingly being used in a variety of manufacturing, heating, ventilating and air conditioning (HVAC), and transportation systems.

1.2 WHAT IS AN ELECTRIC-MOTOR DRIVE?

Figure 1.3 shows the block diagram of an electric-motor drive, or for short, an electric drive. In response to an input command, electric drives efficiently control the speed and/or the position of the mechanical load, thus eliminating the need for a throttling valve like the one shown in Figure 1.2a. The controller, by comparing the input command for speed and/or position with the actual values measured through sensors, provides appropriate control signals to the power-processing unit (PPU) consisting of power semiconductor devices.

As Figure 1.3 shows, the power-processing unit gets its power from the utility source with single-phase or three-phase sinusoidal voltages of a fixed frequency and constant amplitude.

The power-processing unit, in response to the control inputs, efficiently converts these fixed-form input voltages into an output of the appropriate form (in frequency, amplitude, and the number of phases) that is optimally suited for operating the motor. The input command to the electric drive in Figure 1.3 may come from a process computer, which considers the objectives of the overall process and issues a command to control the mechanical load. However, in general-purpose applications, electric drives operate in an open-loop manner without any feedback.

Throughout this text, we will use the term *electric-motor drive* (*motor drive* or *drive* for short) to imply the combination of blocks in the box drawn by dotted lines in Figure 1.3. We will examine all of these blocks in subsequent chapters.

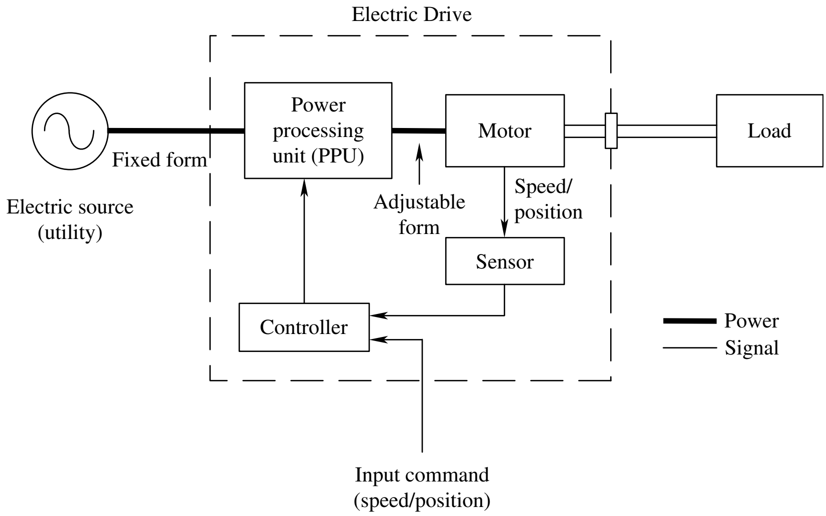

FIGURE 1.3 Block diagram of an electric drive system.

1.3 FACTORS RESPONSIBLE FOR THE GROWTH OF ELECTRIC DRIVES

Technical Advancements. Controllers used in electric drives (see Figure 1.3) have benefited from revolutionary advances in microelectronic methods, which have resulted in powerful linear integrated circuits and digital signal processors [2]. These advances in semiconductor fabrication technology have also made it possible to significantly improve voltage- and current-handling capabilities, as well as the switching speeds of power semiconductor devices, which make up the power-processing unit of Figure 1.3.

Market Needs. The world market of adjustable-speed drives was estimated as a $20 billion industry in 1997. This market is growing at a healthy rate [3] as users discover the benefits of operating motors at variable speeds. These benefits include improved process control, reduction in energy usage, and less maintenance.

The world market for electric drives would be significantly impacted by large-scale opportunities for harnessing wind energy. There is also a large potential for applications in the developing world, where the growth rates are the highest.

Applications of electric drives in the United States are of particular importance. The per-capita energy consumption in the United States is almost twice that in Europe, but the electric drive market in 1997 was less than one-half. This deficit, due to a relatively low cost of energy in the United States, represents a tremendous opportunity for application of electric drives.

