

PUBLICLY AVAILABLE SPECIFICATION

PRE-STANDARD



**The Qi wireless power transfer system power class 0 specification –
Parts 1 and 2: Interface Definitions**



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**The Qi wireless power transfer system power class 0 specification –
Parts 1 and 2: Interface Definitions**

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

THE QI WIRELESS POWER TRANSFER SYSTEM POWER CLASS 0 SPECIFICATION –

Parts 1 and 2: Interface Definitions

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Draft PAS	Report on voting
100/2826/PAS	100/2864/RVDPAS

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1 General

1.1 Introduction

The Wireless Power Consortium (WPC) is a worldwide organization that aims to develop and promote global standards for wireless power transfer in various application areas. A first application area, designated Power Class 0, is wireless charging of low and medium power devices, such as mobile phones and tablet computers. The Wireless Power Consortium maintains the Qi logo for this application area.

1.2 Scope

This document, *Parts 1 and 2: Interface Definitions*, defines the interface between a Power Transmitter and a Power Receiver, i.e. Power Class 0 Base Stations and Mobile Devices. Power Class 0 is the WPC designation for flat-surface devices, such as chargers, mobile phones, tablets, cameras, and battery packs, in the Baseline Power Profile (≤ 5 W) and Extended Power Profile (≤ 15 W).

1.2.1 Current Specification structure (introduced in version 1.2.1)

The Qi Wireless Power Transfer System for Power Class 0 Specification consists of the following documents.

- ***Parts 1 and 2: Interface Definitions*** (this document)
 - *Part 1: Primary Interface Definition*
 - *Part 2: Secondary Interface Definition*
- *Part 3: Compliance Testing*
- *Part 4: Reference Designs*

NOTE WPC publications prior to version 1.2.1 were structured differently, and are listed in Section 1.2.2 below. In particular, the Low Power and Medium Power publications were divided into separate System Description documents. Beginning with version 1.2.1, the Low Power and Medium Power System Descriptions have been merged into the Specification structure shown in this section. Additionally, the terms *Low Power* and *Medium Power* have been replaced in the current Specification by the terms *Baseline Power Profile* and *Extended Power Profile* respectively.

1.2.2 Earlier Specification structure (version 1.2.0 and below)

Before release 1.2.1, the Wireless Power Transfer specification comprised the following documents.

- System Description, Wireless Power Transfer, Volume I: Low Power, Part 1: Interface Definition.
- System Description, Wireless Power Transfer, Volume I: Low Power, Part 2: Performance Requirements.
- System Description, Wireless Power Transfer, Volume I: Low Power, Part 3: Compliance Testing.
- System Description, Qi Wireless Power Transfer, Volume II: Medium Power.

1.3 Main features of the Qi Wireless Power Transfer System

- A method of contactless power transfer from a Base Station to a Mobile Device that is based on near-field magnetic induction between coils.
- A Baseline Power Profile supporting transfer of up to about 5 W and an Extended Power Profile supporting transfer of up to about 15 W of power using an appropriate Secondary Coil (having a typical outer dimension of around 40 mm).
- Operation at frequencies in the 87...205 kHz range.
- Support for two methods of placing the Mobile Device on the surface of the Base Station:
 - Guided Positioning helps a user to properly place the Mobile Device on the surface of a Base Station. The Base Station provides power through a single or a few fixed locations on that surface.
 - Free Positioning enables arbitrary placement of the Mobile Device on the surface of a Base Station. The Base Station can provide power through any location on that surface.
- A simple communications protocol enabling the Mobile Device to take full control of the power transfer.
- Considerable design flexibility for integration of the system into a Mobile Device.
- Very low stand-by power is achievable (implementation dependent).

1.4 Conformance and references

1.4.1 Conformance

All provisions in The Qi Wireless Power Transfer System, Power Class 0 Specification are mandatory, unless specifically indicated as recommended, optional, note, example, or informative. Verbal expression of provisions in this Specification follow the rules provided in Annex H of ISO/IEC Directives, Part 2. For clarity, the word “**shall**” indicates a requirement that is to be followed strictly in order to conform to The Qi Wireless Power Transfer System, Power Class 0 Specification, and from which no deviation is permitted. The word “**should**” indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others, or that a certain course of action is preferred but not necessarily required, or that in the negative form a certain possibility or course of action is deprecated but not prohibited. The word “**may**” indicates a course of action permissible within the limits of The Qi Wireless Power Transfer System, Power Class 0 Specification. The word “**can**” indicates a possibility or capability, whether material, physical, or causal.

1.4.2 References

For undated references, the most recently published Specification applies. The most recent WPC publications can be downloaded from <http://www.wirelesspowerconsortium.com>. (See Section 1.2.1 for a list of documents included in The Qi Wireless Power Transfer System for Power Class 0 Specification.) In addition, the following documents are referenced within The Qi Wireless Power Transfer System for Power Class 0 Specification.

- Product Registration Procedure Web page (WPC Web site for members, Testing & Registration section)
- Qi Product Registration Manual, Logo Licensee/Manufacturer
- Qi Product Registration Manual, Authorized Test Lab
- Power Receiver Manufacturer Codes, Wireless Power Consortium
- The International System of Units (SI), Bureau International des Poids et Mesures

1.5 Definitions

Active Area	The part of the Interface Surface of a Base Station or Mobile Device through which a sufficiently high magnetic flux penetrates when the Base Station is providing power to the Mobile Device.
Base Station	A device that is able to provide near field inductive power as specified in The Qi Wireless Power Transfer System, Power Class 0 Specification. A Base Station carries a logo to visually indicate to a user that the Base Station complies with The Qi Wireless Power Transfer System, Power Class 0 Specification.
Baseline Power Profile	The minimum set of features applying to Power Transmitters and Power Receivers that can transfer no more than around 5 W of power.
Communications and Control Unit	The functional part of a Power Transmitter or Power Receiver that controls the power transfer. NOTE With regard to implementation, the Communications and Control Unit may be distributed over multiple subsystems of the Base Station or Mobile Device.
Control Point	The combination of voltage and current provided at the output of the Power Receiver, and other parameters that are specific to a particular Power Receiver implementation.
Detection Unit	The functional part of a Power Transmitter that detects the presence of a Power Receiver on the Interface Surface.
Digital Ping	The application of a Power Signal in order to detect and identify a Power Receiver.
Extended Power Profile	The minimum set of features applying to Power Transmitters and Power Receivers that can transfer power above 5 W.
Free Positioning	A method of positioning a Mobile Device on the Interface Surface of a Base Station that does not require the user to align the Active Area of the Mobile Device to the Active Area of the Base Station.
Foreign Object	Any object that is positioned on the Interface Surface of a Base Station, but is not part of a Mobile Device.

Foreign Object Detection

A process that a Power Transmitter or Power Receiver executes in order to determine if a Foreign Object is present on the Interface Surface.

Friendly Metal A part of a Base Station or a Mobile Device in which a Power Transmitter's magnetic field can generate eddy currents.

Guaranteed Power The amount of output power of an appropriate reference Power Receiver that the Power Transmitter ensures is available at any time during the power transfer phase. For Power Transmitters that comply with the Baseline Power Profile, the reference is TPR#1A, which is defined in *Part 3: Compliance Testing*. For Power Transmitters that comply with the Extended Power Profile, the reference is TPR#MP1B, which is also defined in *Part 3: Compliance Testing*.

Guided Positioning A method of positioning a Mobile Device on the Interface Surface of a Base Station that provides the user with feedback to properly align the Active Area of the Mobile Device to the Active Area of the Base Station.

Interface Surface The flat part of the surface of a Base Station that is closest to the Primary Coil(s), or the flat part of the surface of the Mobile Device that is closest to the Secondary Coil.

Maximum Power The maximum amount of power that a Power Receiver expects to provide at its output throughout the power transfer phase. The Maximum Power serves as a scaling factor for the Received Power Values that a Power Receiver reports in its Received Power Packets.

Mobile Device A device that is able to consume near field inductive power as specified in The Qi Wireless Power Transfer System, Power Class 0 Specification. A Mobile Device carries a logo to visually indicate to a user that the Mobile Device complies with the Specification.

Operating Frequency

The oscillation frequency of the Power Signal.

Operating Point The combination of the frequency, duty cycle, and amplitude of the voltage that is applied to the Primary Cell.

Packet A data structure for communicating a message from a Power Receiver to a Power Transmitter or vice versa. A Packet consists of a preamble, a header byte, a message, and a checksum. A Packet is named after the kind of message that it contains.

Potential Power	The amount of output power by an appropriate reference Power Receiver that the Power Transmitter can make available during the power transfer phase. For Power Transmitters that comply with the Baseline Power Profile, the reference is TPR#1A, which is defined in <i>Part 3: Compliance Testing</i> . For Power Transmitters that comply with the Extended Power Profile, the reference is TPR#MP1B, which is also defined in <i>Part 3: Compliance Testing</i> .
Power Conversion Unit	The functional part of a Power Transmitter that converts electrical energy to a Power Signal.
Power Factor	The ratio of the active power consumed and the apparent power drawn. The active power is expressed in watts. The apparent power typically is expressed in volt-amperes (VA).
Power Pick-up Unit	The functional part of a Power Receiver that converts a Power Signal to electrical energy.
Power Receiver	The subsystem of a Mobile Device that acquires near field inductive power and controls its availability at its output, as defined in The Qi Wireless Power Transfer System, Power Class 0 Specification. For this purpose, the Power Receiver communicates its power requirements to the Power Transmitter.
Power Signal	The oscillating magnetic flux that is enclosed by a Primary Cell and possibly a Secondary Coil.
Power Transfer Contract	A set of boundary conditions on the parameters that characterize the power transfer from a Power Transmitter to a Power Receiver. Violation of any of these boundary conditions causes the power transfer to abort.
Power Transmitter	The subsystem of a Base Station that generates near field inductive power and controls its transfer to a Power Receiver, as defined in The Qi Wireless Power Transfer System, Power Class 0 Specification.
Primary Cell	A single Primary Coil or a combination of Primary Coils that are used to provide a sufficiently high magnetic flux through the Active Area.
Primary Coil	A component of a Power Transmitter that converts electric current to magnetic flux.

Received Power	The total amount of power dissipated inside a Mobile Device, due to the magnetic field generated by a Power Transmitter. The Received Power includes the power that the Power Receiver makes available at its output for use by the Mobile Device, any power that the Power Receiver uses for its own purposes, as well as any power that is lost within the Mobile Device.
Reference Quality Factor	The quality-factor of Test Power Transmitter #MP1's Primary Coil at an Operating Frequency of 100 kHz, with a Power Receiver positioned on the Interface Surface and no Foreign Object nearby.
Response	A sequence of eight consecutive bi-phase modulated bits transmitted by a Power Transmitter in response to a request from a Power Receiver.
Secondary Coil	The component of a Power Receiver that converts magnetic flux to electromotive force.
Shielding	A component in the Power Transmitter that restricts magnetic fields to the appropriate parts of the Base Station, or a component in the Power Receiver that restricts magnetic fields to the appropriate parts of the Mobile Device.
Specification	The set of documents, Parts 1 through 4, that comprise The Qi Wireless Power Transfer System, Power Class 0 Specification (see Section 1.2.1).
Transmitted Power	The total amount of power dissipated outside the Interface Surface of a Base Station, due to the magnetic field generated by the Power Transmitter.
WPID	A 48-bit number that uniquely identifies a Qi-compliant device.

