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Future Energy Systems

Integrating Renewable Energy Sources into the Smart Power Grid Through Industrial Electronics

Industrialization and economic development have historically been associated with man's ability to harness natural energy resources to improve his condition. Based on this definition, two industrial revolutions occurred in the 18th and 19th centuries, where natural resources such as coal (first revolution) and petroleum (second revolution) were widely exploited to produce levels of energy far beyond what could be achieved by human or animal muscle power. Furthermore, modern power distribution systems made abundant energy reliably available and relatively independent from the plant location. More than two centuries of past industrialization exploited nonrenewable energy resources, however, often with undesirable side effects such as pollution and other damage to the natural environment. In the second half of the 20th century, extraction of energy from nuclear processes grew in popularity, relieving some demands on limited fossil fuel reserves, but at the same time, raising safety and political problems. Meeting the global demand for energy is now the key challenge to sustained industrialization.

On the other hand, network and wireless communication systems have birthed another modern economic and industrial revolution. New industries and economies based on communication services have sprung up from the widespread availability of information. Harnessing information continues to change the course of technological and social development [1]. In this article, the authors suggest that the landscape or history of industrialization is a full circle: from energy

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to services and communications, and now, back to energy (Figure 1). Specifically, the modern focus on renewable sources is explored.

Renewable energy systems (RESs) involve many aspects: efficiency, reliability and cost of the energy conversion, capability to forecast energy production, safe connection to the electric grid and/or capability to manage microgrids, efficient energy storage and transport with low environmental impact, development of advanced control and monitoring algorithms, networking of the sources/consumers, and availability of good tools for simulations and experiments. Furthermore, ad hoc educational programs are needed to transfer the knowledge to the industry without delays and to form a new category of engineers.

These issues are reviewed in this article, beginning in the section "Renewable Energy Around the World," where a brief overview of various renewable energy technologies used around the world is presented. The limitations of a magazine format preclude a detailed presentation of multiple technologies, and it is impossible to pick or rank a particular topic above the other. So, the authors have elected next to focus attention on a theme that could represent the synergies between the power electronics, control, and communication fields. In the section "A Power System Scenario Based on Smart-Grid Technologies," the possible future power system scenarios are discussed. From the systems platform, it is possible to branch out again and reexplore a breadth of engineering issues. For example, the contrast in scales of traditional utility grids and emerging energy systems also brings new challenges, of which some are discussed in the section "Challenges of Scale." Challenges of controlling and maintaining energy from inherently intermittent sources are discussed in the section "Control Challenges." Recent developments in the applications of electrical machines (EMs) and power electronics are highlighted in the section "Technology for Renewable Energy Systems." Emerging renewable energy technologies, those still in their infancy, are mentioned in the section "Other Technologies." Other approaches to presenting renewable energy issues are equally fascinating, but the authors hope that the system-level discussion given here will appeal to a broad audience. In "Renewable Energy—The Next Industrial Revolution," the authors present their views on the historical impact of the renewable energies.

Renewable Energy Around the World

The most exploited RESs are hydroelectric, photovoltaic (PV), and wind. Over the years, renewable energies have experienced one of the largest growths in percentage, being comparable with the growth of coal and lignite energy but still below that of natural gas. In 2007, the world's renewable energy production share has been calculated as 19%. However, 16% is due to hydroelectric energy production; hence, wind and PV (the most promising renewable sources) energy production is still very modest. However, these two most promising renewable energies have different requirements. The wind energy production forecast for 2011 is more than 200 GW. On the other hand, despite the silicon shortage in recent years, the PV industry is growing at more than 30% per year, and the cost of PV energy will reach the break-even point very soon in many countries. As of 2009, it is evident that wind energy is becoming well established with 1% of world energy production, while PV energy is experiencing an impressive growth [2].

Other emerging renewable technologies include wave and tidal energy conversion, biomass energy conversion with focus on combined heat and power (CHP), and small-scale hydroelectric plants (less than 10 MW per site). Estimates vary greatly, but researchers generally agree that small hydropower has significant untapped potential, especially in developing countries. Small plants avoid many of the socioeconomic, environmental, and civil engineering challenges that are associated with large dams.

Examining renewable energy production in different world zones shows that, in 2008, Latin America was the region with the highest share of renewable sources in electricity production (58%), with much due to the high diffusion of hydroelectric generation. In Asia and Australia, renewable energies are growing, but the share within overall energy production is very different from country to country (Australasia is leading, followed by the Commonwealth of Independent States and Asia). The diffusion still continues in the European Union while the North American renewable energy share is comparable to that of Africa and Asia. The goal of the European community

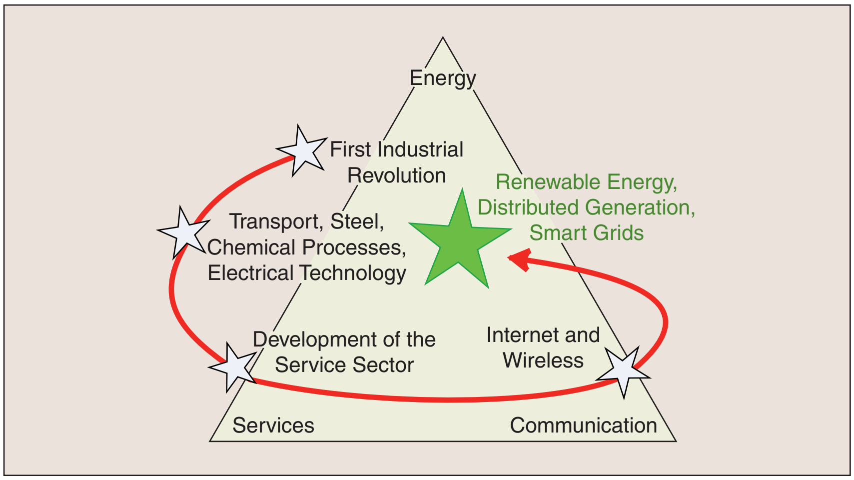

FIGURE 1 – Visual history of industrial revolutions: from energy to services and communication and back again to energy.

RENEWABLE ENERGY—THE NEXT INDUSTRIAL REVOLUTION

MASSIMO GUARNIERI, JOHN Y. HUNG, MARCO LISERRE, and THILO SAUTER

Historians define industrial revolution as an irreversible, rapid change of technology, culture, and socioeconomic conditions—driven by advances in industrial processes. The ongoing development of industries is also called industrialization. Several industrial revolutions can be identified starting around 1750, 1870, and 1950, though some historians propose finer (more articulated) divisions of these revolutions into more periods.

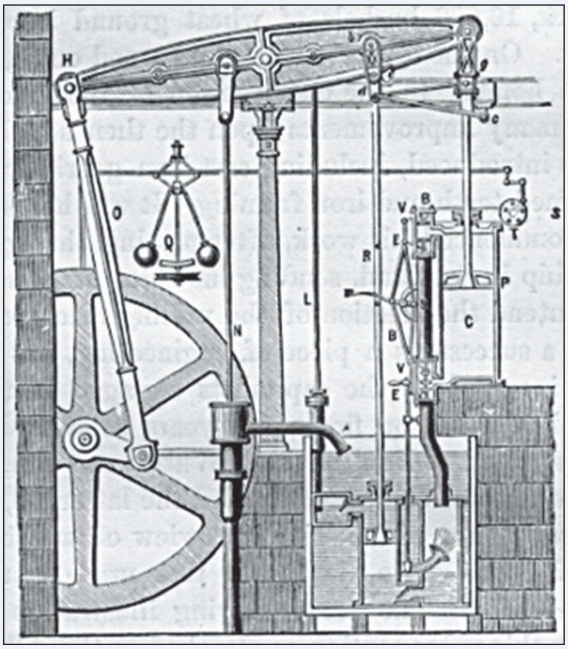

FIGURE S1 – The Boulton and Watt double-action steam engine with rod and shaft transmission (1784). (Image courtesy of Tesla Memorial Society.)

The first industrial revolution started in Great Britain, where traditional farming labor and manual manufacturing were rapidly replaced by machinery. The textile industry was the first to be dominated by machines, which rapidly spread to other compartments such as mechanical and tool production. Around the end of the 18th century, the steam engine (Figure S1), originally developed to power reciprocating pumps for water drainage in mines, was complemented with the rod and crank, becoming suitable for powering factory machines: it was coal and steam that energized the first industrial revolution, providing power order of magnitude larger than water and wind mills.

Around the mid-19th century, heavy steel-making industries emerged, providing the rapid growth of steam railways and steamships in Great Britain, Germany, and the United States. They allowed the widespread of coal energy out of the factory systems and made possible travel speed, which was never seen before for people and goods, changing the perception of space and time.

In the third and fourth decade of the 19th century, early electrical technologies appeared. The telegraph was developed by a sort of international committee. The pioneering work by Pavel Schilling in Russia and Karl Gauss and Wilhelm Weber in Germany was carried on by Charles Wheatstone and William Cooke in Great Britain and later Werner Siemens in Germany, but in 1844 Samuel Morse in the United States conceived a system that definitely succeeded, allowing the transmission of information at almost light speed as far as a 1,000 km.

The second industrial revolution started around 1870 and was driven by the rise of electric power and technology, both of which were considered to be high tech during the period. Outstanding contributors include Thomas Edison (dc systems and lighting, telegraphy), Antonio Meucci and Alexander Bell

is to reach 20% in 2020, but the energy use is only 15% in the 27-country European Union (EU-27). The United States, with 20% of energy share, has adopted similar goals under the pressure of public opinion regarding environmental problems and the desire to overcome the economic crisis. However, the policies of Asian and Pacific countries, with 35% of energy share, will probably be more important in the future energy scenario. In fact, developing countries like China and India continuously require more energy (China's energy share increased 1% every year since 2000) [2].

The demand for more energy by emerging countries and the environmental concerns in North America and the European Union will drive the increase of renewable energy technologies and energy production. The driving forces may differ, but the importance of RESs in the future energy scenario has become accepted. A deeper look at world PV and wind energy use and its associated challenges is dealt with in the next two subsections.

