# 1

# Introduction to Mobile Power Electronics

## 1.1 General Overview of Mobile Power Electronics

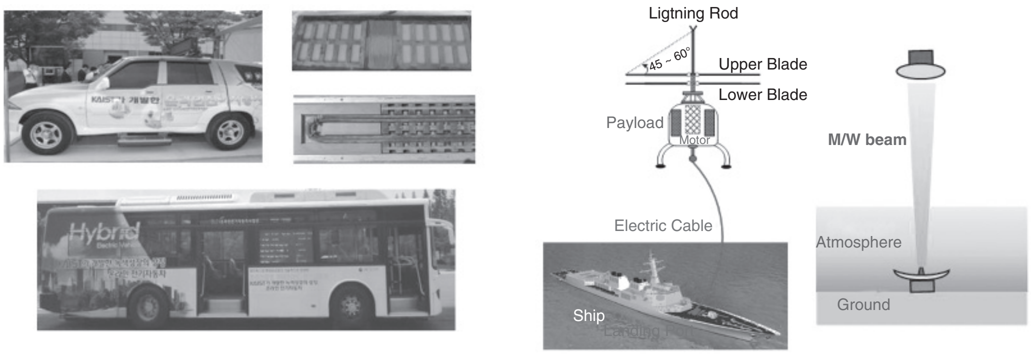
The methods of power transfer for various sources and loads have evolved since the advent of electricity in the nineteenth century. As shown in Figure 1.1, more and more loads are movable now and it has become important to provide seamless power to moving things such as electric transportation, robots, and electric airplanes. Currently, we mainly rely on electric cords and batteries to provide power to movables. As we notice daily, smartphones, tablets, and desktop computers should operate continuously even in the event of disconnection of utility power. The electric cord, however, has a limited range of powering and the battery has a limited time of powering; hence, they inevitably accompany anxiety of range and time. It is important to overcome this range and time limitation for movable things. This was the motivation for "mobile power electronics," a term the author (Dr Rim) coined in 2010. In this light, the motto of mobile power electronics can be said to be "to supply electric energy to all movable things freely."

In general, power transfer (PT) can be classified as stationary and mobile depending on the movement of power receiving (Rx) loads, as shown in Figure 1.2. Stationary PT (SPT) traditionally has been used in the major form of electricity use, which includes fixed SPT of a firmly unchanged configuration of power systems and detachable SPT of a variable configuration of power systems. A majority of power use is still fixed STP such as high-voltage power lines, street lights, and home appliances. Nowadays, detachable STP is more widely used to charge movable things such as cable-type electric vehicles (EVs) and electric shavers, where an electric cord with a naked contact is used. These types of plugged-in chargers have an inconvenient user interface and bring exposure to potential danger of electric shock and fire.

To cope with the strong demand for mobility of Rx loads, various mobile PT (MPT) technologies have been studied; they can be further classified as close MPT and remote MPT depending on the range between the power transmitting (Tx) source and the Rx loads. For the closed MPT, the WPT range is usually from a few cm to a few m. It is remarkable that the inductive, capacitive, and conductive PT correspond to L, C, and R circuit components, respectively. Each close PT uses inductive coupling, capacitive coupling, and conductive coupling between the Tx and Rx. Among the close MPTs, inductive PT (IPT) has been used widely due to its high power transfer capability at relatively low frequency, whereas capacitive PT (CPT) is not as commonly used due to its high operating frequency and small power transfer distance [1, 2]. Note that conductive PT was widely used for a century as a practical means for mobile PT until the advent of IPT.

Among remote MPT strategies, radio frequency (RF) PT and optical PT have been researched to extend the range limit of other PT techniques [3, 4]. RF PT uses electromagnetic waves of frequency ranging from MHz to GHz in practice and is quite different from IPT. For example,

*Wireless Power Transfer for Electric Vehicles and Mobile Devices*, First Edition. Chun T. Rim and Chris Mi.



(a) Road-powered electric vehicles (IPT)

(b) Wired/RF-powered airplanes

(c) Smartphone charger (IPT)

(d) Robots

Figure 1.1 Examples of modern movable things that need seamless electric power.