1.6 Acronyms

AC	Alternating Current
ACK	Acknowledge
AWG	American Wire Gauge
BSUT	Base Station Under Test
CEP	Control Error Packet
DC	Direct Current
DCR	Direct Current Resistance

EM	Electro Magnetic
EMC	Electro Magnetic Compatibility
EMF	Electro Magnetic Fields
EPT	End Power Transfer
ESR	Equivalent Series Resistance
FET	Field Effect Transistor
FOD	Foreign Object Detection
FSK	Frequency-Shift Keying
LSB	Least Significant Bit
MSB	Most Significant Bit
MDUT	Mobile Device Under Test
N.A.	Not Applicable
NAK	Not-Acknowledge
ND	Not-Defined
PID	Proportional Integral Differential
PRx	Power Receiver
PTx	Power Transmitter
RMS	Root Mean Square
TPR	Test Power Receiver
UART	Universal Asynchronous Receiver Transmitter
USB	Universal Serial Bus
WPID	Wireless Power Identifier

1.7 Symbols

C_d	Capacitance parallel to the Secondary Coil [nF]
C_m	Capacitance in the impedance matching network [nF]
C_p	Capacitance in series with the Primary Coil [nF]
C_s	Capacitance in series with the Secondary Coil [nF]
d	Duty cycle of the inverter in the Power Transmitter
d_s	Distance between a coil and its Shielding [mm]
d_z	Distance between a coil and the Interface Surface [mm]
f_{CLK}	Communications bit rate [kHz]
f_d	Resonant detection frequency [kHz]
f_{op}	Operating Frequency [kHz]
f_s	Secondary resonance frequency [kHz]
I_m	Primary Coil current modulation depth [mA]
I_o	Power Receiver output current [mA]
I_p	Primary Coil current [mA]
L_m	Inductance in the impedance matching network [μ H]
L_p	Primary Coil self inductance [μ H]
L_s	Secondary Coil self inductance (Mobile Device away from Base Station) [μ H]
L'_s	Secondary Coil self inductance (Mobile Device on top of Base Station) [μ H]
P_{FO}	Power loss that results in heating of a Foreign Object [W]
P_{PR}	Total amount of power received through the Interface Surface [W]
P_{PT}	Total amount of power transmitted through the Interface Surface [W]
Q	Quality factor
t_{delay}	Power Control Hold-off Time [ms]

t_{CLK}	Communications clock period [μs]
t_{T}	Maximum transition time of the communications [μs]
V_{r}	Rectified voltage [V]
V_{o}	Power Receiver output voltage [V]

1.8 Conventions

This section defines the notations and conventions used in The Qi Wireless Power Transfer System, Power Class 0 Specification.

1.8.1 Cross references

Unless indicated otherwise, cross references to sections include the sub sections contained therein.

1.8.2 Informative text

Informative text is set in italics, unless the complete Section is marked as informative.

1.8.3 Terms in capitals

Terms having a specific meaning in the context of The Qi Wireless Power Transfer System, Power Class 0 Specification are capitalized and defined in Section 1.5.

1.8.4 Units of physical quantities

Physical quantities are expressed in units of the International System of Units.

1.8.5 Decimal separator

The decimal separator is a period.

1.8.6 Notation of numbers

- Real numbers are represented using the digits 0 to 9, a decimal point, and optionally an exponential part. In addition, a positive and/or negative tolerance indicator may follow a real number. Real numbers that do not include an explicit tolerance indicator, are accurate to half the least significant digit that is specified.

EXAMPLE A specified value of $1.23^{+0.01}_{-0.02}$ comprises the range from 1.21 through 1.24; a specified value of $1.23^{+0.01}$ comprises the range from 1.23 through 1.24; a specified value of $1.23_{-0.02}$ comprises the range from 1.21 through 1.23; a specified value of 1.23 comprises the range from 1.225 through 1.234999...; and a specified value of $1.23^{\pm 10\%}$ comprises the range from 1.107 through 1.353.

- Integer numbers in decimal notation are represented using the digits 0 to 9.
- Integer numbers in hexadecimal notation are represented using the hexadecimal digits 0 to 9 and A to F, and are prefixed by “0x” unless explicitly indicated otherwise.
- Single bit values are represented using the words ZERO and ONE.
- Integer numbers in binary notation and bit patterns are represented using sequences of the digits 0 and 1, which are enclosed in single quotes (e.g. ‘01001’). In a sequence of n bits, the most significant bit (MSB) is bit b_{n-1} and the least significant bit (LSB) is bit b_0 . The most significant bit is shown on the left-hand side.
- Numbers that are shown between parentheses are informative.

1.8.7 Bit ordering in a byte

The graphical representation of a byte is such that the most significant bit is on the left, and the least significant bit is on the right. Figure 1 defines the bit positions in a byte.

Figure 1. Bit positions in a byte

MSB				LSB			
b7	b6	b5	b4	b3	b2	b1	b0

1.8.8 Byte numbering

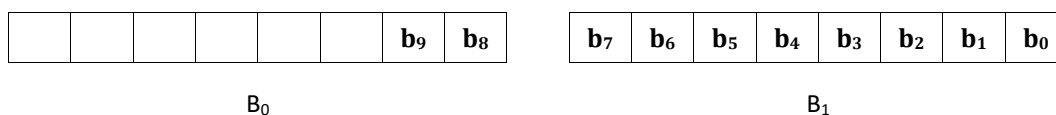
The bytes in a sequence of n bytes are referred to as $B_0, B_1, \dots, B_{n-1}$. Byte B_0 corresponds to the first byte in the sequence; byte B_{n-1} corresponds to the last byte in the sequence. The graphical representation of a byte sequence is such that B_0 is at the upper left-hand side, and byte B_{n-1} is at the lower right-hand side.

1.8.9 Multiple-bit fields

Multiple-bit fields are used in the ID Packet. Unless indicated otherwise, a multiple-bit field in a data structure represents an unsigned integer value. In a multiple-bit field that spans multiple bytes, the MSB of the multiple-bit field is located in the byte with the lowest address, and the LSB of the multiple-bit field is located in the byte with the highest address.

NOTE Figure 2 provides an example of a 10-bit field that spans two bytes.

Figure 2. Example of multiple-bit field



1.9 Operators

This section defines less-commonly used operators that are used in The Qi Wireless Power Transfer System, Power Class 0 Specification. The commonly used operators have their usual meaning.

1.9.1 Exclusive-OR

The symbol ' $\oplus$ ' represents the exclusive-OR operation.

1.9.2 Concatenation

The symbol '||' represents the concatenation of two bit strings. In the resulting concatenated bit string, the MSB of the right-hand side operand directly follows the LSB of the left-hand side operand.

1.10 Measurement equipment

All measurements shall be performed using equipment that has a resolution of at least one quarter of the precision of the quantity that is to be measured, unless indicated otherwise.

EXAMPLE "t_{start}=15 ms" means that the equipment shall be precise to 0.25 ms.

PART 1: Primary Interface Definition

2 Mechanical interface

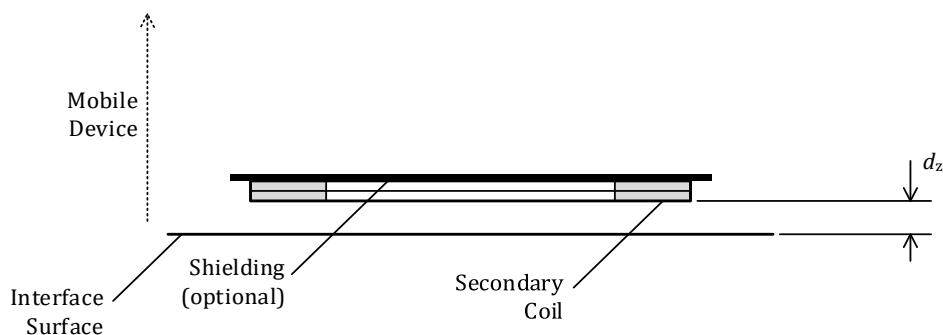
2.1 Power Receiver design requirements (PRx)

A Power Receiver design shall include a Secondary Coil, and an Interface Surface as defined in Section 2.1.1. In addition, a Power Receiver design shall include an alignment aid as defined in Section 0.

2.1.1 Interface Surface

The distance from the Secondary Coil to the Interface Surface of the Mobile Device (see Figure 3) shall not exceed $d_z = 2.5$ mm across the bottom face of the Secondary Coil.

Figure 3. Secondary Coil assembly



2.1.2 Alignment Aid

The design of a Mobile Device shall include means that helps a user to properly align the Secondary Coil of its Power Receiver to the Primary Coil of a Power Transmitter that enables Guided Positioning. This means shall provide the user with directional guidance, i.e. to where the user should move the Mobile Device, as well as alignment indication, i.e. feedback that the user has reached a properly aligned position.¹

NOTE An example of such means is a piece of hard or soft magnetic material, which is attracted to the magnet provided in Power Transmitter design A1. The attractive force should provide the user with tactile feedback when placing the Mobile Device on the Interface Surface.

NOTE The Mobile Device cannot rely on the presence of any alignment support from the Base Station other than the alignment aids specified in *Part 4: Reference Designs*.

¹ The design requirements of the Mobile Device determine the range of lateral displacements that constitute proper alignment.

2.2 Power Transmitter design requirements (PTx)

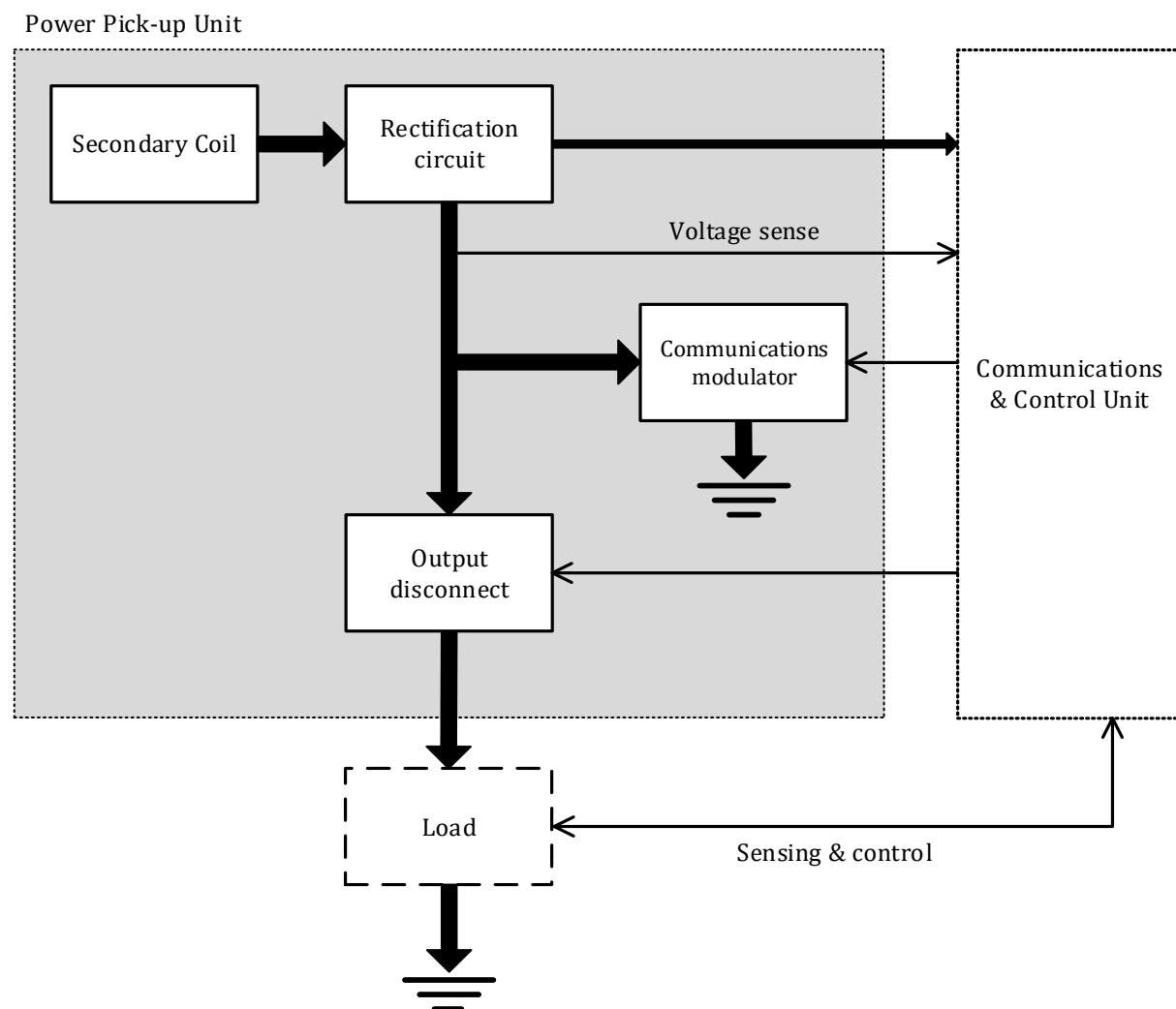
The design requirements for each Power Transmitter type are defined in *Part 4: Reference Designs*.

