Index

Accelerated Technology (ACT) Scenario, 21
Acoustic wireless power transfer, 1
Active front end (AFE), 52, 82–83, 89
Active safety, 24, 31
Antennas, 167–174, 176
Asia-Pacific Partnership, 23
Automated guided vehicles (AGVs), 113–114, 188
Automotive power drive trend, 21–29
automotive industry, 24
classifications of environmentally friendly vehicles, 25–26
key elements of future technology, 24–25
market growth, 26–29
motivation, 23–24
Autonomous driving technology, 25, 31–32

Baseline Scenario, 21
Batteries, 11, 39, 47–49, 61, 89–90, 101, 118, 129
charging sequence, 90
size, 108–109
Battery electric vehicles (BEVs), 21, 25–29, 33, 61
Battery exchange, 33, 34–35, 113
Beam efficiency, 172
Blue Map Scenario, 21–23, 43–44
Boost converters, 65, 69
Brown, William C., 168, 172

Capacitance, 2–3, 68
Capacitive power transfer, 1–2
Catenary, 140
elimination of, 76, 155, 159, 160, 162–163
Center-fed systems, 136–137

CHAdemo, 36
Charge rate control, 81
Charging pad, alignment to, 83–85
Charging stations
installation and commissioning, 102
standardization of, 47–48
Chevy Volt, 58
Chinese market forecasting, 29
Clean-room technology, 192–194
Closely coupled contactless power transfer, 2
CO2 emissions, 21, 23, 27–28, 43–44
Coaxial winding transformer (CWT), 53–54
Coil alignment, 83–85
Conductive charging, 8–9, 33, 47–49
Connected vehicle technology, 24–25
Consumer behavior, 24
Consumer electronics, 7–8, 12, 123
in automotive applications, 130–131
design considerations, 128–129
inductive charging, 124
non-radiative resonance charging, 125–127
Controller area network (CAN), 81, 93, 96
Converters, 69, 80
Cooperative ITS (C-ITS), 32–33
Copenhagen Climate Change Conference, 23
Cost reduction, 106
Coupling coefficient, 87–88
Coupling coils, 80–88, 98
Crane applications, 187

Demographic developments, 24
Dickinson, Richard, 168
Drayson Racing, 107
Driver warning systems, 31
Dynamic charging, 9, 13–17, 58, 107, 146–150

Electric resonant frequency, 5

Electric vehicle supply equipment (EVSE), 47–48

Electric vehicles (EVs), 11–14
  automotive industry, 24
  battery electric vehicles (BEVs), 21, 25–29, 33, 61
  battery size, 108–109
  charging issues and challenges, 36–37, 79–102
  charging technologies, 33–37, 37–41, 47–59
  classifications of, 25–26
  connectors, 48
  dynamic charging, 9, 13–17, 58, 107, 146–150
  fuel-cell electric vehicles (FCEVs), 21, 25, 26
  hybrid electric vehicles (HEVs), 21, 25, 26–29, 41
  infrastructure allocation, 109–110
  key elements of future technology, 24–25
  market trends, 26–29, 35–36, 105–108
  micro electric vehicles (MEVs), 15
  microwave power transfer, 178–179
  optimization problem, 108–110
  personal mobility vehicles (PMVs), 15
  plug-in hybrid electric vehicles (PHEVs), 21–23, 25–29, 33, 43
  power drive trend, 21–23
  power management efficiency, 41–42
  power transfer rate, 109
  system architecture, 38, 73
  see also OLEV

