The Future's Power System: Smart Grid

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Abstract

With the developing technology and the fact that existing electricity systems do not satisfy the nowadays requirements, so many countries have started to make investments for smart grid researches. The goals of the smart grid researches are to integrate renewable energy sources to the power system, decrease carbon emissions, improve transmission part, install advance metering infrastructure, and integrate electric devices and smart buildings in the power system to create smart management system. In parallel to Turkey's developing technology, growing economy, and 2023 targets, to supply the expanding energy needs, Turkey should also focus on smart grid. Therefore, the definition of the smart grid, parts of the new power system, advantages and disadvantages should be known well. The aim of this work is to present an overview of smart grid with a number of its technologies.

Keywords: *Distributed energy sources, energy storage, power electronics, smart grid*

1. Introduction

The current electricity system is the greatest engineering achievement of the 20th century but it does not supply the demands anymore. Nowadays with developing technology and growing population, electricity demand has greater increase and existing power system is under pressure to deliver the growing demand while providing a stable and sustainable supply of electricity. Additionally, most of the countries are focusing on reducing carbon dioxide emissions, so utilization of renewable energy sources in the power system is increasing gradually. On the other hand, our fossil sources which are our main energy source will be ended in 50 or 100 years according to different references. To cope with all these complexity and difficulties, intelligent power network concept that is called as smart grid has appeared.

What is a "Smart Grid" or "Intelligent Grid"? Intelligence can be defined as the talent to learn or understand or to deal with new circumstances or the ability to apply knowledge to control the environment. The analogy to smart grid is that knowledge gathering and communication between the systems are critical to achieve good performance against diverse grid states.

There are many definitions of smart grid. Most of the definitions mention the use of digital technology to achieve an economic and secure energy supply. So, smart grid will be capable of arranging optimal use of large and flexible renewable power sources, deciding operation of power plant for better economic dispatch, and increasing power quality by control of voltage fluctuations, voltage, and current distortion. To be able to do that, every node in the power system should be awake, responsive, adaptive, smart pricing, ecologically sensitive, real time, and interconnected with everything else [1].

After smart grid concept has appeared, to make easier the transition from traditional grid to smart grid, the concept of microgrid was started as a solution for the reliable integration of distributed energy resources, including energy storage systems, power electronic converters, controllable loads, and monitoring and protection devices. So, to deliver smart grid challenges, the future of the smart grid depends on increase in number of microgrids. The objective of this paper is to provide an introduction to smart grid with a focus on main parts with used technologies and researches. This

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paper is organized as follows: Second section presents general information about components which are used in smart grid. Then, standards of smart grid are given in third section. After that, fourth section describes microgrid structure and fifth section explains research and development studies and projects about smart grid. Finally, a conclusion is presented in sixth section.

2. Smart Grid Components

A number of components and technologies have to be developed to transfer traditional power grid to smart grid. These are distributed energy resources, energy storage, power electronics, management (control, automation, monitoring, and protection), and communication. They are also main parts of the smart grid and given in Figure 1. In this section, these features have been explained.

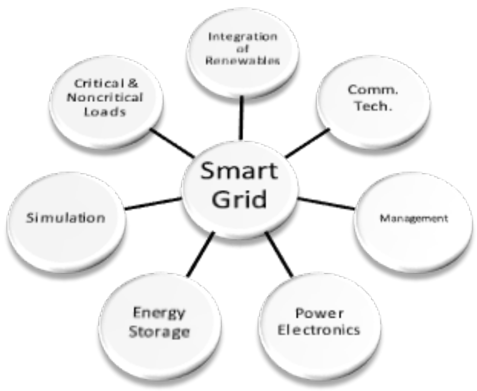

Figure 1. *Fundamental smart grid ingredients*

2.1. Distributed Energy Resources

Distributed energy resources (DER) is an alternative power system application and they can be defined as small rated (typically 15 MW or less per unit) renewable or conventional energy sources which are generally decentralized and located in close to customers in the distribution grid. DER systems use renewable energy sources, including solar, wind, geothermal, fuel cell, biomass, biogas and conventional sources, including coal, natural gas, nuclear powered plants. DER systems are briefly shown in Figure 2 [2, 3, and 4].