1.4 TYPICAL APPLICATIONS OF ELECTRIC DRIVES

Electric drives are increasingly being used in most sectors of the economy. Figure 1.4 shows that electric drives cover an extremely large range of power and speed — up to 100 MW in power and up to 80,000 rpm in speed.

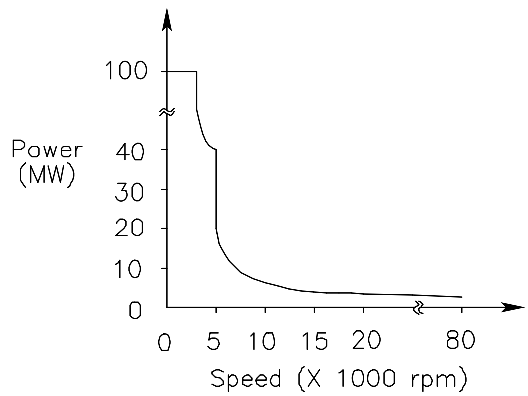

FIGURE 1.4 Power and speed range of electric drives.

Due to the power-processing unit, drives are not limited in speeds, unlike line-fed motors that are limited to 3,600 rpm with a 60-Hz supply (3,000 rpm with a 50-Hz supply). A large majority of applications of drives are in a low-to-medium power range, from a fractional kW to several hundred kW. Some of these application areas are listed below:

- Process Industry: agitators, pumps, fans, and compressors
- Machining: planers, winches, calendars, chippers, drill presses, sanders, saws, extruders, feeders, grinders, mills, and presses
- Heating, Ventilating and Air Conditioning: blowers, fans, and compressors
- Paper and Steel Industry: hoists, and rollers
- Transportation: elevators, trains, and automobiles
- Textile: looms
- Packaging: shears
- Food: conveyors, and fans
- Agriculture: dryer fans, blowers, and conveyors
- Oil, Gas, and Mining: compressors, pumps, cranes, and shovels
- Residential: heat pumps, air conditioners, freezers, appliances, and washing machines

In the following sections, we will look at a few important applications of electric drives in energy conservation, wind-electric generation, and electric transportation.

1.4.1 Role of Drives in Energy Conservation [4]

It is perhaps not obvious how electric drives can reduce energy consumption in many applications. Electric costs are expected to continue their upward trend, which makes it possible to justify the initial investment in replacing constant-speed motors with adjustable-speed electric drives, solely on the basis of reducing energy expenditure (see Chapter 15). The environmental impact of energy conservation, in reducing global warming and acid rain, is also of vital importance [5].

To arrive at an estimate of the potential role of electric drives in energy conservation, consider that the motor-driven systems in the United States are responsible for

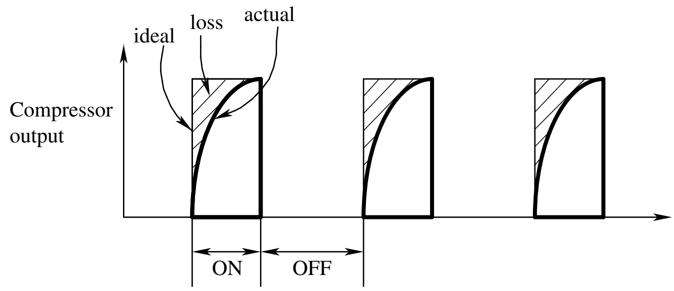

FIGURE 1.5 Heat pump operation with line-fed motors.

over 57% of all electric power generated and 20% of all the energy consumed. The United States Department of Energy estimates that if constant-speed, line-fed motors in pump and compressor systems were to be replaced by adjustable-speed drives, the energy efficiency would improve by as much as 20%. This improved energy efficiency amounts to huge potential savings (see homework problem 1.1). In fact, the potential yearly energy savings would be approximately equal to the annual electricity use in the state of New York. Some energy-conservation applications are described as follows.