Electromagnetic field (EMF), 42, 129, 130
  Elevator systems, 194
  Embedded electronic systems, 24
  Emergency shut-down, 91–94
  Energy exchange pattern, 125–126
  Energy generation, 25
  Energy Harvesting Consortium (EHC), 180
  EU, 28, 37–38
  Evanescent coupling, 125–127
  Extension cord, 91
  FABRIC, 37, 38, 56
  Fast charge, 9, 34, 36, 49, 58–59, 90
  Fault detection, 93–94
  Fixed wireless access (FWA), 177
  Friis transmission equation, 171–172
  Fuel-cell electric vehicles (FCEVs), 21, 25, 26
  Gap variations, 85–88
  Germany
    freight transport, 117–118
    Kindinger Berg, 118
    light rail, 155–159
    TRANSRAPID maglev train, 150–155
  Glaser, Peter, 169
  Global Electric Motors (GEM), 15–17
  Globalization, 24
  GM Spark, 58
  Grid connection power quality, 100–101
  Grid input stage, 80
  Gyror circuit, 134, 156, 184
  Harbor logistics, 108, 113–115
  Heavy-duty (HD) vehicles, 58
  High-frequency isolation transformer, 97–98
  High-temperature operation, 131
  Hybrid electric vehicles (HEVs), 21, 25
    classifications of, 26
    market growth, 26–29
    power management efficiency, 41
  Impedance, 4, 68, 139
  Independent segment system, 138
  Inductance, 2–4, 54, 82, 87, 96
  Inductive power transfer, 2, 12, 47, 124, 183
  Industrial applications of WPT
    automated guided vehicles, 188
    clean-room technology, 192–194
    cranes, 187
    electric monorail system, 190–191
elevator systems, 194
heavy equipment, 8, 12
skillet conveyor, 188–189
sorter technology, 191–192
system overview, 184–186
transfer car, 189
Industrial automation, 8, 12
Infrastructure design, optimized, 110–113
Intelligent transportation systems (ITS), 29–33
Intelligent vehicle technology, 30–32
Interferences, 130
International Commission for Non-Ionizing Radiation Protection (ICNIRP), 42, 56, 98, 99
International Energy Agency (IEA), 21
INTEROP, 55
Inverter, 53, 64–67, 82–83, 133–139, 149, 152, 156, 184
Isolation transformer, 97–98
Japan
charging system, 36
market forecasting, 28
MPT research, 169–170
Japan Aerospace Exploration Agency (JAXA), 170
J-Spacesystems/Ministry of Economy, Trade, and Industry (USEF/METI), 170
Kindinger Berg (Bavaria, Germany), 118
Korea, 140, 143
low-floor train, 159–163
Korea Advanced Institute of Science and Technology (KAIST), 13, 61–62, 159
Kyoto Protocol, 23
Light-duty (LD) vehicles, 57, 58
Light rail, 139–150, 155–159
energy storage, 143–146
Light WPT, 1
Local public transport, 115–117
London Trial, 55
Long-distance heavy truck transport, 117–119
Long-distance power transfer, 167–180
Low-cost high-tech, 24, 25
Low-floor train, 159–163
Magnetic fields, 85–86, 98–99
Magnetic resonance, 2, 5, 10, 50–54, 63–65, 96
Matsumoto, Hiroshi, 170
Maxwell’s equations, 168
Medical implants, 9–10, 12
Micro electric vehicles (MEVs), 15
Microwave Ionosphere Nonlinear Interaction (MINIX), 170
Microwave power transmission (MPT), 1, 12, 167–180
Modularization, 24
Monorail system, 190–191
Mutual inductance, 3
NASA, 12
Nissan LEAF, 58
Non-radiative resonance charging, 125–127
Normal shut-down, 95–97
Oak Ridge National Laboratory (ORNL), 15–17, 51, 146
Oakland University (New Zealand), 12
Obstacle detection, 91
OEMs, business challenges, 10–11
Office for Low Emission Vehicles (OLEV) (UK), 35
OLEV (On-Line Electric Vehicle), 39
background, 61–62
power collection system design, 68–69
pick-up module, 68
rectifier and regulator, 69
power supply infrastructure design, 65–68
inverter and electrical segmentation design, 66–67
power line module, 67
road-embedded power systems, 65–66
segment operation, 65
SMFIR technology, 62–63
application to buses, 70–73
application to trains, 75–76
system architecture, 38f
system operation, 63–65
Onboard charger (OBC), 47, 52, 96, 101