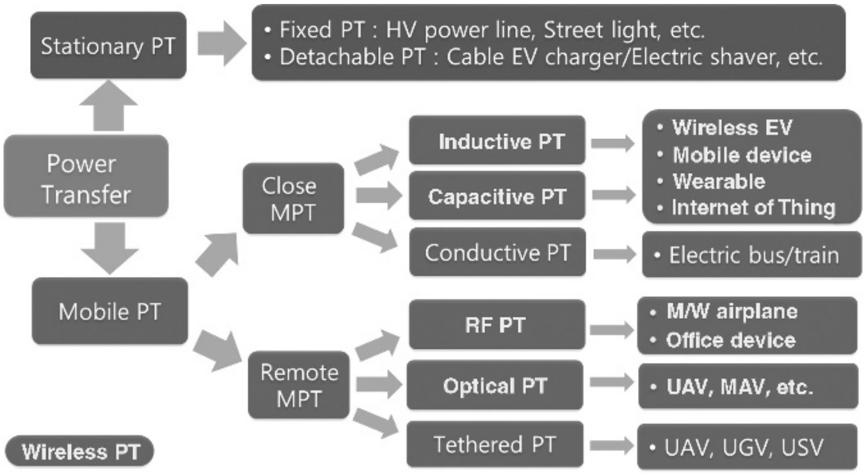


Figure 1.2 A general classification of power transfer in terms of mobility, distance, and means of powering.

the Rx power density of RF PT is usually proportional to the inverse of the square of distance, but that of IPT is typically proportional to the inverse of the sixth power of distance because the Rx magnetic flux density of IPT is typically proportional to the third power of distance. Furthermore, there is no magnetic coupling between the Tx and Rx devices of the RF PT. On the other hand, the tethered PT can provide power over a flexibly long distance if properly designed [5, 6]. As depicted in Figure 1.2, wireless PT (WPT) is not only limited to close MPT such as IPT and CPT but also remote MPT such as RF PT and optical PT. Furthermore, WPT is not only electrical but also optical or even acoustic.

In the era of the ubiquitous, IPT is the most widely used [8, 58]. More mobile devices, home appliances, industry sensors, and EV chargers are becoming wireless due to their convenience, safety against electric shock, cleanness, and competitive power efficiency and price. Eventually, most devices including wearable devices, ubiquitous sensors, and smart cars will merge to the Internet of Things (IoT) and WPT will play a significantly important role in the realization of IoT, which includes compact communication devices, sensors, and power sources.

**Question 1** (1) How can you classify electric shavers and vacuum cleaners that have a stretchable cable? (2) Are the items of (1) SPT or MPT? (3) What are the benefits of the classification of SPT and MPT? (4) Is there any fundamental distinction between SPT and MPT as well as IPT, CPT, RF PT, and Optical PT?

## 1.2 Brief History of Mobile Power Electronics

We cannot discuss mobile power or wireless power without talking about Nikola Tesla, who had carried out many experiments on WPT, as shown in Figure 1.3, and invented a "world system" for "the transmission of electrical energy without wires." Even though he did not succeed in transmitting wireless power over the continent as he desired, he has inspired numerous engineers and scientists with respect to transferring power remotely without wires. Nikola Tesla was the pioneer of wireless telegraphy, which is known to be competitively invented by Guglielmo Marconi in 1895. There were many competitors at that time in utilizing electromagnetic waves, which were discovered by Heinrich Hertz in 1886, for telecommunications. Including his work

