Sparkling Innovation

RAILWAY MECHANICAL FRAMEWORK

CONSUMERS AND THE EV MARKET

SOLID-STATE PROTECTION ON SHIPS

MICROGRID HIERARCHICAL CONTROL
The IEEE Transactions on Smart Grid is intended to be a cross disciplinary and internationally archival journal aimed at disseminating the results of research on smart grid that relates to energy generation, transmission, distribution and delivery. The journal will publish original research on theories, technologies, design, policies, and implementation of smart grid. The Transactions will welcome manuscripts on design, implementation and evaluation of energy systems that include smart grid technologies and applications. Surveys of existing work on smart grid may also be considered for publication when they propose a challenging perspective on the future of such technologies and systems. Topical issues considered by the Transactions include:

- Smart sensing, communication and control in energy systems
- Wireless communications and advanced metering infrastructure
- Smart grid for energy management in buildings and home automation
- Phasor measurement unit applications for smart grid
- Smart grid for plug-in vehicles and low-carbon transportation alternatives
- Smart grid for cyber and physical security systems
- Smart grid for distributed energy resources
- Smart grid for energy savings and financial management
- Smart grid in interdependent energy infrastructures
- Smart grid for intelligent monitoring and outage management

If you are interested in reviewing papers for this journal, please sign up as a reviewer on the Manuscript Central site at: http://mc.manuscriptcentral.com/pes-ieee.

The Transactions on the Smart Grid can be accessed via the drop down menu on the PES portal site. If you are interested in reviewing papers for our new Transactions and you are currently a reviewer for PES Transactions, you can access your account in Manuscript Central and add smart grid to your keywords or areas of expertise. If you have an account in Manuscript Central and are not currently a reviewer for PES Transactions and would like to become a reviewer for PES Transactions, access your account and you will automatically be given a reviewer center, then update your areas of expertise. If you do not have an account, create a new user account and complete all the required fields, you will then be given an author center and a reviewer center.

About the Editor-in-Chief: If you are interested in participating in the publication activities, please contact the Editor-in-Chief, Dr. Mohammad Shahidehpour at: m.shahidehpour@ieee.org. Prof. Shahidehpour (Fellow ’01) has been affiliated with IEEE for the last thirty years. His is currently the Carl Bodine Distinguished Professor of Electrical and Computer Engineering at Illinois Institute of Technology. Dr. Shahidehpour is an IEEE Distinguished Lecturer who has lectured in 30 countries on issues related to power system operation and control. He has served as the Vice President of Publications for the IEEE Power & Energy Society and an Editor of the Transactions on Power Systems.
FEATURES

4 The Dependance on Mechanical Design in Railway Electrification
   Focusing on the ac perspective.

11 Faster than a Speeding Bullet
   An overview of Japanese high-speed rail technology and electrification.

21 Courting and Sparking
   Wooing consumers’ interest in the EV market.

32 Shipboard Solid-State Protection
   Overview and applications.

40 Cutting Campus Energy Costs with Hierarchical Control
   The economical and reliable operation of a microgrid.

57 Cutting the Cord
   Static and dynamic inductive wireless charging of electric vehicles.

MISSION STATEMENT: IEEE Electrification Magazine is dedicated to disseminating information on all matters related to microgrids onboard electric vehicles, ships, trains, planes, and off-grid applications. Microgrids refer to an electric network in a car, a ship, a plane or an electric train, which has a limited number of sources and multiple loads. Off-grid applications include small scale electricity supply in areas away from high voltage power networks. Feature articles focus on advanced concepts, technologies, and practices associated with all aspects of electrification in the transportation and off-grid sectors from a technical perspective in synergy with nontechnical areas such as business, environmental, and social concerns.

DEPARTMENTS & COLUMNS

2 ABOUT THIS ISSUE
3 TECHNOLOGY LEADERS
66 DATES AHEAD
68 NEWSFEED
72 VIEWPOINT

Jacovides wins 2014 IEEE Transportation Technologies Award. Page 68

Digital Object Identifier 10.1109/MELE.2013.2280833

Page 68
WELCOME TO THE INAUGURAL ISSUE OF IEEE Electrification Magazine. This is a quarterly magazine to be published in March, June, September, and December of each year. This magazine, which has a global view of electrification in all types of transportation and off-grid applications, is designed to fill the need of engineers in the industry as well as policymakers who require information on technology, use cases, and field experience in electrification in the 21st century.

This magazine is financially cosponsored by three IEEE technical Societies—the IEEE Power & Energy Society, the IEEE Industry Applications Society, and the IEEE Power Electronics Society. In addition, it is technically cosponsored by three other IEEE Societies—the IEEE Industrial Electronics Society, the IEEE Vehicle Transportation Society, and the IEEE Intelligent Transportation Systems Society—as well as the IEEE Transportation Electrification Initiative (TEI). We have assembled a highly qualified editorial board comprised of ten members from academia, government, and industry in different parts of the world. Each topic of the magazine—electric vehicles, electric ships, electric trains, electric planes, and off-grid electrification—is looked after by one editor and one coeditor. Their contact information is provided to the right. They are the primary points of contact for authors who wish to submit articles for consideration in IEEE Electrification Magazine.

This first issue of the magazine has the following six articles covering electric trains, electric ships, electric vehicles, and microgrids. The authors of these articles, who are from industry as well as academia, are experts in their fields and provide great insight into the technology, best practices, and customer acceptance issues:

1) “The Dependence on Mechanical Design in Railway Electrification: Focusing on the AC Perspective”

(continued on page 70)

Digital Object Identifier 10.1109/MELE.2013.2277493
Date of publication: 23 October 2013
**Welcome to the inaugural issue of IEEE Electrification Magazine!** We are excited to get this first issue out the door and online for our professional community. This publication is a result of collaboration and cooperation between the three IEEE Societies: the Power and Energy Society (PES), the Power Electronics Society (PELS), and the Industry Applications Society (IAS). We hope readers will enjoy our articles and share them with their colleagues.

One of the benefits for our Society members is our work to provide summaries and overviews of best practices around our industry on key topics of interest. The PES has been publishing our award-winning IEEE Power & Energy Magazine for 11 years, and we find that this format is a great dissemination tool for professionals on the state-of-the-art topics in the power and energy field. With the expansion in electrification in technical areas related to renewable energy, smart grid technologies, electrification of transportation, and remote electrification using microgrids, we have seen an increased interest in publications related to these topics including the addition of several IEEE transactions over the last several years. Our PES, PELS, and IAS leadership groups wanted to provide additional professional development support for practicing engineers on many of these topics in a magazine format that highlights current trends, challenges, and opportunities.

Our first issue of IEEE Electrification Magazine covers several hot topics in our field. While many people think of electric cars when we discuss the electrification of transportation, railway electrification provides an excellent platform for developing infrastructure and systems that can be used worldwide. Three of our articles in this issue discuss best practices and opportunities for railway transportation and its electrification, including one on storage.

In addition to trains, shipboard electrification provides some unique challenges and opportunities for engineers, and one article discusses how solid-state protection is impacting the shipboard power system. We have also included an article on electric vehicles and how consumer interest and acceptance is impacting the engineering of electric cars and systems to support them.

Over the last five to ten years, we have seen a migration from traditional, interconnected power systems to discussions of distributed generation and microgrids. In our global society, it does not always make sense economically to build large, centrally located generation stations and long transmission lines to deliver electricity. Small-scale electricity supply in areas away from high-voltage power networks has gained momentum, and efforts are underway to use local fuel resources, such as renewable energy in microgrids, to provide electricity in remote areas.

The microgrid systems bring a new paradigm to the economics, reliability, and operational activities of the power system. Our last article in this issue discusses the control strategies related to microgrid economics and reliable operation. Developing strategies for these systems will be essential for sustainable solutions for rural and off-grid locations without reliable power.

There are also opportunities for you to participate in this publication. Authors, reviewers, and suggestions are welcome. Please send an e-mail to electrification@ieee.org or check out the publication Web site at http://www.ieee-pes.org/publications/electrification-magazine.

Like any IEEE activity, this publication is the result of hard work and cooperation between IEEE volunteers and staff. I would like to personally recognize Dr. Saifur Rahman, (continued on page 70)

---

**Unique Challenges and Opportunities**

By Noel Schulz
LECTRIFICATION OF RAILWAY SYSTEMS becomes a very tricky topic when designing overhead contact lines (OCLs). This article highlights the strong dependence of the mechanical design on the railway electrification. Indeed, only the high sensitivity of the quality of service to the mechanical performance of the OCL can explain the complex designs of the existing railway lines. The interoperability framework of the European Union together with the standards that tackle gauges and clearance calculations are briefly introduced, both for the static and dynamic analyses of the pantograph and catenary.

A railway electrification system is comprised of all of the facilities that are built to transport electricity from the high-voltage power network to anywhere on the railway line capable of providing power. This system includes an installation of lines, usually for transport or delivery, connecting to the network; traction substations, which set up the network voltage to the required voltages; autotransformers; and the OCL, also known as catenary, which runs along the whole line, supplying electricity to the railway rolling stock.

The main difference between the railway electrification system and power transmission or distribution lines is its inherent difficulty of feeding the rolling stock as a moving load. This feature has yielded different electrification options, such as cable-based OCLs, third rails, or rigid OCLs, instead of using the widespread cable structures. Undoubtedly, there is a very strong coupling between the mechanical design and the electrical feeding of the rolling stock, using the commonly known catenary-pantograph interaction. Because of the key influence of the speed of the vehicles on this dynamic interaction and the rapid proliferation of high-speed lines, the research on the design and improvement of this kind of line has taken off.

Railway Electrification System
Since alternating current (ac) electrification is the most common in high-speed lines, this article will focus predominantly on this perspective even though the

By Jesus R. Jimenez-Octavio, Cristina Sanchez-Rebollo, and Alberto Carnicero

The Dependance on Mechanical Design in Railway Electrification

Focusing on the ac perspective.
conclusions of this work can be directly extrapolated to direct current (dc). Figure 1 shows the structure of the electrification of a railway line in ac.

From an electrical standpoint, the railway line is divided into sections that are electrically separated from each other by short lengths without feeding, which are called neutral zones. Generally, the high-speed lines are fed from the three-phase, high-voltage network through traction substations, which usually feed to two subsectors by separate transformers, as depicted in Figure 1. Along the line, the phases, which feed the consecutive subsectors, are swapped to reduce imbalances in the grid. As previously stated, a sector is defined as the extension of railway line fed by the same traction substation. For the sake of reliability, the traction substations are designed to allow simultaneous feeding to two subsectors using a unique transformer so that each subsector supports the adjacent subsectors. In failure situations, the control center may perform the appropriate maneuvers to change the topology of the electrification and thus isolate the fault. Regarding the magnitude of the consumption of the high-speed lines, the railway electrification is connected to the transmission or delivery network (132, 220, or 400 kV depending on the national system) to reduce the impact of railway loads on the network.

In the case of ac electrification, each of the subsectors can employ either mono- or bivoltage feed systems. The
monovoltage system shown in Figure 2(a) uses a set of conductors at the voltage of the rolling stock and a second set of grounded conductors for the return circuit. In the literature, this system is called a monovoltage system, or 125 kV, because of the use of 25 kV. In this system, all the current consumption of a certain train covers the section between the substation and the train.

On the contrary, bivoltage systems are used to transport voltage higher than the supplying voltage of the rolling stock, which is reduced by using autotransformers scattered along the OCL, as shown in Figure 2(b). In certain technical publications, this system is called bivoltage, or 25 kV, because of the use of 25 kV and because it involves the use of two different levels of voltage in the catenary, requiring the use of a third set of conductors. This system reduces the electric current in most of the stretch between the traction substation and the rolling stock; in fact, only part of the consumption current has to go over the whole distance. Thus, it is possible to reduce electrical losses and voltage drops in the catenary, increasing the length of the sectors with the expected reduction of the number of substations. Because intermediate conductors are connected to ground potential, i.e., they are set to zero, negative voltages appear in lower conductors, as illustrated in Figure 2(b). The relationship between the voltage of the positive and negative conductors allows us to call them bivoltage symmetrical systems when they have the same ratio in both autotransformers; they are called bivoltage asymmetrical systems otherwise. The autotransformers mentioned earlier reduce the voltage to the allowable range of values for the rolling stock, while the return current is forced to go through the negative feeders.

The traction substations are those parts of the installation that carry out the connection of any electrified OCL sector to the three-phase network, performing the suitable transformation from one voltage to another. The most common topology in the traction substations is the simple bar, which is less expensive but offers reduced operating flexibility. However, in cases where a unique substation feeds several OCLs, the use of more complex topologies such as rings or double bars is recommended. In some cases, it is even possible to join the traction and transportation substations in a single facility. The topology of the substation can be slightly varied depending on the type of connection of the transformers and to maneuver coordinately several substations via remote-control systems to adapt the topology of electrification to specific necessities. Regarding the connections commonly used to connect the single-phase loads to the three-phase network, different publications remark that the factors that tip the choice toward one or another form of connection are simplicity, cost, and imbalances in the three-phase network.
Overhead Catenary Line

The last element of the electrification system, which is crucial in the railway context, is the OCL or the catenary. This is the cable structure used to supply electricity to the trains by means of the dynamic interaction between the contact wire and the pantograph, i.e., a mechanical device located in the upper part of the locomotive. Figure 3 shows photographs of (a) an OCL and (b) a pantograph. One of the key aspects of designing a railway catenary is ensuring certain margins of its behavior when the pantograph is in contact; overall, the design of the OCL must avoid any loss of contact between the contact wire and the strips of the pantograph. Loss of contact is very undesirable since it can result in electric arcs, which increase the wear of both elements and the mechanical stresses when contact is restored.

Ensuring uniform contact forces require that the contact wire does not present large variations in height above the rails. In situations where the train speed is not high, close to 50 km/h, it may be sufficient to build only the contact wire. However, if the train speed increases, the lowest uplift along any point of the contact wire is highly desirable, which is not possible with the simple contact wire tension. A high-speed system should, therefore, use a catenary configuration with two cables, one for providing the electric energy and the other for supporting the first one. Besides these main components, a high-speed catenary is comprised of other elements that also have their influence on the behavior of the cable system, which is described below.

As discussed earlier, it is typical to distinguish between high-speed catenaries, metropolitan railway catenaries, etc., depending on the characteristics of the railway system. The most common and widespread OCL is similar to that shown in Figure 4, which consists of three basic elements: 1) the messenger wire, which supports the cable system; 2) the contact wire, which feeds the vehicles; and 3) the droppers, vertical cables that connect electrically and link mechanically by means of clamps on the messenger and contact wires. The initial equilibrium of the cable system is not a trivial problem but a very complex one, and some mathematical algorithms have been developed for this purpose.

Electrically speaking, additional feeders are sometimes needed, depending on the system configuration and the energy demand, as depicted in Figure 5. On the other
hand, the pantograph consists of a sliding collector equipped with the contact strips, called skates or pads, located on an articulated frame, which tries to follow the contact wire. Pantographs can be classified depending on their mode of operation (passive versus active) or the characteristics of the line (ac versus dc).

While the force that pushes the strips of a passive pantograph against the contact wire is constant in time, this force varies within an active one due to its integrated and complicated control systems. Although passive pantographs are the most inexpensive and widespread, technical developments in recent years have begun to put active pantographs on the market at competitive prices. Indeed, the monitoring and control of contact forces is becoming an effective way to face the problems associated with the catenary–pantograph control systems. Although passive pantographs are the most inexpensive and widespread, technical developments in recent years have begun to put active pantographs on the market at competitive prices. Indeed, the monitoring and control of contact forces is becoming an effective way to face the problems associated with the catenary–pantograph control systems. Although passive pantographs are the most inexpensive and widespread, technical developments in recent years have begun to put active pantographs on the market at competitive prices. Indeed, the monitoring and control of contact forces is becoming an effective way to face the problems associated with the catenary–pantograph control systems.

The electric nature of the line, ac or dc, leads to the mechanical design of the catenary and pantograph, resulting in almost antagonistic technical solutions. AC pantographs work with higher voltages, which is mainly because the locomotives running within this type of system do not need large current intensities. Therefore, ac catenaries are consequently lighter, implying that the force applied by the pantograph must be as low as possible to prevent excessive displacements of the contact wire. On the contrary, dc pantographs are designed to exert a significantly stronger force because it is believed that the current can be interrupted if the contact force falls below a reasonable level.

For the sake of safe interoperability, the European Committee for Electrotechnical Standardization (CENELEC) was asked by the European Commission (EC) to prepare exhaustive norms for railway systems and, particularly, for OCLs. Clearly, the combination of diverse OCLs and pantographs provides different interaction performances. Regarding this diversity, the European Standard EN 50367 defines the parameters for interoperability in the field of interaction between both of the subsystems. The infrastructure manager must ensure that the values for the geometrical characteristics of the OCL and the pantographs fulfill those specified in the norm, according to the type of infrastructure. The same document also specifies the interface requirements of infrastructure and rolling stock to reach free access to the European railway network. However, the aim of Standard EN 15273 is specifically to define the space to be maintained and cleared to allow the running of rolling stock. Moreover, the rules for the calculation and verification of the sizing of the rolling stock to run on a single infrastructure or on different infrastructures without any interference risk are also established. Finally, the European Standard EN 50119 specifies the structural requirements and tests for the design assemblies and individual parts of any OCL.

Catenary-Pantograph Dynamic Interaction

The limitation on the top velocity of high-speed trains is related to the ability to supply the proper amount of energy required to run their engines through the catenary–pantograph interface. When there is a loss of contact, not only is the energy supply interrupted but also the collector bow of the pantograph and the contact wire of the catenary also appears, leading to the deterioration of the functional conditions of the two systems and causing an important injection of high-frequency harmonic currents. An alternative would be to increase the contact force between the two systems. But such an increase in force would lead to rapid wear of the contact strip of the pantograph and of the contact wire, with negative consequences on the durability of the system. These situations require that the dynamics of the catenary–pantograph interface are properly modeled and that the software used for analysis, design, or to support maintenance decisions is not only accurate and efficient but also allows the modeling of all details relevant to the train overhead energy collector operation.
The last version of the technical specification for interoperability (TSI) gives great importance to the catenary–pantograph dynamic interaction, requiring simulations for the award of the EC certificate of interoperability of the OCLs.

**Simulation and Modeling**

Currently, there are several software programs that allow the computation of the catenary–pantograph interaction based on different methods, from analytic to finite elements, among others. Some of them are commercially distributed, and others are either under development or have been developed only for research purposes. However, the technical–scientific community has not yet reached a consensus on the best technique or formulation to perform these kinds of simulations. This is mainly because of the complexity of the comparison with the experimental values, which are influenced by many factors (temperature, wind, assembly tolerances, etc.) that are really difficult to take into account within numerical simulations.

To establish a regulatory framework that would determine the reliability of the simulation results, the European Standard EN 50318 was adopted on 1 April 2002 on the validation of the simulation of the catenary–pantograph dynamic interaction. This refers explicitly to the TSI on subsystem energy of the Trans-European High-Speed Railway System, Chapter 6, paragraph 1 of Directive 96/48/EC of 30 May 2002. Thus, this TSI of the power subsystem in the Official Journal of the European Community 2002/732/EC was published, and now it has been repealed by Decision 2008/217/CE of the new TSI.

According to this standard, the first step of validation for a simulation method should be the comparison of the results obtained within a given benchmark to assess the confidence in the accuracy of the simulation. Broadly speaking, the two basic elements of contact can be briefly described as a discrete model mass–spring–damper for the pantograph and a simple catenary with ten identical spans and a single contact wire. The dynamic interaction should be evaluated at two speeds of the train, 250 and 300 km/h. If the results obtained in the two central spans are within the ranges established in the regulations, then the simulation method would be validated. This refers to the abovementioned norm and used to certify the high-speed line Madrid–Barcelona in 2008.

To illustrate the results obtained within the reference EN 50318, Figure 6 presents the OCL’s behavior when a pantograph is running at 300 km/h. The dynamic simulation for this purpose has been carried out using the models developed by the authors of this article, which have been validated against the abovementioned norm and used to certify the high-speed line Madrid–Barcelona in 2008. Figure 6 depicts (a) the contact force evolution and (b) the uplift of the pantograph and contact wire at the masts along the central spans. Different diagrams—the assembly state of the catenary, the curve of contact force, and the uplift of catenary—have been overlapped in each figure. Thus, for the abscissa axis, the same scale was applied, while different ordinate axes have been used in the same figure for each diagram to superimpose and compare them without scaling problems.

Assuming that the first requirement of the validation against the reference model was achieved, the simulated results are compared with the experimental measurements. Thus, the standard deviation of the contact force, the uplift of the contact wire on the masts, and the uplift...
of the point of contact with the pantograph must be within a range of 20% around the experimental values of the same parameters. Finally, once a particular simulation model fulfills the abovementioned requirements, it can be considered validated against the standard and can be used to perform the required simulations to obtain the certificate of interoperability for any catenary.