3 Electromagnetic interface

3.1 Power Receiver design requirements (PRx)

Figure 4 illustrates an example of a functional block diagram for a Baseline Power Profile Power Receiver.

Figure 4. Functional block diagram for a Baseline Power Profile Power Receiver



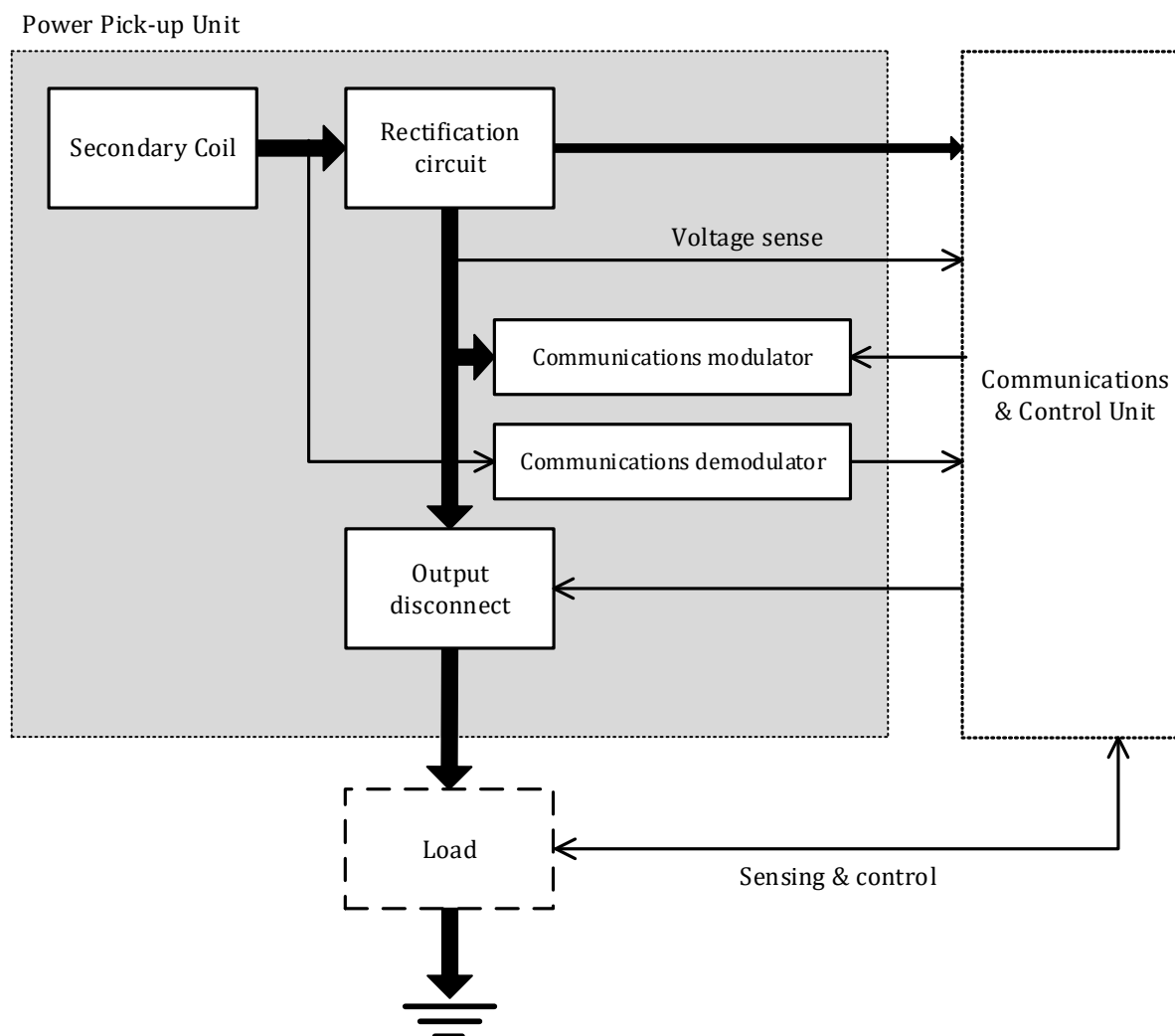
In this example, the Power Receiver consists of a Power Pick-up Unit and a Communications and Control Unit. The Power Pick-up Unit on the left-hand side of Figure 4 comprises the analog components of the Power Receiver:

- A dual resonant circuit consisting of a Secondary Coil plus series and parallel capacitances to enhance the power transfer efficiency and enable a resonant detection method (see Section 3.1.1, *Dual resonant circuit*).
- A rectification circuit that provides full-wave rectification of the AC waveform using, for example, four diodes in a full-bridge configuration or a suitable configuration of active components (see Section 3.1.2, *Rectification circuit*). The rectification circuit may perform output smoothing as well. In this example, the rectification circuit provides power to both the Communications and Control Unit of the Power Receiver and the output of the Power Receiver
- A communications modulator (see Section 3.1.4, *Communications modulator*). On the DC side of the Power Receiver, the communications modulator typically consists of a resistor in series with a switch. On the AC side of the Power Receiver, the communications modulator typically consists of a capacitor in series with a switch (not shown in Figure 4).
- An output disconnect switch, which prevents current from flowing to the output when the Power Receiver does not provide power at its output. In addition, the output disconnect switch prevents current backflow into the Power Receiver when the Power Receiver does not provide power at its output. Moreover, the output disconnect switch minimizes the power that the Power Receiver draws from the Power Transmitter when a Power Signal is first applied to the Secondary Coil.
- A rectified voltage sense.

The Communications and Control Unit on the right-hand side of Figure 4 comprises the digital logic part of the Power Receiver. This unit executes the relevant power control algorithms and protocols, drives the communications modulator, controls the output disconnect switch, and monitors several sensing circuits in both the Power Pick-up Unit and the load. (A good example of a sensing circuit in the load is a circuit that measures the temperature of a rechargeable battery.)

NOTE This version of the Specification minimizes the set of Power Receiver design requirements defined in this section. Accordingly, compliant Power Receiver designs that differ from the sample functional block diagram shown in Figure 4 are possible. For example, an alternative design includes post-regulation of the output of the rectification circuit (e.g., by using a buck converter, battery charging circuit, power management unit, etc.). In yet another design, the Communications and Control Unit interfaces with other subsystems of the Mobile Device, e.g. for user interface purposes.

Figure 5 illustrates an example of a functional block diagram for an Extended Power Profile Power Receiver. The communications demodulator enables the communication of data from the Power Transmitter to an Extended Power Profile Power Receiver. The presence of a communications demodulator is the only difference with the functional block diagram of a Baseline Power Profile Power Receiver.

Figure 5. Functional block diagram for an Extended Power Profile Power Receiver

Power Pick-up Unit components are described in the subsections below.

A Power Receiver design shall include a dual resonant circuit as defined in Section 3.1.1, a rectification circuit as defined in Section 3.1.2, sensing circuits as defined in Section 3.1.3, a communications modulator as defined in Section 3.1.4, and an output disconnect switch as defined in Section 3.1.6.

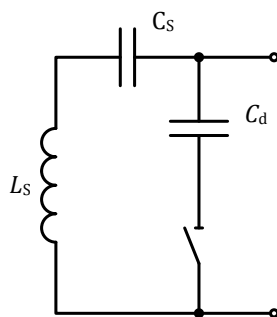
A Power Receiver design for the Extended Power Profile shall also include a communications demodulator as defined in Section 3.1.5, and shall be able to function meaningfully if the Power Transmitter restrictions limit the output of power from the Power Receiver to 5 W; see Section 3.1.7.

3.1.1 Dual resonant circuit

The dual resonant circuit of the Power Receiver comprises the Secondary Coil and two resonant capacitances. The purpose of the first resonant capacitance C_s is to enhance the power transfer efficiency. The purpose of the second resonant capacitance C_d is to enable a resonant detection method.

Figure 6 illustrates the dual resonant circuit. The switch in the dual resonant circuit is optional. If the switch is not present, the capacitance C_d shall have a fixed connection to the Secondary Coil L_s . If the switch is present, it shall remain closed² until the Power Receiver transmits its first Packet (see Section 5.1.3.1).

Figure 6. Dual resonant circuit of a Power Receiver



The dual resonant circuit shall have the following resonant frequencies:

$$f_s = \frac{1}{2\pi \cdot \sqrt{L'_S \cdot C_s}} = 100^{+x}_{-y} \text{ kHz},$$

$$f_d = \frac{1}{2\pi \cdot \sqrt{L_s \cdot \left(\frac{1}{C_s} + \frac{1}{C_d}\right)^{-1}}} = 1000^{\pm 10\%} \text{ kHz}.$$

In these equations, L'_S is the self inductance of the Secondary Coil when placed on the Interface Surface of a Power Transmitter and—if necessary—aligned to the Primary Cell; and L_s is the self inductance of the Secondary Coil without magnetically active material that is not part of the Power Receiver design close to the Secondary Coil (e.g. away from the Interface Surface of a Power Transmitter). Moreover, the tolerances x and y on the resonant frequency f_s are $x = y = 5\%$ for Power Receivers that specify a Maximum Power value in the Configuration Packet of 3 W and above, and $x = 5\%$ and $y = 10\%$ for all other Power Receivers. The quality factor Q of the loop consisting of the Secondary Coil, switch (if

² The switch shall remain closed even if no power is available from the Secondary Coil.