PV Energy Conversion

PV installations are growing rapidly in developed countries, but the United States lags far behind Germany and Spain. These two European countries lead Europe (and the rest of the world) in total generating capacity of PV energy systems. With regard to installed capacity, Germany is clearly the leader, holding more than 85% of Europe's total capacity (in excess of 1,500 MWp). Some examples of recent large PV plants are 60 MW at Olmedilla (Castilla-La Mancha, Spain), 40 MW at Waldpolenz (Germany), 24 MW at Sinan-Gu (Jeollanam-do, Korea), and 14.2 MW at Nellis Air Force Base (United States).

The most relevant goals of PV energy include 40% cost reduction of PV panels and of the power-converter stage within five years, increased efficiency of both panels and converters [3], [4], and considerable improvement (telephone), Galileo Ferraris (rotating magnetic field), George Westinghouse (railroad signaling and ac power systems), Nikola Tesla (electricity, magnetism, ac systems, and polyphase machines—see Figure S2), and Guglielmo Marconi (long-distance wireless communications).

At the start of the new century, electropowered factories began to overcome coal-powered ones, thanks to the large availability of hydropower in areas such as the Great Lakes in the United States and the Alps in Europe, and to the superior versatility and efficiency of electrical machinery. In this period, petroleum emerged, and from the beginning, it was much more an American affair, with the first drilling in Canada and the United States in 1858–1859, which quickly led to the establishment of Standard Oil in 1870. Oil fueled the second industrial revolution, mainly after the development of cracking processes, in 1913. Petroleum boosted mobility, with private cars becoming a mass product starting from the Ford Model T in 1908, and airplanes, which began a new era with the Wright brothers' Flyer, in 1903. In the first half of the 20th century, as electrical demand saturated the hydropotentialities, thermal power stations fed by coal or oil rapidly proliferated.

From the mid-20th century solid-state electronics, information technology, and automation sprang out, boosting extraordinary progresses, mainly in information processing and transmission, with digital technologies increasing their impact in many sectors that were once domains of analog solutions. The correspondent shift of labor from mass production manufacturing to the service sector has been proposed as a third industrial revolution. Recently, some economists have called our present age a new industrial revolution, because of the tremendous effects of the Internet and wireless communication. Throughout these industrial phases, traditional fuels have largely powered the technological progress. Their consumption is expanding at exponential rates, strongly depleting the world fossil resources and increasing greenhouse effects.

However, a different approach to harnessing natural resources has been accelerating over the past ten years. Today, the world is developing means to use RESs, with the belief that renewable energy use must be expanded to support industrialization in a sustainable manner, one that minimizes negative impacts on the environment. Research and engineering activities stretch over the globe, with pervasive technological and economic impacts on emerging nations as well as established powers. At the same time, RESs will not supplant traditional systems overnight. From this perspective, the authors suggest that the next industrial revolution consists in the integration of RESs with established power systems, evolving to new energy system paradigms.

An interesting aspect of this latest industrial revolution is that the desired advances rely heavily on the highly diverse knowledge, training, and skills of the industrial electronics community. Control and communication techniques applied to energy conversion and transmission enable the advancement of the application of renewable energies and distributed power generation.

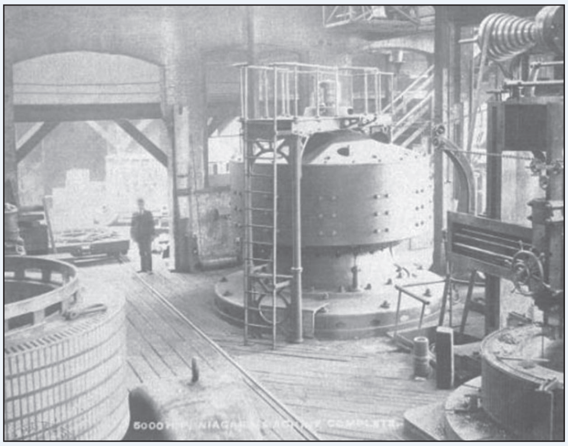

FIGURE S2 – Nikola Tesla's plant in the Power House No. 1 at the 3-MW Niagara power station (1895). (Image courtesy of Tesla Memorial Society.)

in converter reliability [5]. These goals are driving the research toward several directions:

- higher efficiency of the power converter, e.g., transformerless topologies and converters based on silicon carbide (SiC) devices
- maximum power extraction algorithms
- integration of the power converter in the panel to reduce the problem of minor energy production due to panel mismatch
- advanced islanding detection algorithms (also called antiislanding) that help monitor grid condition and compliance with grid standards and codes. These will have an impact on safety, since undetected islands in the power grid may cause hazards to users and utility workers [5].

Wind Energy Conversion

Energy from the sun can also be collected by other natural means. As Earth and the atmosphere are unevenly heated, winds are created. In a sense, winds are a natural form of solar energy concentration. Modern wind turbines are a higher density energy source than direct PV conversion.

Based on 2007 production levels, Germany (20,622 MW) and Spain (11,615 MW) were generally acknowledged to be the world's leaders in total wind power generation [6]. Wind power could be generating up to 16% of Europe's electricity by 2020, which the delegates heard at the opening of the 2007 European Wind Energy Conference (Milan, Italy) [7]. In the United States, total estimated wind power capacity exceeded 20,000 MW in 2008 and is growing explosively from 2007 levels [8], [9]. While wind power accounts for less than 1% of U.S. electricity generation, the total amount of electricity that could potentially be generated from wind in the United States has been estimated at 10,777 billion kWh annually—three times the current total electricity generated in the country.

Wind energy can benefit from huge investments in research and education. Some of the most relevant goals of present research include an increase in the power production of each wind turbine (more than 5 MW), an increase in the penetration of small wind-turbine systems (tens to few hundreds of kilowatts), and the creation of wind plants or farms whose behavior with respect to the grid emulates that of traditional oil and gas-powered plants. The latter may be possible due to wind forecast and proper control strategies. The increase in wind turbine size involves research on high-power converters based on modular technology (interleaved or multilevel), reliability, and on the associated control problems [10]. Interest is also high for university educational activities that prepare future engineers for the wind industry, leading wind energy companies to encourage and support highly specialized engineers through specific Ph.D. programs.

In the next section, a possible scenario for future power systems is explored. The requirements of energy control and information flow are examples of multidisciplinary cooperations that are increasingly common in all areas of renewable energy development, including energy conversion processes, transmissions, and environmental impacts.

A Power System Scenario Based on Smart-Grid Technologies

RESs cannot directly replace the existing electric energy grid technologies. The latter are far too well established to abandon, while the new technologies are not sufficiently developed to meet the total energy demand. Therefore, it is sensible to gradually infuse renewable energy sources into existing grids and transform the system over time.

A smart grid is modeled by two concentric circles—the outer circle represents energy flow and the inner circle models information flow over communication networks. Different approaches to the management of energy flow in active grids integrating distributed power generation have been proposed [11]. One of the most interesting ideas employs energy hubs to manage multiple energy carriers (e.g., electricity, natural gas, and district heating) [12]. Within each hub are energy converters that transform part of the energy flow into another form of energy. Figure 2 is a possible scenario solely for the management of electrical energy flow, based on the use of power electronic nodes that can embedded in a more vast scenario of energy management for multiple energy carriers.

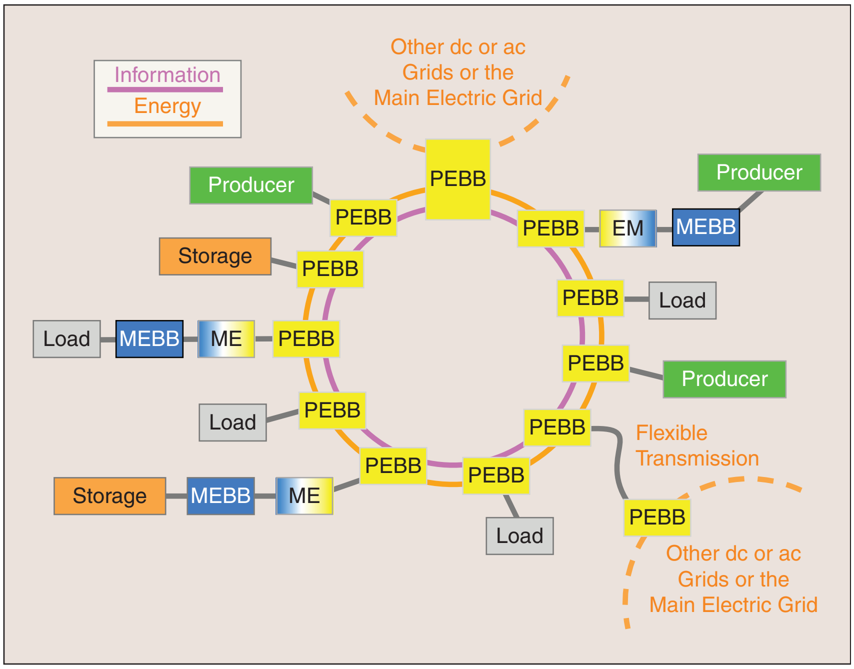

FIGURE 2 – A possible scenario of the future power system based on smart-grid technologies, with power electronic building blocks (PEBBs) and mechanical building blocks (MEBBs) as intelligent energy conversion nodes.

Power Electronics: Handling Energy Flow Between Players

Power converter technology enables efficient and flexible interconnection of the different smart grid players or agents: producers, energy storage systems, and loads. All parties can contribute to the security of the grid and may have the capability to work in different operational modes such as stand alone, microgrid, or cluster.

In the stand-alone case, the power producer is disconnected from the grid and supplies a single load. In the microgrid scenario, several producers, storage systems, and loads are connected together and try to operate in a controlled island that may interact with the main electrical grid and with other islands. In the cluster case, several producers distributed across the main electric grid try to operate together, forming a virtual producer with high cumulative power that can accept supervisory signals from the utility system operator.