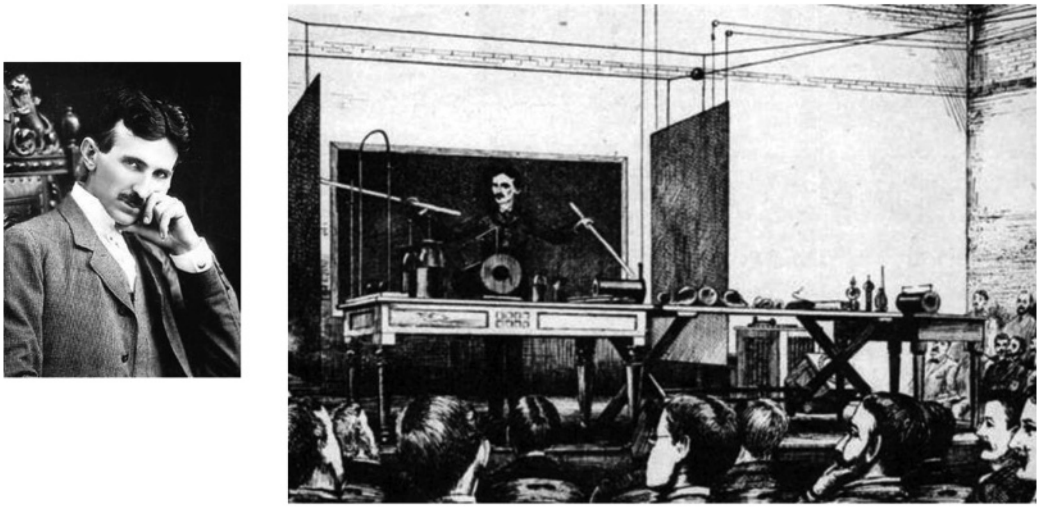


**Figure 1.3** Nikola Tesla (1856–1943) and his experiment on WPT.

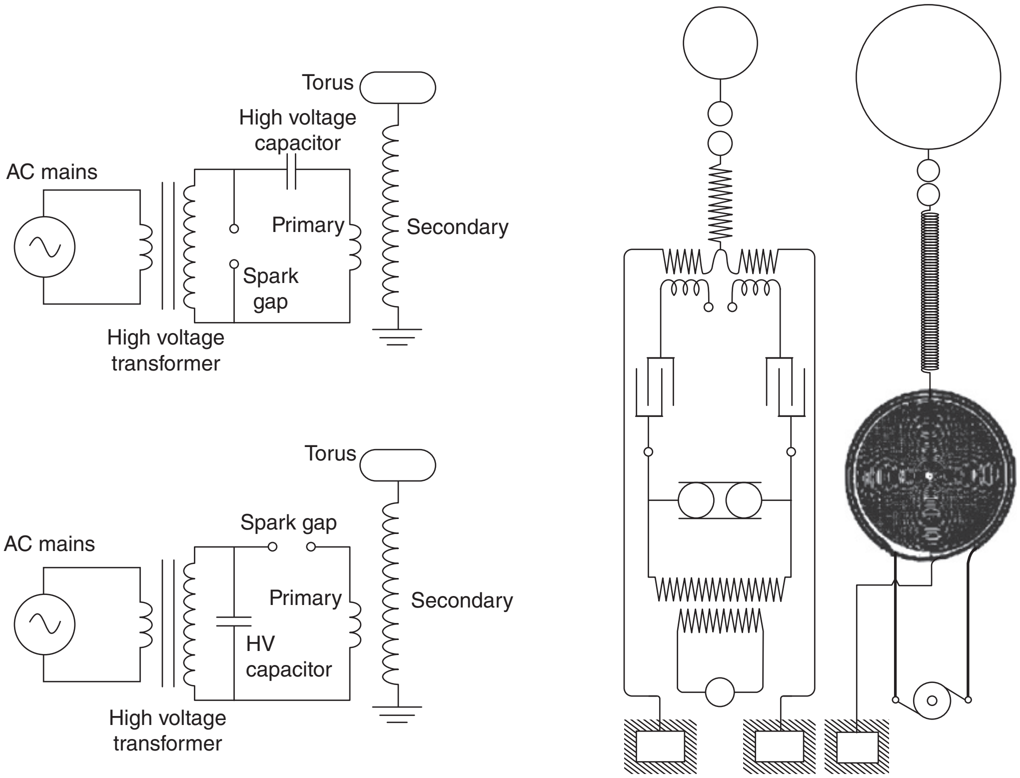


**Figure 1.4** Examples of the Tesla coil, which is a type of resonant transformer (25 kHz–2 MHz), invented in 1891.

on three-phase AC power systems and induction motors, Nikola Tesla made the most significant contributions to the era of electricity of the twentieth century.

Nikola Tesla was very interested in AC magnetic fields, which were the basis of many of his inventions, such as wireless communications, induction motors, and WPT systems. As easily recognized by experienced engineers, magnetic fields are very difficult to deal with compared to electric fields and electric circuits. The design of magnets and coils is regarded as one of the most challenging tasks in electrical engineering. A Tesla coil, as shown in Figure 1.4, is one of the examples that is difficult to design and to understand in terms of its behavior. He invented this coil as a means of generating a high-frequency and high-voltage power source and it is still being used to generate electric sparks. At that time, there were no semiconductor switches that could withstand high voltage, so he used a mechanical switch to ignite resonant ringing of LC circuits. Utilizing the parasitic capacitances and inductances of the secondary transformer, he boosted the resonant voltage to several tens of kV. This “resonant transformer” is a unique characteristic of the Tesla coil and quite different from conventional transformers, which are close to an ideal transformer. For example, the output voltage of a resonant transformer is not simply proportional to the turn ratio of primary and secondary windings of the transformer and it usually becomes much higher than the turn ratio when tuned. This strange phenomenon has been a mysterious issue in the design of the Tesla coil and can be explained by theories such as the coupled inductor model and the gyrator circuit model in Part II of this book.

Understanding the Tesla coil is a good start in understanding WPT and gives us many useful design tips for WPT because the Tesla coil design involves transformer design, coil design, stray inductance and capacitance modeling, compensation circuit design, insulation issues, ground

**Figure 1.5** A conductively powered tram (left) and its pantograph (right), which is one of the oldest types of MPT.

issues, switching, and snubber circuit design. Nikola Tesla used the Tesla coil in Figure 1.4 for his wireless power experiments. For graduate students who wish to understand a "resonant transformer," I would like to recommend that they make a Tesla coil kit and conduct experiments with special caution regarding high-voltage electric shock when operating. Because of safety reasons, it is not recommended that young scientists deal with the Tesla coil even if the source voltage of the experiment kit is only a few volts. For beginners, it will be much easier and safer to carry out a WPT experiment with a two-coil IPT experiment kit.