1.4.1.1 Heat Pumps and Air Conditioners [6]

Conventional air conditioners cool buildings by extracting energy from inside the building and transferring it to the atmosphere outside. Heat pumps, in addition to the air-conditioning mode, can also heat buildings in winter by extracting energy from outside and transferring it inside. The use of heat pumps for heating and cooling is on the rise; they are now employed in roughly one out of every three new homes constructed in the United States (Figure 1.5).

In conventional systems, the building temperature is controlled by on/off cycling of the compressor motor by comparing the building temperature with the thermostat setting. After being off, when the compressor motor turns on, the compressor output builds up slowly (due to refrigerant migration during the off period) while the motor immediately begins to draw full power. This cyclic loss (every time the motor turns on) between the ideal and the actual values of the compressor output, as shown in Figure 1.6, can be eliminated by running the compressor continuously at a speed at which its output matches the thermal load of the building. Compared to conventional systems, compressors driven by adjustable speed drives reduce power consumption by as much as 30 percent.

1.4.1.2 Pumps, Blowers, and Fans

To understand the savings in energy consumption, let us compare the two systems shown in Figure 1.2. In Figure 1.6, curve A shows the full-speed pump characteristic; that is, the pressure (or head) generated by a pump, driven at its full speed, as a function of flow rate. With the throttling valve fully open, curve B shows the unthrottled system characteristic, that is, the pressure required as a function of flow rate, to circulate fluid or gas by overcoming the static potential (if any) and friction. The full flow rate Q_1 is given by the intersection of the unthrottled system curve B with the pump curve A. Now consider that a reduced flow rate Q_2 is desired, which requires a pressure H_2 as seen from the unthrottled system curve B. Below, we will consider two ways of achieving this reduced flow rate.

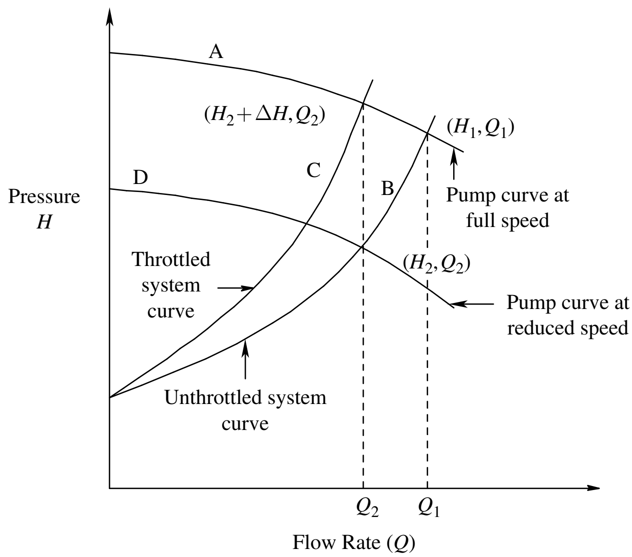

FIGURE 1.6 Typical pump and system curve.

With a constant-speed motor as in Figure 1.2a, the throttling valve is partially closed, which requires additional pressure to be overcome by the pump, such that the throttled system curve C intersects with the full-speed pump curve A at the flow rate Q_2. The power loss in the throttling valve is proportional to Q_2 times ΔH. Due to this power loss, the reduction in energy efficiency will depend on the reduced flow-rate intervals, compared to the duration of unthrottled operation.

The power loss across the throttling valve can be eliminated by means of an adjustable-speed drive. The pump speed is reduced such that the reduced-speed pump curve D in Figure 1.6 intersects with the unthrottled system curve B at the desired flow rate Q_2.

Similarly, in blower applications, the power consumption can be substantially lowered, as plotted in Figure 1.7, by reducing the blower speed by means of an adjustable speed drive to decrease flow rates, rather than using outlet dampers or inlet vanes. The percentage reduction in power consumption depends on the flow-rate profile (see homework problem 1.5).