Partner for Advanced Transit and Highways (PATH), 12, 61
Personal mobility vehicles (PMVs), 15
Petroleum reserves, 24
Phased array, 170, 173–174, 179
Pick-up module, 68
Plant Simulation (Tecnomatix™), 111–113, 116
Plug-in hybrid electric vehicles (PHEVs), 21–23, 25–29, 33, 43
Plug-type charging, 8–9
Plugged in Places (PIP), 35–36
Population, aging, 14–15
Power collection system design
pick-up module, 68
rectifier and regulator, 69
Power factor corrector (PFC), 48, 80, 94, 101
Power generation, efficient, 41–42
Power line module, 67
Power supply infrastructure design
inverter and electrical segmentation, 66–67
power line module, 67
road-embedded power systems, 65–66
Power transfer efficiency (PTE), 2, 5, 39–41, 124
Powermat, 10
Powertrain, 24, 25, 73, 105, 113
Poynting vector, 168
Primary current, 96–97
PRIMOVE, 155–159
Production processes, 106
Pure Energy Solutions, 10
Q-factor, 5–6
Qualcomm HaloIPT, 107
Radio frequency-direct current (RF-DC) conversion efficiency, 172
Radio waves, 167–180
Railway application of WPT
benefits of, 162–163
low-floor train, 159–163
metro and light rail applications, 139–150, 155–159
system overview, 133–135
track segment switching, 136–139
TRANSRAPID maglev train, 150–155
Ramp-up time, 94
Rectenna, 168, 171, 172, 174, 176, 177, 180
Rectifier, 69, 185
Regulator, 69
Regulatory questions, 10
Resistance, 2–3
Resonant magnetic power transfer, 2–6, 10, 12–13, 63–65, 96, 125–127
RESS (regenerative energy storage system), 47
Road-embedded power systems, 65–66
SAE J1772, 8–9, 33, 48
SAE J2954, 50, 96, 105
Safety, 9, 24, 31, 42, 56, 97–98, 130
Segment control, 139
Segway, 15
Semi-dynamic charging, 107
Series connected segment system, 138
Shaped magnetic field in resonance (SMFIR) technology, 62–63
application to buses
power supply infrastructure, 70–72
system architecture, 73
application to trains
concept, 75
main advantages, 75–76
Shut-down
emergency, 91–94
normal, 95–97
Simulation approach to infrastructure design, 110–113, 119–120
Skillet conveyor, 188–189
Solar Power Radio Integrated Transmitter (SPRITZ), 170
Solar power satellite (SPS), 167, 169–170, 174–175
Soljacic, Marin, 125
Index

charging technologies, 47–59
commercial technologies, 55–56
capacitive, 1–3
consumer electronics, 7–8, 12, 123
capacity, 129
dynamic, 9, 13–14, 17, 107, 146–150
efficiency of, 39–41, 129
designed considerations, 128–129
for electric vehicles, 13–14, 37–41,
elements of, 80–81
inductive, 2, 12, 47, 124, 183
industrial applications of, 8, 183–194
infrastructure design, 109–113, 119–120
introduction to, 1–11, 50–54
key aspects of technology, 51
maglev train, 150–155
magnetic resonance system, 63–65
markets, 105–108
medical implants, 9–10
micro mobility, 14–18
microwave-based, 12, 167–180
history of, 168–170
recent applications of, 174–180
theory of, 171–174
non-radiative resonance charging,
OLEV system, 61–76
optimization problem, 108–110
process control, 89–90
railway applications
metro and light rail, 139–150, 155–159
system overview, 133–135
track segment switching, 136–139

V2G, 41–42
V2I, 24–25, 33, 58, 79–83, 92f
V2V, 24, 33
V2X, 24–25, 31–33
Vehicle power interface, 130–131
Voltage, 82
Voltage-fed system, 137

Wardenclyffe tower experiment, 12
Wet environments, 8, 9
Wireless building, 179–180
Wireless power transfer (WPT)
audoustic, 1
business challenges, 10
capacitive, 1–3
capital, 129

Tesla, Nikola, 12, 168
Third rail, 140
Toyota RAV4, 58
Track segment switching, 136–139
Transfer car, 189
Transfer efficiency, 5, 6
Transportation, WPT in, 8–9, 41–44
TRANSRAPID maglev train, 150–155
Transrapid Test Facility Emsland (TVE),
TriMet district (Portland, OR), 145
Twizy, 15
Ubiquitous power source (UPS), 175–176
UK charging stations, 35–36
Ultrasonic energy transfer, 1
UNPLUGGED, 37–38
U.S. charging systems, 35
U.S. market forecasting, 27–28

V2G, 41–42
V2I, 24–25, 33, 58, 79–83, 92f
V2V, 24, 33
V2X, 24–25, 31–33
Vehicle power interface, 130–131
Voltage, 82
Voltage-fed system, 137

Wardenclyffe tower experiment, 12
Wet environments, 8, 9
Wireless building, 179–180
Wireless power transfer (WPT)
audoustic, 1
business challenges, 10
capacitive, 1–3
capital, 129

Solowheel, 15
Sorter technology, 191–192
Southeastern Pennsylvania
Transportation Authority (SEPTA),
Standardization, 11, 47, 50, 89, 105–106
Stationary charging, 8, 13–14, 55, 58, 107,
113–114, 119
Sustainability, 24