On the other hand, energy consumers may accept responsibility to regulate their own power to contribute to the stability of the grid or to provide indirect storage. Indirect storage examples are as follows: 1) heat energy would be stored in the cold/hot elements of refrigeration systems and 2) energy stored in the batteries of hybrid electric vehicles. Consumers may adapt their power environment, even to the point of operation in stand-alone mode, when it is not possible to operate a controlled island. Another scenario would be in emergency response (for example, in the case of a hospital), which requires an uninterruptible power system capability.

Storage systems can be present at different power levels, offering short-, medium-, or long-term energy supply, which are crucial in case of high penetration of RESs, as well as in the case of microgrid operation.

Interconnections of these agents through flexible transmission systems such as HVDC and flexible ac transmission system (FACTS) could allow greater energy transfer, while simultaneously preserving dynamic stability and constraints of land right of way (ROW) with respect to traditional transmission systems. Critical capabilities include foreseeing the operation of different grids at different power levels and employing different technologies (dc or ac, single phase or multiphase). The possibility of these transmission systems to manage a bidirectional and controlled power flow and full control of reactive power relies on the use of bidirectional energy conversion structures adopting pulsewidth modulation (PWM) technology and proper control algorithms. In the smart-grid scenario, all the players may change function and should continuously reconfigure their operation to meet the specific demands while ensuring power processing efficiency and safety.

It is possible to foresee that the PEBB [13] is being used to form complex converter structures to meet the demands in terms of high power density, high reliability, and flexible operation. For each player, the front end to the smart grid will be an energy conversion system possessing intelligence and interacting with the other front ends. In fact, the possible presence of several autonomous and interacting grids and a high penetration of RESs with stochastic energy production will challenge system stability and require the energy conversion unit to be active and cooperative. Moreover, the protocols for exchanging power among the different players in the cooperative network where power flow is bidirectional must be further developed. These protocols will require intelligent conversion systems. It is possible to foresee the presence of two different intelligent levels: one to manage the energy process and one to manage fault conditions, since reliability has always been the limiting factor for introducing more power electronics to the power system [14].

Mechanical transmission optimization will be part of the solution to problems of efficient power processing. For example, consider continuously variable transmissions (CVTs) in Figure 2. Mechanical CVTs are already state of the art in hybrid electrical vehicles, smoothly changing phases under load conditions; such technology offers another degree of freedom with respect to traditional transmission systems. CVTs can play a key role inside the smart grid, becoming a MEBB, i.e., the basic mechanical cell connected through an EM to the electrical energy conversion cell, the PEBB. The control algorithm will be developed for the overall mechatronic system and not for the two systems independently, with the aim of achieving maximum global efficiency for power generation, energy consumption, and even for energy storage.

Communication Systems: Handling Information Flow Between Players

Information plays a crucial role in smart grids, and the communication infrastructure is the decisive component that connects all distributed network elements, enables exchange of information, and therefore makes the grid truly smart [15]. In traditional grids having comparatively few points of energy generation and largely uncontrolled energy consumption, control of the relevant grid parameters can be achieved in a relatively centralized way. The situation in smart grids is, however, quite different. Large numbers of distributed, small-energy generators and the desire to better match energy demand and provision to avoid excessive load peaks require coordination between producers and consumers that go beyond distributed control. Variability of energy sources can be described in both long term, e.g., weather patterns, as well as short term, based on day-ahead and even hours-ahead prediction. The use of such information can lead to improvements in efficiency and long-term investments [16]. To this end, smart grids can benefit today from the rapid evolution of information and communication technology (ICT), which has taken place particularly in the last two decades. As a matter of fact, the only two networks spanning whole continents, power distribution grids and telecommunication systems, are now being combined to make smart grids possible.

From an application perspective, there are three major domains for ICT (Figure 3). Supervisory control and data acquisition (SCADA) is already widely used for remote monitoring and controlling of higher levels of the distribution grid [17]. This area is also well covered by advanced standards such as IEC 61850 for substation automation. Active distribution grids are the core of modern smart grids and enable the integration of distributed energy sources mainly into the mid-level voltage grid. The predominant task of communication in this respect is to collect critical network parameters and to actively influence the distributed energy generation so as to maintain overall power quality. On the lower grid levels, smart metering is the most relevant use case for ICT.

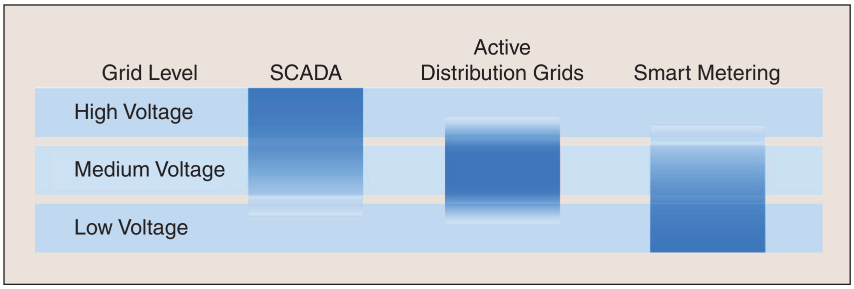

FIGURE 3 – Major ICT application domains in smart grids and their correlation with grid levels.

Originally intended just to remotely retrieve meter values, today, smart metering also includes load profiling, local power quality monitoring, or remote switching of loads [18]. This demands permanent connection to a communication network, even though real-time requirements are not as stringent as in the SCADA control applications, e.g., the overall load balancing on the grid.

From a communication technology point of view, information exchange in the upper grid levels for SCADA applications is usually covered by existing communication networks belonging to utilities or grid operators (Figure 4). These networks are often based on fiber-optic links that are installed in parallel to the high-voltage grid, and connect primary substations, large power plants, and control rooms. Furthermore, they are mostly based on Internet technologies. The challenge of interconnection today lies in the medium- and low-voltage levels, which are usually not reached (or only to a small extent) by utility-owned communication infrastructures. To bridge this gap, several possibilities exist.

The first possibility is to use public telecommunication networks. In the recent past, provider-based communication capacity for mobile services like a global system for mobile communication (GSM), general packet radio service (GPRS), and universal mobile telecommunication system (UMTS) was significantly increased. Easy access, low modem costs, and nearly country-wide coverage of the networks made them economically attractive in comparison to the installation and operation of utility-owned resources, particularly after privatization. Nevertheless, with the increasing amount of mobile subscribers from all sectors, as well as the increasing number of total services, the deficiencies of these public networks have become recently visible. Availability, reachability, and independency—crucial demands for every utility that are not necessarily guaranteed in public networks—are the impetus for rethinking. In the meantime, many utilities and grid operators also prefer having communication resources under their own control.

Wireless networks are the second option. They are flexible and can be used to build utility-owned networks. However, typical broadband computer network technologies like worldwide interoperability for microwave access (WiMAX) and wireless local area network (WLAN) are problematic with respect to their limited transmission range and reachability, especially in urban areas. Hence, they might only serve as communication subsystems for small clusters of devices such as meters. For long-distance transmission, trunked radio systems like Terrestrial Trunked Radio or TransEuropean Trunked Radio (TETRA) are becoming popular in some countries. Installation costs are moderate, even though the frequencies used are not license free. As TETRA is limited in bandwidth (7.2 kb/s per time slot), it can be assumed to be a substitute for services that are currently run over GSM/GPRS. Typical applications are metering (load profile meters and households), supervision of transformer stations, or safety-related applications.

The third possibility exploits the existing power grid as the physical medium for communication. Powerline communication systems overcome range and reachability limitations of wireless networks and are therefore a tempting alternative. On the other hand, the powerline communication channel is problematic, because it is time varying and heavily depends on the actual network topology and the connected electrical loads. To ensure connectivity from the communication viewpoint, network elements such as transformers need to be bridged with phases coupled, which requires additional equipment that is expensive at the higher voltage levels. Furthermore, regulation of the frequency bands used for data transmission is fragmented worldwide and partly still unclear. Powerline communication is both economically and technically challenging and still in its infancy compared to other communication technologies. Yet, it is a promising possibility being investigated at the moment [19].

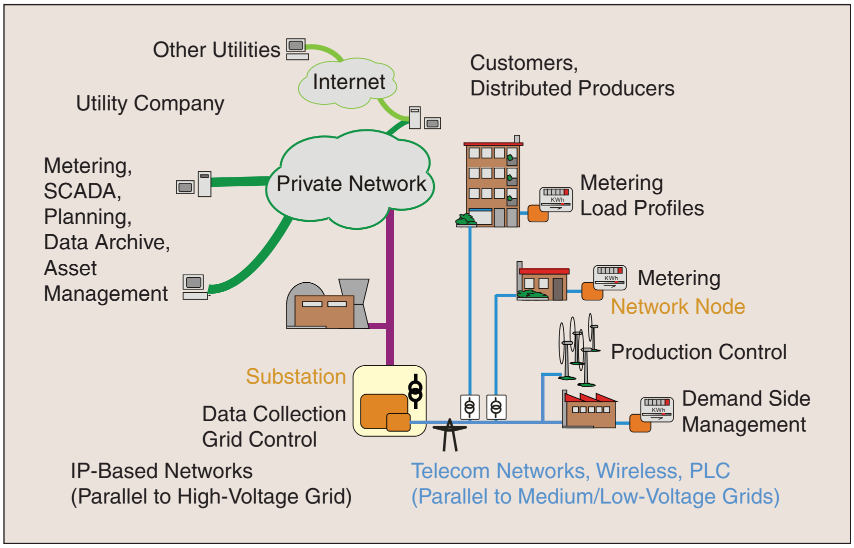

FIGURE 4 – Communication infrastructures for smart grids.

Challenges of Scale

RESs are much smaller than traditional utility generators. For example, the Joseph M. Farley Nuclear Electric Generating plant in rural Alabama has two turbine generators with a combined capacity exceeding 1,700 MW. Each of the 32 generators at China's Three Gorges Dam has a 700 MW capacity. In contrast, the largest wind-turbine generators developed are around 6 MW, while the best sellers on the market are still 2-MW wind turbines.