Electric drives can be beneficially used in almost all pumps, compressors, and blowers employed in air-handling systems, process industries, and the generating plants of electric utilities. There are many documented examples where energy savings alone have paid for the cost of conversion (from line-fed motors to electric-drive systems) within six months of operation. Of course, this advantage of electric drives is made possible by the ability to control motor speeds in an energy-efficient manner, as discussed in the subsequent chapters.

1.4.2 Harnessing Wind Energy

Electric drives also play a significant role in power generation from renewable energy sources, such as wind and small hydro. The block diagram for a wind-electric system is shown in Figure 1.8, where the variable-frequency ac produced by the wind-turbine–driven

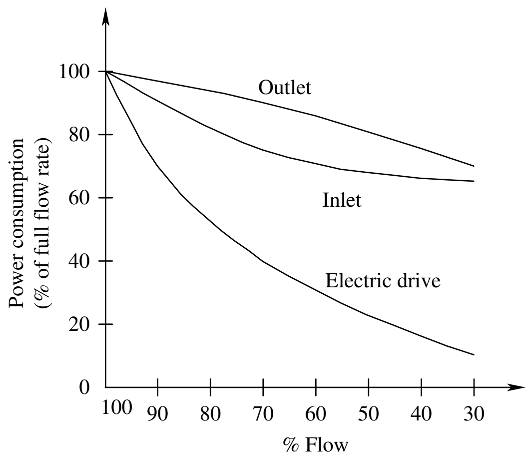

FIGURE 1.7 Power consumption in a blower.

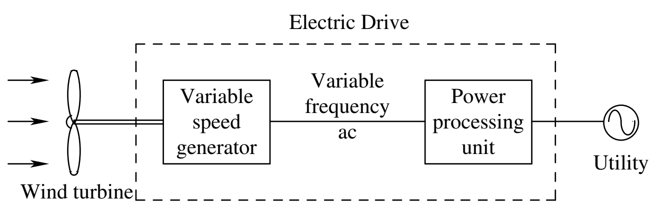

FIGURE 1.8 Electric drive for wind generators.

generator is interfaced with the utility system through a power-processing unit. By letting the turbine speed vary with the wind speed, it is possible to recover a higher amount of energy compared to systems where the turbine essentially rotates at a constant speed due to the generator output being directly connected to the utility grid [7]. Harnessing of wind energy is turning out to be a major application of electric drives and this sector is expected to grow rapidly.

1.4.3 Electric Transportation

Electric transportation is widely used in many countries. Experiments with magnetically-levitated trains are being conducted in Japan and Germany. High-speed electric trains are also presently being evaluated in the United States for mass transportation in the northeastern and southwestern corridors.

Another important application of electric drives is in electric vehicles and hybrid-electric vehicles. The main virtue of electric vehicles (especially to large metropolitan areas) is that they emit no pollutants. However, electric vehicles must wait for suitable batteries, fuel cells, or flywheels to be developed before the average motorist accepts them. On the other hand, hybrid-electric vehicles are already commercialized [1].

There are many new applications of electric drives in conventional automobiles. Also, there is an ongoing attempt to replace hydraulic drives with electric drives in airplanes and ships.

1.5 THE MULTI-DISCIPLINARY NATURE OF DRIVE SYSTEMS

The block diagram of Figure 1.3 points to various fields that are essential to electric drives: electric machine theory, power electronics, analog and digital control theory, real-time application of digital controllers, mechanical system modeling, and interaction with electric-power systems. A brief description of each of the fields is provided in the following subsections.

1.5.1 Theory of Electric Machines

For achieving the desired motion, it is necessary to control electric motors appropriately. This requires a thorough understanding of the operating principles of various commonly used motors such as dc, synchronous, induction and stepper motors. The emphasis in an electric drives course needs to be different from that in traditional electric machines courses, which are oriented towards design and application of line-fed machines.

1.5.2 Power Electronics

The discipline related to the power-processing unit in Figure 1.3 is often referred to as power electronics. Voltages and currents from a fixed form (in frequency and magnitude) must be converted to the adjustable form best suited to the motor. It is important that the conversion take place at a high energy efficiency, which is realized by operating power semiconductor devices as switches.