The modeling of the two subsystems of interaction, the catenary and pantograph, is a trendy research topic around the world. On the one hand, because of the inherent geometric nonlinearity of cable structures, the catenary can be considered a wide and complex field of research. On the other hand, the modeling and active control of the pantograph has become one of the most promising objects of study in high-speed railway systems. Although finite element models are the most unique ones that have proliferated in recent years, certain other purely mathematical models or lumped systems have also been published. Nevertheless, the European Standard EN 50318 does not declare any preference in this regard. On the contrary, the theoretical validation step specifically refers to a pantograph modeled by a system of masses and springs with two degrees of freedom. Such lumped models are commonly used to simulate the dynamic behavior of the pantograph. Despite their simplicity, these models are accurate enough to collect the dynamics and are much more computationally efficient than other models based on multibody techniques, either with flexible or rigid elements. However, the model with two degrees of freedom is too simple so the simulation of real pantographs is commonly carried out by means of models with at least three degrees of freedom.

Despite the described validation standard, there remain doubts about the results of different simulation methodologies. The proof of this is the current interest at the European level—several public and private institutions have carried out a comparison between different simulation models against a benchmark of the catenary–pantograph dynamic interaction. This analysis, presented at the 23rd International Symposium on Dynamics of Vehicles on Roads and Tracks in Qingdao (China), reveals the possible scatter in the results obtained with the standard methodologies validated against EN 50318.

Acknowledgment
The authors gratefully acknowledge the financial support of the of the Spanish Ministerio de Ciencia e Innovación by means of the Plan Nacional TRA2009-13912 and the Spanish Ministerio de Economía y Competitividad by means of the Plan Nacional TRA2012-37940.

For Further Reading


Biographies
Jesus R. Jimenez-Octavio (jesus.jimenez@upcomillas.es) received his M.Sc. and Ph.D. degrees (2009, Best Ph.D. Thesis in Engineering Award) in mechanical engineering from the Universidad Pontificia Comillas (UPCo), Madrid, Spain. He is currently an assistant professor at the Department of Mechanical Engineering and a researcher of the Applied Research Institute at UPCo, where he works on different projects related to continuum mechanics. He has received the Talgo Award for Technological Innovation 2010 for the project “Simulation, Calculation, and Optimization of Railways,” and he is currently a member of the Overhead Contact Line Survey Group chaired by the European Railway Agency.
Cristina Sanchez-Rebollo (cristina.sanchez@upcomillas.es) received her M.Sc. degrees from the Universidad Pontificia Comillas (UPCo) (2010, Best M.Sc. Degree in Mechanical Engineering Award) and the Universidad Carlos III (mechanical engineering), both in Madrid, Spain. She is currently a Ph.D. student of the Applied Research Institute at UPCo, granted by the Spanish Ministerio de Ciencia e Innovacion, and she is also member of the Overhead Contact Line Survey Group chaired by the European Railway Agency.
Alberto Carnicero (alberto.carnicero@upcomillas.es) received his Ph.D. degree in industrial engineering. He is currently a professor at the Department of Mechanical Engineering (focusing on the topic of mechanics of materials) and a researcher of the Applied Research Institute at the Universidad Pontificia Comillas in Madrid. He has worked in numerical simulation of different engineering topics, such as electromagnetic field simulation, electric field simulation, or elastodynamics in active materials. He specializes in numerical simulation on cable structures, mainly applied to catenary-pantograph dynamic interaction. He has received the Talgo Award for Technological Innovation 2010 for the project “Simulation, Calculation, and Optimization of Railways,” and he is currently a member of the Overhead Contact Line Survey Group chaired by the European Railway Agency.
ORTUNATELY, JAPAN’S BIG CITIES HAVE EMBRACED electrified railways as a major method of transportation since the early 20th century. According to the results of Japanese government research, electric railways convey more than 90% of the total person trips of the whole railway system, which carries about 30% of all the person trips in Japan (with the remainder carried 54% by car, 7% by bus, and 7% by air). Thus, we can consider the electric railway to be one of the backbone technologies of Japanese life.

In 1964, the world’s first dedicated high-speed rail (HSR) line—the Shinkansen—was built between Tokyo and Osaka (Figure 1). The Shinkansen opened the door for today’s HSR age. Japanese electrified railways are characterized by their dense traffic and variety of systems. This article provides an overview of the electrification technology and infrastructure of Japanese HSR lines.

Dense Traffic
Figure 2 shows the regions of the Japan Railways (JR) companies and direct current (dc)/alternating current (ac) lines. The statistical data of Japan and JR are shown in Table 1. The high population density in Japan results in intense rail traffic. For example, up to 187 Tokaido Shinkansen trains can depart from Tokyo Station in one day. Under these conditions, rail operators such as
JR companies need to keep punctuality, reliability, and availability at a high level to guarantee effective operation. To keep a mass transit system like the Japanese system running, some redundancy for fixed installations is required.

**Variety of Systems**

Japan is a country of islands and has no land borders. However, in the early 20th century, several railway companies and electric power companies imported from both Europe and the United States. The Japanese government wanted to unite the systems but failed. Hence, JR run on various systems:

- the frequencies 50 Hz (eastern Japan) and 60 Hz (western Japan)
- the gauges 1,435 mm (Shinkansen and some commuter lines) and 1,067 mm (conventional lines)
- three power types—ac 25 kV (Shinkansen), ac 20 kV (conventional), and dc 1.5 kV (conventional).

In Tokyo Station, several types of power supply meet each other. The Tokaido and Tohoku Shinkansen use 25 kV, 60 Hz, 1,435-mm gauge, and 60 and 50 Hz, respectively. Commuter lines use dc 1.5 kV and 1,067-mm gauge. The Metro supplied by dc 600 V via third rails running on 1,435-mm tracks should also be mentioned.

**History and Statistics**

**DC Traction, History, and Today**

Table 2 shows a brief history of Japanese electrification. The electrification of the former Japanese National Railways (JNR) started with dc 600 V in 1904 and was upgraded to 1.2 kV in 1914. Then, JNR decided on dc 1.5-kV traction as standard in 1925. In the early days, all electrification-related devices needed to be imported from Europe or the United States and were very expensive. Therefore, JNR and Japanese electric industries began to manufacture devices in Japan. Before World War II, JNR and many private railway companies had about 6,000 km of electrified lines. After the war, JNR began to electrify all trunk and commuter lines around big cities. Also, many cities expanded metro rail lines in their area.

As of April 2013, JR commuter lines in Tokyo, Osaka, and the Nagoya area and the trunk line from Tokyo to Osaka and other lines use dc 1.5 kV on a total length of 6,363.7 km. Bigger private railways with approximately 2,600 km of dc 1.5-kV lines convey many commuters from suburban areas to city centers, and ten cities have a total combined metro line length of 857 km. About 1,650 substations with about 2,700 rectifiers support 49,000 electrical multiple unit (EMU) cars for all JR.

Beginning in the 1970s, Japanese dc EMUs used chopper control technology for dc traction motors, enabling regenerative braking. After the 1980s, asynchronous traction motors with voltage-fed inverter technology were adopted. Now, more than 80% of Japanese EMUs can use regenerative braking. New materials such as aluminum and stainless steel help to save weight in the bodies. After the Tohoku Earthquake off the Pacific coast on 11 March 2011 and the resulting power shortages, JR had to save more energy. Thus, several railway companies installed energy-storage systems with lithium-ion batteries, supercapacitors, or flywheels.

**AC Traction**

In 1953, Sounosuke Nagasaki, the president of JNR, went to France to learn the state of the art of ac traction from the Société Nationale des Chemins de Fer Français. After that, he decided to test commercial frequency ac traction as a more economical and powerful electrification scheme than dc. The first experimental ac feeding circuit was electrified in 1954 on the Senzan line in the north of Japan. The equipment such as rolling stock and fixed installations were developed in Japan. JNR's conventional lines use a narrower gauge (1,067 mm) and smaller infrastructure gauges compared with those of Europe, especially in tunnels. Most power lines used 20 kV in those days. So, JNR adopted 20 kV.
Today, a total of 3,667 km of conventional lines are electrified with ac 20 kV.

Shinkansen
AC traction showed its effectiveness, and JNR then decided to apply ac traction for the Shinkansen project in 1958. Shinkansen means new trunk line. In those days, the Tokaido conventional trunk line from Tokyo to Osaka had reached its limit of capacity. JNR specified the Shinkansen as a system completely different from conventional lines, with speeds faster than 200 km/h, a standard gauge, larger clearance that enabled five seats in row, and no level crossings. The high speed and larger bodies needed high power, and ac traction was suitable to supply the Shinkansen.

After the Tokaido Shinkansen, JNR engineers developed autotransformer (AT) supplies for commercial frequency, fed by the national ultrahigh-voltage (UHV) grid for the success of the Shinkansen. In 1987, JNR was divided and privatized into six passenger regional companies, one freight company, one seat reservation company, one telecommunication company, and one research institute.

As of 2012, the Shinkansen had been extended to a 2,388-km-long network. It carries 369 million passengers per year. In December 2010, the northern part of the Tohoku Shinkansen from Hachinohe to Aomori was opened. In March 2011, the Kyushu Shinkansen was fully opened from Hakata to Yatsushiro. This connects Aomori, the northernmost city of Honshu Island, and Kagoshima, the southernmost city of Kyushu Island, by a 1,870.8-km-long high-speed line.

AT Supply
The AT supply, sometimes written as 2 × 25 kV, was invented in the United States in 1911 by Prof. Charles F. Scott and planned for use in the Tokaido Shinkansen at first. However, in those days, the JNR engineers could not grasp phenomena in AT configuration with commercial frequency. They investigated the features carefully with computers, and after some field tests, the first AT supply with a 10-km AT interval began revenue service in 1970 on the Kagoshima conventional line (Figure 3). This interval resulted from the calculations made to ensure that the AT system’s induction was equivalent to that of the booster transformer (BT) system. AT systems provide a powerful supply with less induced voltage. Now, AT with commercial frequency supplies most high-speed trains.

Since the Tokaido Shinkansen caused some trouble with imbalances in the high-voltage (HV) power grid, the later Sanyo Shinkansen used an AT system and received power from 275-kV grids in 1972. After the Sanyo Shinkansen and to date, a combination of an AT system and a UHV supply has been standard for Shinkansen. The Tokaido Shinkansen was also updated to an AT supply between 1984 and 1991, still supplied by the HV grid.

Equipment to Suppress Harmonic Resonance
When the first commercial AT feeding was tested on the Kagoshima line in 1969, the JNR engineers faced a serious harmonic resonance problem. Large stray capacitance between conductors and earth on a 65-km-long circuit was the reason. Then, the capacitors and resistors were installed in sectioning posts to diminish the resonance before opening the service in 1970. The installed capacitors increased the capacitance and lowered the peak resonance frequency. The resistors terminated the feeding circuit to stop the reflection of harmonics by matching the surge impedance of the feeding circuit being between 200 and 300 Ω. Later, a reactor was added in parallel with the resistor to reduce Joule loss at basic frequency. Figure 5 shows the

Figure 2. JR electrified lines in 2013.
higher harmonic resonance suppression through matching characteristic impedance with capacitance and resistor (HMCR) equipment. The HMCR equipment is installed on most conventional AT lines and some Shinkansen lines.

**Catenary and Pantographs for HSR**

The pantograph/contact-line system of the Shinkansen has 49 years of history. This system was improved by many technical innovations and today is characterized by several unique features, which will be described here in comparison with those of European systems from a point of view of dynamic interaction between the pantograph and the contact line.

The Tokaido Shinkansen started commercial service with a maximum speed of 210 km/h. An ac 25-kV, 60-Hz feeding system with BTs was adopted. This feeding system required a complex contact-line design at insulated overlaps to prevent arcing, which caused maintenance and other technical problems. Therefore, an AT feeding system was introduced on the Sanyo Shinkansen line in 1972, which was the second Shinkansen line to open. This system allows for simple insulated overlaps, resulting in a reduction of risk for serious contact-line accidents.

On the other hand, a simple contact-line system without a stitch wire was used on the newer lines. These lines link provincial cities, where high-density operations are not required. The simple contact-line system, whose current capacity is lower than that of a compound contact line, is adopted as a standard overhead catenary system of these lines. This contact line consists of fewer components than the compound contact line does, resulting in lower costs for installation and maintenance.

The pantographs of Shinkansen trains can be classified roughly into two categories. One is a traditional diamond-shaped pantograph, and the other is a low-noise pantograph. Until 1997, trains had been equipped with the former pantographs, but after that the low-noise pantographs were generally used.

Since Japan is a mountainous island country and the routes of Shinkansen lines pass through many populated areas, the railway operators have to solve serious trackside environment problems. In particular, wayside noise has been one of the most serious problems, also impacting the high-speed pantograph/contact-line system. That is because the pantograph is one of the most intense noise sources. Figure 7 shows the development of pantographs for

**TABLE 1. Statistics of JR in 2012.**

<table>
<thead>
<tr>
<th>Land Area km²</th>
<th>Italic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population</td>
<td>Million</td>
</tr>
<tr>
<td>Population density</td>
<td>People/km²</td>
</tr>
<tr>
<td>JR lines km</td>
<td>20,124</td>
</tr>
<tr>
<td>JR electrified km</td>
<td>9,841 (41.1%)</td>
</tr>
<tr>
<td>Passenger transport MPkm</td>
<td>404.3</td>
</tr>
<tr>
<td>Shinkansen MPkm</td>
<td>81.4</td>
</tr>
<tr>
<td>Freight transport Mtkm</td>
<td>20.4</td>
</tr>
<tr>
<td>EMU Cars</td>
<td>49,563 (JR22,776)</td>
</tr>
<tr>
<td>EL Cars</td>
<td>675 (JR578)</td>
</tr>
</tbody>
</table>

**TABLE 2. The History of Japanese Electric Traction.**

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1872</td>
<td>Start of rail in Tokyo</td>
</tr>
<tr>
<td>1895</td>
<td>First electrified tram</td>
</tr>
<tr>
<td>1927</td>
<td>First Japanese-made mercury rectifier</td>
</tr>
<tr>
<td>1954</td>
<td>AC feeding test on Senzan line</td>
</tr>
<tr>
<td>1964</td>
<td>Tokaido Shinkansen, 210 km/h, 60-Hz ac supply</td>
</tr>
<tr>
<td>1970</td>
<td>AT feeding system applied</td>
</tr>
<tr>
<td>1987</td>
<td>Privatization and splitting of JNR</td>
</tr>
<tr>
<td>1997</td>
<td>300 km/h on the Sanyo Shinkansen with 500 train series</td>
</tr>
<tr>
<td>2013</td>
<td>320 km/h on the Tohoku Shinkansen with E5 train series</td>
</tr>
</tbody>
</table>

**Figure 3.** AC feeding circuits: (a) BT circuit and (b) AT circuit. (CNF: connection for negative feeder; NF: negative feeder.)
Shinkansen vehicles. The configuration of the pantograph has drastically changed, reflecting strong demands for noise reduction of the pantograph. As a result, pantographs for Shinkansen have unique features, differing from the pantographs of European systems.

**Catenary**

Figure 6 shows the specifications of some typical catenary systems for Shinkansen lines. As mentioned previously, compound catenary systems have been used on the early Shinkansen lines, that is, the Tokaido, Sanyo, Tohoku (southern part), and Joetsu lines. On the other hand, simple catenary systems have been used on the newer Shinkansen lines, that is, the Nagano, Kyushu, and Tohoku (northern part) lines.

The compound catenary system for the Shinkansen has a relatively long history; its specification was upgraded several times to adapt to the increase in traffic and maximum velocity. When the oldest Tokaido Shinkansen was opened, composed compound catenary, which was designed for uniformity of static push-up characteristics in a span, was installed. This catenary employs a dropper with a damping device (composed element) near a support point, and its total tension is 29.4 kN. This catenary led to many troubles because the dropper with the damping device causes high uplift of the contact wire, resulting in excessive abrasions or large stress on wires or components of the catenary. To combat this situation, a heavy compound catenary system was developed as the standard catenary of the Sanyo Shinkansen in 1972. The total tension of this catenary increased to 53.9 kN, and the cross section of each wire (contact wire, messenger wire, and auxiliary wire) increased to suppress the amplitude of contact wire vibration. No damping device was used for this catenary. This catenary has ensured stable operation of the pantograph/catenary system of the Shinkansen. The catenary of the Tokaido Shinkansen was replaced by the heavy compound catenary in 1989.

As maximum operation speed has been increased, the wave propagation velocity of the contact wire had to be improved. The distribution of tension for the three wires was altered or total tension was increased to 58.8 kN to increase the tension of the contact wire. This is named a high-tensile heavy compound catenary.

The simple catenary system for Shinkansen lines has been used since the Nagano Shinkansen opened in 1997. This catenary is equipped with copper–steel contact wire (copper contact wire with a steel core) with a cross section of 110 mm²; thus, this is named CS simple catenary. This contact wire is lightweight but possesses high strength because it is metal composite. This wire can be stretched by a tension of 19.6 kN, resulting in a high propagation velocity of 521 km/h.

This catenary system was also installed on the southern part of the Kyushu Shinkansen and the northern part of the Tohoku Shinkansen. However, use of the metal composite wire has come to be widely recognized as a problem due to low recyclability. Accordingly, a precipitation-hardened copper alloy (PHC) contact wire was developed as an alternative to the CS contact wire. The simple catenary with the PHC contact wire, named PHC simple catenary, has been adopted on the most recently opened Shinkansen lines.

**Pantograph**

The first-generation Shinkansen vehicle was equipped with a lower-arm crossed diamond-type pantograph (Type PS200). This pantograph is small and light to achieve high contact performance in high-speed regions.

As the number of Shinkansen trains has increased, wayside noise has become a serious problem. Diligent research on wayside noise showed that aerodynamic
noise caused by the pantograph was one of the most serious noise sources of the Shinkansen train set. Therefore, a pantograph shield was developed as an effective countermeasure against aerodynamic noise of the pantograph [Figure 7(c)]. It was installed around the pantograph to reduce flow velocity around the pantograph, resulting in effective reduction in aerodynamic noise, as the energy of aerodynamic noise is proportional to the sixth power of the flow velocity.

The pantograph shield was very effective in reducing wayside noise emitted from the pantograph; it helped the improvement of the maximum speed of Shinkansen trains to 270 km/h in 1992. However, since the Japanese noise regulations for wayside noise of high-speed trains are very strict, the combination of the pantograph shield with the conventional diamond-type pantograph was not enough to achieve further speed-up. A low-noise pantograph was developed, consisting of a single-membered and smooth-shaped pantograph head and a simple articulated frame. This pantograph, with an insulator cover or low-noise insulators, achieves a reduction of aerodynamic noise.

Since 1997, all new Shinkansen trains operating at speeds over 240 km/h have been equipped with low-noise pantographs. The low-noise pantograph has contributed to the further speed-up of Shinkansen trains while keeping within the noise regulations. Today, the maximum speed has increased to 320 km/h as of March 2013.

Although the low-noise pantograph is very effective at reducing aerodynamic noise, an improvement of its contact performance has to be exchanged. Smoothing the pantograph members makes the pantograph heavy, and it is difficult to use a long stroke spring for a pantograph head suspension because a large plunger generates significant aerodynamic noise. Since a speed-up of Shinkansen trains without assuring compliance with the noise regulation cannot be implemented, pantograph design must give high priority to noise reduction in Japan.

**Design Policy of the Pantograph/Catenary System for Shinkansen**

**Changeover Switches**

There are about 30 substations and 30 sectioning posts in the Tokaido Shinkansen. If Shinkansen trains had to coast in front of each substation and sectioning post to change electric phase, they would lose much time. JNR engineers installed changeover switches to reduce the coasting time to only 0.3 s. A pair of changeover switches, a neutral section, and a track circuit constitute the equipment. At the beginning, in 1964, air-blast circuit breakers and then vacuum circuit breakers were introduced and have been used until now. Figure 8 shows the arrangement of a changeover switch. The circuit breakers have to work for each passing train. Therefore, on the Tokaido Shinkansen, they have to be replaced every five years. Currently, the Central Japan Railway Company is developing solid-state thyristor switches.

Since any pantograph only shunts sections in the same feeding area in the case of the changeover section, electrical connection between operating pantographs can be permitted. Furthermore, trains can pass through the changeover section without coasting.

![Image of changeover switch](image-url)

**Figure 6.** (a) A compound catenary for the Shinkansen and (b) CS and PHC simple contact lines.

The high speed and larger bodies needed high power, and ac traction was suitable to supply the Shinkansen.
If a pantograph connected electrically with other pantographs loses contact with the contact wire, no arc occurs as long as some of other pantographs keep the contact. In other words, mechanical contact loss of only one pantograph does not cause intense arc. In general, the Shinkansen train set is equipped with two pantographs with electrical connection today.

**Contact Force and Its Advantage**

Pantograph operation with relatively low mean contact force has an advantage in reliability of the pantograph/catenary system. The contact wire is bent strongly by every passage of pantographs. This causes fatigue of the contact wire, and in the worst case, the contact wire will break. Giving a higher mean contact force should make it more probable that high strain occurs in the contact force. Even in the case of Shinkansen with relatively low mean contact force, measurement results of the contact wire strain indicate little margin for error in high-speed regions. Protection from intense strain of the contact wire is essential for further speed-up.

In March 2011, a new series of Shinkansen trains was in commercial operation with a maximum velocity of 300 km/h.