DER systems have some advantages, such as modularity (short time for installation), reduction of transmission losses, reducing the load on the local distribution system with feeding back into the utility with over produced electricity, high reliability, and environmentally friendly with low and zero emissions. Despite these advantages, major drawbacks of DER systems are uncertainties in performance for renewable energy sources, high cost, inadequate standards and knowledge in operation, control problem about peak reduction [2, 3].

DER can also be grouped based on their dispatch ability. Having dispatch ability sources (diesel generators) can be fully controlled but other sources cannot be controlled and they are operated to obtain the maximum power. Renewable DER is intermittent sources and their output is not controllable. In order to successfully integrate renewable distributed energy resources, DER systems must operate in connection with power electronic circuits according to their types. As an example, solar panels, energy storage technologies, and fuel cells generates DC voltage and they require the use of DC to AC conversion stage to obtain suitable and stable AC voltage to connect these sources to the electrical grid. On the other hand, hydro and wind systems generate variable AC voltage. Therefore, grid connection of these sources can be achieved by converting stable AC voltage with AC to AC power electronic converters [4].

2.2. Energy Storage

Energy storage is seen as a main element in the future energy supply chain. The use of energy storage systems allows the power grid to store power at a low rate per megawatt hour and inject power back into the grid. Stored energy enters to the system at three different times. These are stabilization to enable a constant and stable output, the renewable energy sources, such as solar and wind, capacity fall under demand, and ensuring economic dispatch when generator production prices are higher.

It is not possible to store electric energy directly in high quantities, so electric energy must be converted to storable forms such as mechanical or electrochemical energy. Hence, the storing of energy close to the produced energy can be possible with energy storage devices. Mostly used energy storage devices are capacitors, flywheels, battery energy storage systems (BESS), compressed air energy storage (CAES), and pumped hydro storage (PHS). These devices can supply power back into the grid at changing durations, minutes to hours or days according to their storing capacity. All these energy storage systems have some advantages and disadvantages. CAES and PHS provide the greatest energy storage density but they need high capital cost