As discussed above, one of the oldest types of MPT is conductive power for trams and trains, which fetch AC or DC utility power through a detachable pantograph, as shown in Figure 1.5. This conductively powered tram has been used for a century but is being replaced with battery-powered or wireless-powered trams. Because of cumbersome power lines in the air and the problem of pantograph wear, the conductively powered tram is no longer widely used in urban areas, but conductive power is still widely used in subway trains and high-speed trains in many countries due to the absence of an available candidate solution.

The last case that I would like to talk about in the history of mobile power electronics is the tethered electric helicopter, first built and flown by Gustave Trouvé in 1887 and developed for possible military use by the Nazis during World War II. This tethered drone is useful for continuous surveillance and watch missions without landing for several hours to several weeks if desired. Considering the rapid growth of drone markets, this tethered powering is noteworthy even though it has no relationship to WPT.

Note that MPT is not necessarily WPT but could take many different forms, which will be discussed in the following section. If we extend our concern to mobile energy transfer, batteries as well as petroleum, natural gas, coal, and hydrogen can be the means of energy transfer. In particular, the battery is a good means of electrical energy transfer and an excellent power source. Thus far, as we are dealing with MPT issues, we need to consider the battery as a means of delivering power continuously to remote locations as we now daily rely on it.

**Question 2** (1) What is energy harvesting? (2) What are the merits and limitations of energy harvesting compared to MPT? (3) Discuss the potential applications of energy harvesting to IoT when combined with MPT.

## 1.3 Remote Mobile Power Transfer (MPT)

Because the close MPT of Figure 1.2 will be explained in Chapter 2, remote MPT is explained in this section briefly. One of the purposes of this section is to familiarize readers with other MPT techniques aside from conventional WPTs.

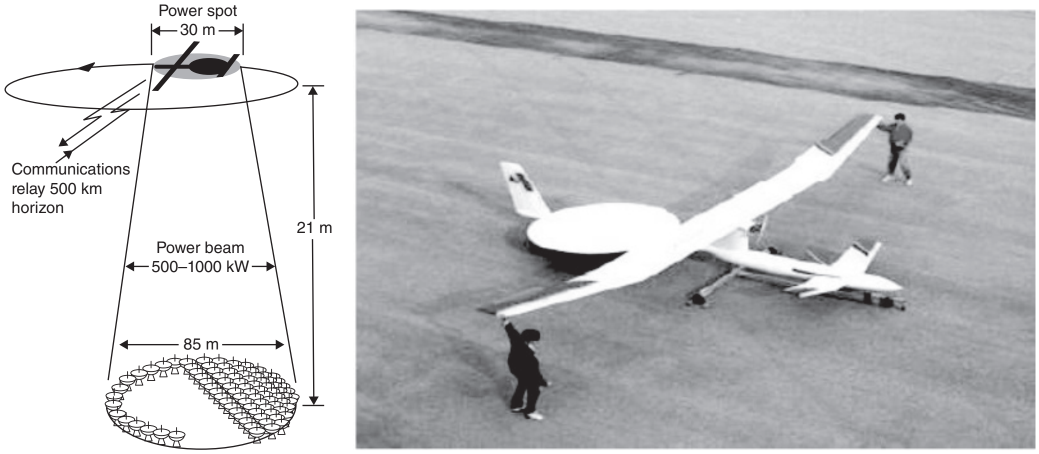


**Figure 1.6** An RF-powered airplane by the Canada SHARP (Stationary High Altitude Relay Platform) project.

### 1.3.1 RF Power Transfer (RF PT)

RF power or energy has been widely used in radars, microwave ovens, electromagnetic pulse (EMP) weapons, and WPT. One of the potential applications of RF PT is wireless-powered airplanes, as shown in Figure 1.6.

According to the Canada SHARP (Stationary High Altitude Relay Platform) project, an electrically propelled airplane is under study at a frequency of 2.45 or 5.8 GHz, using a rectenna array whose RF-to-DC power conversion efficiency is 80%. The rectenna is a device to convert RF receiving power to DC power. The total power efficiency is known to be 10% at 150 m altitude from ground for 10 kW transmission. The airplane is targeted to operate at stratosphere altitude of about 20–30 km, which is a promising altitude where there are almost always no strong wind flows and provides long-distance monitoring comparable to an Earth orbiting low-altitude satellite.