![Figure 7. The development of pantographs for the Shinkansen: (a) the diamond type (1964–2008), (b) the telescopic type (1997–2008), and (c) the single-arm low-noise type with low-noise insulators and a noise barrier.](image)

![Figure 8. Changeover switches for Shinkansen phase separations.](image)
320 km/h. This train set has two low-noise pantographs, but only one is used at a time to keep within the noise regulations by the reduction of the number of raised pantographs. However, the Japanese criterion for strain of the contact wire does not permit high mean contact force. Therefore, this pantograph is equipped with laterally segmented contact strips, which are elastically supported individually to improve dynamic characteristics of the pantograph. The extremely high contact performance of this pantograph has been verified through line tests.

Power Semiconductors Onboard

Electric railways include a wide variety of technologies, such as motor driving, signaling, dispatcher systems, ticketing and vendor machines, illuminating, distributed information networks on the car, networks on the ground, current collecting, and fixed power supply installations on the ground. For each technology, power semiconductors occupy a central position. Fortunately, the Japanese electric railway is supported by a strong national power semiconductor industry.

Topography of Power Semiconductors Onboard HSR

Figure 9 shows the typical topology of an HSR main circuit onboard the rolling stock. Cars derive ac HV power from the catenary and convert it into dc by the pulsewidth modulation (PWM) control method of rectifying with an insulated gate bipolar transistor (IGBT) power device. Then, dc will be converted into ac again to drive the asynchronous motors, also with a PWM and IGBT combination.

At first, in 1964, the Shinkansen was driven by 200-kW dc motors onboard and fed by ac 25-kV, 60-Hz catenary. There were also silicon diode rectifiers onboard the train. The total power for one train set (12 cars with four motors for each) was about 20 MW. In those days, nominal voltage and current of diodes were so small that many diodes were used in parallel and serially instead. The transformer tap control method was used for voltage/speed control of dc motors.

In the 1980s, trains adopted the thyristor Ward Leonard control method with a combination of phase-controlled thyristors and dc motors. Thyristors made the main circuit very simple.

In the 1990s, gate turn-off (GTO) thyristors such as 4,500 V/3,000 A and a microprocessor lead a PWM-controlled voltage source inverter (VSI)-based converter and inverter system for rectifying and controlling asynchronous motors. It was a kind of revolution for rail operator companies, since dc motors have some maintenance problems with their brushes and commutators. In addition, the power factor of the feeding circuit became about 1.0 (formerly 0.75–0.8), allowing the feeding circuit to send more power to HSR lines.

In the 2000s, IGBT devices played a major role. IGBTs offer faster switching speeds (1–2 kHz) than GTOs (400–500 Hz) that realize precise control of motors and lead an electromagnetic compatibility problem easier. At first, the withstand voltage of early generation IGBTs was not high enough (up to 2–3 kV), so three-level VSI converters were introduced. Then, the withstand voltage of latter generations of IGBTs rose to 4–6 kV, enabling two-level VSI circuits. In addition, the generation change of IGBTs ensures less loss and a simpler drive circuit so that converters are smaller than GTOs or early IGBT sets.

Therefore, some next-generation HSR rolling stock will adopt permanent magnet synchronous motors (PMSMs) for higher speed. PMSMs have to control with one motor by one inverter combination.
Some manufacturers propose a power set with an injection-enhanced gate transistor (IEGT) or integrated gate commutated turn-off thyristor devices.

The HSR industry is now waiting for new power devices with lower loss and more switching speed than silicon devices to reduce the weight and size of power converters. Among the several wide-gap devices under development, the silicon carbide (SiC) shot-key barrier diode might be the closest to the application, according to the latest papers. For example, Mitsubishi Electric reported 28% maximum improvement of total loss and 18% average improvement with 300-kW inverter set.

Besides drive systems, the rolling stock carries auxiliary power sources of several hundred kilowatts for air conditioning and lighting for passengers and controlling and cooling. We also have to count information processing systems, telecommunication systems, and signal systems. Every system is full of semiconductors.

Packaging and Cooling
The packaging and cooling technique of the power circuit is one of the key technologies of HSR. From the beginning, each car in the trainset of Japanese Shinkansen had traction motors. This type of system is called a distributed power train or EMU. In this case, although rated power is smaller than concentrated type, every power component should be set within the limited space under the floor.

The cooling system began with forced air driven by a blower. There are several approaches available today, such as forced air, heat pipes, ebullient cooling with perfluorocarbon, natural air, and water cooling. Figure 10 shows the history of cooling.

In any case, all of the power components are integrated in limited space. When engineers design the onboard propulsion system, they should carefully consider a total balance of power flow, thermal flow, air flow, mass balance, ease of manufacturing and maintenance, and cost. The specification of the recent power converter/inverter set for N700 type Shinkansen using 3,300-V, 1,200-A IGBTs with natural air flow cooling is 1,600 kW/1,320 kg.

The expected direction of future HSR improvements might be higher speed and more comfort. Thus, expected power devices for HSR should be higher voltage, larger current, with faster switching and more efficient power devices. Of course, cost is an important problem; however, the market for HSR is growing, and we can hope for a volume efficiency effect.

Since new wide-gap power semiconductors such as SiC or gallium nitride will improve the efficiency of onboard power converters, trains can reduce the weight and size of converters. For example, one of the expected applications of an SiC device is a medium frequency propulsion convertor.

The configuration of the pantograph has drastically changed, reflecting strong demands for noise reduction of the pantograph.
which enables to omit transformer onboard, the heaviest parts of propulsion, and can reduce the total mass. This composition is attractive, especially for 16.7-Hz feeding frequency countries.

We should consider a compromise between reliability, availability, and redundancy of power units with new devices. New devices have to improve their reliability of course. However, for some HSR onboard application, a certain redundancy will prove to introduce new devices in early stage. The medium frequency propulsion converter is one of the candidates.

**Power Semiconductors for Fixed Installations**

**Use of Flexible AC Transmission Systems**

In Japan, some traction substations or sectioning posts have been equipped with flexible AC transmission systems (FACTS) such as static var compensators (SVCs) or static compensators (STATCOMs) for balancing power or suppressing voltage fluctuation of both power grid and feeding circuit, which have been in use since 1987.

As the first Shinkansen, the Tokaido Shinkansen had to use relatively weak 66-, 77-, and 154-kV grids as its power source. The heavy load of the Shinkansen caused a voltage imbalance in the power grid in the early days, so the Tokaido Shinkansen had to deal with this problem carefully. FACTS devices were one of the answers. Now, railways are one of the biggest users of FACTS devices. The rated power of each HSR line is about 10–20 MW; thus, the scale of FACTS equipment should also be 10–60 MVA to compensate for the HSRs.

**SVCs and STATCOMs**

Simple SVCs have been a countermeasure for compensating for the reactive power from loads using ex-commutated thyristors since 1990. There are 23 sets available in the Tokaido Shinkansen.

A self-commutated STATCOM, sometimes called a static var generator, is a countermeasure for voltage fluctuation by balancing actual power and compensating reactive power at three-phase side, using GTOs or IGBTs since 1993. Five sets of 34–60-MVA STATCOMs are available in the Tokaido Shinkansen. A railway static power compensator (RPC) is a countermeasure for voltage fluctuation by balancing actual power and compensating reactive power at feeding side, using GTOs, gate commutated turn-off thyristors, or IGBTs (Figure 1). In the case of extended feeding, an RPC can compensate reactive power at the end of the feeding circuit. In addition, the RPC can act as an active filter for lower harmonics. Two sets of 20-MVA RPCs in the Tokaido Shinkansen and six sets of 20–60-MVA RPCs in the Tokaido Shinkansen are available.

The combination of a long feeding circuit and large train load, especially thyristor-phase control units, causes severe voltage drop at the end of feeding circuit. An SVC at the sectioning post can compensate this problem with Ferranti effect. The Tokaido Shinkansen has 15, the Sanyo Shinkansen has one, and several conventional lines have several SVCs in sectioning posts.

**Frequency Converter**

The Tokaido Shinkansen also uses 60 Hz throughout the 50-Hz area around Tokyo to reduce the weight of the rolling stock. There are four frequency-changer stations along the Tokaido Shinkansen. Most of the 60-Hz electric power is generated from 60-MW sets consisting of a 50-Hz three-phase synchronous motor and a 60-Hz three-phase synchronous generator. Since 2003, JR central company has introduced 60-MVA static frequency converters using GTO thyristors. Another 60-MVA three-phase 50-Hz to single-phase 60-Hz static frequency converter using IEGTs has been available since January 2009.

Electrified rail in Japan is one of the best examples in the world for efficient urban transportation as well as intercity transportation. Huge demands lead rail companies to use sophisticated technologies, with great help from the rail industry. Now, we have to brush up our technologies to welcome the Olympic games to Tokyo in 2020.

**For Further Reading**


**Biography**

Tetsuo Uzuka (uzuka@rtri.or.jp) received his master's of engineering degree in instrumentation engineering from Keio University in Yokohama, Japan. Since 1989, he has been engaged in the development of feeding systems at the Railway Technical Research Institute (RTRI) in Kokubunji, Japan. He is the director of the Power Supply Division of RTRI.
The concept of electrified vehicles (EVs) is the best old “new” idea that has been around for the last century. Designs have changed to make EVs popular, but until now, no design has captured the public’s imagination or gained market traction. This is because consumers need more than facts about EVs; they need to be wooed into making a bigger commitment to the EV.

We all know that EVs are good for us. The fact that we all don’t have more of them in our daily diet of transportation is not the fault of automakers or consumers. Consumers know that, like fiber, EVs make economic sense, benefit the environment, and are enhanced with “vitamins” like the latest technologies. All the ingredients necessary for a healthy and significant EV penetration are already in the marketplace.

What is missing is a certain je ne sais quoi—a winning combination of technology, desire, and marketing to make EVs indispensable to the average North American. Together engineers and policy makers can make this a reality, but they need to lead with more than just the head—they need to appeal to the heart of the consumer as well.
We Need to Talk
To move forward, sometimes you have to look back and reassess past failures and achievements. Past generations of EV designs grabbed the public’s attention. Innovation and evolution are the mainstays of EV development. As shown in Figure 1, the evolution of the EV can be traced back to the 1830s. Scotland’s Robert Anderson built the first prototype of an electric-powered carriage, and during the same time period, German engineer Andreas Flocken built the first four-wheel electric car. Pope Manufacturing Co., Hartford, Connecticut, the first large-scale EV maker in North America, made electric cars for the New York City taxi fleet. These innovations propelled EV technology into a booming industry in the United States that, by 1900, had encompassed 28% of the road vehicle market. This momentum was seriously dampened with the introduction of the petroleum-powered Ford Model T car. The EV market plummeted down to near extinction because of the predominance of internal combustion engines (ICEs) and the availability of cheap petroleum.

Recent years have seen a rekindled interest in EVs because of rising oil prices as well as research and development programs that have significantly improved the technology. Government initiatives such as the zero-emission vehicles program in California, which has made the technology more attractive for automakers, have also energized the EV market. Toyota was the first automaker to release a commercial hybrid vehicle, selling 18,000 units in 1997. Since then, oil prices have increased steadily, peaking at more than US$145 per barrel. Major automakers have responded by developing and commercializing a new generation of energy-efficient vehicles called plug-in hybrid EVs (PHEVs) and all-battery EVs (BEVs).

Does Our Relationship Have a Future?
Today, conventional ICE vehicles are a modern necessity on which society relies. However, large numbers of automobiles in use around the world have caused and continue to cause serious health and environmental problems. Air pollution, global warming, and the rapid depletion of the Earth’s petroleum resources are problems of paramount concern.

According to Navigant Research, “The average price of fuel for conventional vehicles will likely continue to rise through the remainder of this decade, driving demand for electrified (hybrid, plug-in hybrid, and all electric) vehicles” [1]. So far, this prediction is being fulfilled. This is corroborated by Pike Research’s findings of increasing EV sales and market penetration around the world, as noted in Figure 2. In 2012, Japan led sales of pure electric cars with a 28% market share of global sales, followed by the United States with a 26% share, China with 16%, France with 11%, and Norway with 7%. Plug-in hybrid sales in 2012 were led by the United States with a 70% share of global sales, followed by Japan with 12% and The Netherlands with 8%. According to a recent report from Navigant Research, a total of 21.9 million EVs will be sold worldwide during the period from 2012 to 2020.

Making a Long-Term Policy Commitment
The significant reduction in fossil fuel usage and CO₂ emissions is a well-known and attractive feature of EVs that has enabled their market penetration. The public and the industry understand the importance of reducing carbon footprints. They know that the transportation sector, as a whole, has a significant carbon footprint, and only governments, at various levels, have the power to regulate that footprint through legislation. In the United States, for example, the Corporate Average Fuel Economy (CAFE) regulation compels, or you...
could even say “drives,” automakers to improve their motor vehicles’ mileage capabilities every year. Ultimately, this will encourage manufacturers to introduce more EVs into their product lineup because meeting the standard will become increasingly difficult with standard ICE vehicles. Figure 3 shows the CAFÉ standards put forward by the U.S. government from 2011 through 2025, as documented in 2017–2025 Model Year Light-Duty Vehicle GHG Emissions and CAFÉ Standards. Figure 4 shows a short-term forecast of the EV market through individual company shares. On the basis of this forecast, Toyota is predicted to lead the market with a 38.5% share followed by Ford, Nissan, Honda, and General Motors. It is estimated that EV sales will begin to grow rapidly after 2015 and reach a combined 7 million per year by 2020 and 100 million by 2050.

The International Energy Agency has put forward a positive and ambitious road map to achieve widespread adoption and use of EVs and PHEVs worldwide by 2050. The road map targets a 30% reduction in global CO₂ levels by 2050 relative to 2005. The reduction is to be implemented through efficiency improvements and electrified transportation, with an EV share of at least 50% of the global light-duty vehicle sales. To achieve that target, policy support is critical to ensure that the initial cost is as affordable as possible and that an adequate charging infrastructure exists. Furthermore, collaboration between public and private sector companies must be established and strengthened through research programs, standards, and infrastructure development.

**Electric Machines—More than Just a Pretty Face**

Electric machines have proved their ability to provide equal mechanical power at relatively high efficiencies when compared with ICEs over the past few decades. This, along with their ability to mitigate fuel consumption and greenhouse gas emissions, is a substantial reason to replace ICEs with electric machines. This has created a demand for a new generation of electric machines that meet electrified transportation’s specific needs. Every EV has at least one electric machine, and some have multiple motors depending on their drivetrain architecture. The annual production of e-motors for EVs is forecasted to reach millions this decade, based on forecasts by analysts who track hybrid and EV production plans. Navigant Research predicts the global market for electric drive motors in light-duty vehicles to grow from a little less than US$1 billion in annual revenue in 2013 to more than US$2.8 billion in 2020.

The traction motor is key to the synergy of the electric powertrain. Selecting a suitable existing motor is a
challenge for designers. It is important to recognize that motor choice cannot be made without careful consideration of the integration of its controller and associated power electronics. Some automakers have decided to confront this issue by designing, developing, and producing their traction motors in-house, rather than purchasing off-the-shelf machines from specialist suppliers. The off-the-shelf motors, no matter how extensively they are adapted for a specific application, can compromise the efficiencies of the propulsion system.

As in Any Relationship, There Must Be Compatibility

Proper selection of electric machine type is based on key features such as the energy source in the vehicle, space and vehicle dynamics, efficiency, reliability, cost, and the major operating requirements of the machine. The major operating requirements of the traction motor include a wide speed range, impulsive response, high efficiency over a wide torque and speed, high torque at low speeds, fault tolerance, and high power density. Among the major automakers, there is no general consensus as to the type of electric machine best suited for vehicles, but induction and permanent magnet (PM) machines are the two types currently used in EVs and are expected to continue to dominate the market.

These machines fundamentally vary in their rotor architecture (Figure 5). The induction machine rotor contains conducting bars that cut the stator field and develop a voltage that drives a current and produces a secondary field. The rotors in PM machines use magnets to generate the rotor’s magnetic field exclusively, without the need for excitation current or any of the losses associated with it. These machines are found to have higher efficiency, torque density, and heat dissipation capability than their induction machine counterparts. PM motors are widely used in today’s EVs, including the Ford Focus, Toyota Prius (Figure 6), Chevy Volt, and Nissan Leaf, because of their superior performance over the induction machines. Remy is one of the PM e-motor manufacturers whose motors are used by GM, BMW, and Mercedes two-mode hybrids, as well as a growing list of commercial vehicles. Active areas of research on PM machines include studying the effect of rotor and stator configurations on harmonics and the causes and mitigation of demagnetization.

The advantages of PM machines are offset by the increasing price and supply disruptions of magnets due to geopolitical issues. This challenge has inspired companies such as Tesla and Remy to develop next-generation induction machines for vehicles that will be lighter and more efficient than the magnet-type machines. The conventional induction motors use aluminum rotors. However, the electrical conductivity of copper is 60% more than aluminum, making it an enticing substitute. Using copper material can also reduce the motor operating temperatures by 5–32 °C. These data suggest that the lifetime of motors using copper rotors may be extended by 50% or more. An example of the use of the copper rotor induction machines is in the latest generation of U.S. Army heavy-duty hybrid EVs (HEVs) powered by four 520-V, 140-hp induction machines with die cast copper rotors.

Another Innovation Suitor on the Horizon

The switched reluctance motor (SRM) is another candidate for traction motors, apart from the widely used induction and PM types. To date, SRMs have been applied in heavy-duty vehicles, and research is in progress to implement them into the lightweight vehicles. The SRM is a doubly salient machine with no winding or magnet on the rotor. It features a simple, rugged structure with fault-tolerance ability, high-speed operation capability, high power density, and relatively low manufacturing cost. Despite these advantages, SRMs do present some challenges. For example, torque ripple and acoustic noise need to be addressed through fundamental design improvements to develop a viable SRM-based electric propulsion system.

The Power Couple: Torque and Input

Regardless of the type of machine selected, to achieve the performance desired, a suitable drive is required. The drive consists of a bidirectional converter and its control. At the
machine level, during motoring, the goal is to provide the terminals with the proper voltages to meet the torque commands that the driver is imposing through the action of the pedal. Additionally, many vehicles employ regenerative breaking, which uses the electric machine as a generator to convert the energy produced by the action of slowing the vehicle and using it to charge the battery pack. With hybrid vehicles, a supervisory control is necessary to determine the power flow through the system as there are multiple energy sources, the battery, and ICE that work differently during various modes.

To control any machine, a relationship must be established between the input excitation and the resulting torque. The torque in an electric machine arises from the interaction of magnetic fields in the stator and rotor, and the generation of these fields depends on a coupled and complicated interaction of the current and flux linkage of the internal windings. The most commonly adopted ac electric motor control in EVs is the vector-control technique, which is capable of mathematically separating the component of current directly responsible for torque generation (Figure 7). This is done by projecting all the three-phase quantities along two axes: the direct (d) axis, which is in line with the field, and the quadrature (q) axis, which is perpendicular to it. To find these axes, it is necessary to determine the position of the rotor online.

In a PM motor drive, when the motor operates under base speed, the controller calculates the reference d- and q-axis current using a maximum torque-per-ampere technique to ensure the efficiency and torque production of the motor. Over base speed, a field-weakening method is used to estimate the current reference and ensure the power limit is not exceeded. The reference d- and q-axis voltage is generated taking into consideration cross-coupling terms, which arise from the aforementioned coupled electrical interaction, and then converted back to the three-phase quantities. Pulse-width modulation is used to generate a gate signal for the power electronic switches to create the required voltage waveforms (Figure 8).

To meet the advanced requirements of fast dynamics, field-oriented vector or direct-torque control is also the solution for induction machines. With rotor-flux-oriented control in a squirrel cage induction motor, the unstable portion of the natural speed–torque characteristics vanishes, and hence, there is no chance of instability due to certain types of load torques. The additional advantage is the fact that the maximum torque-producing capability of the machine is dictated by thermal considerations only. The electromagnetic torque response becomes as fast as a separately excited dc machine of identical torque rating but with a reduced size and weight. The only disadvantage in a field-oriented controlled induction motor drive is the

---

**Figure 6.** A block diagram of the Toyota Prius e-motor drive system [5].

**Figure 7.** Overall schematic of three-phase ac traction motor drive.
higher cost in realizing and implementing the complex control strategies in real-time field applications. Indirect rotor field-oriented or vector-controlled induction motor drives, where rotor position is estimated instead of measured, are widely used in EVs/HEVs for high-performance applications.

An SRM requires special converter topology, as it is fundamentally different in structure from other ac machines. Variable-frequency control, such as the hysteresis current controller, and current control based on fixed switching frequency, such as the proportional–integral control, have been developed and employed widely. Researchers have also proposed adaptive/intelligent controllers employing artificial intelligence techniques such as fuzzy logic, sliding mode control, emotional control, neural networks, and evolutionary algorithms and their combinations. These methods have proven effective in applications that require four quadrant operations, tracking capability, robustness to load disturbance, and less steady-state error, such as HEVs’ or EVs’ traction applications [6] (Figure 9).