The small size of the present RESs simultaneously presents new challenges and opportunities. To collect sufficient energy, the concept of energy farms has become well known. On an energy farm, hundreds and thousands of energy sources are installed together, often over a vast geographical area so that their combined power is sufficient for demand. The Horse Hollow Wind Energy Center is believed to be the world's large wind farm when it was completed (735 MW) and comprises 420 turbines across 19,000 hectares (47,000 acres) of Texas. Farms of energy sources constitute their own grid, different in both scale and dynamic characteristics compared to the traditional utility grid. On the other hand, the small size of RESs makes it increasingly feasible to produce electric power in rural areas and other locations previously deemed economically infeasible.

Connecting to the Grid

Connecting hundreds and thousands of RESs to the utility network introduces different dynamics to the system. If the distributed sources are not properly controlled, the grid can become unstable and even fail [20]. The challenge of connecting a renewable source to the utility network is largely solved by electronic power converters that handle two main tasks [3], [21], [22]:

1) *Maximum Power Transfer and Power Limit*: On the input side (source), power electronics control and transform the load characteristics so that maximum power is extracted from the source. In special conditions (e.g., during a fault), the power electronics in conjunction with mechanical system controls (e.g., blade pitch control for wind turbine system) may limit the power extraction. At the same time, the power electronics helps to protect the source from sudden load variations.
2) *Active/Reactive Power Control and Power Quality Control*: On the grid side, the power electronics must control active power injection even in view of contributing to frequency control (in the case of large power plants), ensure low harmonic content (distortion), low electromagnetic interference (EMI), and low leakage current (in case of household applications) even in the face of brief faults (ride-through capability).
   a) *Controller Structure*: The general approach to grid-side power converter control is a nested, two-loop feedback system (see Figure 5). An inner loop based on current feedback regulates the current to the grid, and hence, the power quality is maintained. The outer loop based on voltage feedback is responsible for the flow of power, eventually implementing droop characteristics where amplitude and frequency of the voltage are dependent on active and reactive powers. As with most nested loop designs, the inner loop is tuned to have faster dynamics, while the outer loop is designed for overall stability, usually at lower bandwidth. Various power electronic configurations are discussed in the subsection "Power Converters."

   There are several means for implementing the general control structure in Figure 5, especially in the case of wind turbines. Depending on the type of nonlinear coordinate transformation introduced, the control system model may appear to be controlling either dc or sinusoidal variables. For the former case, the proportional plus integral (PI) controller is commonly employed. In the latter case, ac signals are being controlled, so a resonant term is substituted for the integrating component of the PI controller; the resulting controller can be called a proportional plus resonant control. There are various tradeoffs in complexity and performance for the control technique, so advances in computational intelligence and hardware are continually being studied [23].
   b) *Synchronization*: The control of active and reactive power needs the knowledge of grid voltage phase, frequency, and amplitude. The most popular grid synchronization method in the research literature is based on the phase-locked loop (PLL) (Figure 5). Other techniques for synchronization include detecting the zero crossing of the grid voltages or using combinations of filters coupled with a nonlinear transformation. Zero crossings can be falsely triggered by noise, and filters introduce additional delay to the feedback loops. These techniques generally do not perform as well as the phase-locked loop in the presence of noisy grid signals and momentary faults.
   c) *Power Quality*: Power quality is a continual challenge with RESs. Their susceptibility to

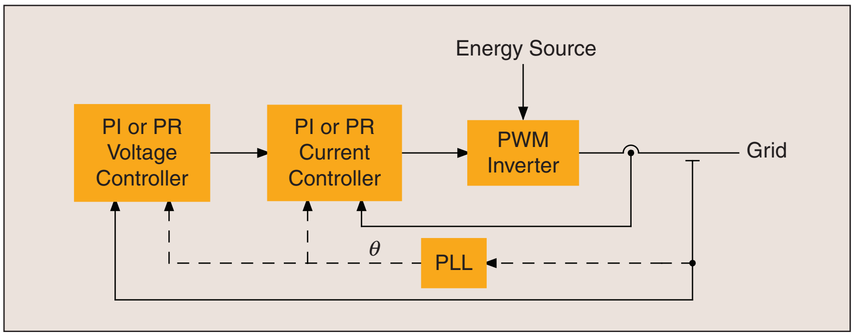

FIGURE 5 – A multiloop controller for grid interface in renewable energy applications.

intermittent operation has resulted in performance standards that specify capability to withstand brief faults as units deenergize and reenergize their area of the grid. The capability to ride through a temporary fault can be greatly improved by integrating other types of energy storage, especially those that can quickly deliver energy. Flywheel energy storage, batteries, and supercapacitors are among the technologies being used. Harmonic distortion is also being tackled by good control algorithm design in the current control loop. For example, resonant filters that are sensitive to undesirable harmonic frequencies can be added so that the system will generate compensating components in the control signal.

Energy for Communities: Microgrids

As mentioned earlier, the relatively small size of many RESs makes it feasible to develop smaller-scale networks for geographically remote or isolated areas not previously served by a traditional utility network. Combinations of sources can be grouped together, forming a microgrid. Control of the multiple sources to ensure high-quality voltage waveforms is increasingly enhanced by advances in power converters, computational intelligence, and communication systems. The size of a microgrid, measured both spatially and with respect to the number of network nodes, is considered a relatively small extension from modern automation fields such as factories and buildings. Therefore, communication networks that have been developed for automation fields can be applied to distributed control of RESs. Issues such as load sharing, power factor control, and power quality management are common research themes today.

Division of control effort is an ongoing area of research. One technique is to allow local sources to independently respond to higher frequency objectives. Lower frequency demands such as power sharing can be coordinated among several sources linked by a communication network. Bandwidth of the communication network does not have to be high, because the control demands are of low bandwidth.

Small-scale renewable generation systems for isolated, remote locations are generally more expensive than traditional systems. Multiple types of sources are often employed, forming hybrid systems that are more robust than single-source systems. At the same time, hybrid systems are more complex and require some form of information exchange between elements. In very small systems, the cost of centralized control and the communication system becomes an issue. Implementation of distributed control may be preferred, e.g., using control strategies based on drooping active and reactive powers as a function of frequency/amplitude of the voltage. This is often referred as wireless control. However, low-cost communication strategies are also being explored. Again, classical industrial automation networks may be used as communication subsystems that can also be attached to grid-wide communication system to achieve integration into the overall information flow [24], [25]. To this end, a network node in Figure 4 might act as a gateway interconnecting two networks.

Control Challenges

RESs also have markedly different dynamic characteristics compared to traditional utility generation sources. In this section, various control system hurdles are reviewed. First, the challenges of extracting maximum power from various energy sources are reviewed. Smoothing wide power variations through hybrid implementations of energy sources presents additional challenges that are surveyed. Some control functions common to either PV or wind-turbine systems are depicted in Figure 6.

Maximum Power Point Tracking

PV and wind energy are intermittent sources and produce power P that varies with environmental conditions. Current–voltage (i-v) characteristic of a PV panel is a function of irradiance

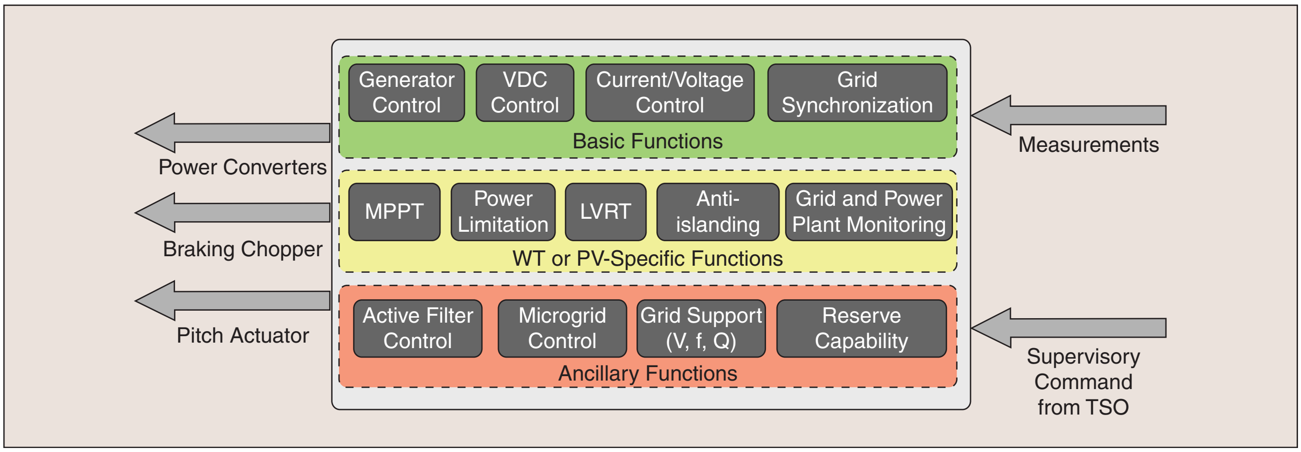

FIGURE 6 – Control functions of PV or wind turbine systems. TSO is the transmission system operator.

and temperature, while torque-speed (T-ω) characteristic of a wind turbine is a function of wind speed and humidity. To take full advantage of the available energy, it is necessary to operate the system at its maximum power point. Shown in Figure 7 are curves that intersect optimal operating points on a family of i-v curves for a hypothetical panel and on a family of T-ω curves for a hypothetical wind turbine.

For the PV energy system, the two most common techniques for finding the optimal operating point are the perturbation and observation method and incremental conductance method. The names are different due to their implementations, but the underlying theoretical principles are similar. In both cases, the voltage of the solar array is regulated to follow an optimal value. The optimal voltage value is continually computed and updated (hence the term "tracking") from measured values of voltage and current. Optimality can be expressed in several mathematically similar ways. For the perturbation and observation approach, the optimal operating point, in case of a PV- or WT system, satisfies

$$\frac{dP}{dx} = 0,$$

where x is the control input (current i, voltage v, or torque T)—see Figure 8. In the incremental conductance method, the optimal operating point satisfies the relationship

$$\frac{di}{dv} = -\frac{i}{v}.$$

These well-known approaches often have practical imperfections in their implementation, resulting in small oscillations around the optimal operating point. Practical alternatives to find the maximum power point in real time remains an ongoing area of investigation.