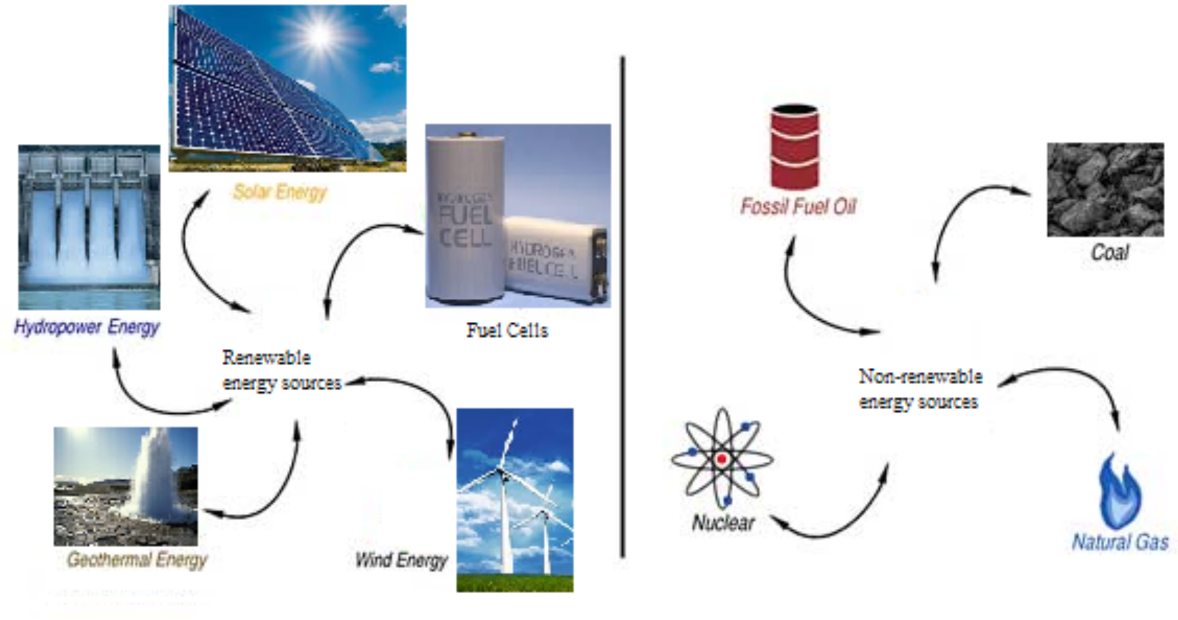

Figure 2. *Distributed energy resources*

and huge settling place. On the other hand, flywheels are small and expensive for high power applications. Furthermore, BESS has gained an important place in energy storage because of its capital investment, operation cost, and fast response time [5].

Energy storage systems are used for dynamic stability, transient stability, voltage support, frequency regulation, and load leveling. Especially, load leveling has taken a great interest at some peak hours due to increase in population, commerce, and industry. Load leveling, also referred to as peak load shaving or peak shifting, used to eliminate the peaks and valleys at the grid side. This procedure brings direct or indirect advantages to utilities, such as decreasing costs savings to utilities and customers, reducing line losses, and voltage support to the grid [5].

Research in energy storage is being subsidized by governments. Main research topics are about evaluating energy storage technologies and trying to find new energy storage methods.

2.3. **Power Electronics**

In smart grid infrastructure, the number of renewable energy sources is increasing. In particular, many of the renewable energy sources, such as solar and wind, generate variable and unsuitable AC voltage. Hence, the major part of the connection between renewable energy sources and the grid is the conversion stage. As a result of that, the need for power electronic converters is increasing. Power electronic converters must supply bidirectional power flow, electromagnetic interference, high efficiency, measuring and controlling power flows with smart meters and communication, and synchronization features. Classification of power electronic converters transformation for major distributed energy sources is given in Figure 3 [2]. In Figure 4, as an example of detailed connection, block diagram of the solar array connection to the grid is shown. Many of renewables and distributed generation such as photovoltaic, wind, fuel cells, compressed air, and energy storage interface to the grid through DC-AC inverters. Three phase grid connected DC-AC inverter block diagram is given in Figure 2.

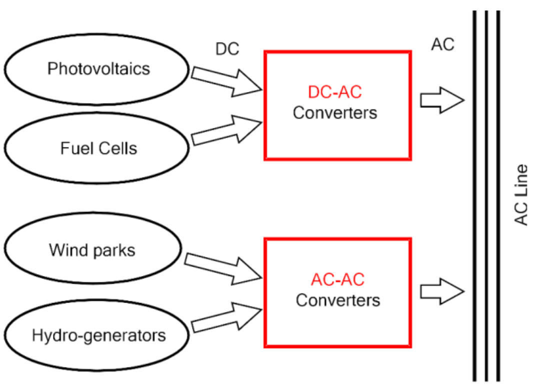

Figure 3. *Power electronic transformation for major sources*

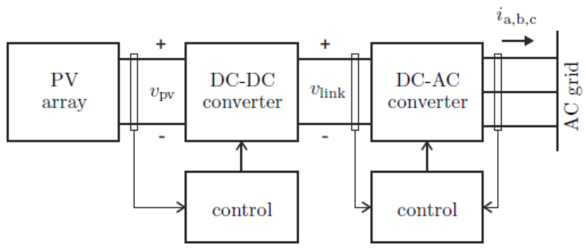

Figure 4. *Block diagram of the photovoltaic system*

Generally, three phase two level voltage source sinusoidal inverters, DC-DC buck or boost converters, and rectifiers are used as power electronic converters for this conversion [6, 7]. Inverters are vital for many renewables to convert their output into an AC voltage to be interfaced with either a load or the grid and the schematic of three phase grid connected inverter is given in Figure 5. Power quality problems in the grids are magnitude of the supply voltage, voltage fluctuations, voltage and current distortion, voltage dips, and short supply interruptions [7]. Accordingly, inverters have to contribute to keep the power quality conditions. Ongoing research activities on inverters are improved circuit topologies, improved system communication, grid stability, synchronization at different loads and variable grid conditions, and customer friendly products [6].