Multifaceted Technology for Power Electronics: Integrated Motor Drive and Battery Charger

Conventional battery chargers have been either on- or off-board chargers. The onboard chargers have limitations of cost, power handling capacity, and charging time. An integrated charger topology using the power electronics already available on board can be used for battery charging when they are not used for traction, and this can lead to fast-charging technology [7]. The challenge is to design power electronic converters that are compatible with the motor and the battery pack, which usually are manufactured by two different companies. The companies designing the motor-drive system and the battery pack for the same vehicle can be coordinated by the original equipment manufacturer (OEM) in such a case. Because the battery is only charged when the vehicle is parked using the same power electronics converter, reduction in the initial vehicle cost and space used can be achieved. Moreover, in such a case, the motor windings can also be used as filters to improve power quality issues. Figure 10 shows a futuristic system that is expected to be on board vehicles for fast charging and traction application.

Gaining Traction in a Relationship

One idea to improve the performance of the EV drivetrain is to add multiple machines. It then becomes a matter of
determining if the advantages of having multiple machines outweigh the cost of adding them in. The main advantage is expected to be a significant increase in vehicle efficiency, especially in heavy-duty vehicles such as buses where space is less of a concern. One motor can be used when the transit bus is empty, and the other motors can be added when the load on the bus exceeds the rating of the other machine(s). Such a motor-drive system will result in symmetric loading of all machines, operating them near their rated conditions, which can yield better motor efficiency. The added complexity to the system amounts to the necessity of adaptive-control strategies and planetary gear systems and clutches for the mechanical connections.

Multimotor technology is currently being used in the Mercedes SLS AMG electric drive. Four compact PM synchronous motors with combined ratings of 552 kW and 1,000 Nm, weighing 45 kg and a reaching a maximum speed of 13,000 r/min, make up the drivetrain. It uses a unique concept of transmission, allowing each motor to selectively drive all four wheels. This helps in individual wheel torque distribution; however, it is only achievable under the significant disadvantage of unsprung masses with wheel hub motors.

Another recent innovation under investigation is the integration of the traction motor housing inside the wheel rim. This in-wheel motor design (Figure 11) saves significant space and eliminates the need for a transmission, differential, and related mechanical parts. This reduces energy losses due to friction. The in-wheel motors also improve traction by allowing precise control over each wheel, and they allowed greater flexibility in vehicle design since there is no need to mechanically link the wheels to a common driveshaft. They show great promise in increasing the overall efficiency.

In Innovation, Marketing, and Consumer Wooing, It Always Comes Down to Chemistry: The Li-Ion Battery

The successful deployment and mass adoption of EVs depends greatly on cost and performance. One of the big hurdles presently faced by EV manufacturers is the disproportionately high manufacturing cost associated with the EV battery pack. For instance, Allan Mulally, CEO of Ford Motors, indicated that the manufacturing cost of a battery pack for a Ford EV could range anywhere between US$12,000 and US$15,000 per car, while the car itself sells for US$22,000. Clearly, to achieve long-term competitiveness, this battery problem needs to be solved.

From lead-acid battery technology, with specific energy as low as 30 Wh/kg in the late 19th century, to the currently used lithium ion (Li-ion) batteries, various battery chemistries chosen as energy storage systems (ESSs) for the transportation sector are numerous. The main requirements of a battery are: 1) high power density to ensure rapid vehicle acceleration and the ability to use regenerative braking power; and 2) high energy density to ensure an extended drive range. Low cost, extensive cycle life, and safety are other key requirements.

Li-ion batteries are the latest trend in battery chemistry. With the nominal values of cell voltage of 3.2–3.65 V, specific energy of 130–150 Wh/kg and power density of 2,300–2,400 W/kg, these batteries are considered to be one of the best performers for automotive applications to date. Li-ion batteries contain multiple anodes and cathodes. By choosing the structure carefully, power and energy application requirements can be well satisfied. Despite its many advantages, there is always a tradeoff between performance and cost. The major disadvantage of Li-ion batteries is their high cost, which accounts for more than one-third of the total vehicle cost. Other disadvantages are aging, requirement of thermal protection, and immature technology compared to lead-acid or nickel metal hydride (NiMH) batteries.

Battery Technology Roadmap

The quest for improved EV battery technologies goes as far back as the 1970s. One of the first commercially feasible technologies adopted by automakers was the NiMH battery. NiMH batteries became the choice for early hybrid vehicles because they have a higher energy density and

Figure 10. Futuristic integrated power electronics for a traction motor drive and an on-board fast battery charger.
are lighter than lead-acid batteries of comparable power. They are commonly used in many hybrid vehicles today, including the Toyota Prius and Honda Insight. After testing several alternatives, Toyota announced in 2009 its continued use of NiMH batteries in many of its hybrid vehicles. Recently, manufacturers have extensively started using Li-ion as the preferred energy source, especially in EV and PHEV applications.

In 2008, Li-ion batteries were considered too costly to be used on a wide scale, costing around US$1,200/kWh to deliver specific energy of 110 Wh/kg and power density of 1,000 W/kg. However, with the invention of new electrode and electrolyte materials, the technology was advanced and the cost reduced to US$700–800/kWh in 2011. The specific energy and power density increased significantly to more than 120 Wh/kg and 1,800 W/kg, respectively. Currently, these batteries cost about US$400–500/kWh and have a specific energy of 130–140 Wh/kg and a power density of 2,400 W/kg. Their life is around 3,500 cycles. In 2015, the target cost for Li-ion batteries is US$200–300/kWh for a PHEV. Specific energy and power density targets are as high as 250–300 Wh/kg and 3,500 W/kg, respectively, in 2020, with a cost target of US$100–150/kWh. The electric range targeted is approximately 150 mi in 2020. As of now, the range is approximately 38–40 mi for a midsize PHEV like the Chevy Volt and approximately 100 mi for a full EV like the Mitsubishi i-MiEV. Figure 12 explains the technological advancement and future targets for Li-ion batteries from 2008 to 2020.

**Harvesting Energy: Lessening Burden on the Battery Pack**

Energy harvesting is another answer to reduce the load on the battery pack. The generation of electricity on board a vehicle without chemical conversion can significantly enhance the autonomy of electric driving and extend the life and improve the performance of energy storage devices. The e-tire concept is one of the energy harvesting methods using the deflection of the tire while the vehicle is in motion [8]. More specifically, this new concept uses local changes in pressure and shape of a vehicle tire to generate electricity. The idea uses the principle of electromagnetism to generate electricity inside the tire of a vehicle in a new way that is yet to be exploited in electrification of vehicles. The rolling of the wheel on the road causes local changes in the tire’s symmetric shape and makes it flat at the contact area with the road surface, as shown in Figure 13(a). The dynamic deflection changes the radial distance between the wheel axis and the circumference area of the tire when it is in contact with the ground. This localized deflection in the tire leads to the generation of electricity.
can be utilized by adopting a number of linear generators incorporated in a vehicle wheel, as depicted in Figure 13(b).

**How Fast Can You Charge?**

Supported by government incentives, the market for EVs can grow if adequate fast-charging facilities are placed in convenient permanent locations, such as gas stations. Such large-scale installations of charging stations will advance the charging infrastructure and technology for EVs. It will also create a trend of charging the EVs at permanent charging stations just like filling up gasoline in the existing gas stations for gasoline vehicles. The advancement in charging technology has to go hand in hand with the advancement in battery technology, as the battery should be able to handle the high inrush of power from such fast-charging dc stations.

These vehicles connected simultaneously to the grid consume a large amount of electrical energy. This demand for electrical power can lead to extra-large and undesirable peaks. Also, power-quality problems, such as poor power factor and higher total harmonic distortion during charging and discharging, may cause equipment malfunction and component failures. It is an economic and safety concern to the utility companies as transformers and feeders are prone to overloads. Hence, the effect of harmonics alone would be a reason to shut down the power transfer between the grid and the vehicle. Also, the effect of load increase and its inherent low power factor on the distribution systems should be considered. As the number of cars increases, load increases and, hence, it might worsen the current trend of harmonic distortion.

Higher-efficiency Level 3 sustainable charging stations are expected to mitigate issues of charging time, quantity of power consumed, and power quality. Moreover, the market for EVs can expand if adequate fast-charging facilities are provided in permanent locations such as gas stations and provided with high-amperage connections from a mixed power system containing onsite solar power generation and the grid. Such large-scale installations of charging stations will advance the charging infrastructure and technology for EVs and create a trend of charging EVs at permanent charging stations just like filling up gasoline in the existing gas stations for gasoline vehicles. Figure 14 shows one such futuristic fast-charging station.

The utility companies can own/manage these charging stations, which will reduce their power-quality concerns, as they will have greater control over these monitored charging stations. Level 3 charging infrastructure costs between US$30,000 and US$160,000. It is expected that commercially available EVs will be charged within 15–30 min to approximately 80% of the battery capacity using a dc fast-charging station.

**The Energy That Comes when Couples, Transportation Policy, and EV Charging Resonate**

While some researchers are trying to solve the EV battery problem through improvements in battery chemistry, others are trying to solve the problem by alternate means external to the battery. Accordingly, recent studies have shown the feasibility of charging EVs wirelessly with greater than 90% efficiency from utility supply to battery. This technology has come to be broadly known as inductive power transfer (IPT), and its application to electrified transportation for static and in-motion charging is gaining much attention worldwide from OEMs, government agencies, and academic institutions. The proponents of IPT-based EV charging aim to reduce the battery size and, by extension, its associated cost by ensuring that it is charged more frequently and seamlessly. The increase in charge frequency would be accomplished through opportunity charging, whereby EVs could easily charge up while stopped at a stop sign, traffic light, bus stop, or even while driving over an electrified section of roadway.

At the heart of IPT-based EV charging systems are two of the oldest and most well-known laws of classical electromagnetics: Ampere’s law and Faraday’s law of induction. The fundamental difference between the modern magnetic
induction and the conventional low-frequency magnetic induction that has now been in use for nearly a century in devices such as transformers and close proximity chargers is the use of matched high-frequency (i.e., >60 Hz) resonances at the source and receiver devices involved in the energy exchange so as to facilitate efficient power transfer across larger distances.

The distance and alignment between the primary and secondary inductive structures plays a critical role in all magnetically coupled systems but especially in modern IPT systems. The magnetic coupling coefficient is a figure of merit that quantifies the amount of magnetic energy generated at the primary that ends up being captured by the secondary. Conventional inductively coupled systems are tightly coupled, having coupling coefficients in the range of 0.92–0.98. On the other hand, in IPT-based wireless EV chargers, the large separation and misalignment possible between primary and secondary result in coupling coefficients that are typically in the range of 0.1–0.4, making such systems very loosely coupled. In turn, this very loose magnetic coupling results in very large leakage fields. These stray fields are lost from the perspective of transferring power from the primary to the secondary and also produce large inductive reactances that can be modeled as being in series with the windings of the primary and secondary magnetic structures. These large reactances severely limit the flow of primary and secondary currents; consequently, capacitive compensation of primary and secondary and operation at resonance are necessary to reduce the reactances to manageable levels.

From Figure 15, it can be seen that the design of a practical contactless EV charging system based on loosely coupled resonant IPT involves at least four main challenges: 1) the design of the low-loss and high-coupling electromagnetic structures that will participate in the magnetic energy exchange; 2) the design of an efficient high-power and high-frequency circuit, known as the IPT power supply, capable of driving the entire system; 3) the processing and conditioning of the received power on the secondary side; and 4) the automated control of the entire system [9]. With a formal SAE standard (SAEJ2954) on wireless charging due to be completed in 2015 [10], much work is presently being undertaken by different institutions to make wireless EV charging a practical and attractive reality that has the potential of significantly alleviating—if not eliminating—the "range anxiety" that has until now made consumers so reluctant to fully embrace EVs [11]. Figure 16 shows one such 6-kW, 20-kHz IPT system that was developed for conducting research.
on the primary side power supply topologies most commonly used for EV charging applications. The system shown has been tested at 3 kW over a 7-in air gap and achieved 93% efficiency as measured from the dc link of the inverter to the load being energized.

**Electric Powertrain Testing: Measuring the Endurance of a Relationship**

The accurate testing and validation of the components and control algorithms is a major stage in research and development of various technologies for electrified transportation. Generally, the drivetrain tester is a regenerative system that can be used to test the electric machine, power electronics, control algorithms, and battery performance by inputting the vehicle drive cycle and engine characteristics. D&V, Horiba, AVL, and A&D Technologies have all developed products specifically to test hybrid and EV components, such as the one in Figure 17. The centerpiece of the system is a powerful dynamometer capable of applying the load torque for the drive cycle. To support the dynamometer, all systems include a variable-frequency drive, which feeds on a variable dc link that can be used to model the battery. Most systems are regenerative in nature; that is, when the machine under test is braking and generating energy, it is fed back to the dc link where it can be used to help power the testing machine itself. This recycling of power means less has to be pulled from the mains, which reduces the cost of long tests. This is a big issue for an endurance test that can last for days.

That missing je ne sais quoi to make EVs indispensable to the average North American consumer can be found in accessible charging infrastructures, reliable long-life batteries, and increased mileage. Consumers want to be wooed—they want a relationship with EVs. Vehicle manufacturers want a better-quality EV to offer consumers to increase market penetration. Engineers and policy makers, to make this relationship a reality, need to appeal to more than just consumers’ minds and go beyond testing and performance statistics and test results. They also need to appeal to the hearts of consumers to woo them into making the long-term commitment and the emotional and financial investment in EVs. Consumers know that EVs are healthy and good for them—they just want a bit more romance in the relationship.

**For Further Reading**


**Biographies**

**Narayan C. Kar** is with the Centre for Hybrid Automotive Research and Green Energy (CHARGE), University of Windsor, Canada.

**K.L.V. Iyer** is with the Centre for Hybrid Automotive Research and Green Energy (CHARGE), University of Windsor, Canada.

**Amin Labak** is with the Centre for Hybrid Automotive Research and Green Energy (CHARGE), University of Windsor, Canada.

**Xiaomin Lu** is with the Centre for Hybrid Automotive Research and Green Energy (CHARGE), University of Windsor, Canada.

**Chunyan Lai** is with the Centre for Hybrid Automotive Research and Green Energy (CHARGE), University of Windsor, Canada.

**Aiswarya Balamurali** is with the Centre for Hybrid Automotive Research and Green Energy (CHARGE), University of Windsor, Canada.

**Bryan Esteban** is with the Centre for Hybrid Automotive Research and Green Energy (CHARGE), University of Windsor, Canada.

**Maher Sid-Ahmed** is with the Centre for Hybrid Automotive Research and Green Energy (CHARGE), University of Windsor, Canada.
HIPBOARD ELECTRICAL SYSTEMS INCREASINGLY USE dc distribution as an integral part of low-voltage (LV) ship service power for direct connection of variable-frequency drives (VFDs) and other mission loads to a dc feed, eliminating space and weight overhead of front-end ac/dc conversion. The future shipboard systems will have many of the same characteristics and requirements as dc microgrids because they will allow multiple generating sources and loads to interface into a common bus. An overriding consideration for shipboard systems is survivability. So dc systems have the advantage because they can readily interface with energy storage systems, and they are able to connect redundant buses through auctioneering diodes. The vision for power transmission from generation to electrical zones on future shipboard systems is leaning toward medium-voltage dc (MVDC) systems.

Key design criteria for fault protection on any such system are predictability of the system response to faults, the speed at which the fault is removed from the system, and the continuity of service to the loads. As with any electrical distribution system, shipboard dc systems are architected so that faults can be isolated between electrical zones and within a zone. Off-the-shelf solutions that meet these objectives are limited. This has motivated much research in the development and use of solid-state protective devices (SSPDs). In addition, new paradigms for fault protection are needed where SSPDs are applied. This article provides an overview of the present art of dc protection using SSPDs, including integrated gate-commutated thyristor (IGCT) versus insulated-gate bipolar transistor (IGBT) solutions, for LV and MVDC systems. This article also demonstrates a means of achieving protective coordination between upstream and downstream SSPDs. Experimental results are provided, showing coordination between one IGBT-based and two IGCT-based SSPDs.

Zonal Electrical Distribution and Protection

The dc zonal electrical distribution system (dc ZEDS) concept uses a static switch to isolate faulted section(s) of a dc bus that extends
throughout the ship, while loads connected to the faulted bus are temporarily switched to an opposite redundant dc bus during fault isolation. Present techniques fold back the voltage on the faulted bus using an upstream phase-controlled rectifier (PCR) to force currents to zero while an electromechanical switch isolates the faulted part of the bus. However, such systems are slow in response and jeopardize power continuity. The application of SSPDs to dc ZEDS has received considerable attention because of their fast response speed.

**Distribution and Protection Within an Electrical Zone**

Within an electrical zone and between sources and loads, there is an additional challenge presented by the current-limiting nature of SSPDs. Because the SSPD actively limits the current during the fault-isolation process, the current is the same upstream and downstream from the fault location. Therefore, conventional approaches to fault protection and coordination—which rely on voltage droop to ensure that protective devices closest to the fault trip off first—will not work. Instead, the local intelligence and speed of the SSPDs must be fully used to guarantee predictability in the response of the protection scheme to short circuits, no matter where in the system they may occur.

**System Overview**

Figure 1 shows a hypothetical shipboard dc system that includes aspects of both ZEDS protection and protection within electrical zones. The system shown in Figure 1 achieves both bus segmentation and isolation of faults from the bus for fault management. Using SSPDs, this system implements fault protection between electrical zones by using the SSPDs to quickly drive fault currents to zero or low levels and fold back the affected dc distribution bus (if necessary) instead of allowing the PCRs to perform that function. This enables electromechanical switches (S1A, S2A, S2, S3, S3A) to open, isolating the fault from the rest of the system. When faults occur internal to a zone, cascaded SSPDs in combination with electromechanical switches (S2B, S2C) perform coordinated protective functions with conventional circuit breakers only being used for protection of single downstream loads or load panels with low current ratings.

As suggested above, two fault-isolation paradigms need to be considered. The first is one where a fault occurs on the dc bus itself. In this scenario, the SSPDs on the bus (i.e., SSPD 1A and SSPD 2, if the fault occurs on the bus in Zone 2) in Figure 1 will limit fault current, assuming that shore power is the only source. A fault-location algorithm (such as the one described in [3]) determines the location of the fault and which of the electromechanical switches needs to be opened (i.e., S1A and S2). Meanwhile, as long as the fault is on this bus, the voltage supplied to any loads connected to the bus is nearly zero, and many of the loads will lose power continuity. Critical portions of the electrical zones will be fed by dc/dc converters (CONV) or inverters (INV) whose inputs are diode auctioneered with the opposite bus (according to the architecture described in [2]). Because the SSPD limits the fault current to safe...
levels, which allows isolation in a time response on the order of tens of microseconds (as opposed to several hundred milliseconds if the PCR limits the fault current), the loss of power continuity is minimized. The power interruption is limited only by the response time of the electromechanical switch.

The second paradigm considers faults occurring downstream of the SSPDs feeding loads within an electrical zone. For example, in Zone 2 of Figure 1, a fault occurs downstream of SSPD 2C, but upstream of the circuit breakers. In this scenario, the upstream SSPDs will see the same current as SSPD 2C. The desired reaction is for SSPD 2C to isolate the fault without any upstream SSPD tripping and commanding its associated switch (i.e., S2A, S2B, or S3, assuming the ship service TG and ship service battery are sources) to open. In this case, it is assumed that the current rating of SSPD 2C is low enough to enable the galvanic isolation mechanism to be built into the circuit breaker. For higher-current-rated SSPDs, the electromechanical device is physically too large to be incorporated into the circuit breaker enclosure.

SSPD Device Architecture

SSPDs can be constructed using many types of power semiconductors, including IGBTs and IGCTs. Both types of SSPDs have been built and tested.

The ratings of the SSPD are determined by the voltage and current ratings of the semiconductor power switches used in the circuit breaker. Both IGCT-based SSPDs rated at 1,000 V, 1,000 A and IGBT-based SSPDs rated at 1,000 V, 1,800 A are considered to be single SSPD building blocks. A unidirectional SSPD has one main current-carrying semiconductor device, which can interrupt current in only one direction, whereas a bidirectional SSPD has two main current-carrying semiconductors and can interrupt current regardless of direction. Figure 2 illustrates the unidirectional SSPD.

Adding another semiconductor to the unidirectional SSPD in an anti-series configuration yields the bidirectional SSPD shown in Figure 3. The main advantages of this SSPD implementation include: 1) reduced fault-current level due to the fast device opening speed (operation in microseconds instead of milliseconds), 2) limitation of arc-flash energy to a much lower level, also due to the fast breaker opening speed, 3) superior acoustic performance, and 4) lower maintenance costs.
Galvanic Isolation Concept

Galvanic isolation of SSPDs is a vital feature for achieving fault detection, isolation, and reconfiguration. To achieve galvanic isolation in an SSPD, physical isolation must be provided, and therefore, a mechanical method is required, which is shown in Figure 4. This method requires a main mechanical switch or contactor for the high current through the SSPD (which opens after the semiconductors have interrupted the fault current) and a secondary mechanical switch for interruption of the leakage current during isolation.

Protective Coordination Approach

The design concept for dc protective coordination using IGCT- and IGBT-based SSPDs within a dc distribution system is implemented using restraint signals between SSPDs. Along with using different SSPD trip levels, restraint signals provide the communication between SSPDs, resulting in proper coordination of the system during faults. Each SSPD makes coordination decisions locally and then, through the use of these restraint signals, communicates its decisions to other connected upstream and/or downstream SSPDs. This ensures that maximum power continuity is provided and that isolation only occurs at the location of the fault. Note that the restraint signals are mainly required when series SSPDs have the same or similar current trip levels.