Tesla, Nikola, 12, 168
Third rail, 140
Toyota RAV4, 58
Track segment switching, 136–139
Traffic congestion, 14
Transfer car, 189
Transfer efficiency, 5, 6
Transportation, WPT in, 8–9, 41–44
TRANSRAPID maglev train, 150–155
Transrapid Test Facility Emsland (TVE),
TriMet district (Portland, OR), 145
Twizy, 15
Ubiquitous power source (UPS), 175–176
UK charging stations, 35–36
Ultrasonic energy transfer, 1
UNPLUGGED, 37–38
U.S. charging systems, 35
U.S. market forecasting, 27–28
Wireless power transfer (WPT) (Cont.)
- TRANSRAPID maglev train, 150–155
- wireless low-floor train, 159–163
- regulatory questions, 10
- resonant coupling, 12
- rollout of, 56–59
- standardization, 11, 47, 50, 89, 105–106
- stationary, 8, 13–14, 55, 58, 107, 113–114, 119
- technical issues and challenges, 79–102
  - alignment to primary charging pad, 83–85
  - control of charging process, 89–90
  - emergency shut-down, 91–94
  - emissions, 96–99
  - gap variations, 85–88
- grid connection power quality, 100–101
- installation and commissioning, 102
- normal shut-down, 95–97
- obstacle detection, 91
- safety, 97–98
- vehicle to infrastructure communications, 79–83
- technology development potential, 10–11
- theory of, 2–6
- Wireless Power Transfer Consortium for Practical Applications (WiPoT), 180
- ZeEUS, 37, 38
- ZigBee sensor, 177
About the Authors

In-Soo Suh, Lead Author

In-Soo Suh is an associate professor in the Cho Chun Shik Graduate School for Green Transportation, KAIST. His research fields are electric vehicle systems with wireless and conductive charging infrastructure strategies, vehicle system integration focused on the electrical powertrain, noise vibration harshness (NVH) and structural acoustics, and future intelligent transportation technology related to smart grids and communication technology. In addition to Dr. Suh’s 15-year industrial experiences in global automotive OEMs with Chrysler Corporation and GM Korea, he pursues the expansion of his career in academia with emphasis on applied engineering research and education. As a vehicle group manager in KAIST’s Wireless Power Transfer Project Group, during 2009-10, an important contribution was to lead the systematic efforts in the historic launch of the OLEV system in Seoul Grand Park and to build ten different types of OLEV vehicles. In the fall of 2013, he invented and unveiled a foldable microelectric vehicle, called “Armadillo-T,” a prototype concept vehicle for future urban application of micro mobility. He is an associate editor of IEEE Intelligent Transportation System Magazine and a research planner of Korean National Research Foundation. Dr. Suh holds a PhD in mechanical engineering from Massachusetts Institute of Technology, specializing in structural acoustics. He obtained a BS and MS in mechanical engineering from Seoul National University, Korea.

Dong-Ho Cho

Dr. Dong-Ho Cho has been a professor in the Department of Electrical Engineering of KAIST since 1998, and he was a director of KAIST Institute for Information Technology Convergence from 2007 to 2011. He has been a director of KAIST Online Electric Vehicle Project since 2009, and he has served as the head of The Cho Chun Sik Graduate School for Green Transportation since 2010. He was a vice president of KAIST from 2011 to 2013. From 1987 to 1997, Dr. Cho was a professor in the Department of Computer Engineering at Kyunghee University. He received his PhD in electrical engineering from KAIST. His major research interests include mobile communication, the online electric vehicle system based on wireless power transfer, and genomics based on bioinformatics.
**Jörg Franke**

*Prof. Dr.-Ing. Jörg Franke* has headed the Institute for Factory Automation and Production Systems (FAPS) at the Friedrich-Alexander-University of Erlangen-Nuremberg, Germany, since 2009. His research focuses on manufacturing of mechatronic products, starting from packaging of electronic circuits, structured metallization of circuit carriers, surface mount technology, assembly of electric motors, and automation solutions; and ending with engineering, planning, and simulation of complex mechatronic systems. Previously, he led management positions with global responsibilities at McKinsey&Co, Robert Bosch GmbH, ZF Lenksysteme GmbH, Schaeffler AG, and ABM Greiffenberger AG. Jörg Franke studied and prepared his doctor’s thesis in the field of production engineering.

**Dr. Soon-Man Hong**

*Dr. Soon-Man Hong* has been a visiting professor of the Graduate school for Green Transportation at KAIST, Korea, from 2014, since his completed term of president of Korea Railroad Research Institute (KRRI), Korea. He has been actively involved in the transportation sector with the Ministry of Land, Transport and Maritime Affairs (MLTM), Korea. He served as the Deputy Minister for the Office of Transport Policy in 2010, the Assistant Minister as the Head of Aviation Safety Authority, and the Director General for Railroad Policy in MLTM, Korea. He was also a visiting professor of the Graduate School for Green Transportation at KAIST just before he joined KRRI. Dr. Hong obtained a PhD and an MS in Civil Engineering (majored in transportation) from the University of Washington, and he also holds a CPA license.
Sung-Kwan Jung