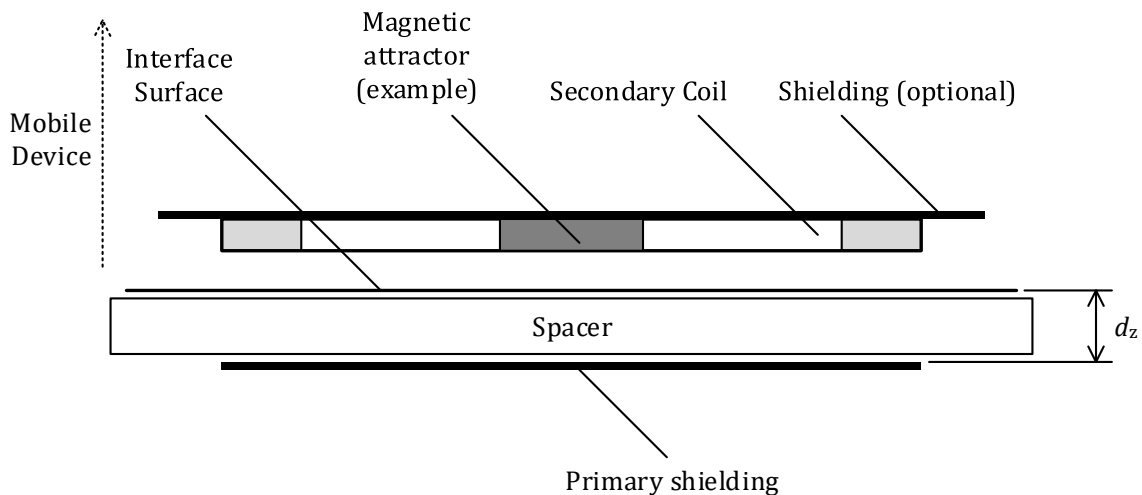
present), resonant capacitance C_s and resonant capacitance C_d , shall exceed the value 77. Here the quality factor Q is defined as:

$$Q = \frac{2\pi \cdot f_d \cdot L_s}{R}$$

where R is the DC resistance of the loop with the capacitances C_s and C_d short-circuited.

Figure 7 shows the environment that is used to determine the self-inductance L'_s of the Secondary Coil. The primary Shielding shown in Figure 7 consists of material PC44 from TDK Corp. The primary Shielding has a square shape with a side of 50 mm and a thickness of 1 mm. The center of the Secondary Coil and the center of the primary Shielding shall be aligned. The distance from the Receiver Interface Surface to the primary Shielding is $d_z = 3.4$ mm. Shielding on top of the Secondary Coil is present only if the Receiver design includes such Shielding. Other Mobile Device components that influence the inductance of the Secondary Coil shall be present as well when determining the resonant frequencies—the magnetic attractor shown in Figure 7 is an example of such a component. The excitation signal that is used to determine L_s and L'_s shall have an amplitude of 1 V RMS and a frequency of 100 kHz.

Figure 7. Characterization of resonant frequencies



3.1.2 Rectification circuit

The rectification circuit shall use full-wave rectification to convert the AC waveform to a DC power level.

3.1.3 Sensing circuits

The Power Receiver shall monitor the DC voltage V_r directly at the output of the rectification circuit.

3.1.4 Communications modulator

The Power Receiver shall have the means to modulate the Primary Cell current and Primary Cell voltage as defined in Section 5.3.2.1, *Modulation scheme*.³ This version of the Specification leaves the specific loading method as a design choice to the Power Receiver. Typical methods include modulation of a resistive load on the DC side of the Power Receiver and modulation of a capacitive load on the AC side of the Power Receiver.

3.1.5 Communications demodulator

For the Extended Power Profile or for the Baseline Power Profile with FOD extensions, the Power Receiver shall have the means to demodulate frequency-shift keying (FSK) data from the Power Signal frequency as defined in Section 5.3.2.1, *Modulation scheme*. This Specification leaves the specific method up to the designer of the Power Receiver.

3.1.6 Output disconnect

The Power Receiver shall have the means to disconnect its output from the subsystems connected thereto. If the Power Receiver has disconnected its output, it shall ensure that it still draws a sufficient amount of power from the Power Transmitter, such that Power Receiver to Power Transmitter communications remain possible (see Section 5.2.2.1, *Modulation scheme*).

The Power Receiver shall keep its output disconnected until it reaches the *power transfer* phase for the first time after a Digital Ping (see Section 5.1, *System Control*). Subsequently, the Power Receiver may operate the output disconnect switch any time while the Power Transmitter applies a Power Signal.

NOTE The Power Receiver may experience a voltage peak when operating the output disconnect switch (and changing between maximum and near-zero power dissipation).

³ NOTE The dual resonant circuit as depicted in Figure 6 does not prohibit implementation of the communications modulator directly at the Secondary Coil.

3.1.7 Meaningful functionality

A Power Receiver shall be able to function meaningfully if the Power Transmitter restrictions limit the output of power from the Power Receiver to 5 W. Meaningful functionality includes:

- Charging a connected battery at a rate that is lower than intended.
- Providing a clear and unambiguous indication to the user that the Power Receiver cannot draw the amount of power from the Power Transmitter that it needs to function properly. See Section 13.2, *User interaction with a Mobile Device*.

NOTE The following are cases in which the Power Receiver cannot provide a desired amount of power greater than 5 W to its output.

- The Power Receiver is positioned on a Baseline Power Profile Power Transmitter (see the Power Transmitter designs in *Part 4: Reference Designs*).
- The Power Transmitter is powered by an external power supply that is designed to provide no more than 5 W of power.

3.1.8 Shielding

An important consideration for a Power Receiver designer is the impact of the Power Transmitter's magnetic field on the Mobile Device. Stray magnetic fields could interact with the Mobile Device and potentially cause its intended functionality to deteriorate, or cause its temperature to increase due to the power dissipation of generated eddy currents.

It is recommended to limit the impact of magnetic fields by means of Shielding on the top face of the Secondary Coil, as shown in Figure 3. This Shielding should consist of material that has parameters similar to the materials listed in *Part 4: Reference Designs*. The Shielding should cover the Secondary Coil completely. Additional Shielding beyond the outer diameter of the Secondary Coil might be necessary depending upon the impact of stray magnetic fields.

NOTE The Power Receiver design examples discussed in *Part 4: Reference Designs* include Shielding.

3.2 Power Transmitter design requirements (PTx)

3.2.1 Load step and load dump (informative)

A Mobile Device may perform load steps and dumps that are beyond the control of its Power Receiver. A load step or dump causes an immediate impedance change, which is reflected from the Secondary Coil to the Primary Coil and results in a change of the rectified voltage. Due to the latency of the control loop (which is mainly due to the time that is required to communicate Control Error Packets), it takes a while before the rectified voltage is readjusted to a (new) desired value. The Power Transmitter should ensure that the established Power Transfer Contract is not terminated during such an event. Therefore, an implementation of a Power Transmitter—following one of the designs defined in *Part 4: Reference Designs*—should meet load steps from 10% to 100% of the Maximum Power (as communicated by the Power Receiver in the Configuration Packet) and load dumps from 100% to 10%.

3.2.2 Load step test procedure

3.2.2.1 Baseline Power Profile load step test

The following procedure is recommended to verify that the Power Transmitter contained in a Base Station is able to handle load steps and dumps:

1. Position Test Power Receiver #1 in configuration B on the Interface Surface of the Base Station with an initial load of $32\ \Omega$, a Power Control Hold-off Time of $t_{\text{delay}} = 100\ \text{ms}$, and an interval time between consecutive Control Error Packets of $t_{\text{interval}} = 250\ \text{ms}$.
2. Establish communication and regulate the rectified voltage to $V_r = 7^{\pm 2\%}\ \text{V}$.
3. Change the load from its initial value to $127\ \Omega$ and regulate the rectified voltage to $V_r = 7^{\pm 2\%}\ \text{V}$.
4. Change the load from $127\ \Omega$ to $10\ \Omega$, $\Delta t_1 = 50\ \text{ms}$ before a sending a Control Error Packet.
5. Verify that the Test Power Receiver continues to regulate and that the Base Station responds to the Control Error Packets by adjusting V_r .
6. Measure the rectified voltage (V_0 , V_1 , and V_{min}) with timings as shown in Figure 8, where $\Delta t_2 = 1800\ \text{ms}$.
7. Verify that the measured values comply with the limits provided in Table 1.

Figure 8. Load step test diagram

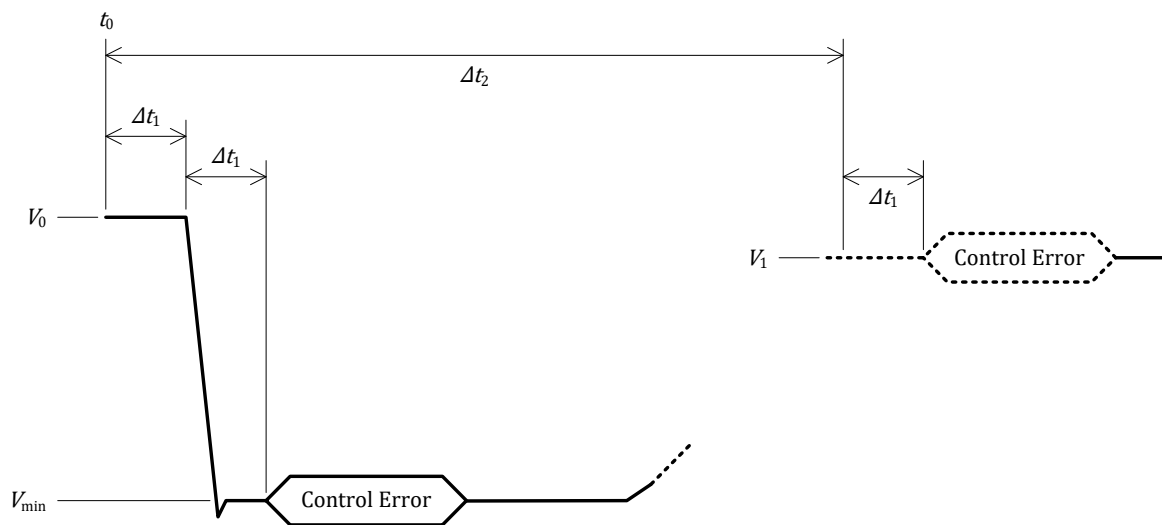


Table 1. Load step limits

Voltage	Minimum	Target	Maximum	Unit
V_0	6.9	7.0	7.1	V
V_{min}	4.0	7.0	7.1	V
V_1	6.0	V_0	7.1	V

3.2.2.2 Extended Power Profile load step test

1. Position the Test Power Receiver on the Interface Surface of the Base Station, with an initial load of R_{init} , a Power Control Hold-off Time of $t_{delay} = 100$ ms, and an interval time between consecutive Control Error Packets of $t_{interval} = 250$ ms. See Table 2 for relevant parameters.
2. Establish communications and regulate the rectified voltage to V_r .
3. Change the load from its initial value to R_{light} and regulate the rectified voltage V_r .
4. Change the load from R_{light} to R_{heavy} at $\Delta t_1 = 50$ ms before a sending a Control Error Packet.
5. Verify that the Test Power Receiver continues to regulate and that the Base Station responds to the Control Error Packets by adjusting V_r .
6. Measure the rectified voltages V_0 , V_1 , and V_{min} with timings as shown in Figure 8 above, where $\Delta t_2 = 1800$ ms.
7. Verify the measured values with the limits provided in Table 1.