Hardware Validation—Coordination

A series arrangement of SSPDs was set up, as shown in Figure 5, and tested to illustrate proper coordination between upstream and downstream SSPDs with a simplified three-stage system. The testing was performed using a combination of three SSPDs in series-two IGCT-based SSPDs with the same current trip level and a third IGBT-based SSPD, which is farthest downstream, with a lower current trip level than the two upstream SSPDs. Testing was performed using a high current pulse generator (HCPG) source to mimic the effect of dynamically stiff upstream power sources (as will be the case in converter-fed distribution systems).

For the test performed, the farthest downstream SSPD had a current trip level lower than that of each of the upstream SSPDs so that restraint signals were not needed based on the large difference in current trip levels. However, other testing (not described here) was performed on two-series SSPDs with the same current trip level, and proper coordination was demonstrated between these two SSPDs, validating the protective coordination method using restraint signals.

The test results of the fault interruption at the output of the farthest downstream SSPD are shown in Figures 6 and 7. The source inductance was 8 μH, and the test voltage was 800 V dc, resulting in a rate of rise (di/dt) of the current of approximately 100 A/μs during the fault event. Based on the test results, both series upstream SSPDs remained in the conducting state when the farthest downstream SSPD was closed into a fault at its output and tripped to interrupt the fault current.
The testing demonstrates that during the fault event, the HCPG current continued to flow through both upstream SSPDs, charging the bus snubber networks, while the downstream SSPD3 interrupted the fault current. As a result, the fault was properly isolated, and the power continuity was maintained to the loads at the output of each of the two upstream breakers. During the fault interruption, the downstream SSPD3 input transient voltage reached a peak value of 1,040 V because of the interruption of the current and the source inductance. Before the interruption, the downstream SSPD 3 output current reached a peak value of 1,220 A. Based on these test results, it was shown that the fault was isolated from the coordinated distribution system several orders of magnitude faster than can be done in an equivalent system using conventional air circuit breakers.

SSPD Two-Pole Parallel Architecture

The SSPD two-pole parallel architecture consists of connecting two single SSPDs in a parallel configuration. Paralleling the SSPDs demonstrates the ability to provide scalable, higher-current SSPDs based on connecting universal SSPD building blocks in parallel. Two parallel SSPDs were tested for fault-current interruption, with each SSPD having a current trip setting of 5,000-A peak. The testing illustrates the dynamic current-sharing characteristics of two parallel IGBT-based SSPDs during a fault event with a current interruption level of 10,000 A. Testing was performed with the SSPDs initially conducting, and then the HCPG source was applied to the SSPDs, which had a fault applied to their output terminals. The test setup is shown in Figure 8. The hardware for the two-pole parallel architecture is shown in Figure 9.

Hardware Validation—Paralleling

The test results of the fault interruption using two parallel SSPDs are shown in Figure 10, which illustrates balanced dynamic current-sharing...
and interruption capability throughout the fault event. For this test, the source inductance was 8 μH, and the test voltage was 800 Vdc, resulting in a di/dt of the fault current of approximately 100 A/μs during the fault event, which is 50A/μs per SSPD. The current reached 4,800-A peak through SSPD 1 before it was interrupted by the breaker. In the same test, the current reached 5,020-A peak through SSPD 2 before it was interrupted by that breaker. The test results show that the fault currents through the two solid-state circuit breakers remained balanced within 5% of each other.

**SSPD Device Considerations**
The trend in shipboard power distribution systems is to transition to higher system voltage levels, which reduces the amount of current required to distribute a given amount of power. DC power systems with line voltages up...
to 6 kV dc are presently envisioned. Because of the limitations in voltage capabilities of present power semiconductors, interrupting medium system voltages requires multiple devices connected in series. Figure 11 shows a summary of the voltage and current ratings of silicon power semiconductors presently available.

Much progress is being made in increasing the voltage capability of silicon power semiconductors, particularly because there is now much interest in using solid-state power switching for MV power control applications in the electrical utility industry. Typically, the semiconductor devices used for these applications are four-layer thyristor devices, such as GTOs, ETOs, and IGCTs, but the voltage capability of three-layer nonlatching devices, such as IGBTs and metal-oxide semiconductor field-effect transistors (MOSFETs), continues to increase.

The MVDC SSPDs can now be made by using multiple series-connected power semiconductors. Note that many types of power semiconductors can be used, such as IGBTs, IGCTs, GTOs, and ETOs, taking into consideration whether the device is capable of blocking voltage or carrying current in the reverse direction. Figure 12 shows a generic example of a single-pole SSPD using three power semiconductors connected in series, but the concept can easily be expanded to have more devices in parallel to accommodate feeds having a higher rating.

The higher-current SSPDs can be made by paralleling series-connected groups of power semiconductor devices. The multiple-pole SSPD breakers can be made with multiple groups of series/parallel-connected power semiconductors, using one group for each pole.

Much progress is also being made in the voltage and current ratings of power semiconductor devices using new semiconductor materials such as silicon-carbide (SiC) and gallium-nitride. For example, wide-bandgap SiC MOSFETs are now available in voltage ratings up to 1,700 V and may soon be available in voltages up to 10 kV. The current capabilities of these devices are relatively low at present, being about 10–33 A, but they are being paralleled into power modules for higher current capabilities. Present research indicates that 10-kV SiC MOSFETs are expected to cover ratings up to the 100–200-A range, while 10-kV SiC IGBTs are expected to handle ratings well beyond 1,000 A. SiC Thyristors are being developed to handle systems that require device voltage ratings that exceed 10 kV with ampere ratings that exceed 1,000 A.

**Conclusions**

This article presented an overview of the present art of LV dc power distribution system protection using SSPDs. It described how IGBT- and IGCT-based SSPDs are constructed and how the important feature of galvanic isolation can be included in them. The article outlined the advantages of SSPDs, which include reduced fault-current level, greatly reduced current interruption time, limitation of arc-flash energy, improved acoustic performance, and reduced maintenance. It also demonstrated protective coordination using three of these solid-state circuit breakers and discusses new paradigms to consider.

Test results were presented validating the use of restraint signals to aid in proper protective coordination in a generic three-level power distribution system. The article also showed test results for two paralleled SSPD building blocks used to make higher-current-rated solid-state circuit breakers, showing very good dynamic current sharing. Trends in shipboard power distribution systems were discussed as well as the present and future capabilities of silicon and silicon-carbide power semiconductor devices used in SSPDs. The article concludes by showing a viable approach for creating MV SSPDs by operating several power semiconductors in series/parallel combinations.

**For Further Reading**


**Biographies**

**Rich Schmerda** (richardschmerda@drs.com) is a senior electrical engineer at DRS-PCT in Milwaukee, Wisconsin, with 32 years of experience developing power converters, motor drives, circuit breakers, and semiconductor power modules.

**Rob Cuzner** (robcuzner@ieee.org) is a staff systems engineer at DRS-PCT with 25 years of experience designing power conversion systems, VFDs systems, and their controls.

**Rodney Clark** is a senior electrical engineer at DRS-PCT in Milwaukee, Wisconsin, with 15 years of experience developing analog and digital circuit board assemblies and engineered components for applications including power conversion systems, VFDs, and solid-state circuit breakers.

**Dan Nowak** is a senior electrical engineer at DRS-PCT in Milwaukee, Wisconsin, with 15 years of experience designing power conversion systems, VFDs, and solid-state protective systems.

**Steve Bunzel** is an engineering manager at DRS-PCT with 15 years of experience designing high-speed protective relaying systems as well as power distribution and power conversion systems.

---

**Figure 12.** The topology of one-pole MV dc SSPD.
ITH THE INTRODUCTION OF THE SMART grid, there is an intense interest in the integration of intelligent and flexible microgrids in large-scale power systems. Microgrids would be operated locally in grid-connected and island modes and can provide black start operation, frequency and voltage support, active and reactive power control, and better energy management through storage technologies. The proximity of power generation to microgrid consumptions could result in improved power quality, lower power losses, better voltage stability, and higher reliability (fewer customer outages) by engaging fewer components and eliminating additional transmission services.

Distributed energy resources (DERs), which include distributed generation (DG), distributed storage, and adjustable load, are a key component in microgrid operations.

The economical and reliable operation of a microgrid.
Microgrids could be clustered at distribution levels to enhance the economics and the reliability of small DGs such as microturbines and wind-generation turbines as well as DGs with power electronic (PE) interfaces such as photovoltaic (PV) arrays and fuel cells. PE interfaces are fast, enabling full control of transients by introducing virtual inertia implemented through control loops known as droops. The implementation of droops would enable adjustments in frequency and voltage, which are in proportion to real and reactive power at converter terminals. Microgrids use small generators with low or no inertia, which are mostly equipped with PE interfaces in resistive networks, whereas the utility grid includes large synchronous machines with high inertias and an inductive network.

The microgrid control architectures are offered in grid-connected and island modes. Microgrids use two control architectures: multiagent system control and hierarchical control. The multiagent control system provides generation unit autonomy, reduces large data manipulation, and increases the control system reliability; however, the implementation would require a more complicated control infrastructure, which is not recommended for industrial applications. The hierarchical control of microgrids includes primary-, secondary-, and tertiary-level operations. The primary control would share the load among DER units using droops while eliminating circulating currents. The secondary control would eliminate steady-state errors imposed by primary control. The tertiary control would ensure the economical and secure operation of the microgrid and manage the microgrid’s energy imports/exports with the utility grid. The hierarchical control of microgrids would minimize operation costs and increase the microgrid reliability and enhance the dynamic performance of a highly nonlinear system through various control strategies. The hierarchical control of islanded microgrids would use existing DERs for regulating the system frequency in different time spans. In addition, using microgrids would reduce communication requirements among local DER units.

In this article, we discuss microgrid objectives and present options for microgrid operations and their monitoring and control in the context of a functional system at the Illinois Institute of Technology (IIT) in Chicago. The microgrid represents a multitier hierarchical control of self-sustaining energy infrastructure with islanding and resynchronization, self-healing, and demand response capabilities. The intelligent high-reliability distribution system (HRDS) at IIT is equipped with phasor measurement units (PMUs) for real-time monitoring, nondispatchable renewable energy production, as well as conventional and dispatchable energy resources.

**Status of a Typical Distribution Network at a University Campus**

IIT is located approximately 2.5 mi south of downtown Chicago, bounded by 35th Street on the south, Michigan Avenue on the east, 29th/30th Street on the north, and the Metra Rock Island train line on the west. Starting with the campus substations, IIT owns, manages, and operates its underground electricity distribution system. A cross-tie feeder between the substations allows for the seamless operation of the microgrid in the case of a utility grid failure in the shared feeder or one of the individual feeders in the North or the South Substation. The on-site generation can also feed the northern part of the campus through the cross-tie between the North and the South Substations.

In the decade preceding the implementation of the IIT microgrid, the university experienced several outages within the campus infrastructure and the utility feeders, which resulted in partial or complete loss of loads in buildings and research facilities. Several campus buildings lost power, including laboratories, resulting in the loss of experimental data and subjects. The substantial annual loss of revenue as a result of the outages included the replacement costs of damaged equipment due to undervoltage or unbalanced voltages (campus facilities as well as laboratories), the personnel and administrative costs of restoring and sustaining research and educational experiments, and the cost and aggravation associated with disrupted academic classes and laboratories and any other major campus events such as open houses and conferences that were interrupted by the outages.

The IIT microgrid, funded mostly by a grant from the U.S. Department of Energy, empowers the campus consumers with the objective of establishing a microgrid that is economically viable, environmentally friendly, fuel efficient, robust, and resilient with a self-healing capability. The IIT microgrid enhances its operation reliability by applying a real-time reconfiguration of power distribution assets, real-time islanding of critical loads, and real-time optimization of power supply resources.

**Objectives for Establishing a Microgrid**

The IIT microgrid is powered by a master controller, which offers the opportunity to eliminate costly outages and power disturbances, supply the hourly campus load profile, reduce daily peak loads, and mitigate greenhouse gas production. The distribution system topology consists of several loops, which provide redundant electricity supply to the end consumers. The IIT microgrid would specifically:

- Demonstrate the higher reliability introduced by the microgrid system at IIT
- Demonstrate the economics of microgrid operations
- Allow for a decrease of 50% of the grid electricity load
- Create a permanent 20% decrease in the peak load from the 2007 level
- Defer a planned substation through load reduction
- Offer a distributed system design that can be replicated in urban communities.

The criteria for achieving these objectives are short-term reliability and economical operation. Figure 1 shows the microgrid elements, functions, and control tasks associated
with each criterion. To achieve the optimal economics, microgrids apply coordination with the utility grid and economical demand response in island mode. The short-term reliability at load points would consider microgrid islanding and resynchronization and apply emergency demand response and self-healing in case of outages.

**Campus Microgrid Components**

In this section, the components of the IIT microgrid, including DERs, HRDS switches, meters and PMUs, and building controllers, are introduced. DER units include dispatchable units such as natural-gas turbine generator and battery storage units, and nondispatchable units such as solar PV and wind turbine units. The storage unit includes a flow battery and several lead-acid batteries. Building controllers would provide control and monitoring functions for building loads on campus. Figure 2 depicts the seven-loop configuration established at IIT in which three loops are connected to the North Substation and four loops are connected to the South Substation. The components of the IIT microgrid are described in the remainder of this section.

**Natural-Gas Turbine Synchronous Generation**

The IIT microgrid is equipped with an 8-MW natural-gas-fired power plant with two 4-MW Rolls Royce gas turbines. The natural-gas turbine consists of five sections, including air intake, compressor, combustor, turbine, and exhaust. The air sucked into the inlet is compressed by the compressor and mixed with the fuel (natural gas) to form an air–fuel mixture. The mixture is burned in the combustor to form a high-pressure air, which drives the turbine. The synchronous generator installed on the turbine shaft will convert the mechanical energy into electrical energy. Figure 3 shows the full-scale model of the natural-gas turbine generator located at the IIT campus.

**Solar PV Generation**

A total of 140 kW of solar PV cells are installed on three building rooftops, including a 20-kW solar canopy (shown in Figure 4) installed at the electric vehicle charging station to supply portions of the IIT campus load. The solar PV units are not dispatchable and use the maximum power point tracking (MPPT) control system shown in Figure 5 to maximize the solar power output for a given insolation. A solar PV cell is a controlled-current source with a nonlinear current–voltage relationship corresponding to a given insolation and temperature. Generally, as the solar PV cell voltage increases, its output current will decrease. To achieve the highest efficiency and capture maximum solar energy, a solar PV array voltage-control mechanism is developed for a given insolation. Here, the inverter output voltage $V_o$ and solar PV units is determined by the microgrid. The dc/ac inverter uses an angle control to stabilize the dc bus voltage $V_{bus}$ based on the fixed $V_o$, and also used a magnitude control to regulate the reactive power output at a reference value (typically zero). Based on the stabilized $V_{bus}$, the dc/ac converter adopts MPPT control to regulate the solar PV array voltage $V_{pv}$ and reach the maximum real power output. The objective of solar PV generation control is to withdraw maximum real power without injecting any reactive power to the microgrid.

**Wind Turbine Unit**

An 8-kW wind turbine unit is installed on the north side of the campus in the Stuart soccer field, connected to Loop 1, as shown in Figure 6. The wind turbine unit on the IIT campus

![Figure 1](https://example.com/figure1.png)

**Figure 1.** The objectives and functions for the control and operation of the IIT microgrid.
Figure 2. An IIT Microgrid based on a looped distribution system.
uses a Viryd wind turbine unit. The wind turbine features continuous variable transmission (CVT) technology, which provides automatic and continuous variable ratio change that maintains stable rotor speed for the generator as wind speed changes. This would enable the generator to maintain high efficiency at all wind speeds. The CVT can also precisely slow the rotor in high wind speed, curtailing the excess wind power. Figure 7 shows the structure of the CVT-based wind turbine unit. The role of the variable gear ratio is to regulate the power output close to the rated value when the wind speed is within the acceptable range. The cut-in and cut-off wind speeds for this turbine are 4.5 and 25 m/s, respectively, and the turbine has an 8-m diameter and 50-m² sweep area. Figure 8 shows the hourly power output and the wind speed for the wind turbine unit on May 2013. Here, the wind turbine unit would spin when the wind speed is higher than 10 mi/h (4.47 m/s).

**Battery Storage**

The IIT microgrid is equipped with a 500-kWh battery storage system (including ten 50-kWh battery cells) with 250-kW power capacity, which is connected to Loop 1. Figure 9 shows a stack of the flow battery and the battery inverter, which can regulate the real and reactive power output.

**HRDS Switches**

The HRDS at IIT uses underground closed-loop fault-clearing Vista switchgear with SEL-351 directional overcurrent protection relays. The fault isolation takes place in a quarter of a cycle by automatic breakers. The communication via fiber-optic cables facilitates the coordination between Vista switches. Figure 10 shows the underground installation of a HRDS switch at IIT. In HRDS, at least two simultaneous failures in the cable segments feeding a building from both paths will lead to a complete outage in the building. As the chances of two coincident failures is far less than single failures in cables feeding, the interruption indices of the buildings are improved significantly by the installation of HRDS. Figure 11 shows a loop configuration in distribution system at IIT. Here, in Loop 1, any cable failure between Vista switches 1C and 1D will be cleared, and the Stuart and Life Sciences Buildings fed by the switches will not face any interruptions.

**Meters and PMUs**

The IIT microgrid is equipped with building meters and PMUs, which report building electricity consumptions to the master controller. The master controller will receive an energy consumption update every 15 min. The load data recorded on 17 July 2012 at the McCormick Tribune Campus Center (MTCC) at the IIT microgrid are shown in Figure 12. Approximately 30% of building consumptions at IIT are shiftable loads, which can be served when the electricity price is lower. The IIT microgrid is equipped with 12 PMUs that monitor and record the real and reactive generation and consumption in real time and provide the information on instantaneous voltage and current of DER units (including the magnitude and phase angle) at a sampling rate of one signal per cycle to the master controller. Figure 13 shows a PMU installed at the North Substation. Figure 14 shows the real and reactive power of critical loads and DER units, which are calculated by master controller based on the instantaneous values.

**Building Controllers**

Building controllers facilitate the building consumption manage-
The reduction in building consumption is accomplished by defining several operating modes representing consumption levels in each building. Once the operation mode for each building is set by the master controller, the building controller will send a signal to the sub-building controllers to set the requested load level associated with the selected mode and feed back the confirmation signal to the master controller to acknowledge the mode change. Figure 15 shows the buildings equipped with building controllers in Loop 1, in which the blue squares represent command signals from the master controller, and the green squares represent acknowledgment signals originating from the building controllers. The building controllers are also able to monitor and control the energy flow within the buildings, including hot and cold water flow, heating and cooling loads, and monitoring the temperature of different spaces within the building.

**Microgrid Control**

Figure 11 shows the DER units (including DG and rechargeable storage) implemented in the IIT microgrid. The IIT microgrid integrates DG units, which are classified into conventional DGs and PE coupled DGs. Table 1 shows that the DER control schemes are categorized into grid-following and grid-forming control.

In grid-forming control, DER units maintain the microgrid voltage and frequency, while in the grid-following control, the units maintain their individual real and reactive power dispatch. In other words, DER units with grid-forming control would act as the swing bus in microgrids and should have adequate real, reactive, and reserve power capacity and fast response to control microgrid voltage and frequency. The DER unit using this control scheme can either collaborate with other DER units (interactive control) or operate autonomously (noninteractive control). Dispatchable DER units, which follow set points determined by their controllers, can interact with other DER units using a grid-forming interactive control scheme. DER units with load-sharing capability, which would collaborate in setting their output real and reactive power dispatch according to the microgrid frequency and voltage, are an example of grid-forming interactive controlled DER units. Dispatchable units can also use grid-forming noninteractive control to maintain a fixed set-point for microgrid voltage and frequency. This control scheme can be used in dispatchable units with sufficient real and reactive power capacity (such as microturbines) to maintain nominal microgrid voltage and frequency.

The grid-following control is used when the DER unit is not required to directly control the microgrid voltage and/or frequency. In this control scheme, the real and reactive power output of the DER is maintained within permissible limits, and the voltage and frequency is regulated by other DER units in the microgrid. Similar to the grid-forming control scheme, DER units using a grid-following control scheme can either collaborate with other DER units in the microgrid or operate autonomously.
autonomously. Nondispatchable units in a microgrid (such as solar PV units with MPPTs or wind turbine units) often apply a noninteractive control, which maximizes their output power. Dispatchable units apply a grid-following interactive control in which the real and reactive power output is determined by the respective set points. This control scheme can be applied to PV units equipped with storage in microgrids, where the output real and reactive power is regulated irrespective of the control strategy for microgrid voltage and frequency.

Depending on the microgrid operating mode, a proper DER control scheme, shown in Table 1, is used. An interactive grid-forming control can be used either in island or grid-connected mode. In island mode, DERs apply this control scheme to share the load, while in the grid-connected mode, DERs apply this control scheme to regulate the power exchange between the microgrid and the utility grid. The noninteractive grid-forming control can be used only in island mode, as the frequency and voltage will be set by DER units in the island mode. In the grid-connected mode, if the utility frequency or voltage deviates from the DER set point, the DER real or reactive power may reach its physical limit once its controller apply the set point voltage or frequency. The DER unit with grid-following control follows the microgrid voltage and frequency, which is set by the utility grid in grid-connected mode and other DER units in island mode.