It is worth noting that medium-sized wind turbines (rated at hundreds of kW) may adopt anemometers; hence, they do not need maximum power point tracking algorithms. Smaller wind turbines are usually torque controlled and adopt a $T(\omega)$ look-up table, whose data points correspond to the maximum power extraction for a given set of wind speed. When the wind changes its speed, the turbine will naturally accelerate or decelerate, eventually settling again at its maximum power point, as illustrated in Figure 9. This open-loop optimization algorithm is based on the mechanical inertia of the generator, and it is not possible for PV systems.

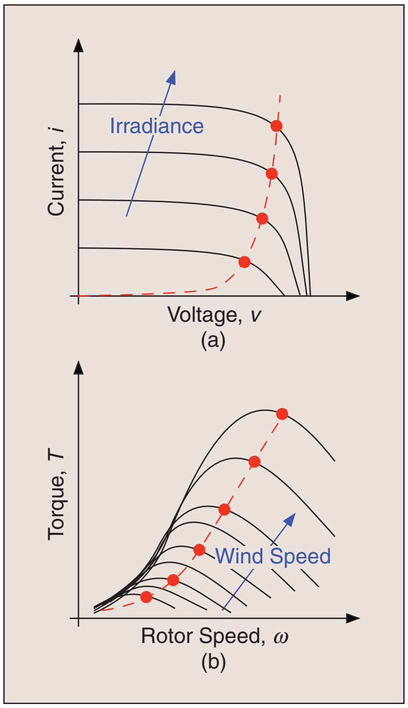

FIGURE 7 – Red dots are optimal operating points for (a) hypothetical PV and (b) wind turbine characteristics.

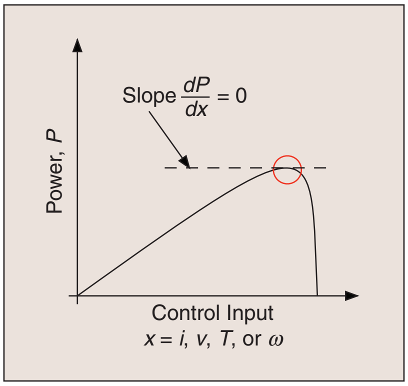

FIGURE 8 – Maximum power point is achieved when the derivative of power respect to the control variable is equal to zero ($x = i, v, T, w$).

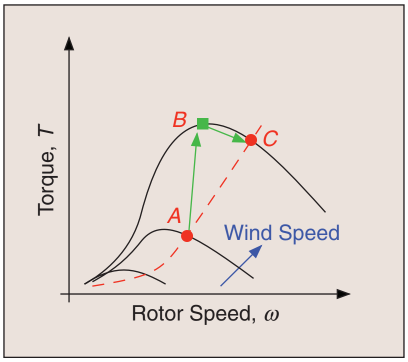

FIGURE 9 – Maximum power point tracking with open-loop control for a wind turbine system (point A represents a stable operating condition; wind growth leads the system to work at B, and then at the new equilibrium point C).

Decoupling Demand and Generation

Wind turbine systems also require other forms of optimization. Since peak aerodynamic efficiency occurs at a fixed ratio of blade tip speed to wind speed, variable speed operation of the turbine is essential to capture maximum energy. Variable speed operation enables the system to store power fluctuations in the machine inertia and also extends the life of the equipment by reducing mechanical stresses compared to fixed speed operation.

Variable speed operation requires some electrical mechanism to accommodate the differences between the wind turbine's variable speed (generation side) and the fixed frequency of the electrical utility grid (demand side). A widely used commercial practice is to employ some variation of induction machine along with ac–dc power converters. Differences in turbine speed and grid frequency manifest as the induction machine slip frequency. Turbine speed is controlled by adjusting the electrical load via the front-end power converter.

Another commercial approach is to rectify the ac energy of the turbine to a dc link, from which the energy is inverted to ac form for the utility grid. In this second approach, a synchronous generator is more commonly used. Optimal operation of the wind turbine is achieved by adjusting the load presented by the front-end rectifier or converter. Besides decoupling generation from demand, the dc link provides a high-bandwidth energy-storage mechanism, smoothing power fluctuations from either side of the system.

Variations of these variable speed systems are further described in the

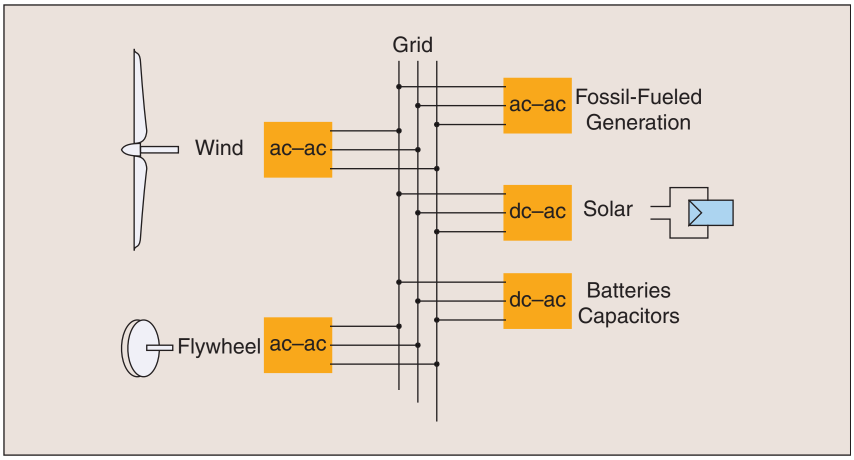

FIGURE 10 – A hybrid energy system.

technology section of this paper (see section "Technology for Renewable Energy Systems"). The concepts are also well documented in the research and commercial literature.

Hybrid Energy System Control

RESs are often coupled with other mechanisms to improve ride through, which refers to the capability of providing energy when the prime mover (e.g., wind or sun) dies for a brief period of time. For example, batteries, flywheels, and diesel generators are several examples of mechanisms that can be linked on a common grid to wind turbine systems (see Figure 10). The resulting hybrid energy systems present numerous challenges. Each of the elements is capable of operating at variable speed and power output, yet the stress and durability due to variable speed operation must be considered. As an example, it is well known that the diesel generator does not endure frequent start/stop cycles well, yet fuel consumption from continuous operation is undesirable. Finding the proper balance of loading the various hybrid system components can be considered a constrained optimization problem. Fuzzy logic-based supervisory control has been applied to the problem of deciding when to store energy in the auxiliary system or to extract energy from storage.

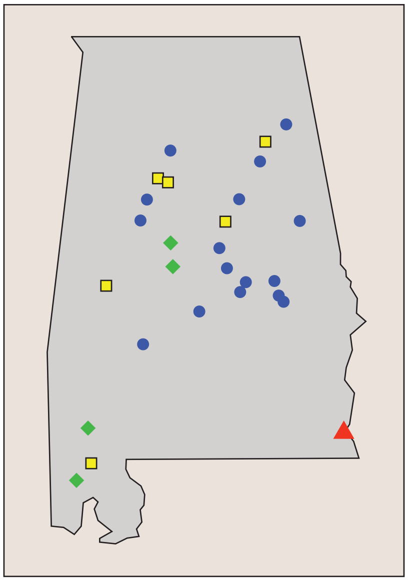

FIGURE 11 – Power generation plants in Alabama. Blue: hydro; yellow or green: fossil fuel; red: nuclear.

Dynamic Stability and Power Quality

Utility systems incorporating renewable energy elements face other challenges that are not present in traditional generation. A traditional system has far fewer generators, often of similar design. Consider that Alabama Power operates 81 electric generating units with a combined capacity of more than 13,000 MW. These generating units are located at 24 locations and use either coal, natural gas, hydro, or nuclear sources (see Figure 11). To produce the same power with 2.5-MW wind turbines would require more than 5,200 generating units. The layout and dynamic characteristics of such a system would be remarkably different. Stability analysis and control of utility grids having RESs presents ongoing research challenges. On the other hand, the power system is evolving toward active distribution grids with a significant amount of medium-scale and small-scale generators (ranging from hundreds of kilowatts to tens of megawatts), involving both conventional and renewable technologies, together with storage systems and flexible high-voltage transportation systems connecting those grids with lower ROW restrictions.

Within active grids, generators and loads can both play a role as operators in electricity markets. Furthermore, distribution grids have to be equipped with protection systems and real-time control systems, thus leading to smart microgrids. Smart microgrids are usually operated with connection to distribution grids but have the capability of automatically switching to a stand-alone operation if faults occur in the main distribution grid and then reconnecting to the grid at a later time. The safe operation in any condition (grid connected or stand alone) relies also on good simulation tools to predict the behavior of the overall system considering the specific operation of the RESs.

The operation of a smart microgrid can result in higher availability and quality compared with strictly hierarchical management of power generation and distribution. The security of the system can be improved by quickly reacting to short-term demand variations and redispatching energy feeds to final users. Such ability allows operators to reduce risks and consequences of blackouts while also avoiding the need to increase global production. These goals are achievable only under efficient networking of the distributed sources. Contrary to normal generation planning and load balancing, which can be scheduled well in advance, such short-term interventions impose more stringent requirements on the communication networks. Communication latencies must be reasonably short to enable fast reactions and to synchronize actions, like switching of transmission lines in case larger grid areas are affected. This also requires that communication channels be available with sufficient quality of service even in critical situations. Such requirements do not just apply to locally concentrated communication subsystems but to the entire grid.