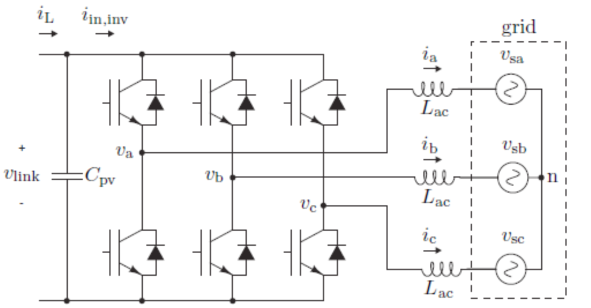

Figure 5. *Three phase grid connected DC-AC inverter*

Hereby, the variety of system topologies and large numbers of power electronic devices complicate to build a test bed or pilot plant with real equipment for smart grid projects. Therefore, simulation becomes a powerful and important element in researches.

2.4. **Simulation**

Modeling and simulation is commonly used for analyzing the behavior of complex systems without having to make huge investments and put at risk the reliability of the real power grid since the mid-twentieth century. The improvement in simulation programs has progressed with the evolution of computing technologies. In smart grid, it is unsafely, difficult to change and repeat tests, and expensive to set up a test bed or pilot plant with real components for research and development, because of the variety of system components and complex power electronic circuit topologies [8, 9, and 10].

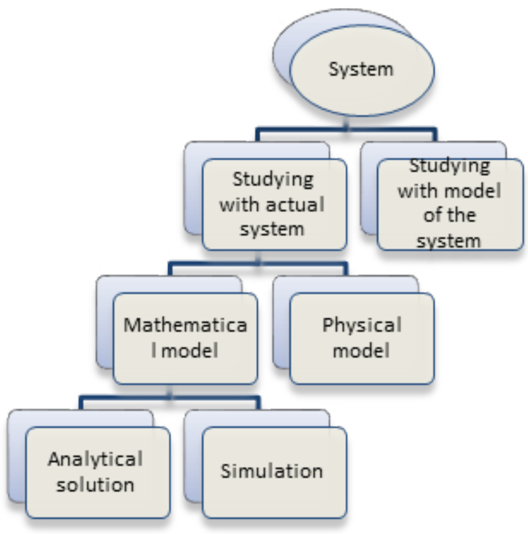

Figure 6. *Studying with a system*

Studying and testing the actual smart grid system is limited because the elements in the smart grid infrastructure are not in place today on a large scale. Therefore, smart grid model have to be used for testing. To realize a physical model at this stage may be a small scale laboratory test bed and it can be still unadvisable because of safety reasons. Thus, smart grid model, mathematical model, and simulation parts have to be done respectively to obtain a model that is close to real system. The chart of studying a complex system is given in Figure 6 [8].

Nearly 15-20 years ago, to get rid of the complexity and long period simulations of traditional off-line simulators, real time simulators for power system integrated with power electronics components have been used. Real time simulators can run a large and complex power system model at the physical time. Several network simulation toolsets are currently available such as NS2, Exata, and OPNET [9]. NS2 is an open source network simulation package while Exata and OPNET are commercial. For the simulation, discrete time and constant step duration is used. Variable time step technique is not proper for real time simulation. At each time step, the simulator executes respectively that: reading inputs and generating outputs, solving model equations, exchanging results with other simulation nodes, and waiting for the next step.

In addition to the real time simulator, Hardware in the Loop (HIL) application can be used to test prototype of a part or the entire system before implementing the actual system [9]. Thus, real time HIL simulation platform works to combine physical system with management and communication parts [9, 11].

2.5. Management

Smart grid will require advanced sensing and control technologies due to its complexity and nonlinear dynamic network infrastructure. Management defines monitoring, controlling, automation, and protection functions located out on the feeder. Most important features are protection and switching. Management devices can interrupt fault current, monitor voltages and currents, communicate other systems, and spontaneously reconfigure the system to rearrange customers and achieve system features [13].