Table 2. Load step definitions

Test Power Receiver	Initial Load R_{init}	Light Load R_{light}	Heavy Load R_{heavy}	Rectified Voltage V_r
TPR#1B	32 Ω	127 Ω	10 Ω	$7^{\pm 2\%}$ V
TPR#MP1B	72 Ω	96 Ω	10 Ω	$12^{\pm 2\%}$ V

Table 3. Load step limits

Test Power Receiver	Voltage	Minimum [V]	Target [V]	Maximum [V]
TPR#1B	V_0	6.9	7.0	7.1
	V_{min}	4.0	7.0	7.1
	V_1	6.0	V_0	7.1
TPR#MP1B	V_0	11.8	12.0	12.2
	V_{min}	6.9	12.0	12.2
	V_1	10.3	V_0	12.2

3.2.3 Load dump test procedure

3.2.3.1 Baseline Power Profile load dump test

1. Position Test Power Receiver #1 in configuration B on the Interface Surface of the Base Station, with an initial load of 32 Ω , a Power Control Hold-off Time $t_{\text{delay}} = 100$ ms, and an interval time between consecutive Control Error Packets $t_{\text{interval}} = 250$ ms.
2. Establish communication and regulate the rectified voltage to $V_r = 7^{\pm 2\%}$ V.
3. Change the load from its initial value to 10 Ω and regulate the rectified voltage to $V_r = 7^{\pm 2\%}$ V.
4. Change the load from 10 Ω to 127 Ω , $\Delta t_1 = 50$ ms before a sending a Control Error Packet.
5. Verify that the Test Power Receiver continues to regulate and that the Base Station responds to the Control Error Packets by adjusting V_r .
6. Measure the rectified voltage (V_0 , V_1 , and V_{min}) with timings as shown in Figure 9. Load dump test diagram, where $\Delta t_2 = 1800$ ms.
7. Verify that the measured values comply with the limits provided in Table 4.

Figure 9. Load dump test diagram

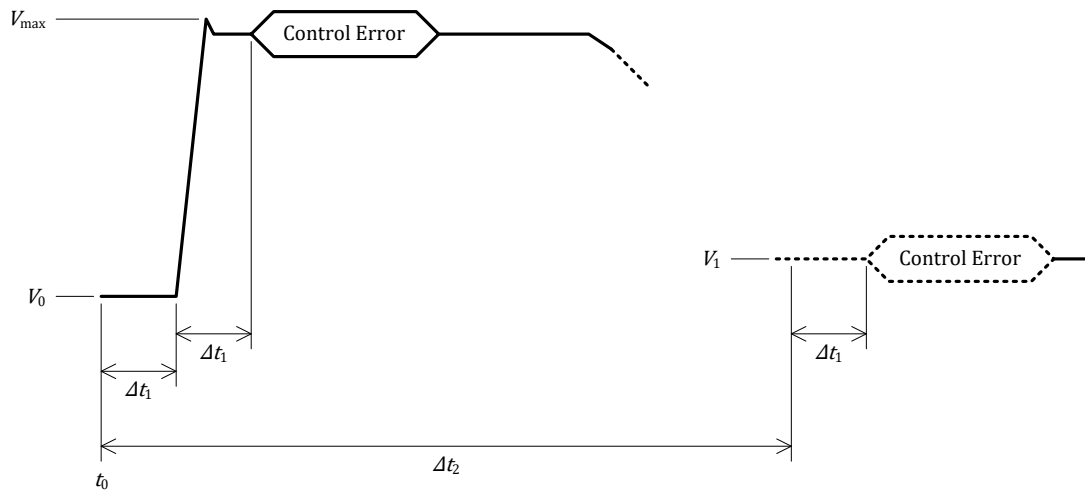


Table 4. Load dump limits (Baseline Power Profile)

Voltage	Minimum	Target	Maximum	Unit
V_0	6.9	7.0	7.1	V
$V_{\min}$	6.9	7.0	12.0	V
V_1	6.9	V_0	8.0	V

3.2.3.2 Extended Power Profile load dump test

- Position the Test Power Receiver on the Interface Surface of the Base Station, with an initial load of R_{init} , a Power Control Hold-off Time of $t_{\text{delay}} = 100$ ms, and an interval time between consecutive Control Error Packets of $t_{\text{interval}} = 250$ ms. See Table 5 for the relevant parameters.
- Establish communications and regulate the rectified voltage to V_r .
- Change the load from its initial value to R_{heavy} and regulate the rectified voltage V_r .
- Change the load from R_{heavy} to R_{light} at $\Delta t_1 = 50$ ms before sending a Control Error Packet.
- Verify that the Test Power Receiver continues to regulate and that the Base Station responds to the Control Error Packets by adjusting V_r .
- Measure the rectified voltages V_0 , V_1 , and $V_{\min}$ with timings as shown in Figure 9 above, where $\Delta t_2 = 1800$ ms.
- Verify the measured values with the limits provided in Table 5.

Table 5. Load dump definitions (Extended Power Profile)

Test Power Receiver	Initial Load R_{init}	Light Load R_{light}	Heavy Load R_{heavy}	Rectified Voltage V_r
TPR#1B	32 Ω	127 Ω	10 Ω	$7 \pm 2\%$ V
TPR#MP1B	72 Ω	96 Ω	10 Ω	$12 \pm 2\%$ V

Table 6. Load dump limits

Test Power Receiver	Voltage	Minimum [V]	Target [V]	Maximum [V]
TPR#1B	V_0	6.9	7.0	7.1
	V_{min}	6.9	7.0	12.0
	V_1	6.9	V_0	8.0
TPR#MP1B	V_0	11.8	12.0	12.2
	V_{min}	11.8	12.0	20.5
	V_1	11.8	V_0	13.7

3.2.4 Power Receiver over-voltage protection

A Power Transmitter shall limit the amplitude of its Power Signal (or magnetic field strength) such that it does not generate a rectified voltage higher than 20 V at the output of a properly designed Power Receiver.

NOTE: Examples of properly designed Power Receivers are provided in *Part 4: Reference Designs*. In addition, the set of Test Power Receivers defined in *Part 3: Compliance Testing* are also examples of properly designed Power Receivers.

The Power Signal depends on the amount of current that runs through the Primary Coil. This amount is primarily determined by the Power Transmitter's Operating Point, the Power Receiver's load impedance, and the coupling between the Primary Coil and Secondary Coil. Whereas the Power Receiver can—to a certain extent—control its load impedance and the Power Transmitter's Operating Point by transmitting appropriate Control Error Packets, it has little control over the coupling. As a consequence, scenarios exist in which a higher-than-expected voltage can result at the Power Receiver's output.

In one scenario the user initially places the Power Receiver at a position where the coupling is poor and subsequently moves it to a position where the coupling is strong. In practice this can happen when the user keeps the Power Receiver hovering at a small distance above the Interface Surface before setting it down, or when the user places the Power Receiver with a large misalignment between the Primary Coil and Secondary Coil and subsequently slides it into better alignment.

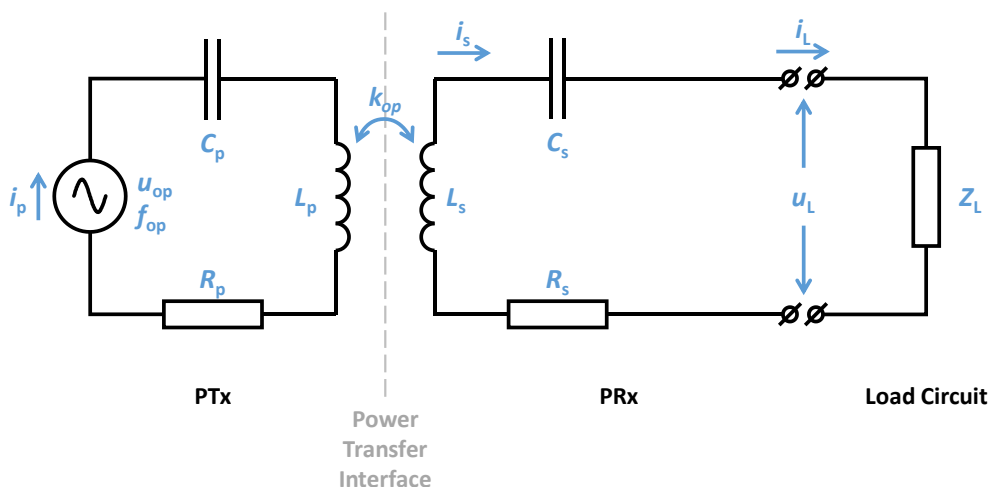
In either case, the Power Transmitter can detect the Power Receiver and establish communications before the coils are properly aligned. The Power Receiver can then start to control its output voltage to a higher level, such as 12 V, in order to prepare for connecting its load. If the coupling is poor, the Power Receiver typically can reach its target voltage only by driving the power Transmitter to use a high Primary Coil current (and therefore a strong Power Signal or high magnetic field). If the coupling suddenly improves substantially, as in the above scenarios, the Power Receiver does not have time to drive the Power Transmitter back to a lower Primary Coil current. As a result, its output voltage can substantially increase—up to tens of volts if no special precautions are taken.

Many Power Receiver implementations that are based on common IC technology cannot handle such voltages, with 20 V being a safe upper limit. Moreover, design constraints often are of such a nature that commonly used solutions for over-voltage protection cannot be applied. For example, large Zener diodes or dummy loads that can handle the excess power typically are too bulky to fit in space-limited designs. Accordingly, the Power Receiver typically has no alternative but to rely on the Power Transmitter to keep its voltage below the safe limit.

Whereas a Power Transmitter can hold its Primary Coil current to a sufficiently low level, placing a hard limit on the Primary Coil current can prevent a Power Receiver from reaching its target power level when it has connected its load. A better solution is to define more than one limit according to the amount of power that is transmitted: the Power Transmitter should use a low current limit if the Transmitted Power is low to prevent an over-voltage from occurring in the Power Receiver, and it should use a high current limit if the Transmitted Power is high to enable the Power Receiver to reach its target Operating Point without creating an over-voltage in the Power Receiver. The system model and analysis below explain this approach in more detail.

Figure 10 illustrates a simplified model of the system comprising a Power Transmitter on the left and a Power Receiver on the right. For clarity, the load circuit is drawn separately from the Power Receiver. The Power Transmitter consists of a power source (u_{op}, f_{op}), a capacitance C_p , an inductance L_p , and a resistance R_p . The power source supplies a sinusoidal voltage u_{op} at a frequency f_{op} . The Power Receiver consists of a capacitance C_s , an inductance L_s , and a resistance R_s . A load having an impedance Z_L is connected to the output terminals of the Power Receiver. The symbols u_L , i_L , i_p , and k_{op} represent the load voltage, load current, Primary Coil current, and coupling factor.

Figure 10. Simplified system model



For simplicity the Power Receiver in the model includes neither a rectifier nor a resonance at a frequency f_d as defined in Sections 3.1.2 and 3.1.1. The absence of the additional resonance does not significantly affect the results discussed below. The effect of the rectifier is described at the end of this section.

Table 7 lists the parameters associated with the system model in Figure 10. Instead of the resonant capacitances C_p and C_s , and the resistances R_p and R_s , the resonant frequencies f_p and f_s , and quality factors Q_p and Q_s are provided. The relations between these parameters are as follows:

$$f_p = \frac{1}{2\pi\sqrt{L_p C_p}}, \quad f_s = \frac{1}{2\pi\sqrt{L_s C_s}}, \quad Q_p = \frac{2\pi f_p L_p}{R_p}, \quad Q_s = \frac{2\pi f_s L_s}{R_s}$$

The Power Transmitter controls the amount of power it transfers by adjusting the amplitude of its voltage and frequency in the ranges given in Table 7. At start-up, it uses the ping voltage u_{ping} and ping frequency f_{ping} . To control the power up, it decreases its frequency while keeping its voltage constant at the maximum value. To control the power down, it increases the frequency at constant voltage, and after reaching the maximum frequency value decreases the voltage while keeping the frequency constant at that maximum.