Today, power processing is being simplified by means of “Smart Power” devices, where power semiconductor switches are integrated with their protection and gate-drive circuits into a single module. Thus, the logic-level signals (such as those supplied by a digital signal processor) can directly control high-power switches in the PPU. Such power-integrated modules are available with voltage-handling capability approaching 4 kilovolts and current-handling capability in excess of 1,000 amperes. Paralleling such modules allows even higher current-handling capabilities.

The progress in this field has made a dramatic impact on power-processing units by reducing their size and weight, while substantially increasing the number of functions that can be performed [3].

1.5.3 Control Theory

In the majority of applications, the speed and position of drives need not be controlled precisely. However, there are an increasing number of applications, for example in robotics for automated factories, where accurate control of torque, speed, and position are crucial. Such control is accomplished by feeding back the measured quantities, and by comparing them with their desired values, in order to achieve a fast and accurate control.

In most motion-control applications, it is sufficient to use a simple proportional-integral (PI) control as discussed in Chapter 8. The task of designing and analyzing PI-type controllers is made easy due to the availability of powerful simulation tools such as PSpice.

1.5.4 Real-Time Control Using DSPs

All modern electric drives use microprocessors and digital signal processors (DSPs) for flexibility of control, fault diagnosis, and communication with the host computer and with other process computers. Use of 8-bit microprocessors is being replaced by 16-bit and even 32-bit microprocessors. Digital signal processors are used for real-time control in applications that demand high performance or where a slight gain in the system efficiency more than pays for the additional cost of a sophisticated control.

1.5.5 Mechanical System Modeling

Specifications of electric drives depend on the torque and speed requirements of the mechanical loads. Therefore, it is often necessary to model mechanical loads. Rather than considering the mechanical load and the electric drive as two separate subsystems, it is preferable to consider them together in the design process. This design philosophy is at the heart of Mechatronics.

1.5.6 Sensors

As shown in the block diagram of electric drives in Figure 1.3, voltage, current, speed, and position measurements may be required. For thermal protection, the temperature needs to be sensed.

1.5.7 Interactions of Drives with the Utility Grid

Unlike line-fed electric motors, electric motors in drives are supplied through a power electronic interface (see Figure 1.3). Therefore, unless corrective action is taken, electric drives draw currents from the utility that are distorted (nonsinusoidal) in wave shape. This distortion in line currents interferes with the utility system, degrading its power quality by distorting the voltages. Available technical solutions make the drive interaction with the utility harmonious, even more so than line-fed motors. The sensitivity of drives to power-system disturbances such as sags, swells, and transient overvoltages should also be considered. Again, solutions are available to reduce or eliminate the effects of these disturbances.

1.6 STRUCTURE OF THE TEXTBOOK

Chapter 1 has introduced the roles and applications of electric drives. Chapter 2 deals with the modeling of mechanical systems coupled to electric drives, as well as how to determine drive specifications for various types of loads. Chapter 3 reviews linear electric circuits. An introduction to power-processing units is presented in Chapter 4.

Magnetic circuits, including transformers, are discussed in Chapter 5. Chapter 6 explains the basic principles of electromagnetic energy conversion.

Chapter 7 describes dc-motor drives. Although the share of dc-motor drives in new applications is declining, their use is still widespread. Another reason for studying dc-motor drives is that ac-motor drives are controlled to emulate their performance. The feedback-controller design for drives (using dc drives as an example) is presented in Chapter 8.

As a background to the discussion of ac motor drives, the rotating fields in ac machines are described in Chapter 9 by means of space vectors. Using the space-vector theory, the sinusoidal waveform PMAC motor drives are discussed in Chapter 10. Chapter 11 introduces induction motors and focuses on their basic principles of operation in steady state. A concise but comprehensive discussion of controlling speed with induction-motor drives is provided in Chapter 12. The reluctance drives, including stepper-motors and switched-reluctance drives, are explained in Chapter 13. Loss considerations and various techniques to improve energy efficiency in drives are discussed in Chapter 14.