One example of the management studies in the literature is watching energy consumption in the system and if the consumption amount is higher than the desired demand value, system can disconnect loads according to their priority until the system be normal [13, 14]. For this reason, smart grid needs real time energy information about the power system to enable its capabilities. Through advanced metering infrastructure (AMI), accommodating higher penetration and cost effective integration of renewable energy generation is possible with demand response and distributed storage at all customer service locations.

In the smart network system, information from smart metering devices in the distribution system is collected by an energy management system (EMS). EMS can respectively measure, collect, store, analyze, manage, monitor and control the instantaneous information about the entire system in real time [3]. The aim of the EMS is to send control commands to devices in order to achieve energy efficiency, and the power electronic devices respond to this control commands quickly and rightly to satisfy the high efficiency. Also, EMS provides utilities information about the condition of distributed energy sources and other system components, remotely connect and disconnect services, support time duration, and monitor and record grid information with two way communication system. Management system satisfies communication between utilities and metering devices via wired or wireless connection.

2.6. Communication

Smart grid topology, by contrast traditional power grid, has many active devices and allows the integration of lots of different power sources. Due to this complexity, it is hard to predict and control system behavior. In addition to that, all control and protection strategies rely on a large number of measurement values that

Table 2. *IEC Smart Grid Core Standards*

Technology	Data Rate	Applications	Limitations
GSM	14.4 Kpbs	AMI and energy management	Low processing capabilities, small memory size, small delay requirements.
GPRS	170 Kpbs	AMI and energy management	Low data rates
PLC	2-3 Mpbs	AMI, monitoring, and control in urban areas	Harsh, noisy environment
3G	2 Mpbs	AMI and energy management	Costly spectrum fees
WiMAX	75 Mpbs	AMI and energy management	Not widespread
ZigBee	250 Kpbs	AMI, smart lighting, home automation	Low data rates, short range

are obtained from the various actors in the power grid. Therefore, communication is critical and important stage to rightly coordinate the operation of power grid. The problem of to become widespread of smart grid is reliability. A system which is 99.9% reliable and 0.1% unreliable means that the system is unreliable. Therefore, communication is important and reliable and bidirectional communication technologies such as wired and wireless can be used for data transmission between utilities and metering devices. Wireless communications have low cost infrastructure and provide easy connection for unreachable areas. On the other hand, wired communications do not have interference problems and their operation is not dependent on supplies of the communication, as batteries. Communication technologies and their features are given in Table 1 [15, 16].

3. STANDARDS

Smart grid contains lots of devices and it needs standards to work safely together. International Electro-technical Commission (IEC) is the most trusted international electrical standards development organization and they have identified many standards as relevant to smart grid. Core standards are given in Table 2 [17].

IEC 61970 and IEC 61968 (CIM) are the important standards which are widely used in the smart grid. The idea in the CIM is to provide a common information model to support the information exchange between different EMS to prevent reliability. IEC 61850 is the other important core standard in the future smart grid. It is used in power system automation to achieve interoperability between intelligent electronic devices.

4. SMART GRID APPLICATION: MICRO-GRID

Microgrid system is modern, localized, and small scale grids. The development of microgrid gains popularity as a necessity for the integration of renewable energy sources in the remote areas and it is also very important for the realization of the smart grid [4]. In the microgrid architecture, the electrical system is connected to the distribution system with a static transfer switch or circuit breaker at point of common coupling (PCC). Each feeder and load in the system has circuit breaker.

The microgrid can be operated in two different modes: grid connected or islanded mode. In grid connected mode, microgrid system connected in parallel with grid and the control aim in this mode is to achieve power flow regulation by the power control of distributed generation inverters. In islanded mode, microgrid system operates alone like an autonomous system and the control aim in this mode is to maintain the voltage amplitude and frequency of the microgrid system within the limit levels while achieving reasonable power sharing with taking into account sources and loads. In all conditions, the microgrid must have the ability to operate stable and autonomously. Microgrid researches study on the stability performance of the system during the transition from grid connected mode to islanding mode or vice versa with different control topologies and compare the results.