In addition to challenges of controlling electric power quality, RESs can also introduce other physical dynamics that are coupled to electrical phenomena. For example, in wind turbine systems, the wind flow, blade aerodynamics, blade loading, generator dynamics, nacelle dynamics, and tower dynamics are interrelated. If the tower is in an offshore environment, then hydrodynamics of wind and sea must also be considered in system control [26]. Traditional control systems were based on multiple, single-input, single-output linear feedback loops, independently controlling generator torque and blade pitch from generator speed measurement. Multi-input, multioutput linear designs using generator speed, tower measurement, and blade measurements are being currently investigated. Feedforward, nonlinear, and adaptive control methods based on additional measurements such as wind speed are open areas for future study [27].

Ancillary Services

The IEEE standard 1547.3 [28] defines ancillary services, which are those provided by DPGSs (called DRs, for distributed resources) interconnected to the electric power systems. Issues addressed in the standard include load regulation, energy losses, spinning, and nonspinning reserve reactive supply. Future ancillary services may also include power quality enhancement. Ancillary services contribute to a systemic approach for management of the new power system characterized by an higher inflow from distributed resources.

In fact, they are based on the specific characteristic of inverter-based distributed resources that can be used to inject active power, reactive power, and harmonics (the second and third are chosen even if the energy source is not available). Some of the ancillary services are similar to those that traditional power plants provide to ensure safe and stable system operation. However, they are mainly considered at a distribution level and are neither part of the features of an active distribution grid (smart grid) nor at the transmission level (where traditional power plants are usually connected). Moreover, when a distributed resource is low-voltage connected, the grid frequency and the grid voltage cannot be controlled independently, since low-voltage distribution lines have non-negligible resistance. Hence, these issues cannot be considered as a mere transposition of known concepts at a different level, since they are involved in a wider change of the power system.

Meeting the global demand for energy is now the key challenge to sustained industrialization.

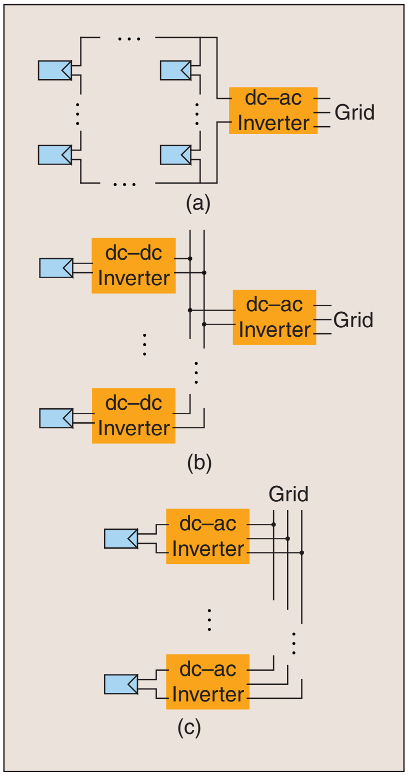

FIGURE 12 – PV systems: (a) centralized and (b) and (c) modular. (a) Centralized PV system. (b) Using dc–dc converters. (c) Using dc–ac inverters.

Technology for Renewable Energy Systems

Electronics technology perfected over many decades for industrial applications is being redesigned, integrated, and applied in novel ways for RESs. In this section, an overview of how these systems are being used is presented. In addition, emerging technologies are also reviewed.

Power Converters

Electronic power converters are the essential commodities of RESs. Energy sources such as the PV module produce dc energy that must be converted to ac form to connect to the utility grid. In addition, RESs typically produce low levels of power compared to traditional generation, so some means of collecting the outputs of many sources is required. In this sense, there is a growing interest toward the use of dc-distribution grids, either in the wind or PV plant, or in support to the ac distribution or even in replacement of ac distribution (there are microgrids that already use dc networking of sources and loads). Sources such as wind turbines operate at frequencies that are different than the grid, and speeds can vary significantly. Accommodating the differences in frequency is possible only through the modern electronic power converter. RESs are more intermittent in operation than traditional generators, so it is common to supplement their operation with other sources—power converters provide the means to physically combine the outputs of different sources.

1) *In PV Systems*: The simplest PV systems gather energy by series and parallel combinations of modules to achieve sufficient voltage and current. A central dc–ac inverter converts the energy to ac form [see Figure 12(a)]. These systems are easy to construct,

Latin America is the region with the highest share of renewable sources in electricity production.

but their efficiency dramatically decreases when the modules are not identically matched in power output. Mismatches can occur for many reasons, including differences in current-voltage (*i-v*) characteristic, shadowing of portions of the system by obstruction (and even dust or dirt), and different orientations resulting from architectural constraints. When a module is unable to produce the same current as its series neighbors, then it is unable to operate at its own maximum power point. If the series current exceeds the short-circuit current of a low-producing module, then it becomes a load to the system, dissipating energy rather than producing it. The power loss is greatly reduced (though not eliminated) by incorporating bypass diodes, but the power characteristic of the array becomes more complex, and the maximum power point operation for the overall array may not be achieved.

In one type of decentralized system, PV modules are isolated from each other by dc–dc converters [Figure 12(b)], most commonly the boost-type converter. The converters permit every module to work at its optimal voltage while also enabling flexible interconnection of modules. A centralized dc–ac inverter enables connection to the ac grid. Yet, another approach is to isolate PV modules by dc–ac inverters, as illustrated in Figure 12(c).

To achieve higher efficiency, transformerless topologies are being deeply investigated, as well as the use of new converter architectures combined with new semiconductors such as SiC (though not yet commercially available). In the first case, the challenge of eliminating the transformer from either the low-frequency ac side or from the high-frequency intermediate stage embedded within the dc–dc converter has two main obstacles: the previously mentioned need of adapting voltage levels for grid connection and the need to minimize the path for possible leakage current.

One possible solution is represented by the multilevel inverters that are increasingly finding application in PV systems. Many structures of multilevel inverters have been described in the literature over the past two decades, but the unifying concept is that high-level ac power can be synthesized from several lower-level dc sources through creative arrangements of power semiconductor devices. The power devices switch among the available dc sources (e.g., PV modules) to create the desired, higher ac voltage waveform, yet the switches themselves only have to withstand the lower dc voltage levels. Other advantages of multilevel inverters include the following:

- *High Power Quality*: Multilevel inverters are capable of producing ac waveforms having low distortion, without the need for large filters.
- *Lower Noise (EMI)*: In addition to lower static stresses on the switches, the transient currents and voltages are smaller compared to traditional inverters. Therefore, less electromagnetic noise is produced.
- *Lower Leakage Current*: A switching strategy can be implemented so that it does not lead to alternating high-frequency common mode voltage that is the cause of the leakage current.

Current research has produced many topologies to overcome some of the multilevel converter's disadvantages, mainly, the complexity of the structure (and control) and the need for many switches (which hurts reliability).

2) *In Wind Turbine Systems*: From the aerodynamic standpoint, wind turbines operate most efficiently when the ratio of the blade tip speed to wind speed is maintained at the design condition. Therefore, the maximum wind energy is transferred by allowing the turbine to run at variable speed. Typically, a three-phase diode-bridge plus boost converter or an ac–dc PWM converter is connected to the generator. With proper control, the mechanical load on the turbine can be adjusted to maintain the optimal tip speed. In many turbine systems, another ac–dc converter is used to connect to the grid; the two converters are joined by a dc link, thus providing a mechanism for energy storage as well as decoupling of the grid and generator frequencies. Typically, the converter is a voltage-stiff converter (capacitive storage in the intermediate dc bus); however, current-stiff topologies (inductive storage) taking advantage of the natural inductivity of long cables present in wind farms are also being investigated. Also, direct conversion structures like matrix converters (no dc storage) have been considered even though low-voltage ride-through capability (LVRT) without dc storage elements is very challenging. Specifically, the need for higher power management (all the major manufacturers have or are going to have commercial products for 4.5 MW power level) has driven the research toward the use of multilevel or converters connected in parallel, adopting interleaved modulation

to reduce PWM harmonics. Specifics of these converter applications depend on the type of electric machine being used; further descriptions are given in the next section.

3) *In Transmission Systems*: Transformers are the primary method of converting voltages and currents in traditional ac systems. As renewable sources are being integrated to the grid, the dc transmission system is being revived as an alternative transmission scheme for several reasons. PV systems are inherently dc sources. In wind turbine systems, the dc link is a popular way to decouple the fixed frequency of the grid from the variable frequency of the generator. With state-of-the-art dc transmission for crossing long distances and/or the sea, the skin effect losses of ac power are eliminated, so cable losses are reduced. Moreover, dc transmission systems (see Figure 13) offer the following advantages:
   - HVDC systems require less physical space to transport the same energy as HVAC, because pylons are smaller and there are fewer cables. Consequently, ROW restrictions can be smaller.
   - Increase of power-carrying capability while preserving transient stability.
   - Transmission of large amount of power over long overhead lines.
   - Link between asynchronous ac systems while offering control of the power exchanged between the two areas.

In general, the use of dc transmission systems offers a possible answer to the need of connection between production and consumers, allowing economics of scale, wider choice of generating plants, and reduction in reserve capability. In the dc transmission system, the electronic power converter takes the place of the iron core transformer. The solution may be well suited for large offshore wind parks.

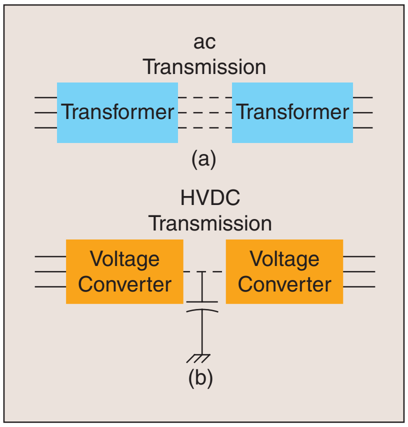

FIGURE 13 – Comparison of ac and dc transmission systems. (a) Traditional ac transmission. (b) HVDC transmission.

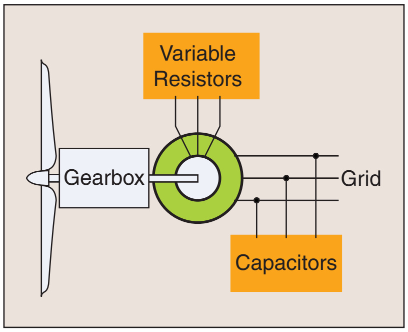

FIGURE 14 – A limited speed system employing wound-rotor induction generator and variable resistance on the rotor side.