SUMMARY/REVIEW QUESTIONS

1. What is an electric drive? Draw the block diagram and explain the roles of its various components.
2. What has been the traditional approach to controlling flow rate in the process industry? What are the major disadvantages that can be overcome by using adjustable-speed drives?
3. What are the factors responsible for the growth of the adjustable-speed drive market?
4. How does an air conditioner work?
5. How does a heat pump work?
6. How do ASDs save energy in air-conditioning and heat-pump systems?
7. What is the role of ASDs in industrial systems?
8. There are proposals to store energy in flywheels for load leveling in utility systems. During the off-peak period for energy demand at night, these flywheels are charged to high speeds. At peak periods during the day, this energy is supplied back to the utility. How would ASDs play a role in this scheme?
9. What is the role of electric drives in electric transportation systems of various types?
10. List a few specific examples from the applications mentioned in section 1.4 that you are personally familiar with.
11. What are the different disciplines that make up the study and design of electric-drive systems?

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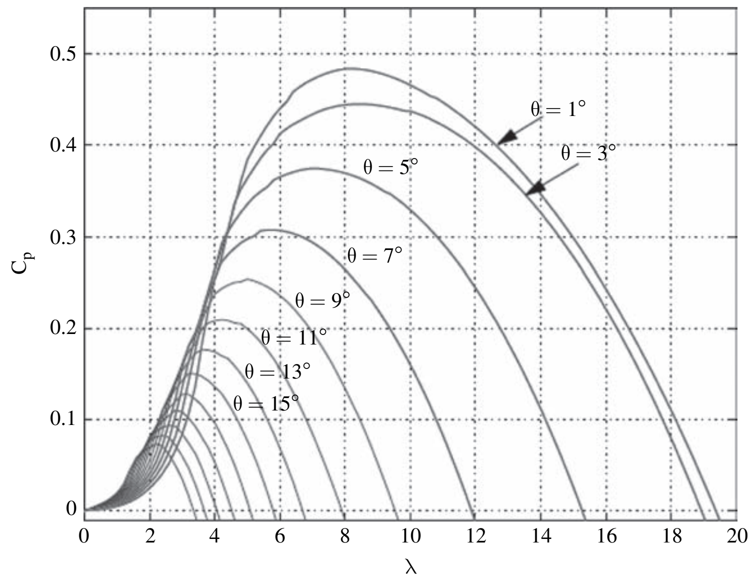

FIGURE P1.5 Plot of C_p as a function of λ [9].

PROBLEMS

1.1 A U.S. Department of Energy report estimates that over 100 billion kWh/year can be saved in the United States by various energy-conservation techniques applied to the pump-driven systems. Calculate (a) how many 1000-MW generating plants running constantly supply this wasted energy and (b) the annual savings in dollars if the cost of electricity is 0.10 $/kWh.

1.2 Visit your local machine-tool shop and make a list of various electric drive types, applications, and speed/torque ranges.

1.3 Repeat Problem 1.2 for automobiles.

1.4 Repeat Problem 1.2 for household appliances [8].

1.5 In wind-turbines, the ratio (P_{shaft}/P_{wind}) of the power available at the shaft to the power in the wind is called the Coefficient of Performance, C_p, which is a unitless quantity. For informational purposes, the plot of this coefficient, as a function of λ is shown in Figure P1-5 [9] for various values of the blades pitch-angle θ, where λ is a constant times the ratio of the blade-tip speed and the wind speed.

The rated power is produced at the wind speed of 12 m/s where the rotational speed of the blades is 20 rpm. The cut-in wind speed is 4 m/s. Calculate the range over which the blade speed should be varied, between the cut-in and the rated wind speeds, to harness the maximum power from the wind. In this range of wind speeds, the blades' pitch-angle θ is kept at nearly zero. Note: this simple problem shows the benefit of varying the speed of wind-turbines, by means of a variable-speed drive, for maximizing the harnessed energy.