In the literature, recent researches examine the microgrid with different resources (photovoltaic, wind, fuel cell, battery, or conventional sources) and load types (critical or non-critical, resistive or inductive) [4, 9-11, and 18-21]. Block diagram of the one example application in the literature is given in Figure 7. The example system consists of a Local Energy Storage (LES) device (8.3 kW), a photovoltaic plant (5.3 kW), a wind turbine system (10 kW), and 4 different loads that is totally 25 kW. Transition time from grid connected to islanding and stability after load shedding is examined [9].

Microgrid has gained importance for the reliable

Table 2: *EC Smart Grid Core Standards*

IEC Standard Number	Definition
IEC 61508	Functional safety of electrical/electronic/programmable electronic safety related systems
IEC 61850	Power utility automation
IEC 61968	Common information model (CIM) – Distribution management
IEC 61970	Common information model (CIM) – Energy management
IEC 62056	Data exchange for meter reading, tariff, and load control
IEC 62351	Security

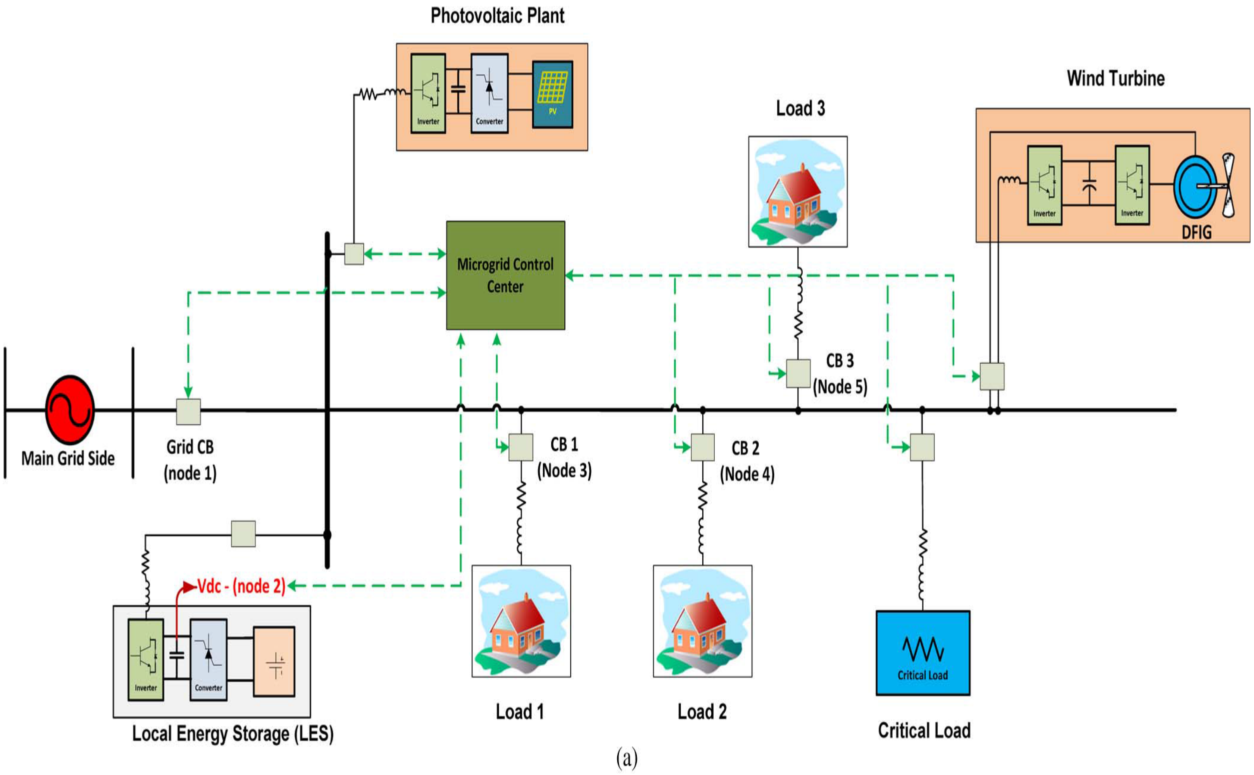

Figure 7. *Block diagram of microgrid [10]*

integration of distributed energy resources, including energy storage systems, power electronic converters, controllable loads, monitoring and protection devices, and providing islanding operation during outages. Accordingly, microgrid applications focus on comparing the stability performance of the microgrid system during the transition from grid connected mode to islanding mode or vice versa with different control topologies.