As shown in Figure 1.7, I and Prof. Chul Park with the Department of Aerospace Engineering at KAIST have studied the feasibility of the stratosphere RF-powered airplane, which has a tandem wing antenna structure to receive RF power from a ground Tx antenna and to obtain lift force with a propeller operating by electricity [59]. The mass and height of the airplane are $m_s$ and $h_s$, respectively.

The required velocity and power of the airplane to obtain lifting force against gravity are ideally determined as follows:

$$F_g = 0.5C_L\rho V^2 A = m_s g \Rightarrow V = \sqrt{\frac{m_s g}{0.5C_L\rho A}} \tag{1.1a}$$

$$P \equiv F_D V = 0.5C_D\rho V^3 A = 0.5C_D\rho\left[\frac{m_s g}{0.5C_L\rho A}\right]^{\frac{3}{2}} A, \tag{1.1b}$$

where $C_L$, $C_D$, $\rho$, $A$, and $g$ are lift coefficient, drag coefficient, air density, wing area, and gravity constant, respectively.

As shown in Figure 1.8, the required velocity and power are found to be 22 m/s and 8.5 kW, respectively, for a wing span of 30 m and weight of 200 kg, which is a reasonable airplane system.

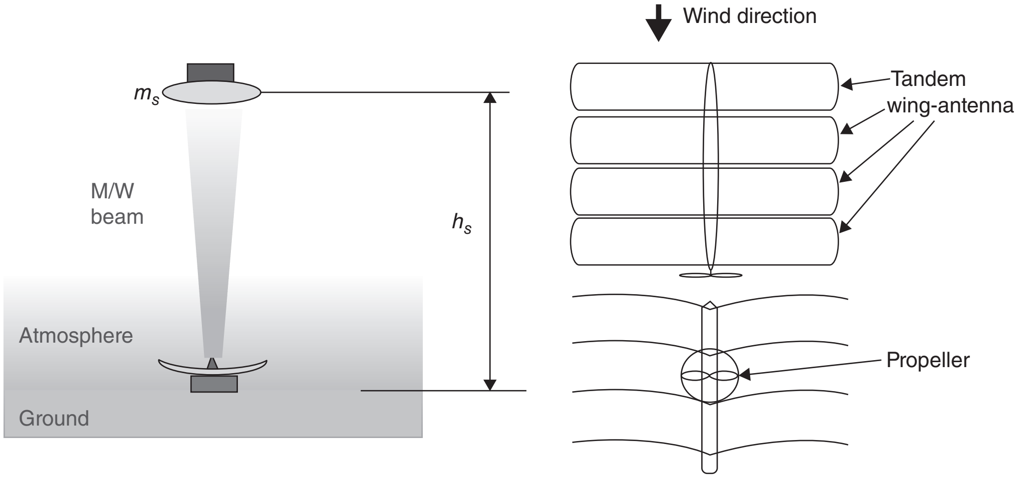


**Figure 1.7** An RF-powered airplane designed by KAIST (Chun T. Rim and Chul Park).

As shown in Figure 1.9, the diameter of a ground station to transmit RF power can be calculated for a wing span of 30 m, altitude of 30 km, and RF frequencies of L-band (2.45 GHz) and X-band (10.0 GHz) as follows:

$$L_{WS} \cong \frac{\lambda}{D} h_s = \frac{ch_s}{fD} \quad \Rightarrow D \cong \frac{ch_s}{fL_{WS}}, \tag{1.2a}$$

$$D_{2.45\ \mathrm{GHz}} = \frac{ch_s}{fL_{WS}} = \frac{3 \times 10^8 \cdot 30\ \mathrm{k}}{2.45\ \mathrm{G} \cdot 30} = 122\ \mathrm{m} \tag{1.2b}$$

$$D_{10\ \mathrm{GHz}} = \frac{ch_s}{fL_{WS}} = \frac{3 \times 10^8 \cdot 30\ \mathrm{k}}{10\ \mathrm{G} \cdot 30} = 30\ \mathrm{m} \tag{1.2c}$$

As identified from (1.2b) and (1.2c), the diameters of a ground station for L-band and C-band are 122 m and 30 m, respectively, which are quite reasonable to build. Frequency can be selected considering the ground station size and total power efficiency, where the L-band has higher power efficiency than the C-band. Considering currently available RF components and propagation loss, the power requirement of a ground station is found to be roughly 200 kW [59].