The most widely used HVDC systems are line commutated, even though the use of voltage-source converters have been recently studied and even commercialized [29]. This new family of HVDC has several potential advantages, including full control of reactive power on both sides, the minimization of the filters, and simpler transmission cables. On the other hand, there are still some voltage and power limitations. Multilevel converters may likely become the standard technology in this field [30].

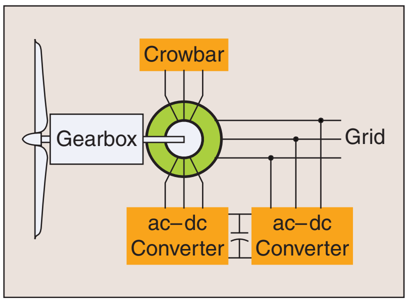

FIGURE 15 – The DFIG system.

To provide traditional power systems with more flexibility, FACTS based on series or parallel compensators have been proposed. More recently, variable-frequency transformers (or rotary power-flow controllers) based on doubly fed EMs have been proposed to connect asynchronous power systems, thus offering some of the advantages of HVDC technology [31], [32].

Electric Machines

The industrial workhorse known as the induction machine is also widely used in renewable energy generators, especially the wind turbine. The most basic turbine employs the induction generator with stator windings connected to the utility grid, and variable resistors connected on the rotor. This together with mechanical active stall control allows the system to manage limited speed variations. Compensating capacitors are usually necessary to correct suboptimal power factor (see Figure 14). This is a relatively lower cost solution, and power electronics are a minimum.

The doubly fed induction generator (DFIG) has a wound rotor with connections to the outside achieved through slip rings. A power converter controls the electrical frequency of the rotor, while the stator windings are directly connected to the utility—the result is that the mechanical speed of the rotor/turbine is decoupled from electrical frequency of the grid (see Figure 15). This system accommodates much greater speed variation, and more importantly, the power factor can be controlled. The power electronic systems add to the system cost, but the improvement in energy conversion and ability to accommodate larger wind variations means that the physical structure is often lighter and less costly; the net result is a better performance/cost ratio. The DFIG is the most popular type among modern turbines offering variation up to 60% of the nominal speed. However, new transmission system operator grid codes pose more stringent requirements in terms of LVRT and even request injection of large amount of reactive power to sustain the voltage profile under a fault. These requirements challenge the use of DFIGs and may require extra hardware, e.g., crowbar, static synchronous compensator, or dynamic voltage restorer (STATCOM/DVR) at the windfarm level [33].

Hence, it is possible to foresee the use of full-power back-to-back ac–dc converters, as illustrated in Figure 16. The front-end converter (closest to the electric generator) converts the ac energy to the dc form while also providing torque control on the machine. The converter closest to the grid converts the dc energy back to ac form and enables the control of power factor. The dc link between the converters absorbs transient energy surges (generator side) and can rapidly deliver energy to counteract sudden changes in grid-side loads. Mechanical frequency of the turbine is decoupled from the grid frequency. The drawback of this approach is that the converters must be rated for the full power of the generator.

Synchronous multipole machines are also being used in wind turbines. Permanent magnet machines (axial or radial flux) are considered the most interesting solution. In such a system, the generator is not connected directly to the grid, but the energy must first pass through a power converter. The difference between generator output frequency and grid frequency is absorbed in the power converter system. The permanent magnet generator is a slightly more efficient machine, because the working field is provided by the magnets. In theory, the system is slightly simpler than the doubly fed induction system—the gearbox could even be eliminated (in case of a multipole machine), as illustrated in Figure 17. The tradeoff or disadvantage is that the power converter must be rated to handle the full power of the generator. In contrast, systems based on the DFIG use power electronics that can be one third to one half the rated machine power. Furthermore, a permanent magnet machine is generally more expensive to produce than the induction machine.

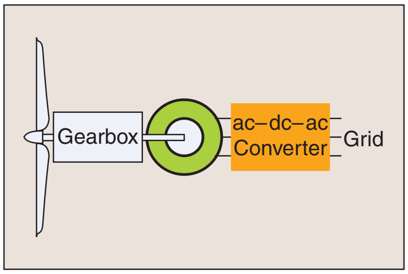

FIGURE 16 – Variable speed system employing ac machines (asynchronous or synchronous) and full-power back-to-back converters.

From a cost and robustness standpoint, the variable reluctance machine may be the optimum. The rotor of the reluctance machine is easiest to construct of all machines, since there are neither windings nor magnets present. The sturdy rotor makes the reluctance machine a good candidate not only for wind turbines but also for high-speed operation. Consequently, researchers have also employed the reluctance-type generator in flywheel systems that supplement the wind energy conversion system. The drawback of the reluctance machine is its highly nonlinear electromagnetic characteristic. Therefore, the electronic control system for this type of machine is arguably among the most sophisticated for EMs. A common approach is to store the compensating control in a memory table and then linearly interpolate between stored data points as necessary.

Energy Storage

Even if connected to the utility grid, RESs are usually coupled with other energy sources to improve robustness against intermittent outages. Hybrid energy systems are absolutely essential for remote off-grid installations. The popular approaches include the use of fossil fuel-driven generators (diesel), batteries, flywheels, supercapacitors, and compressed air systems. Their environmental impact is important, since the use of RESs is strictly related to providing a more sustainable energy processing. An ad hoc hydrogen network in parallel to the electric grid may offer an effective storage system, leading to the use of RESs directly producing hydrogen and fuel cells as a transportable storage. This may eventually lead to the hydrogen era foreseen by some scientists.

1) *Batteries*: The battery bank is commonly found in remote PV systems but also can be used wherever a dc link may appear, as in certain wind turbine systems. In remote PV applications, the battery may be sized to supply energy cloudy days or evenings. As a supplemental energy source, the interface to the battery could be a power converter or a motor/generator set. Lead-acid batteries are a proven technology characterized by low cost and high modularity. Their high failure rate, together with environmental problems, has led to new experimental batteries, such as those based on sodium nickel chloride chemistry; these, however, are more costly and have higher self-discharge rates.
2) *Flywheels*: Flywheels can be either low speed (higher mass) or high speed (lower mass). Long used for space applications, the flywheel energy system is being considered for power-smoothing applications. An EM drives the flywheel to store mechanical energy when excess energy is available and is driven by the flywheel to draw energy during power dips. In contrast to batteries, which are limited by chemical reaction rates and

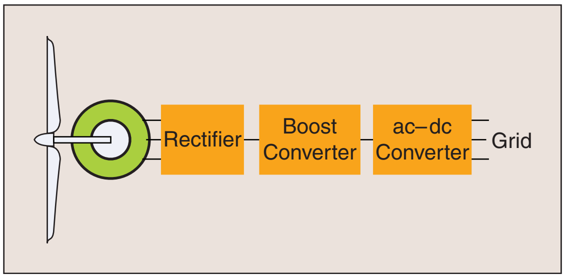

FIGURE 17 – Direct drive system with permanent magnet generator.

typically by their environmental impact, the flywheel system rapidly manages the stored kinetic energy with minimal consequences for the environment. The power ratings of the EM and its associated power electronics together with the audible noise are the major limiting factors.

3) *Supercapacitors*: Also known as ultracapacitors, these low-voltage devices are configured in systems of cells to provide sufficient voltage. The advantage of the capacitor is its ability to be quickly charged and discharged, making it a good candidate to provide instantaneous power or to help integrate other sources. They have a low environmental impact and very high power density, but they suffer balancing problems.
4) *Compressed Air Systems*: These systems store energy by means of a compressor in a fluid that can be stored underground. Compressed air systems can have a very long service life and low environmental impact, making them a good candidate for a long-term solution for RESs. However, the complexity of the systems is still a limiting factor that can make them an impractical solution for small power-distributed resource systems.

FIGURE 18 – The Solúcar PS-10 solar thermal power plant near Seville, Spain (courtesy of Solúcar Energia, S.A.).

Other Technologies

PV energy conversion is still a low-efficiency process. The best research cell efficiencies are in the range of 35%, and commercial modules have much lower ratings. The majority of solar energy is lost. Part of the problem is that current semiconductor bandgap technologies can only convert narrow portions of the solar spectrum to electric energy. An alternative to PV energy conversion is to gather the solar energy in thermal form and then use the thermal energy to drive electric generators.

One approach is to drive steam turbine type electric generators from solar collectors. The Spanish firm Solúcar Energia, S.A. has installed an 11-MW plant at Sanlúcar la Mayor, near Seville. Called PS-10, it is the world's first commercial solar thermal power plant [34]. Hundreds of mirrors track the sun and concentrate its power on a collection tower (see Figure 18). A second, larger facility named PS-20 is under development.

A second approach to concentrate the sun's energy is to drive an external combustion engine, such as the Stirling cycle. Sandia National Laboratory (the United States) joined with Sterling Energy Systems, Inc. (the United States) to build and test a six-unit system of solar dish/Stirling engines to produce 150 kW of power. Each unit operates independently, automatically tracking the sun from dawn to dusk. The reflective dish concentrates the solar energy on to a receiver that is mounted much like a radar receiver (see Figure 19). Thermal energy drives the Stirling engine, producing mechanical power that in turn drives an electric generator.


FIGURE 19 – Solar Stirling engine (courtesy of SES, Inc.).