Sung-Kwan Jung has been a research associate professor of IT Convergence (KIITC) at KAIST Institute since 2012. From 2007 to 2012, he was a senior researcher at KIITC. At KIITC, he has researched wireless power transfer technologies for consumer devices, especially on small mobile devices. He also researched wireless power transfer and communication technologies for small sensor nodes. For the last three years, he studied resonant wireless power transfer technologies for small mobile devices in home and office application environments. Currently, his research interest is the wireless power-data co-transfer technology for lightweight sensor nodes including M2M (machine-to-machine) and IoT (Internet-Of-Things) devices. As a team leader in KIITC, he also has research interests in IoT/WoT (Web-Of-Things) protocol and architecture, sensor-web integration, and UI/UX (user interface/user experience) for smart devices. Dr. Sung-Kwan Jung received a BS, MS, and PhD in electrical engineering from the Korea Advanced Institute of Science and Technology (KAIST), Korea.

Byung-Song Lee

Dr. Byung-Song Lee has been a senior and principal researcher at the Korea Railroad Research Institute since 1998. He is a leader of the Railroad Electric Traction & Wireless Power Transfer System Research Team. His research interests include wireless power transfer and energy conversion systems for railway trains. Currently, he is working on development of wireless power transfer systems and a linear pulse motor for railway vehicles. From 1996 to 1997, he worked as a senior researcher in the Railway Vehicle R&D Center at KHRC (Korea High Speed Rail Construction Authority), where he developed the propulsion system for high-speed trains. He received a BS in electrical engineering from Seoul National University of Technology, and an MS and PhD in electrical engineering from Chung-Ang University, Korea.
**John M. Miller**

John M. Miller was a distinguished research scientist at the Oak Ridge National Laboratory (ORNL) and former director of the Power Electronics and Electric Power Systems Research Center prior to his retirement in 2014. Dr. Miller’s research interests include all aspects of wireless power charging of electric vehicles, including advancement of international standards on wireless power transfer, interoperability, and control of leakage fields. He is also active in electric machine design, specifically electric traction motors for plug-in and battery electric vehicles (PEV). In the area of PEV traction drive systems, he is an advocate of motor rating standardization, performance metrics, and efficiency standardization. He received a BSEE from the University of Arkansas, MSEE from Southern Methodist University, and PhD in electrical engineering from Michigan State University.

---

**Florian Risch**

Florian Risch has worked at the Institute for Factory Automation and Production Systems (FAPS) of Friedrich-Alexander-University of Erlangen-Nuremberg, Germany, since 2008. Since 2011 he has served as a team leader of the research group of the Bavarian Technology Center for Electric Drives (E|Drive-Center). His research includes stationary and in-motion wireless power transfer systems for electric vehicles, with a focus on planning and verifying different fields of application and the development of efficient production processes for wireless charging infrastructure and vehicle components. Mr. Risch received a Dipl.-Wirtsch.-Ing. from Friedrich-Alexander-University of Erlangen-Nuremberg, Germany.

---

**Naoki Shinohara**

Naoki Shinohara has been a professor at the Research Institute for Sustainable Humanosphere, Kyoto University, Japan, since 2010. He has been engaged in research on the Solar Power Station/Satellite and Microwave Power Transmission System. He was a research associate at the Radio Atmospheric Science Center, Kyoto University from 1996 to 2000. He was a research associate at the Radio Science Center for Space and Atmosphere, Kyoto University from 2000 to 2001, and there he was an associate professor from 2001 to 2004. He was an associate professor at the Research Institute for Sustainable Humanosphere, Kyoto University from 2004 to 2010. Prof. Shinohara received BS, ME, and PhD degrees in electrical engineering from Kyoto University, Japan.
Faical Turki

Dr. Faical Turki is a power electronics specialist with more than 14 years’ experience in research and development of industrial electronics. He spent four years researching IGBT-based power electronics for wind turbines, and was involved in development of the first wireless inductive power supply systems. Starting with his work in the Institute for Electrical Machines, Traction and Drives in Braunschweig, Germany, he holds more than ten years of research experiences in the field of wireless power supplies. Since 2007, he has worked at Paul Vahle GmbH & Co.KG, Germany, in the development department for Contactless Power Systems CPS®, and he is currently head of the research and development of contactless power and data transfer systems for electric vehicles, trams, and industrial applications. His research includes polyphased inductive high power supply, bidirectional approaches, magnetic design, high-frequency resonant converter topologies, and data transfer on magnetically coupled power transfer circuits. Dr. Turki received the Dipl.-Ing. degree in electrical engineering and a PhD in electrical engineering at the Technical University of Braunschweig, Germany.