There are some important assumptions in microgrid [22]:

- Uninterruptible islanding operation is desired for power quality.
- Mostly inverter based resources are used in microgrids.
- Energy storage is required for transients and load changes.
- Peak shaving, load shedding, and integration of renewable energy resources are main objectives of microgrid.

5. RESEARCHES AND PROJECTS

Mostly ongoing research activities for Smart Grid are cost effectiveness, reliability, and flexibility in generation, and taking into account customer choice systems.

Smart grid current research and development study topics are [12]:

- Self-healing: to be able to protecting stability by fixing system alone after any fault
- High reliability, flexibility and power quality
- Improving communication, resistant to cyber attacks
- Integration of a wide variety of distributed generation, plug-in vehicles, and storage systems
- Minimizes operations and maintenance experiences
- Intelligent load management: peak load shaving, load leveling, peak shifting with storage systems [5]
- Customer choice systems and cost effectiveness.

Furthermore, the microgrid projects aim that investigation, developing, and demonstration of microgrid infrastructure to determine operation, control, safety, and communication.

There are already many projects to demonstrate and test a part of smart grid. Major projects are listed below [12].

EPRI IntelliGrid: Project is created by the Electric Power Research Institute (EPRI) in 2001. IntelliGrid project creates a roadmap to the next generation power system, with advanced metering, distribution automation, and demand response that can more reliably, efficiently, and securely manage the supply and delivery of energy needs of future. IntelliGrid architecture has the goal of creating a self-healing power system capable of handling emergency situations, while able to accommodate current and future utility business environments, market requirements, and customer needs. Southern California Edison, Long Island Power Authority, Salt River Project, and TXU Electric Delivery have applied IntelliGrid architecture.
Modern Grid Initiative: This project is collaboration between the U.S. Department of Energy's (DOE) the Office of Electricity Delivery and Energy Reliability (OE) and the National Energy Technology Laboratory (NETL) with utilities, customers, and researchers. The aim of this project is modernizing the U.S. electrical grid. In order to do that, DOE funds demonstration projects which developing information technology and move the grid through modernization.

GridWorks: It is a DOE OE new program to improve the reliability of the electric system through the modernization of key grid components such as cables and conductors, substations and protection systems, and power electronics.

California Energy Commission Public Interest Energy Research Program: This program has the Energy Systems Integration subprogram to examine the integration of distributed energy sources, evaluation of distribution automation, demand response of distributed generation.

Europe 5th Framework Program: It was a consortium with National Technical University of Athens (NTUA) and 14 partners from 7 countries, including utilities, manufacturers, research institutions, and universities. The aim of the project was integration of renewable energy sources, microgrid islanding operation, and microgrid control methods. Two demonstrations (Kythnos Island, Greece and Continuon holiday camp, Netherlands) have been done to test the microgrid operation.

6. CONCLUSION

In this paper, the important points of smart grid application are explained. Smart grid can be viewed as a digital upgrade of the existing power system infrastructure. Smart grid operation will demand intelligent systems, including computational intelligence. These systems will be expensive but its value will be large. Clearly, a combination of power electronics, management strategies, and communication will play a key role for new developments and realization of future smart grid. For smart grid researches, power electronics, management studies, and communication technologies will be important subjects in the future.

In parallel with Turkey's 2023 goal about energy, Turkey's energy needs can be met by developing the necessary power electronic converter circuits which satisfy the new grid features, for integration of distributed energy resources.

REFERENCES

[1] Amin, S. M. and Wollenberg, B. F., "Toward a smart grid: power delivery for the 21st centu ry", IEEE Power and Energy Magazine, vol. 3, no. 5, pp. 34-41, September-October 2005.