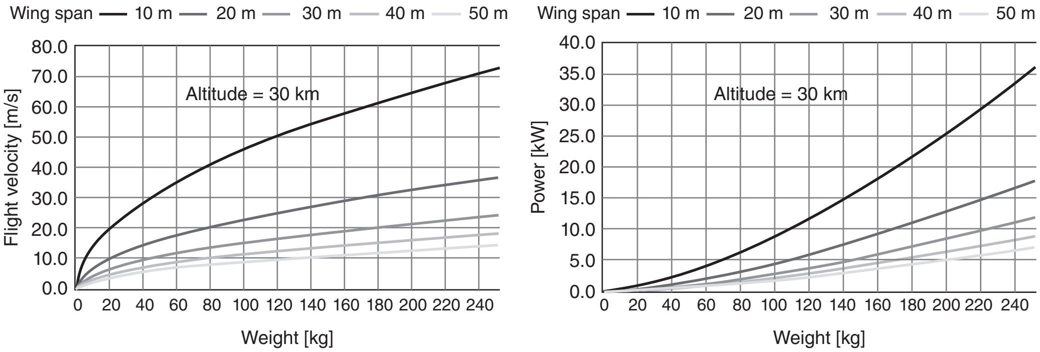


**Figure 1.8** Required flight velocity (top) and power (bottom) for the given weight of the KAIST RF-powered airplane.

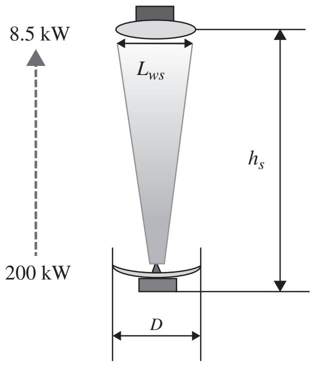


**Figure 1.9** Required ground power and diameter of a ground station of the KAIST RF-powered airplane.

It has been outlined that the stratosphere RF airplane can be built if appropriate RF components are used and the RF airplane is properly designed.

The NASA plan of sending solar power generated at a geostationary orbit satellite through microwaves started in 1978. It was designed to have 1 km and 10 km diameter Tx and Rx antennas at 2.45 GHz to achieve 750 MW receiving power on Earth ground. Experiments at a few kW power level with reduced size Tx and Rx antennas were conducted at Goldstone in California in 1975 and Grand Bassin on Reunion Island in 1997, respectively. This NASA plan was finally cancelled due to several issues such as low Tx efficiency, potentially harmful Rx power density, and extremely poor cost-effectiveness compared to ground solar power generation.

Recently, low-power applications of RF PT have been widely explored as the energy source of distributed sensor networks and IoT. RF energy harvesting [60] is currently a hot issue, where very low power of less than 1 mW or a very small amount of energy lower than 1 mJ is pursued. RF power delivery to mobile devices in an office or room is also an interesting application, where dynamic directing of the Tx antenna and the narrow receiving angle of the Rx antenna of arbitrarily positioned mobile devices are important problems. Avoiding harmful RF power exposure to the human body and adjacent electronic equipment is also a challenging issue together with expensive Tx and Rx devices and strong RF interference regulations.

**Question 3** (1) What happens to a stratosphere drone with RF PT if the power transfer is abruptly stopped due to breakdown of power systems or bad weather? (2) What are the remedies for (1)?

**Question 4** (1) Estimate the cost of launching and maintaining a geostationary satellite for solar power generation and transmitting. (2) Compare (1) to the cost of a conventional ground solar power generator.

### 1.3.2 Optical Power Transfer (Optical PT)

Optical power is a good candidate for wireless power if good clearance between Tx and Rx is maintained. As shown in Figure 1.10(a), the NASA Marshall Space Flight Center has developed a laser-powered drone whose total power efficiency from the input power of a laser Tx to the output power of solar cell is 6.8%. The rationale for this efficiency is as follows:

- Current laser efficiencies of 25% (it can be improved up to 50% in the near future)
- Solar cell conversion efficiencies of 50%
- Power conditioning efficiency of 80%
- Receiver efficiency of 75%
- Atmospheric transmission efficiency of 90%.