At start-up, the Power Receiver uses a load impedance Z_{ping} , which represents the load of its control electronics such as a microprocessor. After start-up, the Power Receiver can adjust its load impedance to reach its target Operating Point as given by the target voltage u_L and target current i_L .

Table 7. Parameters of the simplified model

Power Transmitter			Power Receiver		
L_p	25	μH	L_s	35	μH
f_p	100	kHz	f_s	100	kHz
Q_p	100		Q_s	40	
u_{op}	2...24	V (pk)	u_L	12	V (rms)
f_{op}	100...200	kHz	i_L	1.5	A (rms)
u_{ping}	24	V (pk)	Z_L	0.1...1000	Ω
f_{ping}	175	kHz	Z_{ping}	800	Ω

Power Transmitter operation is subject to these constraints:

- The PTx only uses the part of its operating frequency range where the Primary Coil current decreases while the operating frequency increases. This constraint ensures that the Control Error Packets from the Power Receiver have a consistent effect: a positive Control Error Value causes the Primary Coil current to increase, and a negative Control Error Value causes the Primary Coil current to decrease.

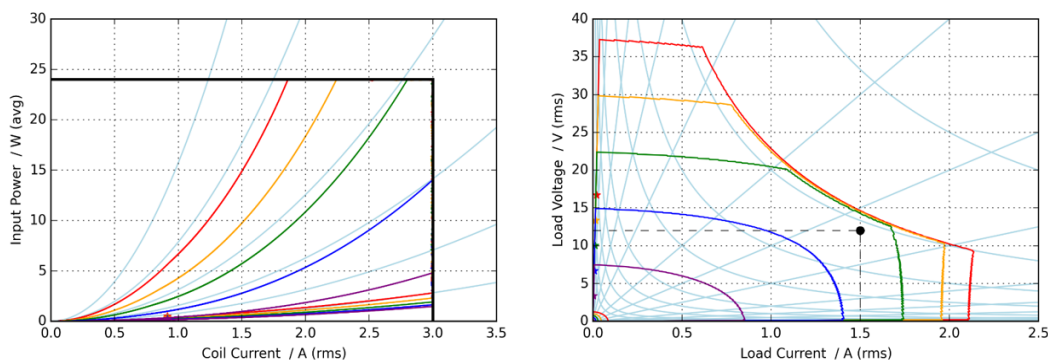
NOTE: A positive Control Error Value directs the Power Transmitter to increase its voltage, or to decrease its operating frequency if the voltage has reached its maximum value. A negative Control Error Value directs the Power transmitter to increase its operating frequency, or to decrease its voltage if the operating frequency has reached its maximum value. This method of power control is used by many of the Power Transmitter designs provided in *Part 4: Reference Designs*.

- The PTx limits the amount of power that it takes from its power source. In the simplified model, the maximum average power is 24 W.

- The PTx limits the amount of Primary Coil current. Two examples are discussed below. In the first example, the Primary Coil current is limited at the fixed value of 3 A rms. In the second example, the Primary Coil current limit depends on the Transmitted Power, increasing from 0.75 A (rms) at near zero Transmitted Power up to about 2.7 A (rms) at near maximum Transmitted Power.

The diagram on the left in Figure 11 illustrates the full operating space of the Power Transmitter in terms of its Primary Coil current and the power it takes from its power source. The diagram on the right illustrates the operating space of the Power Receiver in terms of its load current and voltage. The solid black lines in the Power Transmitter's diagram indicate its power and current limits. The solid black dot in the Power Receiver's diagram indicates its target Operating Point. The colors of the different curves represent different coupling factors. The red curve corresponds to a coupling factor of 0.56 (good coupling). The yellow, green, blue, and purple curves correspond to 80%, 60%, 40%, and 20% of the "red" value. Each curve forms a closed contour limiting the operating space of the Power Transmitter and Power Receiver for the associated coupling factor (for the parts of the contour that coincide with the power limit, the current limit, or the diagram axes this may be difficult to see). The Power Transmitter and Power Receiver can reach any point within a contour given appropriate values of the Power Transmitter's operating frequency and voltage. Finally, the stars indicate the ping Operating Points of the Power Transmitter and Power Receiver.

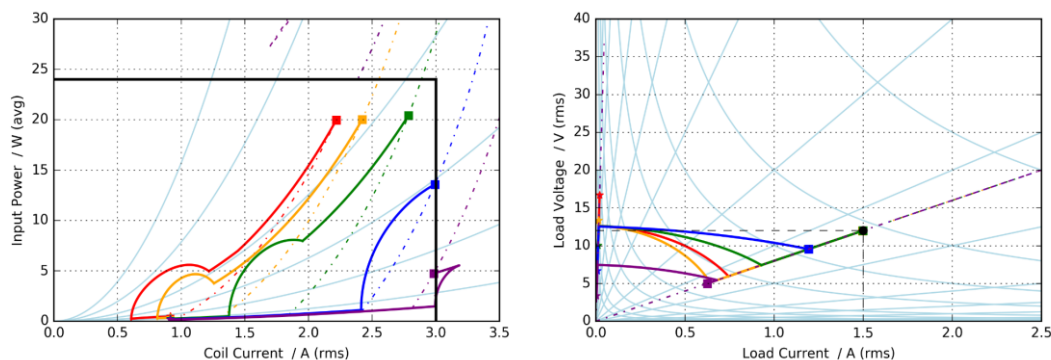
Figure 11. Operating space with a fixed-maximum Primary Coil current



The diagram on the right shows that the Power Receiver can reach its target Operating Point for a coupling factor greater than about 0.3, because that Operating Point lies well within the green contour (a coupling factor of 60%·0.56). The diagram also makes clear that the load voltage can potentially reach levels well above 20 V (rms) for coupling factors greater than 0.3. For example, the top left corner of the yellow curve, representing a coupling factor of 80%·0.56 and a load impedance of 1 kΩ, reaches a load voltage of 30 V (rms).

The solid curves in Figure 12 illustrate the “trajectories” that the Power Transmitter and Power Receiver follow through their operating space when controlling from the ping Operating Point to the target Operating Point at different coupling factors. Each trajectory starts from the ping Operating Point, which is indicated by a star. The Power Receiver first controls its load voltage to a value just over 12 V (rms). In the Transmitter’s diagram this is the slightly slanted line near the bottom (less than 1 W of input power). In the Power Receiver it is the steep line close to the vertical axis. Next the Power Receiver changes its load from the ping load impedance to the target load impedance ($12 \text{ V} / 1.5 \text{ A} = 8 \Omega$). This load step increases the Power Transmitter’s power and Primary Coil current, and it decreases the load voltage. For the lowest coupling (purple curve) the Primary coil current even exceeds the limit. In this example, the Power Transmitter does not enforce its current limit instantly, but instead controls its Operating Point back to the limit after completion of the load step. Finally, the Power Receiver controls its voltage to the target value, which is possible for the highest coupling factors only (red, yellow, and green curves). At the lower coupling factors (blue and purple curves), the Power Transmitter hits its current limit. The solid squares indicate the final Operating Point for each coupling factor.

Figure 12. System control with a fixed-maximum Primary Coil current (1)



As a clear illustration of the scenarios described earlier in this section, the dashed and dotted curves in Figure 12 show the trajectories that the Power Transmitter and Power Receiver follow if the coupling factor changes between zero and 0.56. The load impedance and the Power Transmitter’s Operating Point are fixed on these trajectories (i.e. the Power Transmitter does not enforce its limits during the coupling step). As shown in the diagram on the right, the load voltage can reach values up to about 20 V (rms) at the target load impedance of 8Ω . To reach this voltage, the input power and Primary Coil current exceed their limits substantially (see the left diagram). The behavior is radically different at the ping impedance of 800Ω , where the load voltage can reach values well over 20 V (rms). Corresponding trajectories are not visible in the diagram on the left because the coupling step causes hardly any change in the Primary Coil current and input power. Even if the Power Transmitter would instantly enforce its limits, the load voltage would reach these high levels. This is clearly visible in Figure 13, where the maximum load voltage is much reduced at the target load impedance but not at the ping impedance. In fact, the maximum reachable load voltages can be read directly from the red contour in Figure 11 (diagram on the right).

Figure 13. System control with a fixed-maximum Primary Coil current (2)

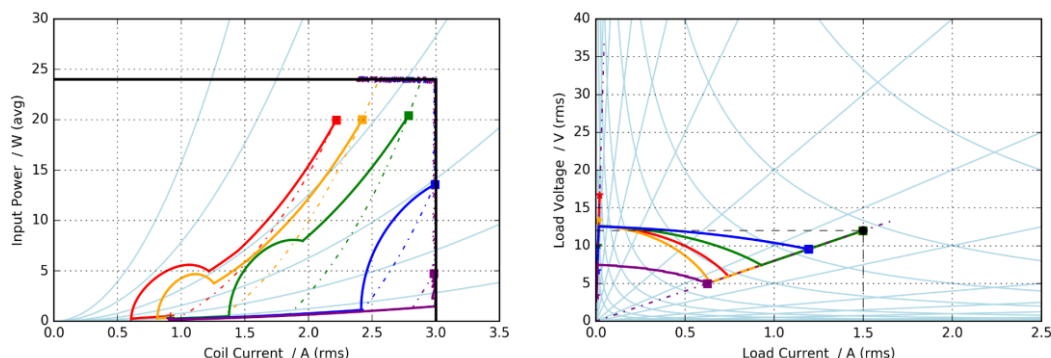
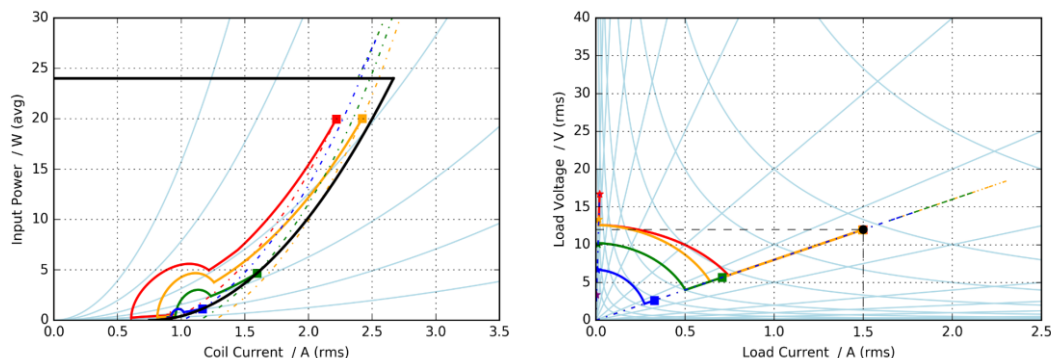
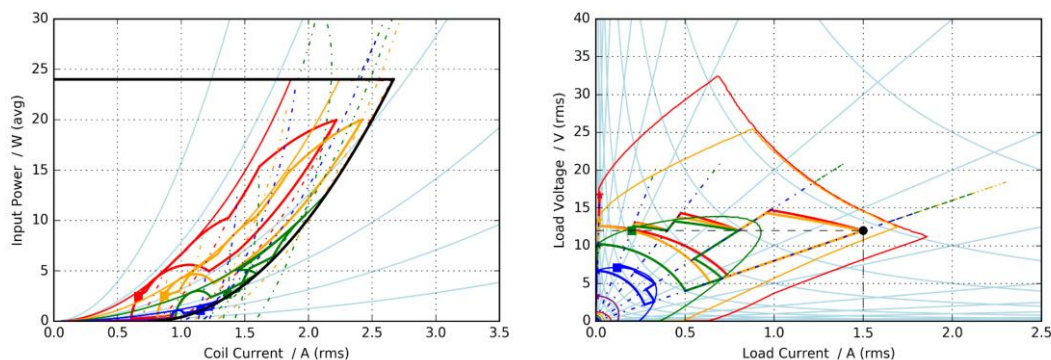


Figure 14 illustrates that a Primary Coil current limit that depends on the Transmitted Power (or on the input power) is a means to mitigate high load voltages in the Power Receiver. Clearly, the highest load voltages reached using this limit stay well below 20 V (rms). This example also illustrates that the cost of this approach is a reduced coupling range over which the Power Receiver can reach its target Operating Point (the green curve representing a coupling factor of 60%-0.56 does no longer reach the target Operating Point). This means that proper alignment of the Power Transmitter and Power Receiver becomes important. Different shapes of the current limit yield a different trade-off between maximum load voltage and the coupling range.