Ocean Wave and Tidal Energy Conversion

If winds are considered a form of concentration of solar energy acting on the earth's surface, then the energy of the ocean waves and tides represents an even higher energy density source. The Electric Power Research Institute (EPRI) of the United States concluded in a 2005 report that wave power conversion has the potential to be one of the most environmentally

RENEWABLE ENERGY—AN EDUCATIONAL AND RESEARCH PERSPECTIVE

MARCO LISERRE, THILO SAUTER, and JOHN Y. HUNG

Renewable energy installations are blossoming worldwide, yet there is still a strong need for education and research. Lack of understanding or vision often leads to economic and public policy decisions that hinder growth even in the presence of technical expertise. Until very recently, the low acceptance of renewable energy technologies in the United States is a good example where social, economic, and political agendas have actively resisted change. In the southeastern part of the country, approximately two thirds of electricity is produced by coal-burning plants—it has been very difficult to overcome the massive economic inertia, and politicians have generally been reluctant to promote change [S1]. Fortunately, the rate of change has greatly improved in the past five years. Much of the change has been driven by world events, but science and research publication have made it possible to educate the diversity of stakeholders.

1) *Meeting the Science Shortfall*: Having the will to change is not sufficient for growth and expansion. As an example, consider that China's explosive economic growth coupled with a huge population has put a heavy strain on traditional fossil fuel energy sources. The country is already the second largest producer of energy. It is believed that China is now the world's eighth largest wind power producer. Yet, the adoption of clean renewable energy still faces great challenges, because the per capita lack of energy resources is still very deep. Although the country is learning rapidly and investing vast financial resources, China is still relatively underdeveloped in scientific and technological resources as related to renewable energy [S2]. Other areas of Asia and the western Pacific share a similar plight: strong recognition of need and desire for technology, yet hampered by lack of resources and education.
2) *Europe: Leading by Action*: In contrast to the previous two examples, Europe has experienced a strong convergence of social will, public policy, economic incentive, and technological resources—most of the necessary ingredients to develop RESs [S3]. For example, legislators in Spain recently passed a law allowing development of offshore wind power farms. The country is already one of Europe's leading producers of wind (and PV) energy systems, and the government has set a target to have more than 10% of the country's energy consumption come from renewable energy [S4]. In the immediate future, the only hindrance to Europe's expansion of renewable energy sources will be raw materials. This is especially true for PV energy conversion, where semiconductor-grade silicon is being rapidly consumed by the growing global demand for solar cells.
3) *Joint Industry–Academia Educational Programs*: Industries, especially wind turbine manufacturers, are currently involved in cooperation programs with universities to develop specific high-level (Ph.D. and postdoctoral) specialized educational programs to form a new class of engineers ready to tackle the most up-to-date problems in the field of RESs and distributed resources. Hot topics related to the electrical and electronic fields include storage, high-voltage dc (HVDC), high power converters, and interaction with the power systems [S5].
4) *Spreading the Word*: With regard to engineering education and research, there are many international venues for sharing scientific understanding. The world's largest professional organization, the Institute for Electrical and Electronics Engineers (IEEE), has sponsored numerous conferences and publications, with a special focus on renewable energy technologies. Moreover, IEEE is issuing a series of standards to help harmonize the interconnection issues of all distributed power generation sources with aggregate power capacity below 10 MVA [S6]–[S10]. Within the IEEE, leading organizations include the IES, Industry Applications Society, Power Electronics Society, and the Power Engineering Society.

The IES, having the highest international membership of all the IEEE technical societies, has been instrumental in organizing worldwide conferences and publishing papers that cover a broad spectrum of renewable energy topics. Activities that recognize the importance of this field include the following:

- IES awarded the 2004 Best Paper in *IEEE Transactions on Industrial Electronics* to Prof. Roberto Cárdenas and Prof. Rubén Peña of the University of Magallanes (Punta Arenas, Chile) and their coresearchers at the University of Nottingham (Nottingham, United Kingdom), for a paper describing the integration of flywheel technology with sensorless control of an induction generator to achieve smooth power [S11]. The research team has been involved with renewable energy studies for over a decade.

friendly, yet predictable methods of collecting energy. The total available incident wave energy at the United States is estimated to be 2,100 TWh/year, almost ten times the country's 2003 total hydroelectric generation [35]. High values of wave power flux exist off the coasts Northern Europe, southern Chile, South Africa, southwestern Australia, and Alaska.

Tidal behavior, caused by gravitational effects of the moon, has even greater energy density and is most predictable. Considering the expanse of the ocean, there is a compelling argument to develop wave and tidal energy conversion technologies, which are still in the emergent or infancy stage. The challenges are great, as the ocean environment delivers tremendous punishment to man-made systems, and the problems of bringing the power back to shore limits the distance from land. Several technologies are on

- In 2006, *IEEE Transactions on Industrial Electronics* published 30 papers in two special sections devoted to renewable energy and distributed generation systems.
- In 2007, Prof. Antonio Luque of Universidad Politécnica de Madrid, founder of the Spanish PV manufacturer Isofotón, gave a plenary presentation at the IEEE International Symposium on Industrial Electronics (ISIE 2007, Vigo, Spain).
- In 2008, IES launched a specific technical committee (TC), dealing with all the aspects of electronics, control, communications, instrumentation, and computational intelligence for the research, development, enhancement of industrial and manufacturing systems, and processes related to the employment of RESs, taking into account the sustainable development of such technologies [S12]. Topics addressed by this TC include stand-alone and/or grid-connected systems, modeling and simulation, control, fault detection, and diagnosis of power plants converting green energies into electricity or into other forms of energy. The range of applications is broad and includes systems for signal processing, instrumentation, measurement and testing, sensors, and actuators dedicated to RESs. The main goals of this TC are to encourage, organize, and support the activities of the researchers operating in this area of expertise, stimulate contacts with similar TCs of sister societies, and establish links with and between industry and academia to drive RESs.
- Two panel sessions were organized within ISIE 2007 and IES (IECON) 2008 (Orlando). The aim of the first one was to highlight the research activity of several research groups that have contributed to the creation of the TC (a video of the panel session is available at http://tv2.uvigo.es/es/video/31). The second one discussed selected issues related to the use of industrial electronics in renewable energy: energy conversion, simulation tools, energy storage systems, network-based energy management, and educational programs developed by companies [5].
- In 2009, the TC on RESs collaborated with the IES Educational Activity Committee to organize the first Seminar on Renewable Energy (SERENE) in Salerno, Italy. Several topics were covered, including PV and wind systems as well as wave energy potential and fuel cells. Some speakers from industry have outlined recent trends in the products developed for RESs and distributed power generation systems (DPGSs) [S13].
- In 2009, the 14th IEEE International Conference on Emerging Technologies and Factory Automation, held in Mallorca, Spain, and cochaired by Antoni Grau and James C. Hung, organized an Energy Day focusing on "Distributed Generation—Toward a New Energy Paradigm." (Presentations are available online at http: //www.etfa2009.org/program/energy-day.)
- In 2009, *IEEE Transactions on Industrial Electronics* organized a special section on RESs, attracting more than 100 submissions. This issue will appear in 2010. In addition, there will be a special section on methods and systems for smart-grid optimization.
- In 2010, two new IEEE journals will be launched: *IEEE Transactions on Sustainable Energy* and *IEEE Transactions on Smart Grids*. These journals are sponsored by the IEEE Power and Energy Society, and the IES is among the several other technical cosponsors.

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the verge of demonstrating readiness, including:

- Floating snakes whose flexing action drive electric generators [36].
- Networks of floating buoys, whose bobbing motion is transited through tethers to drive linear generators.
- Submerged cylinders of compressed air, whose buoyance is changed by the variation of total water column due to wave crest and trough (Archimedes principle). The induced motions are used to drive linear generators [37].
- Transplanted hydroelectric turbine technology. In this scenario, wave energy causes water to flow over the side walls of elevated reservoirs. The water is then drawn downward by gravity through traditional turbines that drive a permanent magnet generator. The

Tidal behavior has even greater energy density and is most predictable.

first 1/4 scale prototype (at Nissum Bredning, Denmark) used 2.3 kW generators. Future designs call for generators ranging from 250 to 750 kW [38].

Biological and Chemical Technologies

Befitting its global importance, renewable energy is being examined far beyond electrical engineering fields. In the biological and chemical sciences, systems based on biomass (trees and other agricultural products) are being studied. Fuel cell development is at the forefront of both chemical and materials sciences. In this article, the authors have chosen to focus on the technologies that pertain most strongly to industrial electronics. Yet in time, industrial electronic advances will likely be required to successfully incorporate these new technologies.

Concluding Remarks

The transition away from fossil-based energy sources to RESs is being globally addressed on two fronts. On the one hand, fundamental sciences are developing economically viable means to produce energy with less environmental damages. These RESs (solar, wind, wave, and biomass) have remarkably different dynamic characteristics than traditional energy sources. Consequently, energy delivery from renewable sources presents a whole new set of challenges for both energy providers and users. The evolutionary path to future energy systems also involves gradual integration of RESs to the existing energy grid. Therefore, on the other hand of renewable energy developments are the technologies needed to integrate a growing array of renewable sources. These industrial electronic technologies are necessary, either to create new forms of energy distribution systems or to integrate new energy sources into existing grids.

In this article, the authors have surveyed some of the technologies and challenges that have been at the forefront of research and development for the past ten to 15 years. Given the breadth of technologies, it was impossible to give the depth of treatment that each issue deserves; a choice had to be made. Therefore, the smart grid concept was described in slightly more detail, as a way to suggest that energy flow and information flow are ways to categorize the many technologies that will solve the integration issues. From the smart-grid overview, the authors then presented slightly more detailed descriptions of relevant technologies being examined in the industrial electronics community. Not all systems and issues could be discussed in the space allotted; the authors have elected to focus on the larger, industrial scale systems, but openly acknowledge that the combined impacts of microgrid and nanogrid technologies could be just as significant in the global view.

It is equally important to recognize that RESs are not solely in the domains of science and engineering research. Education has a well-documented impact on socioeconomic understanding and impetus for change. In "Renewable Energy—An Educational and Research Perspective," the authors address these issues. Therefore, the authors have also highlighted some recent education efforts. As was true with the technology overview, the review of academic activities was from an industrial electronics viewpoint. In summary, the adoption and integration of renewable energies are complex topics requiring multidisciplinary solutions. Developing these solutions requires a holistic understanding of the problems, and therefore, adequate education programs are essential.

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