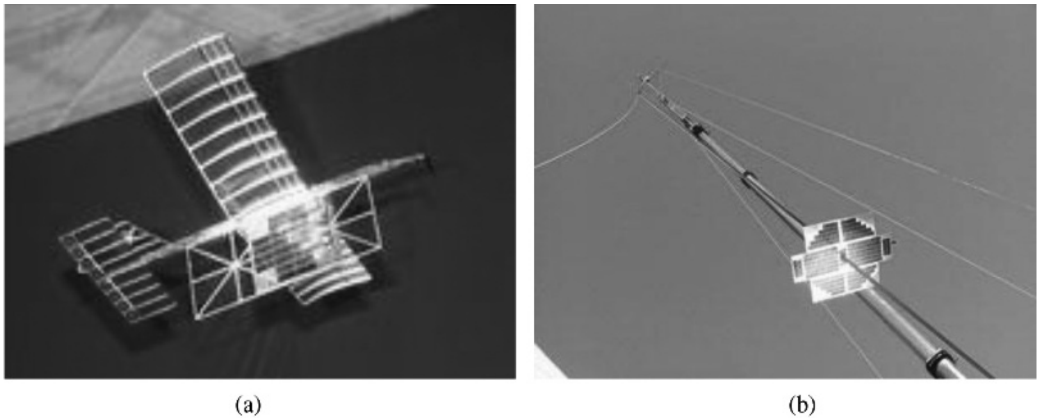


**Figure 1.10** (a) NASA laser-powered drone and (b) a climber at the NASA Beam Power Challenge test.

Even though the power efficiency of 6.8% is much lower than that of a modern IPT device, the optical drone shows the possibility of low-power WPT to indoor mobile devices without any electromagnetic interference (EMI) problems. If the wavelength of the laser is infrared (IR), it is quite safe to the human body unless the power level is very high. Like RF PT, this optical PT has the problem of dynamic directing of the Tx and a narrow receiving angle of Rx of arbitrarily positioned mobile devices. Furthermore, it is very difficult for the optical PT to have electronic beam steering, which is available for RF PT, although it is expensive and has a limited steering angle.

As shown in Figure 1.10(b), a climber built by the University of Saskatchewan Space Design Team reached 40 feet up a 200-ft climbing ribbon in the NASA Beam Power Challenge test in 2005. Sunlight is free and abundant but is not available in cloudy weather and at night; therefore, an artificial LED or laser light is crucial for an optical PT in order to provide a reliable light power source. One of the fundamental drawbacks of optical PT is that power can be delivered only in the line of sight and cannot be delivered through obstacles or opaque materials, which can be easily overcome by IPT for instance.

**Question 5** (1) What would happen to a drone with an optical PT when the power transfer is abruptly stopped due to a breakdown of power systems or bad weather? (2) What are the remedies for (1)? Discuss whether an on-board battery is a good solution. (3) What if the angle of incidence to the drone is variable and sometimes extremely large?

### 1.3.3 Tethered Power Transfer (Tethered PT)

As discussed, tethered PT is suitable for a stationary drone for persistent missions such as surveillance, environment monitoring, fire and crime monitoring, traffic control, communication relay, broadcasting, search and rescue, and video capture. There had not been many studies when I started to research a tethered unmanned helicopter (UTH) in 2007, as shown in Figure 1.11 [61]. As an example of tethered drones, a summary of this study [61] is provided in the following.

The target altitude, total mass, and total power of the UTH are 1 km, 200 kg, and 25 kW, respectively, as listed in Table 1.1. A power cable of 1 kV, 25 A ratings is used, where the mass and resistance for 1 km of power cable are 95 kg and 12.1 ohms, respectively. Considering a

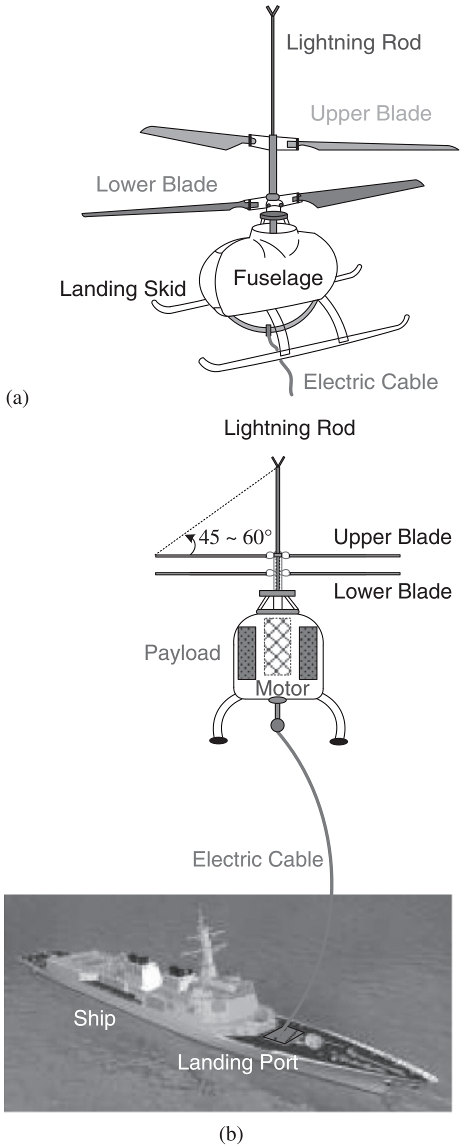


**Figure 1.11** A tethered helicopter designed by KAIST (Chun T. Rim): (a) configuration and (b) and operation concept.

9.5 kW total power loss including the power cable loss, the delivered power to the UTH is 15.5 kW, which is enough power to lift the UTH and to provide for mission payloads.