Figure 14. System control at power-dependent maximum Primary Coil current (1)



As a final example, Figure 15 illustrates the full operating space that results from the power-dependent current limit; the trajectories that result if the Power Receiver scales its power back from its target to load powers of 10 W, 5 W, and 3 W; and the maximum voltages that result from coupling steps at these additional Operating Points. In most cases, the maximum voltage does not exceed 20 V (rms), and where it does exceed 20 V (rms) it is not by much.

Figure 15. System control at power dependent maximum Primary Coil current (2)

All practical Power Receiver implementations use a rectifier as part of the load circuit shown in Figure 10 (see also Section 3.1.2). Moreover, most Power Receiver implementations include a capacitor directly after this rectifier to smoothen the ripple on the rectified voltage. In combination with a high load impedance (low load current), this smoothing capacitor typically charges to a level approaching the peak voltage that is present at the input to the rectifier. When determining the appropriate (power-dependent) current limit this effect should be taken into account. Special care should be taken in designing Power Transmitters that use duty-cycle control (instead of frequency or voltage control), because the peak voltage in those designs can be substantially higher than the rms voltage that is used in the above examples. (The voltage waveform at the input to the rectifier resembles the waveform generated by the Power Transmitter's power source.)

4 Thermal interface

4.1 Interface Surface temperature rise

The Base Station shall limit the top surface temperature of the thermal Test Power Receiver (TPR-THERMAL, defined in *Part 3: Compliance Testing*) to at most 12 °C above the ambient temperature, while TPR-THERMAL is operating at its desired Control Point for 1 hour in an environment that is shielded against spurious thermal contributions due to air flow, radiation, etc. It is recommended that the Base Station limits the Interface Surface temperature to at most 5 °C above the ambient temperature, while powering TPR-THERMAL for 1 hour.

5 Information interface

5.1 System Control

As noted in Section 1.4.2, this Power Class 0 Specification includes both the Baseline Power Profile (power transfers up to 5 W) and the Extended Power Profile (power transfers greater than 5 W). While much of the information presented in this Specification applies to both power profiles, there are some differences. Those differences are identified in this specification as they occur.

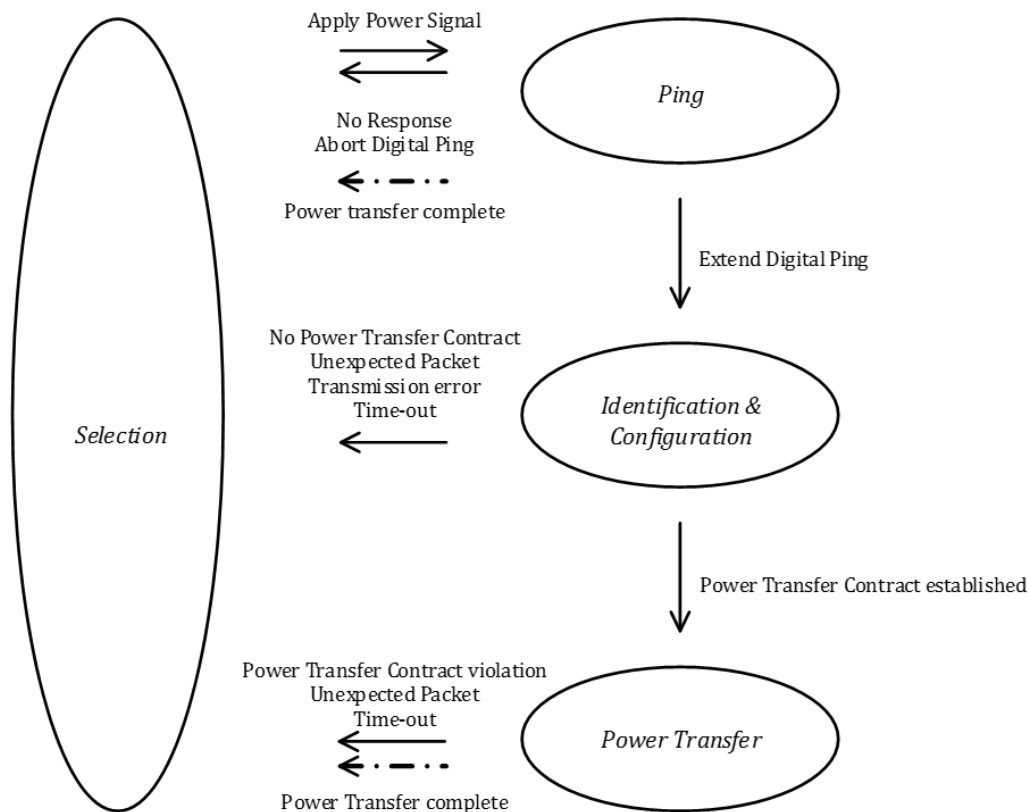
This Specification also describes FOD extensions, which use bidirectional communications and negotiation between the Power Transmitter (PTx) and Power Receiver (PRx) to enhance the options for Foreign Object Detection. Support for FOD extensions is optional in the Baseline Power Profile but mandatory in the Extended Power Profile:

- Baseline Power Profile Power Transmitters and Power Receivers **may** support the FOD extensions.
- Extended Power Profile Power Transmitters and Power Receivers **shall** support the FOD extensions.

5.1.1 Overview (informative)

From a system control perspective, power transfer from a Power Transmitter to a Power Receiver comprises four phases in the Baseline Power Profile, namely *selection*, *ping*, *identification & configuration*, and *power transfer*. Figure 16 illustrates the relation between the phases. The solid arrows indicate transitions, which the Power Transmitter initiates; and the dash-dotted arrows indicate transitions that the Power Receiver initiates. By definition, if the Power Transmitter is not applying a Power Signal, the system is in the *selection* phase. This means that a transition from any of the other phases to the *selection* phase involves the Power Transmitter removing the Power Signal.

Figure 16. Power transfer phases—Baseline Power Profile



The main activity in each of these phases is the following:

- *selection* In this phase, the Power Transmitter typically monitors the Interface Surface for the placement and removal of objects. The Power Transmitter may use a variety of methods for this purpose. See Section 10, *Object Detection (Informative)* for some examples. If the Power Transmitter discovers one or more objects, it should attempt to locate those objects—in particular if it supports Free Positioning. In addition, the Power Transmitter may attempt to differentiate between Power Receivers and Foreign Objects, such as keys, coins, etc. Moreover, the Power Transmitter should attempt to select a Power Receiver for power transfer. If the Power Transmitter does not initially have sufficient information for these purposes, the Power Transmitter may repeatedly proceed to the *ping* and subsequently to the *identification & configuration* phases—each time selecting a different Primary Cell—and revert to the *selection* phase after collecting relevant information. See Annex B, *Power Receiver Localization (Informative)* for examples. Finally, if the Power Transmitter selects a Primary Cell, which it intends to use for power transfer to a Power Receiver, the Power Transmitter proceeds to the *ping* phase and eventually to the *power transfer* phase. On the other hand, if the Power Transmitter does not select a Power Receiver for power transfer and is not actively providing power to a Power Receiver for an extended amount of time, the Power Transmitter should enter a stand-by mode of operation.⁴ See Section 9 for performance requirements on such a mode of operation.

⁴ Note that it is up to the Power Transmitter implementation to determine whether this stand-by mode of operation is part of the *selection* phase or is separate from the *selection* phase.

- *ping* In this phase, the Power Transmitter executes a Digital Ping, and listens for a response. If the Power Transmitter discovers a Power Receiver, the Power Transmitter may extend the Digital Ping, i.e. maintain the Power Signal at the level of the Digital Ping. This causes the system to proceed to the *identification & configuration* phase. If the Power Transmitter does not extend the Digital Ping, the system shall revert to the *selection* phase.
- *identification & configuration* In this phase, the Power Transmitter identifies the selected Power Receiver, and obtains configuration information such as the maximum amount of power that the Power Receiver intends to provide at its output. The Power Transmitter uses this information to create a Power Transfer Contract. This Power Transfer Contract contains limits for several parameters that characterize the power transfer in the *power transfer* phase. At any time before proceeding to the *power transfer* phase, the Power Transmitter may decide to terminate the extended Digital Ping (for example, to discover additional Power Receivers). This reverts the system to the *selection* phase.
- *power transfer* In this phase, the Power Transmitter continues to provide power to the Power Receiver, adjusting its Primary Cell current in response to control data that it receives from the Power Receiver. Throughout this phase, the Power Transmitter monitors the parameters that are contained in the Power Transfer Contract. A violation of any of the stated limits on any of those parameters causes the Power Transmitter to abort the power transfer, and returns the system to the *selection* phase. Finally, the system may also leave the *power transfer* phase on request of the Power Receiver. Section 5.1.2 defines the system control protocols in the *ping*, *identification & configuration*, and *power transfer* phases from a Power Transmitter perspective. Section 5.1.3 defines the system control protocols in these four phases from a Power Receiver perspective.

NOTE This version of the Specification does not define the system control protocol in the *selection* phase.