Table 1 shows that the natural-gas turbine and the battery storage at IIT are using interactive grid-forming control and the wind turbine and PV units are using noninteractive grid-following control. The interactive grid-forming control scheme on the natural-gas turbine and the battery storage units would enable the microgrid to operate in both island and grid-connected modes.

The proper monitoring and control of DERs at the IIT microgrid would satisfy the following objectives:

1) load sharing among DERs
2) voltage and frequency regulation in island mode
3) islanding and resynchronization to the utility grid
4) optimal generation and consumption at IIT microgrid
5) real-time monitoring of the distribution system components.

Functionally, three control levels (shown in Figure 1) are applied to the IIT microgrid:

1) primary control, which is based on droop control for sharing the microgrid load among DER units
2) secondary control, which performs corrective action to mitigate steady-state errors introduced by droop control
3) tertiary control, which procures the optimal dispatch of DER units in the microgrid and manages the power flow between the microgrid and the utility grid for optimizing the grid-connected and island operation schemes.

The control levels at the IIT microgrid are discussed next.

**Tertiary Control**

Tertiary control is the upper most level of the control system in Figure 1; it ensures the optimal operation of the microgrid by determining the set points of generation and load entities at the IIT microgrid. The master controller, which is regarded as the most important control element of the IIT microgrid, is responsible for applying the tertiary control. The master controller uses the data supplied by the supervisory control and data acquisition (SCADA), which enables the real-time monitoring and control of microgrid elements including HRDS controllers, on-site generation, storage, and individual building controllers and meters. The master controller signals, which are relayed through SCADA, will adjust building loads and the generation dispatch for economical operation.

Figure 16 shows a hierarchical operation within the tertiary control that would provide generation and load management at normal and emergency conditions. The hierarchical tertiary control includes the following components.

- The master controller determines the optimal and reliable operation of the microgrid through optimal generation dispatch and load signals. The generation
dispatch signals are sent to dispatchable DER units on campus, and the load signals are sent to the building controllers.

The building controllers are responsible for setting the building loads according to the dispatch signal received from the master controller.

The sub-building controllers perform device-level load management by controlling the operation status of devices located in buildings.

The hierarchical tertiary control approach would receive the information from loads and power supply entities on campus as well as the information on the status of campus distribution network and procure the optimal solution via an hourly unit commitment and real-time economic dispatch for serving the campus load in the normal operation mode and contingencies. In Figure 16, the monitoring signals provided to the master controller indicate the status of DER and distribution components, while the master controller signals provide set points for DER units and building controllers. Building controllers will communicate with sub-building controllers through a ZigBee wireless control and monitoring system to achieve a device-level rapid load management.

Figure 11. The DER units and HRDS in the IIT microgrid.

Figure 12. The MTCC load on 17 July 2012.
### Secondary Control

Secondary control in Figure 1 is the middle level control at the IIT microgrid. Secondary control is used to eliminate frequency and voltage deviations caused by lower control level (primary control). As illustrated in the Figure 17, once there is a sudden decrease in demand in microgrid, the frequency and voltage increases. Once the frequency or voltage increases, the operating point may slide from A to B with primary control to decrease the generation dispatch and match the generation with demand. As the frequency or voltage is above the rated value, the secondary control is used to lower the operating point from B to C, where the frequency or voltage is restored to the rated values. As shown in Figure 17, only the frequency or voltage is restored in secondary control, while the real or reactive power dispatch is not changed. Thus, with secondary control, dispatchable DER units would maintain the frequency and voltage at the rated value while adjusting their dispatch according to the tertiary control signal to serve the microgrid load. The secondary control is a centralized and performed by master controller. The master controller will set the microgrid voltage and frequency and send the set points to primary control at DER level. Restoration, load sharing, and management can be performed in secondary control.

### Primary Control

The primary control, shown in Figure 1, is the lowest level of control in the IIT microgrid. The primary control is mainly used for load sharing among controllable and dispatchable fast-response DER units, which have adequate capacity to serve the microgrid load. The most widely used primary control strategy is droop control, which is shown in Figure 18. DER units equipped with droop control, which are connected in parallel, would not need to communicate with each other to perform load sharing; instead, individual dispatch levels are calculated based on predefined droop characteristics and microgrid frequency and voltage.

### PMU Information

<table>
<thead>
<tr>
<th>ID No</th>
<th>Building Name</th>
<th>P (kW)</th>
<th>Q (kVAR)</th>
<th>Frequency</th>
<th>Power Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Engineering 1</td>
<td>590.18</td>
<td>832.45</td>
<td>60.0150</td>
<td>0.5784</td>
</tr>
<tr>
<td>2</td>
<td>Life Sciences</td>
<td>302.70</td>
<td>289.27</td>
<td>60.0150</td>
<td>0.7230</td>
</tr>
<tr>
<td>3</td>
<td>Stuart Building</td>
<td>442.60</td>
<td>210.45</td>
<td>60.0180</td>
<td>0.9031</td>
</tr>
<tr>
<td>4</td>
<td>Gunsaulus</td>
<td>46.28</td>
<td>33.48</td>
<td>60.0150</td>
<td>0.8102</td>
</tr>
<tr>
<td>5</td>
<td>MTCC</td>
<td>335.25</td>
<td>234.14</td>
<td>60.0160</td>
<td>0.8198</td>
</tr>
<tr>
<td>6</td>
<td>Hermann Hall</td>
<td>447.39</td>
<td>18.12</td>
<td>60.0150</td>
<td>0.9992</td>
</tr>
<tr>
<td>7</td>
<td>Wishnick Hall</td>
<td>426.30</td>
<td>200.09</td>
<td>60.0150</td>
<td>0.9052</td>
</tr>
<tr>
<td>8</td>
<td>Siegel Hall</td>
<td>138.09</td>
<td>260.82</td>
<td>60.0170</td>
<td>0.4679</td>
</tr>
<tr>
<td>9</td>
<td>North Substation</td>
<td>7017.33</td>
<td>165.26</td>
<td>60.0160</td>
<td>0.9997</td>
</tr>
<tr>
<td>10</td>
<td>IIT Tower</td>
<td>628.78</td>
<td>312.70</td>
<td>60.0120</td>
<td>0.8954</td>
</tr>
<tr>
<td>11</td>
<td>IIT Tower (20th Floor)</td>
<td>1238.62</td>
<td>537.08</td>
<td>60.0160</td>
<td>0.9175</td>
</tr>
<tr>
<td>12</td>
<td>Power Plant</td>
<td>0.00</td>
<td>0.00</td>
<td>59.9600</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

*Figure 13.* The PMU at the North Substation.

*Figure 14.* Real and reactive power based on PMUs on DER units.
Figure 15. The building controllers showing the status of controllable loads in three buildings in Loop 1 at IIT.

Figure 18, the DER dispatch $P$ is at its rated value $P_{\text{rated}}$ at the rated frequency $f_{\text{rated}}$, which are determined by the master controller through tertiary control level. As the frequency increases, there will be a slight decrease in power dispatch to compensate the frequency deviation. Similarly, as the microgrid voltage increases, the injected reactive power decreases to compensate the voltage drop. In Figure 18(a) and (b), $m_r$ and $m_q$, respectively, represent the slopes of the $f$–$P$ and $v$–$Q$ curves. The DER units at the IIT microgrid, which are equipped with primary and secondary control, are the natural-gas turbine synchronous generator and the battery storage unit.

Natural-Gas Turbine Synchronous Generator
Figure 19 shows the control diagram for the natural-gas turbine synchronous generator. Here, $\omega$, $\omega_{\text{rated}}$, $V$, and $V_{\text{rated}}$ are the measured speed, rated speed, measured voltage, and rated voltage of the synchronous generator, respectively; $P$, $P_{\text{rated}}$, $Q$, and $Q_{\text{rated}}$ are the measured real power, rated real power, measured reactive power, and rated reactive power of the generator, respectively; $\omega_{\text{ad}}$ and $V_{\text{ad}}$ are the adjustment signals used for secondary control. As shown in Figure 19, the natural-gas turbine and exciter provide the input mechanical torque $T_m$ and excitation to the generator. The primary and secondary control modules for $\omega$–$P$ and $v$–$Q$ generate signals to the turbine and exciter, respectively, to regulate the real and reactive power output and maintain the microgrid frequency and voltage at the rated values. At steady state, if the generator dispatch is deviated from the rated value through primary droop control, the secondary control will generate a nonzero adjustment signal shown in (1) to restore the frequency or voltage back to the rated value. Thus, the natural-gas turbine synchronous generator would serve the campus load while maintaining the microgrid frequency and voltage at the rated value.

\[
\omega_{\text{ad}} = m_r (P - P_{\text{rated}}) \\
V_{\text{ad}} = m_q (Q - Q_{\text{rated}}). \tag{1}
\]

Battery Storage Unit
The control structure of the battery storage system is shown in Figure 20, where the battery storage is connected to the microgrid through a bidirectional dc/ac inverter, an ac filter, and a transformer. Here, the output real and reactive power denoted by $P$ and $Q$ is calculated by measuring the terminal voltage and current $V$, and $I$. The measured real and reactive power are used in the primary droop control to provide a reference voltage signal $V_r$. The voltage loop is used to stabilize the inverter terminal voltage using the reference voltage signal and to ensure that the DER output impedance is inductive at
rated frequency, which is an important factor in implementing $f-P$ droop control. The current loop is used to obtain a fast response in a wide frequency band. The biloop block output (voltage and current loops) is the pulsewidth modulation (PWM) ratio, which would trigger dc/ac inverter switches. If the microgrid frequency $f_{\text{ac}}$ or the microgrid voltage $V_{\text{ac}}$ deviates from the rated value, the secondary control module will generate secondary control signals $f_{\text{ac}}$ or $V_{\text{ac}}$ to restore the rated frequency or voltage. The inverter power output is limited between $-250$ and $250$ kW as enforced by primary control module. In Figure 20, the battery storage system would maintain the rated frequency and voltage of microgrid in case of any disturbances in the island mode. Moreover, the battery storage system would perform the following functions:

- contain abrupt load changes in island mode
- help mitigate frequency deviations in island mode
- participate in frequency regulation when the microgrid operates in grid-connected mode
- charge and discharge periodically for the economical operation of the IIT microgrid.

**Economical and Reliable Operation of the Microgrid**

The hierarchical tertiary control is used to ensure the economical and reliable operation of the microgrid. In Figure 1, the economical operation pertains to unit commitment and economical dispatch as well as economical demand response in grid-connected and island modes. Also, the short-term reliability of microgrid is satisfied through islanding and resynchronization, emergency demand response, and self-healing. In this section, the economical and reliable operations of microgrid performed by the hierarchical tertiary control are discussed.

**Economical Operation**

The cost of economical operation includes the cost of utility grid energy transactions (in both directions), cost of microgrid energy supply, and load curtailment costs (value of lost load.) Microgrid outages
could result in a loss of revenue estimated at US$80/kWh (value of lost load), which covers the replacement cost of damaged equipment, and personnel and administrative cost of restoring and sustaining research and education at IIT. Once the real-time price exceeds 6–8 cents/kWh (marginal cost of microgrid generation), the campus load is supplied by the local microgrid generation. The master controller uses a security-constrained unit commitment to calculate the day-ahead optimal operation of microgrid. The optimal hourly solution includes the dispatch of the microgrid generation and renewable energy resources, exchanges with the utility grid, charge/discharge schedule of the battery storage unit, and adjustments to set points of building loads.

To perform the tertiary control, the master controller procures the day-ahead forecasts for building loads and renewable energy resources. The forecasted price of electricity is procured by ComEd. The forecasted values are calculated based on the historical data and forecasted weather data using nonlinear regression methods. The integration of renewable energy generation in microgrids will reduce carbon footprints while decreasing the cost of supplying the campus load. The drawback of integrating renewable technologies is the variability of their generation portfolio. To overcome this challenge in the microgrid, several approaches are used including the coordination of dispatch with the utility grid and hourly demand response. The economical operation of microgrid is implemented by two master controller functions, which are discussed below.

Unit Commitment and Economical Dispatch

To ensure the economical operation of the microgrid, the master controller performs unit commitment and economical dispatch in island and grid-connected modes to procure the optimal generation scheduling of DER units as well as the utility grid dispatch. In grid-connected mode, the microgrid load is compensated by adjusting the power generation exchange with the utility grid. Here, the primary and secondary controls of DER units will not respond to disturbances, as the microgrid voltage and frequency are set by the utility grid. Figure 21 shows the day-ahead hourly control signals provided by the master controller for supplying the campus load on 17 July 2012. On this day, the campus reached its annual peak load of 11.263 MW at hour 15.

The master controller dispatched the microgrid generation once the electricity price was higher than 6 cents/kWh. In Figure 21, the battery storage was charged when the electricity price was lowered to 2.8 and 2.7 cents/kWh at hours 4 and 5, respectively. In addition, the battery storage was discharged as the price of the electricity was increased to 22.4 and 24.5 cents/kWh at hours 16 and 17, respectively. The cost of supplying the campus energy on this day was US$15,524.

The real-time optimization is based on real-time information, such as the price of electricity, campus load, renewable energy generation, and the topology of the campus microgrid including the state of Vista switches and cables. The master controller will perform the campus energy management by procuring the optimal 15-min economical demand response and the dispatch and commitment of campus generation.

Economical Demand Response

The master controller will adjust shiftable building load schedules to calculate optimal generation schedules. Shiftable loads can often be served at delayed hours without jeopardizing the convenience of campus residents. Moreover, the tertiary control will schedule the charging/discharging sequence of battery storage to optimize the supply of campus load with respect to the utility price of electricity. In island mode, the microgrid load is supplied by dispatchable DER units, which respond according to their droop characteristics using primary and secondary control scheme. The tertiary control would also set the optimal operating point of dispatchable DER units. The nondispatchable DER units including solar PV and wind turbine units will not respond to deviations in real and reactive campus loads. In Figure 22, the master controller would apply demand response through tertiary control.

Figure 17. The secondary control in DER units.

---

**Figure 18.** The (a) frequency and (b) voltage droop characteristics of a DER unit.
signals when the price of electricity is high, which would lower the cost of supplying the campus load. Here, the building load is shifted from peak hours 16–18 to off-peak hours 4–6. The set points shown in Figure 22 are sent to DER units and building controllers to set the campus load and generation. The local microgrid generation is also used to supply the peak demand at the utility grid. Accordingly, the daily energy cost of the microgrid is reduced from US$15,524 to US$13,715. Figure 23 shows the economical load reduction at IIT on 19 August 2010, which was recorded by ComEd. Here, the campus load is reduced by 60% through curtailing building loads, shifting campus loads, and dispatching the natural-gas turbine at IIT.

**Short-Term Reliability**

The IIT microgrid connects to the utility grid through four 12.47-kV feeders located at the North and South Substations. The IIT microgrid can operate in both grid-connected and island (autonomous) modes. In the grid-connected mode, the microgrid frequency and voltage...
are regulated by the utility grid. In island mode, the natural-gas turbine and battery storage would maintain the microgrid frequency and voltage, while solar PV and wind turbine units serve portions of the campus load. The short-term microgrid reliability is enhanced by implementing three major functions at IIT: islanding and resynchronization, emergency demand response, and self-healing, which are discussed in this section.

Islanding and Resynchronization

The microgrid may increase its load point reliability indices by setting up its operation in island mode. Generally, there are two major reasons for setting up a microgrid in island mode: 1) poor power quality at the utility grid, such as frequency or voltage deviations, and 2) major faults at the utility grid. PMUs and voltage/current meters at the point of common coupling (PCC) would report the utility grid malfunction to the master controller, which will initiate the islanding process at the tertiary control level. The master controller will monitor building meters for supplying the local generation dispatch. At islanding, the master controller may reduce the campus load through emergency demand response to match the load with the local generation dispatch. The load reduction may entail shifting building loads and reducing curtailable building loads. Matching the load with generation at islanding will reduce transients and ensure a feasible microgrid operation considering the ramping limits of DER unit generation.

Figure 24 shows the campus load restoration in island mode at the Engineering 1 and Stuart Buildings located in Loop 1 on 19 July 2012. The load restoration started at 6:19 a.m. on both buildings and was fully restored at 6:29 a.m. Figure 24(b) shows the inrush current of a switched-on transformer located in the Stuart Building. In island mode, any abrupt changes in the local microgrid load are served by the battery storage through primary and secondary controls. Once the normal operation at the utility grid is restored, the microgrid will be resynchronized with the utility grid. In island mode, the microgrid could be operated at a frequency and a voltage magnitude that are different than those of the utility grid, which could cause transients during the resynchronization process and damage the substation equipment. The master controller will send synchro-

ization signals to the campus DER units through secondary control for mitigating any possible transients.

The following criteria are to be satisfied for transition from island to grid-connected mode:

1. The voltage magnitude difference at the PCC would be small.
2. The frequency difference would be small to match the voltage phase angles at the switching instance.
3. The voltage angle with the lower frequency should lag behind that of the higher frequency. Figure 25 shows the voltage angle difference between the microgrid and the utility grid at resynchronization instance. Assuming that the microgrid frequency is slightly smaller than that of the utility grid if \( V_{\text{mg}} \) leads \( V_{\text{grid}} \), then the power flow will be from the microgrid to the utility grid and in the reverse direction at steady state. The flow from the microgrid to the utility grid at resynchronization may result in the overloading of the microgrid DER units. The IIT microgrid resynchronization process is presented as follows. At first, the master controller will send the

![Figure 21. The day-ahead storage, microgrid, and utility grid supply on 17 July 2012.](image)

![Figure 22. The day-ahead economical demand response by building controllers on 17 July 2012.](image)
frequency adjustment signal to the natural-gas turbine and the battery storage unit to adjust the microgrid frequency to less than nominal frequency (59.9 Hz). The secondary control will maintain a lower microgrid frequency than that of the utility grid before resynchronization. When the microgrid voltage angle lags behind that of the utility grid slightly (fewer than 10°), the PCC switch will be closed, and the IIT microgrid will be resynchronized with the utility.

Emergency Demand Response
The objective of emergency demand response is to maintain the microgrid voltage and frequency within acceptable levels in island mode or to supply the utility grid partially in grid-connected mode in case of an emergency. In either case, the IIT microgrid will perform emergency demand response. In island mode, the emergency demand response will match the load with the generation (e.g., dispatch the battery storage or curtail building loads), while in grid-connected mode, the microgrid would curtail loads as required. The master controller will communicate with building controllers to curtail or shift loads and monitor the updated load level through building meters. Once the campus load is reduced, DER units on campus will be redispached through primary and secondary controls to maintain the nominal voltage and frequency. After the completion of emergency demand response, the tertiary control provided by master controller will procure the steady-state optimal generation dispatch of dispatchable DER units.

Self-Healing
Self-healing relies on robust HRDS protection and switching schemes as well as on-campus storage to supply the load.
during campus contingencies (e.g., component outages). The integration of HRDS provides a looped distribution network by integrating Vista switches to automatically detect and isolate microgrid faults while maintaining the service to buildings through redundant distribution paths. Moreover, the integration of battery storage will serve critical campus loads in case of generation deficiency or distribution cable contingencies. The interruption indices are calculated in for load points on Loop 3 with and without Vista switches, which show that the integration of HRDS will result in a dramatic reduction in load interruption indices. Rapid fault detection and clearance will result in fewer transients in distribution systems.

Figure 26 shows two induction motors in non-HRDS and HRDS systems. The response of motor 1, located close to the Vista switch 1, to a nearby cable fault is shown in Figure 27. As shown in this figure, HRDS has cleared the fault in 0.1 s, which has retained the normal motor speed quickly. In Figure 26(a), without the HRDS system, the cable fault would lead to a dramatic drop in the motor 1 speed as the fault clearing time is longer and the fault clearance would lead to the loss of load downstream, i.e., motor 2.

Conclusions
This article discusses the hierarchical control of microgrids and the role of primary, secondary, and tertiary controls in enhancing the microgrid reliability and economics and introduced the control applications to a functional microgrid at IIT. The IIT microgrid is analyzed as a test bed, and the functions for implementing microgrid objectives are discussed. The functions include unit commitment and economical dispatch, economical demand response, islanding and resynchronization, emergency demand response, and self-healing. The master controller applies tertiary and secondary control to ensure the economical and reliable operation of the microgrid. Primary control is applied at the DER unit level to respond to disturbances in a short time, while the secondary and tertiary control signals eliminate errors introduced by primary control to regulate the voltage and frequency and maintain the optimal dispatch of DER units. The functions are performed by the master controller, DER units, building controllers, and meters, which can achieve economical and reliable operations of a microgrid. The effect of HRDS switches in reducing the transients that occur during distribution network faults and component failures in microgrids is discussed. Transients occur when switching a microgrid between island and grid-connected modes, and options such as emergency demand response, load restoration, and DER unit response are considered in this article to maintain steady-state operations in microgrids.

Acknowledgment
This project was funded in part by the U.S. Department of Energy Grant DE-FC26-08NT02875.