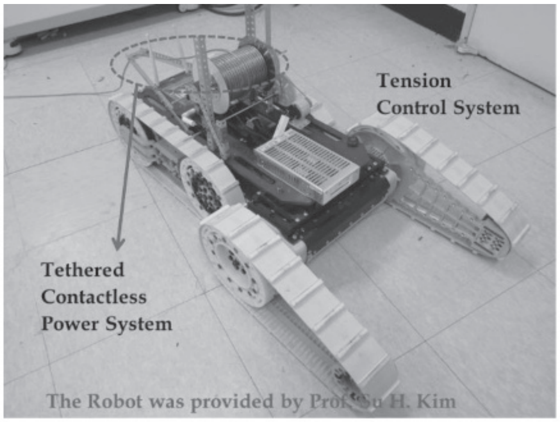
As shown in Figure 1.11, a lightning rod is installed to the UTH, which resulted from the lesson learnt by Nazis when the tethered helicopter failed due to lightning. It is assumed that the cable is wrapped on the ground and a brush contact is installed to have an electric connection of the cable to the ground power source.

Another tethered PT is for ground vehicles, as shown in the example in Figure 1.12(a). This tethered ground vehicle (TGV) has been developed by my team since 2011. For the TGV, cable is wound on the vehicle and a constant tension is always provided to the cable so that it can travel around corners without fear of getting stuck. The conventional cabletype ground vehicle carries the cable but easily becomes stuck at corners.

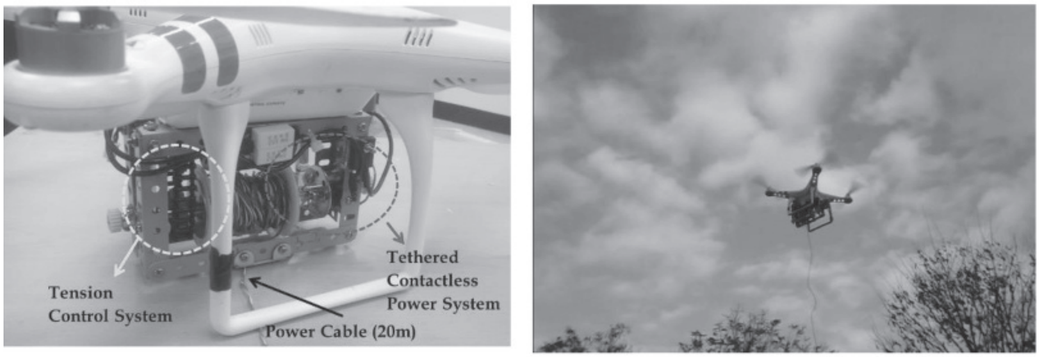
**Table 1.1** The mass and power budgets of KAIST UTH designed by Chun T. Rim

| Items | Mass (kg) | Power (kW) |
|---|---|---|
| TUH platform (lifting) | 25 | 12.0 |
| TUH platform (others) | 40 | 0.5 |
| TUH payload (radar, IR) | 30 | 1.0 |
| Electric cable | 95 | 9.5 |
| Design margin | 10 | 2.0 |
| Total | 200 | 25.0 |

Recently, my team has developed tethered drones, where the cable is wound either on the ground or on the drone, as shown in Figure 1.12(b) [62]. When the tension control system is on the drone, it is appropriate for roaming missions; in contrast, when the tension control system is on the ground, it is good for stationary missions. By designing a novel cable wrapping mechanism, there is no brush contact for the ground tension control case [62].



(a) Tethered ground vehicle for surveillance



(b) Tethered drone for environment monitoring

**Figure 1.12** Tethered ground vehicle and small drone designed by KAIST (Chun T. Rim).

**Question 6** Discuss detail methods for protecting a tethered drone from lightning. (1) For example, what about using a current fuse that is blown up when large lightning current flows? (2) How can the tethered electric cable be grounded for lightning current bypass? Remember that the wound electric cable under lightning is exposed to an extremely high voltage (~MV) and may not withstand the electric shock.

## 1.4 Conclusion

An overview of MPT has been provided in this chapter. The most important competitors in mobile power electronics will be the battery versus WPT. If a very light, small size, cheap, long lasting, and quick chargeable battery is available, then batteries will dominate over WPT. However, WPT is becoming more important in MPT because of the convenience and inherent safety and batteries need to be recharged. WPT is thus not only a competitor but also an ally of the battery. Moreover, WPT may substitute or dominate the battery, as identified by RPEV. Tethered PT is also a good candidate for MPT and may provide a replacement for the battery. Most WPT and tethered PT require batteries for their emergency power to provide a reliable power source to the system. Therefore, all parts of MPT should be enhanced together to achieve progress in mobile power electronics.

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