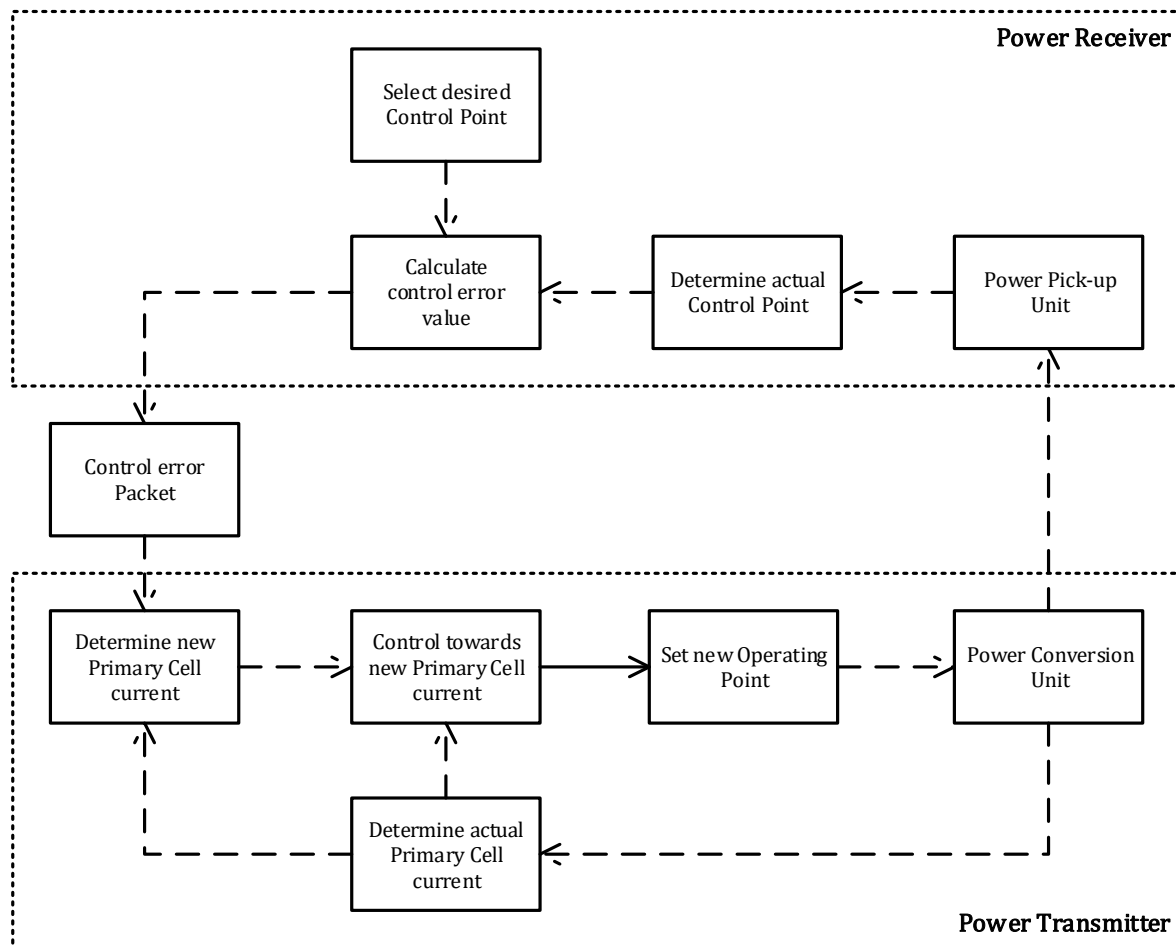
NOTE From a power transfer point of view, the Power Receiver remains passive throughout most of the *selection* phase.

At any time a user can remove a Mobile Device that is receiving power. The Power Transmitter can recognize such an event from a time-out in the communications from the Power Receiver, or from a violation of the Power Transfer Contract. As a result, the Power Transmitter aborts the power transfer and the system reverts to the *selection* phase.

Throughout the *power transfer* phase, the Power Transmitter and Power Receiver control the amount of power that is transferred. Figure 17 illustrates a schematic diagram of the power transfer control loop, which basically operates as follows: the Power Receiver selects a desired Control Point: a desired output current and/or voltage, a temperature measured somewhere in the Mobile Device, etc. In addition, the Power Receiver determines its actual Control Point. The Power Receiver may use any approach to determine a Control Point. Moreover, the Power Receiver may change this approach at any time during the *power transfer* phase. Using the desired Control Point and actual Control Point, the Power Receiver calculates a Control Error Value—for example, by simply taking the (relative) difference of the two output voltages or currents. The result is negative if the Power Receiver requires less power in order to reach its desired Control Point and positive if the Power Receiver requires more power in order to reach its desired Control Point. Subsequently, the Power Receiver transmits this Control Error Value to the Power Transmitter.

The Power Transmitter uses the Control Error Value and the actual Primary Cell current to determine a new Primary Cell current. After the system stabilizes from the communications of the Control Error Packet, the Power Transmitter has a short time window to control its actual Primary Cell current towards the new Primary Cell current. Within this window, the Power Transmitter reaches a new Operating Point: the amplitude, frequency, and duty cycle of the AC voltage that is applied to the Primary Cell. Subsequently, the Power Transmitter keeps its Operating Point fixed in order to enable the Power Receiver to communicate additional control and status information. For details, see Section 5.1.2.6.1, *Power transfer control*.

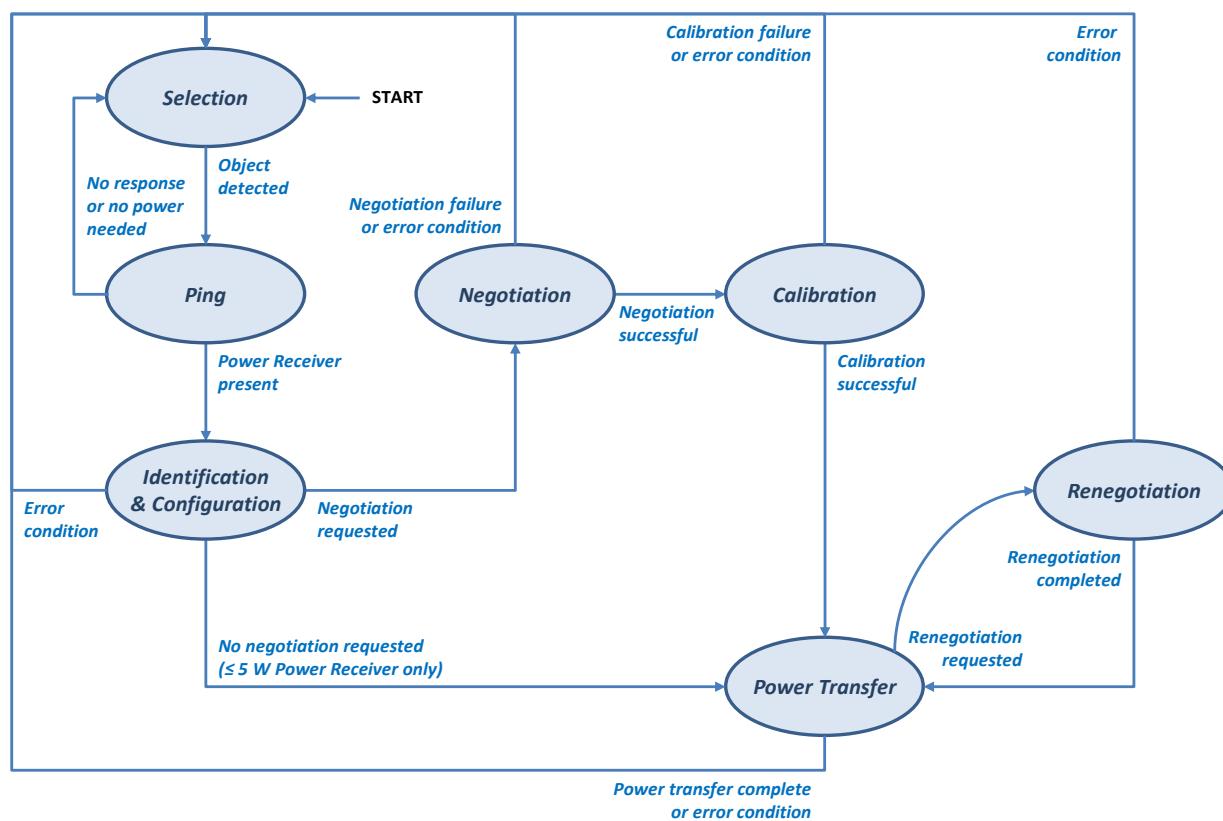
Figure 17. Power transfer control loop



5.1.1.1 FOD extensions

The FOD extensions add a *negotiation* phase, a *calibration* phase, and a *renegotiation* phase to the basic system control functionality, as shown in Figure 18.

Figure 18. Power transfer phases—Extended Power Profile



These additional phases mostly deal with improved Foreign Object Detection capabilities, as described below:

- **Selection phase.** In this phase, the Power Transmitter typically monitors the Interface Surface for the placement and removal of objects using a small measurement signal. This measurement signal should not wake up a Power Receiver that is positioned on the Interface Surface. For more details, see Section 10, *Object Detection (Informative)* and Annex B, *Power Receiver Localization (Informative)*. If the Power Transmitter detects a Foreign Object on its Interface Surface, it should stay in the *selection* phase and should not provide a Power Signal in order to avoid heating up the Foreign Object.
- **Negotiation phase.** In this phase, the Power Receiver negotiates with the Power Transmitter to fine-tune the Power Transfer Contract. For this purpose, the Power Receiver sends negotiation requests to the Power Transmitter, which the Power Transmitter can grant or deny. In addition, to improve its initial assessment of whether Foreign Objects are present, the Power Transmitter can compare the quality factor reported by the Power Receiver with its own measurement (see Section 11.3, *FOD based*

on *quality factor change*). If the Power Transmitter detects a Foreign Object, it should return to the *selection* phase.

- *Calibration* phase. In this phase, the Power Transmitter can improve its ability to detect Foreign Objects during power transfer. In particular, the Power Transmitter can adjust parameters of the power loss method (see Section 11.4, *FOD based on calibrated power loss accounting*). Hereto, the Power Receiver provides its Received Power at two different load conditions.
- *Power transfer* phase. In this phase, the Power Transmitter continues to check if new Foreign Objects have been placed on its Interface Surface. Hereto, it may use, e.g. the power loss method (see Section 11.4, *FOD based on calibrated power loss accounting*). The Power Receiver may also check for the placement of new Foreign Objects. If the Power Transmitter or the Power Receiver detects a Foreign Object, the Power Transmitter and/or the Power Receiver should either reduce the Power Signal or remove the Power Signal and return to the *selection* phase.
- *Renegotiation* phase. In this phase, the Power Receiver can make adjustments to the Power Transfer Contract, if so desired. If necessary, this phase may be aborted prematurely without changing the Power Transfer Contract.

5.1.2 Power Transmitter (PTx) perspective

This section defines a protocol that the Power Transmitter shall execute to transfer power to a Power Receiver. Note that three of the seven phases are applicable only to the Extended Power Profile if the Power Transmitter supports the FOD Extensions.

1. *Selection* phase. Section 5.1.2.1 defines the protocol to select a Power Receiver for the power transfer.
2. *Ping* phase. Section 5.1.2.2 defines the Digital Ping.
3. *Identification & configuration* phase. Section 5.1.2.3 defines the part of the protocol that the Power Transmitter shall execute in order to identify the Power Receiver and establish a default Power Transfer Contract. This protocol extends the Digital Ping in order to enable the Power Receiver to communicate the relevant information.
4. *Negotiation* phase (FOD extensions only). Section 5.1.2.4 defines the part of the protocol that the Power Transmitter shall execute if the Power Receiver requests to negotiate changes to the default Power Transfer Contract.
5. *Calibration* phase (FOD extensions only). Section 5.1.2.5 defines the part of the protocol that the Power Transmitter shall execute in the *calibration* phase. The Power Transmitter can use the information obtained from the Power Receiver in this phase to improve its ability to detect Foreign Objects during power transfer.
6. *Power transfer* phase. Section 5.1.2.6 defines the part of the protocol that the Power Transmitter shall execute during power transfer. In this part of the protocol, the Power Transmitter controls its Primary Cell current in response to control data received from the Power Receiver.
7. *Renegotiation* phase (FOD extensions only). Section 5.1.2.7 defines the part of the protocol that the Power Transmitter executes to update the Power Transfer Contract during power transfer.