The microgrid represents a multitier hierarchical control of self-sustaining energy infrastructure with islanding and resynchronization, self-healing, and demand response capabilities.
IEEE Electrification Magazine / SEPTEMBER 2013

**For Further Reading**


**Biographies**

Mohammad Shahidehpour (ms@iit.edu) is the Bodine chair professor and director of the Robert W. Galvin Center for Electricity Innovation at the Illinois Institute of Technology. He received an honorary doctorate in 2009 from the Polytechnic University of Bucharest in Romania. He is a research professor at King Abdulaziz University in Jeddah, Saudi Arabia; North China Electric Power University in Beijing; and Sharif University in Tehran. He is an IEEE Distinguished Lecturer, chair of the 2012 IEEE Innovative Smart Grid Technologies Conference, chair of the 2012 Great Lakes Symposium on Smart Grid and the New Energy Economy, and editor-in-chief of IEEE Transactions on Smart Grid. He was the recipient of the 2012 IEEE Power & Energy Society Outstanding Power Engineering Educator Award. He is a Fellow of the IEEE.

Mohammad E. Khodayar (mkhodayar@smu.edu) received his B.S. and M.S. degrees in electrical engineering from Amirkabir University of Technology (Tehran Polytechnic) and Sharif University of Technology, respectively. He received his Ph.D. degree in 2012 in electrical engineering and was a visiting faculty member in 2013 at the Robert W. Galvin Center for Electricity Innovation at the Illinois Institute of Technology. He is an assistant professor in the Electrical and Computer Engineering Department at Southern Methodist University in Dallas, Texas. He is a Member of the IEEE.
MID GROWING CONCERNS ABOUT ENERGY security, environmental impacts, and resource limitations, both public and private-sector groups are calling for greater investments in renewable energy and alternative energy sources. However, despite calls to reduce the nation’s dependence on oil, moving away from petroleum as an energy source has proven to be extremely difficult, especially in the energy-intensive transportation sector. Petroleum, with its high energy and power density, is ideally suited for transportation. To make matters worse, the number of vehicles worldwide is expected to increase dramatically in the coming years because of increased purchasing power in developing countries, leading to a higher portion of air pollution and greenhouse gases coming from transportation as well as greater competition for petroleum.

Transportation systems powered by electricity can help to reduce the consumption of petroleum. In the case of personal electric transportation, vehicles would be plugged into the grid, and their onboard energy-storage systems would be recharged using clean, renewable electricity. If properly...
managed, plug-in vehicles could be charged during low demand periods (at night) when there is excess capacity on the grid, minimizing the strain on the grid and obviating major generation and transmission infrastructure additions.

In this article, we present an emerging technology—inductive power transfer (IPT)—that holds the key to more convenient charging by means of contactless or wireless power transfer through induction. We review the fundamentals of the IPT technology and its history and also present some considerations for designing IPT systems for static and dynamic vehicle charging.

Moving Toward Better Electric Transportation

An electric transportation model requires on-the-vehicle (onboard) energy storage capable of supplying the energy and power demands of the vehicle. Unfortunately, the currently available energy-storage devices, with lithium-ion (Li-ion) batteries being the most promising, need substantial performance improvements to effectively compete with petroleum. The main issues with the state-of-the-art Li-ion batteries are 1) their low energy density (200 Wh/kg versus 12,000 Wh/kg for petroleum), 2) their high initial cost (up to US$1,000/kWh with a long-term goal of US$300/kWh), 3) charge rate limitations due to their internal electrochemical processes, 4) degradation that limits the acceptance of battery-powered vehicles due to hard-to-predict component life, and 5) the environmental costs associated with producing and disposing of electrochemical batteries.

Given the limitations of onboard energy storage, drive-train hybridization and battery swapping concepts have been proposed as possible approaches to mitigate the limitations of state-of-the-art batteries. In the case of hybridization, an internal combustion engine (ICE) is added to the electric vehicle (EV) drivetrain to make a plug-in hybrid EV (PHEV). The ICE is then used only when the battery is sufficiently depleted. While hybridization enables a longer driving range, it also increases the vehicle weight, cost, and complexity, in addition to introducing the use of hydrocarbons. In the case of battery swapping, the vehicle battery is exchanged at a specialized station that stores an equivalent replacement battery. This concept brings with it the issues of battery ownership and standardization, the need for additional battery packs for swapping, and significant swapping infrastructure costs.

An alternative hybridization method to extend the utility of PHEVs and EVs is to enable a power exchange between the vehicle and the grid while the vehicle is moving. This concept has been referred to as dynamic charging, move-and-charge, or roadway powered EVs. Dynamic charging can mitigate the high initial cost of plug-in EVs by allowing the vehicle energy-storage system to be substantially downsized. In addition, dynamic charging can provide a very effective utilization of the installed infrastructure, since a large number of vehicles use the same road segments that can be dynamic-charge enabled. In essence, dynamic charging would represent a hybridization of the EV with the electric grid. Importantly, dynamic charging is compatible with other methods of extending the EV range, such as vehicle hybridization and battery swapping.

Wireless charging makes stationary EV charging more convenient by allowing the charging to take place automatically without the user having to provide a physical contact path between the utility power supply and the vehicle battery. The longer-term vision for wireless charging is to enable the power transfer between the grid infrastructure and the vehicle while the vehicle is moving.

Some examples of dynamic charging systems are shown in Figure 1. The stationary wireless charger can replace the conductive charger used today, with a single inverter powering multiple charging pads. Contactless charging can also be used to deliver power to a bus while passengers embark and disembark. The concept can be used to continuously power a lane of a highway or to power a section of the roadway in the vicinity of high-congestion areas, such as traffic lights, where the vehicle speed is low.

**Figure 1.** IPT systems for vehicle applications: (a) an IPT-powered parking deck, (b) an IPT-powered bus stop, (c) an IPT section placed at a traffic light in an urban environment, and (d) a track section on a highway powering multiple vehicles (PS stands for IPT power supply).
An Incomplete History of EV Wireless Charging

The history of the wireless power transfer began in 1891 when Nikola Tesla invented his famous Tesla coil or magnifying transmitter. The system contains two loosely coupled and tuned resonant circuits: a primary and a secondary. The coils were built using large, single-layer solenoids, which significantly reduces the coil resistance and increases the quality factor. The primary and secondary coils were tuned using an external capacitor and the parasitic self-capacitance, respectively. Periodic spark gap discharges were used to short out the primary resonant circuit and initiate the power transfer. Even with the significant spark losses, the Tesla coil was able to transfer power with 85% efficiency. Tesla’s experiments demonstrate the majority of modern IPT design concepts: 1) he used the strongly coupled resonant circuit to enhance the power transfer capability of the system, 2) he used the self-capacitance to tune the secondary and to obtain a high quality factor, and 3) he used the spark discharge over the air gap to control the power in the resonant circuit, similar to how modern resonant converters use electronic switches.

The next milestone in vehicle dynamic charging took place in 1894, when Hutin and LeBlanc filed a patent that describes a transformer for powering streetcars without contact. The proposed system included a single-wire elongated primary coil carrying 2-kHz ac and coupled by multiple secondary windings. They used ferromagnetic materials and suspension systems that lower the receivers to increase the coupling. Although the proposed topology has some similarities to modern solutions, because of component limitations at the time, the system was not a commercial success.

In the 1990s, researchers at the University of California, Berkeley, built a proof-of-concept roadway-powered 35-passenger electric bus. The complete infrastructure was built for a 213-m-long test track with two 120-m powered sections. The bipolar primary track was supplied with 1,200-A, 400-Hz ac current and coupled to a receiver with an area of 4.3 m², at a distance of 7.6 cm. The system efficiency was around 60%. These results proved the potential of the technology but were limited by the size of the system due to the very low operating frequency.

Researchers at Auckland University laid the theoretical groundwork in the 1990s for much of the research that is presently ongoing in the design of wireless chargers. It is worth noting their recent achievement in designing the optimal pad for the stationary charging of EVs. One of the designs is a 766 mm × 578 mm pad that delivers 7 kW of power with more than 90% efficiency at a distance of 20 cm. They also proposed using multicoil designs for dynamic charging applications.

Starting in 2008, researchers at the Korea Advanced Institute of Science and Technology (KAIST) have built several prototypes of roadway powered EVs, which they named online EVs. Three generations of IPT systems have been developed, and three different vehicles have been tested, with system efficiency peaking at about 70%. In each generation, a different structure of the ferromagnetic material and a different track layout has been designed.

Components of the IPT System

A typical IPT system consists of two physically detached subsystems with power transfer through induction. Typically, the system supplying the power is stationary and is named the primary, transmitter, or source. The system receiving the power is attached to a movable frame and is named the secondary, pickup, or receiver. The power is transferred via induction between two magnetically coupled coils, much like in a transformer. The coupling medium between the coils is air, which has a much higher magnetic reluctance than do the ferromagnetic materials used in transformers. As a result, the coupling coefficient is in the range of 0.1–0.2 for stationary charging applications and less than 0.1 for midrange resonant applications. Therefore, these systems are usually referred to as loosely coupled systems to distinguish them from the tightly coupled transformer coils.

![Figure 2. The typical topology of a high-power IPT system.](image)
The components of the state-of-the-art IPT system are shown in Figure 2. The characteristics of each block are discussed in detail in the following sections. In addition to the components described below, the primary and secondary are equipped with all necessary sensors and control circuits to generate the firing signals for the switches and to control the transferred power. Additionally, communication modules are used to add a further level of intelligence and controllability to the system and ensure safe and efficient power transfer.

**Primary Converter and Compensation Circuit**

On the primary, a power supply delivers high-frequency current and voltage at its output by using modern switching elements and converter topologies. Although direct ac–ac conversion from the grid input to the high-frequency output is possible through the use of matrix converters, most topologies are based on the well-known two-stage ac–dc–ac conversion. A unity power factor stage or three-phase line filters might be considered at the input to reduce the reactive power exchange and harmonic pollution of the grid. Modern IPT systems make use of voltage-fed full-bridge resonant topologies, taking advantage of modern metal–oxide–semiconductor field-effect transistor (MOSFET) and insulated-gate bipolar transistor (IGBT) switches. Although IGBTs are more suitable for high-power systems, paralleling MOSFET devices can provide higher operating frequencies and lower losses but typically at a higher price.

Since the primary coil is dominantly inductive, the increase in the signal frequency will linearly increase the volt–ampere (VA) ratings required to drive the current into the unloaded coil, increasing the VA ratings of the inverter. As a result, a compensation circuit is placed between the inverter and the primary coil. The compensation circuit consists of one or more reactive elements (inductors and capacitors) that are arranged in a particular formation to achieve different design goals. The commonly used primary compensation topologies include series compensation with matching transformer, series-parallel inductor–capacitor (LC) compensation, and series-parallel inductor–capacitor–capacitor (LCC) compensation (Figure 3). The series compensation with matching transformer, shown in Figure 3(a), makes use of the series capacitor to eliminate the reactive power flow, and the transformer for galvanic isolation and impedance matching. The main limitations of the topology are that it fails to keep the track current constant in face of load variations and that the capacitor VA rating is quite high. The series-parallel LC compensation topology distributes the VA rating over two elements, reducing the stress on individual components. In addition, the current in the coil is controlled by the magnitude of the input voltage source, making the coil current load independent. Another variant of this topology, shown in Figure 3(c), includes a series capacitor that can be used as an additional degree of freedom to control the VA rating of the inverter or to ensure zero-current-switching in the inverter.

**Inductively Coupled Coils**

The design of the coupled coils has a profound impact on system efficiency, and their design is therefore a critical component of the IPT system. The coil conductors are typically made using Litz wires because of their small resistance at high frequencies. At very high frequencies and for designs with special requirements, planar and tubular conductors have also been considered. Ferromagnetic material is commonly used to improve the coupling coefficient and to contain the magnetic flux. In the case of stationary wireless chargers, a combination of ferromagnetic material and aluminum is used to maximize the coupling coefficient while ensuring that the produced flux is fully contained underneath the vehicle, even when there is a misalignment between the source and the receiver. In the case of weakly coupled coils, the use of ferromagnetic materials to

---

An alternative hybridization method to extend the utility of PHEVs and EVs is to enable a power exchange between the vehicle and the grid while the vehicle is moving.

---

**Figure 3.** The IPT primary compensation circuits: (a) a series compensation circuit with matching transformer, (b) a series parallel LC compensation circuit, and (c) an LCC compensation circuit.
improve the coupling is relatively limited; however, it may still be used to contain the flux in the vicinity of the source and the receiver. The design of the magnetic link is probably the most challenging part of the IPT system optimization. Although the use of finite element modeling software provides a method of evaluating the system performance, it requires substantial time and iterations to achieve a satisfactory design.

**Secondary Compensation Circuit and Power Conditioner**

The power transferred to a receiver coil of an IPT system is directly proportional to the product of the open-circuit voltage and its short-circuit current. Since the open-circuit voltage increases proportionally, while the short-current decreases proportionally with the number of turns, generally, changing the number of turns does not directly lead to better coupling or improved power transfer capability. However, by using the compensation circuit and the resonance phenomenon at the secondary, the power capability and efficiency can be increased in proportion to the quality factor of the resulting resonant circuit. The typical configuration of the secondary compensation circuit (resonant tank) is similar to that of the primary compensation circuit, but the criteria that lead to an optimal structure and design are different. Since the receiver load is typically a battery, the high-frequency power is rectified and controlled using a rectifier and a dc-voltage regulator. The dc regulator essentially controls the quality factor of the receiver and delivers a constant power to the load in face of changes in the coupling coefficient between the source and the receiver. The design of the dc regulator is a function of the compensation circuit structure, with the buck or boost topologies employed in most applications.

**Health and Safety Concerns Related to the Leaking Magnetic Flux**

Because of concerns about the long-term health effects of exposure to magnetic fields, wireless charging designs must comply with the well-established standards on magnetic emissions. These standards limit the maximum power and distance at which energy can be transferred using induction. For example, for the 3–100-kHz frequency range, the International Commission on Non-Ionizing Radiation Protection electromagnetic field exposure guideline specifies the maximum level for occupational exposure to be 100 μT and the maximum level for general public to be 27 μT. In general, minor system-design modifications are needed to contain the magnetic field to meet the pertinent standards. Frequently, aluminum metal shields are used at the back of the pickup pad to protect the interior of the vehicle, while aluminum rings are used on both the primary and secondary pads to limit the stray field in the lateral direction.

**IPT Systems for EV Charging**

**Stationary Wireless Charger for EVs**

Although it is challenging to match the efficiency of the conductive (wired) charger, which is a significant drawback,
stationary wireless charging has its merits. First, stationary wireless charging systems can be completely autonomous, requiring minimal action from the driver. This feature can maximize opportunity charging since the user often forgets or chooses not to charge when the vehicle is parked for short periods of time. In addition to convenience, wireless charging improves the safety of the charging process. By removing cords and cables, the trip hazard associated with wired chargers is nonexistent. The chargers are vandal proof and have no risk of electric sparks. Low maintenance requirements increase the reliability of the charger. On the other hand, the electromagnetic emissions of the charger must be considered in the system design. The magnetic field can present a hazard when an object is placed in the magnetic link. Therefore, the system must have a robust foreign-object identification system that turns the system off when there is an obstruction in the magnetic link.

In addition to one-for-one replacements of conductive chargers, wireless charging technology is ideally suited for opportunity charging scenarios, where the vehicle is parked at a predetermined location for a short period of time. The concept is particularly well suited for mass transit applications, where the wireless charger can be installed at bus stops, allowing the vehicle to charge while the passengers are embarking and disembarking from the bus. This concept is being used successfully for two lanes of public transportation in Turin, Italy, and many other cities.

The design of a stationary charger consists of a primary pad buried in the ground and a pickup pad mounted on the underside of the vehicle. The primary pad is typically sealed in rubber or covered with plastic to prevent the coil from flooding and/or other hazardous situations. It frequently contains ferromagnetic materials to shape the magnetic field, and metal rings or plates that reduce the leakage of the magnetic field. An implementation of the system is shown in Figure 4, with a representation of the system in Figure 5. A similar pad structure to the one shown in Figure 4 is attached on the underside of the vehicle. The primary pad might sometimes be elevated by several centimeters to reduce the vertical distance between the coils. An automatic guidance system can be installed in the vehicle to help the driver align the vehicle directly above the primary pad. The charging station and the vehicle exchange data by using the inductive link or other short-range communication methods. This feature allows the charging station to adjust the charging procedure according to the condition of the battery or the driver’s preferences.

**Dynamic Charging of EVs**

First, we look at the infrastructure requirements for dynamic wireless charging. These results were first reported in a previous publication [1]. We considered three vehicle types (compact car: Honda Insight; large car: Chevrolet Impala; and SUV: Ford Explorer) fitted with small battery packs (8, 11, and 15 kWh, respectively) operating on three types of driving cycles [low-demanding urban driving cycle (UDDS), highway driving cycle (HWFET), and highway driving in a mountainous region (HW-MTN)]. Our simulations show that the vehicles have a very short driving range, never exceeding 50 mi (see Table 1). We then determined the section of the roadway that needs to be IPT-enabled to extend the vehicle range to 300 mi. The results, when the optimization algorithm tries to minimize the length of the roadway that needs to be powered, are summarized in Table 2. Figure 6 shows a graphical representation of

<table>
<thead>
<tr>
<th>TABLE 1. Driving Range Without IPT (in Miles).</th>
<th>UDDS</th>
<th>HWFET</th>
<th>HW-MTN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insight (8 kWh)</td>
<td>38.17</td>
<td>37.14</td>
<td>22.99</td>
</tr>
<tr>
<td>Explorer (15 kWh)</td>
<td>36.09</td>
<td>33.00</td>
<td>18.83</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE 2. IPT Coverage Required for 300-mi Range (30 kW Delivered to Vehicle).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insight</td>
</tr>
<tr>
<td>Coverage (%)</td>
</tr>
<tr>
<td>Coverage (%)</td>
</tr>
<tr>
<td>Coverage (%)</td>
</tr>
</tbody>
</table>

**Dynamic Charging of EVs**

First, we look at the infrastructure requirements for dynamic wireless charging. These results were first reported in a previous publication [1]. We considered three vehicle types (compact car: Honda Insight; large car: Chevrolet Impala; and SUV: Ford Explorer) fitted with small battery packs (8, 11, and 15 kWh, respectively) operating on three types of driving cycles [low-demanding urban driving cycle (UDDS), highway driving cycle (HWFET), and highway driving in a mountainous region (HW-MTN)]. Our simulations show that the vehicles have a very short driving range, never exceeding 50 mi (see Table 1). We then determined the section of the roadway that needs to be IPT-enabled to extend the vehicle range to 300 mi. The results, when the optimization algorithm tries to minimize the length of the roadway that needs to be powered, are summarized in Table 2. Figure 6 shows a graphical representation of
the results of the third row of Table 2, depicting the IPT coverage required on the UDDS drive cycle. Figure 6 shows the velocity versus time plot of the UDDS on the left y-axis. On the right y-axis, the distance versus time plot is shown for the same driving cycle, for the three vehicles of interest. The three plots are offset from each other for clearer viewing. The black lines on the distance versus time plot signify the sections of the driving cycle that were chosen (using an optimization routine) as optimal sites for installing the dynamic charging system. The power transfer to the vehicle is considered to be 30 kW. The results of this simplified study show promising results: if only 1% of the roadway is powered in urban environments, most vehicle types can easily meet the 300-m target range with the relatively small battery pack described earlier. The assumptions and details of the study can be found in [1], along with other interesting results that, for brevity, are not repeated here.

Dynamic Charging System Implementation
As described earlier, a dynamic charging system consists of a source coil embedded in the road, and a receiver system attached to the vehicle chassis. As a result of the vehicle movement, the receiver of a dynamic charging system moves laterally and longitudinally in a plane parallel to the source coil. The source coil designs can be categorized as single-coil designs, where the source coil is substantially larger than the receiver, or segmented coil designs where the source is made of multiple lumped coils that are commensurable in size with the receiving coil.

Considering the single-coil designs, an obvious advantage is a reduction in system complexity due to the simplified system control, reduced number of converters, and relatively constant coupling between the source and the receiver. The demerits of the approach are that 1) the resulting coupling coefficient between the source and the receiver is relatively low because of the large uncoupled flux of the source coil; 2) field emissions in the uncoupled sections of the coil need to be contained to ensure safety; and 3) the large inductance of the coil for which the distributed capacitors must compensate to limit the voltage at the coil terminals.

Because of their simplicity, single-coil designs are quite popular in practical implementations of dynamic charging systems, as evidenced in the systems developed by researchers at Bombardier and KAIST. An example of the elongated track is illustrated in Figure 7. The receiver system in this application is similar to the one used in stationary chargers, with multiple receiver pads used for higher-power applications. For example, KAIST’s second-generation IPT-supplied bus carries ten 6-kW pickups. On the source side, however, the lumped coil used for stationary wireless chargers is replaced with an elongated conductive cable buried in the road. Some implementations, including the ones mentioned earlier, make use of ferromagnetic material at the primary to direct the magnetic flux, reduce magnetic reluctance, and minimize the field emissions when the receiver coil does not couple with a section of the source coil.

Although the systems using single-coil designs achieve acceptable efficiency, peaking at around 70%, there is still substantial room for improvement, given that stationary chargers attain 90% efficiency. Because of an increased misalignment during dynamic charging, it is reasonable to expect lower system-level efficiency compared to stationary applications. In theory, the efficiency

Currently available energy-storage devices, with lithium-ion (Li-ion) batteries being the most promising, need substantial performance improvements to effectively compete with petroleum.

![Figure 6](Reproduced from [1].)

![Figure 7](An illustration of the dynamic charging concept.)
of the dynamic chargers could reach that of stationary chargers if the optimized segmented source coils designed for stationary charging are used, and the system transfers power only when the misalignment is within prescribed limits that guarantee 90% or higher efficiency.

Considering the segmented source coil design, the issues of field containment, large source–coil self-inductance, and difficulties with coil impedance compensation are easily addressed. However, developing a strategy for powering the coupled segments is challenging, since it requires complex receiver position feedback as well as a method to energize and de-energize coils as needed. Further reduction in the size of each segment exacerbates the issues and advantages associated with coil segmentation: small coils can further contain the leakage flux of nonenergized coils, thus improving the coupling, but result in a complicated design with many bypass switches and sensors.

Figure 8 shows a test-bench implementation of a dynamic charging system, built in North Carolina. The system consists of three source coils, identical to the receiver coil, with small indicator receivers placed on each segment of the source coil that are used as qualitative gauges of the strength of the magnetic field present in the coil. The source–coil segments are powered by a common inverter, with the compensation capacitors located at the inverter. The goal of the test-bench demonstration was to show the ability of a novel method of focusing the field produced by the source–coil underneath the receiver. The system uses a single inverter to power multiple coil segments, by connecting each segment in parallel to the inverter. The power is limited by compensating the coil segments so that the coil resonance occurs at a frequency offset from the system operating frequency. Because of the large reactive impedance, the current in given coil segments is limited when the coil is uncoupled, resulting in a relatively weak field in the uncoupled segments of the sectionalized source coil. By designing the receiver to reflect a large reactance back onto the source coil section, the magnetic field of the source coil is automatically increased when the receiving coil becomes aligned with that particular segment of the source coil. This way, the field produced by the segmented source coil can be controlled by the position of the receiver.

Conclusions
In this article, we have reviewed the state of the art of IPT systems and have explored the suitability of the technology to wirelessly charge battery powered vehicles. The review shows that the IPT technology has merits for stationary charging (when the vehicle is parked), opportunity charging (when the vehicle is stopped for a short period of time, for example, at a bus stop), and dynamic charging (when the vehicle is moving along a dedicated lane equipped with an IPT system). In the case of stationary chargers, the products are reaching maturity, with pertinent standardization initiatives taking place. The opportunity charging systems have also been implemented in bus charging applications, with systems installed on many commercial lines throughout the world. Dynamic charging is a concept that is still in its infancy, and there is a lot of work ahead that is needed for the systems to reach their full potential. The main stumbling blocks for this technology, beyond the technical challenges and efficiency concerns, are safety and infrastructure costs.

On the other hand, dynamic wireless charging holds promise to partially or completely eliminate the overnight charging through a compact network of dynamic chargers installed on the roads that would keep the vehicle batteries charged at all times, consequently reducing the range anxiety and increasing the reliability of EVs. Dynamic charging can help lower the price of EVs by reducing the size of the battery pack. Indeed, if the recharging energy is readily available, the batteries do not have to support the whole driving range but only supply power when the IPT system is not available. Depending on the power capability, the use of dynamic charging may increase driving range and reduce the size of the battery pack.

For Further Reading

Biographies
Srdjan Lukic (smlukic@ncsu.edu) is with the Department of Electrical and Computer Engineering, North Carolina State University, Raleigh.

Zeljko Pantic (zpantic@ncsu.edu) is with the Department of Electrical and Computer Engineering, North Carolina State University, Raleigh.
Submit a Transactions paper for Review to the IEEE Power & Energy Society

All papers should be in double column format with all figures in place (complete formatting instructions can be found in the PES Authors Kit at: http://www.ieee-pes.org/meetings-and-conferences/calls-for-papers/pes-authors-kit. The source file of your document must be submitted to the IEEE PES on line paper submission and review site at:

http://mc.manuscriptcentral.com/pes-ieee

Submission sites for all of the PES Transactions can be accessed from the above link.

IEEE Transactions on Energy Conversion
Research, development, design, application, construction, installation, and operation of electric power generating facilities (along with their conventional, nuclear, or renewable sources) for the safe, reliable, and economic generation of electrical energy for general industrial, commercial, public, and domestic consumption, and electromechanical energy conversion for the use of electrical energy.

IEEE Transactions on Power Delivery
The scope of the Society embraces planning, research, development, design, application, construction, installation and operation of apparatus, equipment, structures, materials and systems for the safe, reliable and economic generation, transmission, distribution, conversion, measurement and control of electric energy. It includes the developing of engineering standards, the providing of information and instruction to the public and to legislators, as well as technical scientific, literary, educational and other activities that contribute to the electric power discipline or utilize the techniques or products within this discipline.

IEEE Transactions on Power Systems
Requirements, planning, analysis, reliability, operation, and economics of electrical generating, transmission, and distribution systems for industrial, commercial, public, and domestic consumption.

IEEE Transactions on Smart Grid

The IEEE Transactions on Smart Grid is intended to be a cross disciplinary and internationally archival journal aimed at disseminating the results of research on smart grid that relates to energy generation, transmission, distribution and delivery. The journal will publish original research on theories, technologies, design, policies, and implementation of smart grid. The Transactions will welcome manuscripts on design, implementation and evaluation of energy systems that include smart grid technologies and applications. Surveys of existing work on smart grid may also be considered for publication when they propose a challenging perspective on the future of such technologies and systems.

IEEE Transactions on Sustainable Energy

The IEEE Transactions on Sustainable Energy is intended to be a cross disciplinary and internationally archival journal aimed at disseminating results of research on sustainable energy that relates to, arises from, or deliberately influences energy generation, transmission, distribution and delivery. The journal will publish original research on theories and development on principles of sustainable energy technologies and systems. The Transactions will also welcome manuscripts on design, implementation and evaluation of power systems that are affected by sustainable energy. Surveys of existing work on sustainable energy may also be considered for publication when they propose a new viewpoint on history and a challenging perspective on the future of sustainable energy.
DATES AHEAD

2013

10–13 NOVEMBER

8–11 DECEMBER
APPEEC 2013: IEEE PES Asia–Pacific Power and Energy Engineering Conference. Kowloon, Hong Kong. Contact Dr. C.Y. Chung, e-mail: eecychun@polyu.edu.hk http://www.ieee-appeec.org

2014

19–22 FEBRUARY
ISGT 2014: IEEE PES Innovative Smart Grid Technologies Conference. Washington, D.C., USA. Contact Saifur Rahman, e-mail: s.rahman@ieee.org www.ieee-isgt.org

14–17 APRIL
T&D 2014: IEEE PES Transmission and Distribution Conference and Exposition. Chicago, Illinois, USA. Contact Tommy Mayne, e-mail: t.w.mayne@ieee.org www.ieeet-d.org

20–23 MAY
ISGT ASIA 2014: IEEE PES Innovative Smart Grid Technologies Asia. Kuala Lumpur, Malaysia. Contact Titik Khawa Abdul Rahman, e-mail: titikkhawa@gmail.com

15–18 JUNE
ITEC 2014: IEEE Transportation Electrification Conference and Expo. Dearborn, Michigan, USA. Contact Mahesh Krishnamurthy, e-mail: kmahesh@ece.iit.edu www.itec-conf.com

27–31 JULY
GM 2014: IEEE PES General Meeting. National Harbor, Maryland (Washington, D.C., metro area), USA. Contact Paula Traynor, e-mail: ptraynor@epri.com www.pes-gm.org/2014/

12–15 OCTOBER
ISGT Europe 2014: IEEE PES Innovative Smart Grid Technologies Europe. Istanbul, Turkey. Contact Dr. Omer Usta, e-mail: ustao@itu.edu.tr
The IEEE Transactions on Sustainable Energy is intended to be a cross disciplinary and internationally archival journal aimed at disseminating results of research on sustainable energy that relates to, arises from, or deliberately influences energy generation, transmission, distribution and delivery. The journal will publish original research on theories and development on principles of sustainable energy technologies and systems. The Transactions will also welcome manuscripts on design, implementation and evaluation of power systems that are affected by sustainable energy. Surveys of existing work on sustainable energy may also be considered for publication when they propose a new viewpoint on history and a challenging perspective on the future of sustainable energy.

The journal will cover the following topical areas:
> Wind Energy
> Solar Energy
> Biomass and Hydroelectricity
> Ocean energy (tidal, wave, geothermal, etc.)
> Grid interconnection issues
> Sustainable energy & the environment

Forthcoming special issue sections:
> Microgrids for Sustainable Energy Systems
  Guest EIC – Prof Nikos Hatzigiorgiou (deadline for abstract is closed)
> Large Scale Grid Integration & Regulatory Issues of Variable Power Generation – Guest EIC – Prof Syed Islam (deadline for extended abstract 29th April, 2013)

If you are interested in reviewing papers for this journal, please sign up as a reviewer on the Manuscript Central site at: http://mc.manuscriptcentral.com/pes-ieee

The Transactions on Sustainable Energy can be accessed via the drop down menu on the PES portal site. If you are interested in reviewing papers for our new Transactions and you are currently a reviewer for PES Transactions, you can access your account in Manuscript Central and add sustainable energy to your keywords or areas of expertise. If you have an account in Manuscript Central and are not currently a reviewer for PES Transactions and would like to become a reviewer for PES Transactions, access your account and you will automatically be given a reviewer center, then update your areas of expertise. If you do not have an account, create a new user account and complete all the required fields, you will then be given an author center and a reviewer center.

About the Editor-in-Chief: If you are interested in serving as a topic area editor, please contact the Editor-in-Chief, Dr. Bikash Pal at b.pal@imperial.ac.uk. Dr. Pal leads the research group in energy system control and computation and UK-India Solar research programme at Imperial College London. He was Mercator International Professor in Germany in 2011. He is a PES Distinguished Lecturer (2008-2010). He served on the PES New Initiative and Outreach Committee between 2009 and 2011.

Saifur Rahman: Founding Editor-in-Chief
HE 2013 IEEE TRANSPORTATION Electrification Conference and Expo (ITEC’13) was held at the Adoba hotel in Dearborn/Detroit, 16–19 June 2013. Thanks to the ITEC’13 Organizing Committee’s dedication and countless hours of work as well as ITEC’s strategic and business plans and the leadership of the IEEE Power Electronics Society, IEEE Industry Applications Society, and IEEE Power & Energy Society for making ITEC a great success.

ITEC has quickly become the main global technical event for transportation electrification. The aim of the conference is to help the industry in the transition from conventional vehicles to advanced electrified vehicles. ITEC is focused on components, systems, standards, and grid interface technologies related to efficient power conversion for all types of electrified transportation, including electric vehicles (EVs), hybrid EVs (HEVs), and plug-in HEVs, as well as heavy-duty, rail, and off-road vehicles, airplanes, and ships.

With about 600 attendees, the conference featured world-class plenary speakers, covering the current status and future trends in transportation electrification. With 50% attendance from industry, the conference embraced a comprehensive program including 200 presentations, numerous panel discussions, a sold-out industry exhibition, four educational EV/HEV boot camps, and two short courses offered by internationally renowned industry experts. This program was exceptionally attractive to industries, government agencies, and the general public, in addition to academic researchers, students, and educators. Furthermore, this year, ITEC included a track, sponsored by the U.S. Department of Energy’s electric drive vehicle engineering program, known as E3—Electrifying the Economy—Educating the Workforce: Taking Charge of the Electric Vehicle Industry’s Educational Needs.

If you are not part of the broader organizing community of ITEC and would like to be directly involved with the conference, we welcome you to join forces with us in improving ITEC and addressing the needs of the industry—after all, ITEC is your conference.

—Alireza Khaligh
General Chair, ITEC’13

INOS JACOVIDES (FIGURE 1) was awarded with the 2014 IEEE Transportation Technologies Award for his pioneering contributions to the analysis and design of electromechanical systems and power electronics for transportation applications.

Jacovides has spent his entire career developing and promoting the practical use of electric technology for transportation. His name is associated with almost all key developments in transportation electrification during the past 40 years, either as a personal contributor or as a manager spearheading research in these fields. The list includes early ac
drives for motorized vehicles (locomotives and cars), with the first detailed digital simulations of a cyclo-converter, and the first-ever motor with rare-earth magnets in an automobile, a cranking motor.

Jacovides was the engineering leader for the Electrovair project, General Motors’ first modern foray in electric vehicles, placing him at the earliest stages of modern drivetrain electrification, years before the better-known EV1, its eventual successor. He led the development of high-efficiency alternator and electric power steering and had the vision to champion the design of safety critical systems, with particular application to electronic throttle control. These techniques have become the basis for international standards for the design of safety systems and validation. This technology has been a key enabler for electric power steering and is one of the foundations for drive-by-wire systems. His involvement reaches to traction control systems, magnetorheological fluid-activated shock absorbers, numerous sensors and electromechanical components, and a best-in-class diesel fuel injector.

Jacovides was elected to the National Academy of Engineering in 2010, and he is a Fellow of both the IEEE and the Society of Automotive Engineers. He retired as director of Delphi Research Labs and has served on six U.S. National Academies Committees for which he has written the chapters on electric and hybrid vehicles. He was president of the IEEE Industry Applications Society in 1990.

—Bruno Lequesne
Eaton Corporation and Past President, IEEE-IAS

Figure 1. Linos Jacovides has spent his career promoting the practical use of electric technology for transportation.

IEEE Power and Energy Society's Upcoming Elections

In August 2013, the voting membership of the IEEE Power & Energy Society (PES) once again opened up the election process for the Society’s future leadership. There are many accomplished candidates that will be involved in the election. The first race is for the position of president-elect of the PES. Bruno Meyer, chief executive officer of ARTERIA—a telecom subsidiary of RTE (the French transmission system operator)—and Damir Novosel, the president of Quanta Technology, are in the running. Novosel is also an adjunct professor at North Carolina State University. The position of secretary is open, and two very capable candidates are running: Mini Shaji Thomas, who is a professor and former head of the Department of Electrical Engineering at Jamia Millia University, New Delhi, India, and Lina Bertling Tjernberg, who is a professor in power grid technologies with the Royal Institute of Technology, Sweden. The final available position is that of treasurer. Both candidates have had long and illustrious careers. Jovica Milanovic has worked in Yugoslavia and Australia and is currently a professor of electrical power engineering and the director of external affairs at the University of Manchester, United Kingdom. Our next candidate is Christopher Root, who recently retired as senior vice president of network strategy for National Grid and has had a career split between power system engineering and operations.

Once again, the caliber of candidates for all of the open positions is remarkable, and the Society will benefit from the candidates’ expertise and contributions for years to come. We wish all of the candidates the best of luck in the upcoming elections.

—Maureen L. Dalton
IEEE PES—Senior Manager of Marketing, Communications, and Membership

Digital Object Identifier 10.1109/MELE.2013.2278108
Date of publication: 23 October 2013

IEEE Electrification Magazine / SEPTEMBER 2013 69
The PES Scholarship Plus Initiative

The IEEE POWER & ENERGY Society (PES) Scholarship Plus Initiative encourages students to pursue a career in the power and energy fields by providing multiyear scholarships and career experience opportunities to qualifying U.S. and Canadian electrical engineering undergraduate students. The goal is to increase the number of well-qualified, entry-level engineers in the power and energy industry. Scholars receive up to three years (US$7,000) of funding interspersed with up to two years of valuable, hands-on career experience. Since 2011, the program has supported a total of 265 scholars attending 109 universities, including Ivy League colleges, flagship state universities, and prestigious engineering colleges across the United States. The list of 2013 scholarship recipients will be announced in October.

The program has provided US$642,000 in scholarships and has raised more than US$5 million in cash and pledges from donors to the program. The IEEE PES Scholarship Initiative is made possible by donations to the IEEE PES Scholarship Fund of the IEEE Foundation (United States) and the IEEE Canadian Foundation. Charitable contributions are tax deductible to the fullest extent allowed by law in the United States and/or Canada. Information on how to support the program or to make a donation is available at http://www.ee-scholarship.org/sponsorship/.

—Daniel C. Toland
IEEE PES Scholarship Plus Program Director

Digital Object Identifier 10.1109/MELE.2013.2278109
Date of publication: 23 October 2013

About This Issue (continued from page 2)

2) “Faster than a Speeding Bullet: An Overview of Japanese High-Speed Rail Technology and Electrification”
3) “Courting and Sparking: Wooing Consumers’ Interest in the EV Market”
4) “Shipboard Solid-State Protection: Overview and Applications”
5) “Cutting Campus Energy Costs with Hierarchical Control: The Economical and Reliable Operation of a Microgrid”
6) “Cutting the Cord: Static and Dynamic Inductive Wireless Charging of Electric Vehicles.”

The September and December 2013 issues of the magazine will cover multiple topics addressing various transportation and off-grid issues. Beginning in 2014, each issue will focus on a particular topic. For example, the first three issues in 2014 will focus on electric vehicles, microgrids, and electric ships. For future issues, we welcome guest editors to propose articles on particular themes covering our topics of interest. Please contact me or any of the other editors or coeditors if you are interested in proposing a topic for a special issue of this magazine.

Technology Leaders (continued from page 3)

PES vice president for publications and inaugural editor-in-chief for IEEE Electrification Magazine, for his leadership and perseverance in getting this publication approved and off the ground. Special thanks to the editorial board of this magazine and our PES staff for their efforts.

I encourage you to read these articles and learn about the happenings in electrification in our engineering space. It is an exciting time to be part of the electrification solution.
Innovation doesn’t just happen. Read first-person accounts of IEEE members who were there.

IEEE Global History Network
www.ieeeghn.org

IEEE electrification magazine representative

Parker Marshall
James G. Elliott Co. Inc.
626 Wilshire Blvd., Ste 500
Los Angeles, CA 90017
Phone: +1 213 596 7209
Fax: +1 213 624 0997
p.marshall@jameselliott.com
Promoting New and Important Technologies

By Russell Lefevre

As the major worldwide professional society for engineers and computer scientists in the electrical and electronics fields, the IEEE is at the forefront of emerging technologies. IEEE Electrification Magazine (EM) is a major milestone in the process of developing our position in the new arena of transportation electrification. As the chair of the EM Steering Committee and the past chair of the IEEE Transportation Electrification Initiative (TEI), it has been one of my goals to develop a publication that would address this important technology. The electrification of the transportation sector offers the future a reduction of the dependence of the world on carbon-based fuels with their attendant negative effects on the environment.

An important observation is that a microgrid can be thought of as loads and energy sources within electrical boundaries that act as a single controllable entity with respect to the grid. Using this definition, the electrical system on board electric vehicles, electric ships, electric trains, and electric planes can be considered a microgrid with a limited number of sources and multiple loads. This enables the transportation electrification community to develop new insights into how such entities can be integrated into a modern transportation system. EM is dedicated to providing a forum for those developing related concepts and disseminating information on all matters related to onboard microgrids.

This magazine is also intended to address off-grid microgrid applications including small-scale electricity supply in areas far away from high-voltage power networks. Feature articles will focus on advanced concepts, technologies, and practices associated with all aspects of electrification in the transportation and off-grid sectors from a technical perspective in synergy with non-technical areas such as business, environmental, and social concerns. EM is especially intended to provide essential information to practitioners in the microgrid fields.

The IEEE has a history of promoting new and important technologies and methodology to promote these technologies consists of conferences and publications. A field closely related to transportation electrification, the smart grid, has two influential transactions and a very successful newsletter. Other initiatives, including cloud computing and life sciences, have followed this model. EM is the first publication in the field to provide a venue for technologists. This first issue begins to fulfill the goal of promoting transportation electrification technology. We look forward to a continuing dialogue with practitioners, academics, and other stakeholders who enable a continuing increase in the state of knowledge in this very important field.

The magazine is sponsored by the three IEEE Societies—the Power & Energy Society, the Power Electronics Society, and the Industrial Applications Society—that have been the most active and influential in the transportation electrification community. The technical co-sponsors are the IEEE Industrial Electronics Society, the IEEE Vehicle Transportation Society, and the IEEE Intelligent Transportation Systems Society. EM will support the work of these Societies as well as the TEI. The editorial board of the magazine includes world-class acknowledged experts in each of the fields of interest. These Societies and the TEI intend that EM will become the most influential entity in the rapidly developing field of transportation electrification, especially as applications using microgrid concepts come to the forefront.
The IEEE PES Scholarship Plus Initiative™ is attracting top engineering candidates to pursue power engineering careers. The continued success of the initiative depends on leaders like you, who can provide financial support, career experience opportunities and mentoring.

To find out how you can get involved, visit www.ee-scholarship.org today.
Think you know about the latest technology?
You haven’t even scratched the surface.

See all the layers of technology with *Proceedings of the IEEE*.
Every issue brings comprehensive, in-depth coverage on technology breakthroughs. From outlining new uses for existing technology to detailing cutting-edge innovations in a variety of disciplines, you’ll find the breadth of content and depth of knowledge that only IEEE can provide.

Go beyond the surface—subscribe today.
www.ieee.org/proceedings