[2] Benysek, G., Kazmierkowski, M. P., Popczyk, J., and Strzelecki, R., "Power electronic sys tems as a crucial part of smart grid infrastruc ture – a survey", Bulletin of the Polish Acade my of Sciences, Technical Sciences, vol. 59, no. 4, pp. 455-473, 2011.

[3] Farhangi, H., "The path of the smart grid", IEEE Power and Energy Magazine, vol. 8, no. 1, pp. 18-28, January-February 2010.

[4] Canizares, C. A., "Trends in microgrid con trol", IEEE Transactions on Smart Grid, vol. 5, no. 4, pp. 1905-1919, July 2014.

[5] Rahimi, A., Zarghami, M., Vaziri, M., Vadh va, S., "A simple and effective approach for peak load shaving using battery storage sys tems", in Proc. IEEE North American Power Symposium, Manhattan, 22-24 September 2013, pp: 1-5.

[6] Bouzguenda, M., Gastli, A., Al Badi, A. H., and Salmi, T, "Solar photovoltaic inverter re quirements for smart grid applications", in Proc. 2011 IEEE PES Conference on Innova

tive Smart Grid Technologies, 17-20 Decem ber 2011, pp. 1-5.

[7] Paal, E. and Tatai, Z., “Grid connected invert ers influence on power quality of smart grid”, in Proc. 2010 14th International Power Elec tronics and Motion Control Conference, 6-8 September 2010, pp. T6-35 – T6-39.

[8] Schütte, S., “Simulation model composition for the large scale analysis of smart grid con trol mechanisms”, Ph. D. Thesis in Carl Von Ossietzky Universitat, Oldenburg, Computing Science, Business Administration, Economics and Law Department of Computing Science, November 2013.

[9] Guo, F., Herrera, L., Murawski, R., Inoa, E., Wang, C., Huang, Y., Beauchamp, P., Ekici, E., and Wang, J., “Real time simulation for the study on smart grid”, in Proc. 2011 IEEE Energy Conversion Congress and Exposition, 17-22 September 2011, pp. 1013-1018.

[10] Guo, F., Herrera, L., Murawski, R., Inoa, E., Wang, C., Beauchamp, P., Ekici, E., and Wang, J., “Comprehensive real-time simula tion of the smart grid”, IEEE Transactions on Industry Applications, vol. 49, no. 2, pp. 899-908, March/April 2013.

[11] Graf, C., Maas, J., Schulte, T., and Weise-Em den, J., “Real-time HIL simulation of power electronics”, in Proc. 2008 34th Annual Con ference of IEEE Industrial Electronics, Orlan do, 10-13 November 2008, pp. 2829-2834.

[12] Brown, R. E., “Impact of smart grid on Dis tribution System Design”, in Proc. 2008 IEEE Power and Energy Society General Meeting, Conversion and Delivery of Electrical Engi neering in the 21st Century, 20-24 July 2008, pp. 1-4.

[13] Adinolfi, F., Massucco, S., Silvestro, F., Dan ieli, A. D., Fidigatti, A., and Ragaini, E., “In telligent load management for shopping mall model in a smart grid environment”, in Proc. 2013 IEEE Grenoble PowerTech Conference, 16-20 June 2013, pp. 1-6.

[14] Herrera, L. C., Guo, F., Murawski, R., Ekici, E., and Wang, J., “Combined studies of power electronics and communication networks for the smart grid”, 2011 IEEE Energytech Con ference, 25-26 May 2011, pp. 1-5.

[15] Güngör, V. C., Şahin, D., Kocak, T., Ergüt, S., Buccella, C., Cecati, C., and Hancke, G., “Smart grid technologies: communication technologies and standards”, IEEE Transac tions on Industrial Informatics, vol: 7, no. 4, pp. 529-539, November 2011.

[16] Mahmood, A., Javaid, N., and Razzaq, S., “A review of wireless communications for smart grid”, Renewable and Sustainable Energy Re views, Elsevier, vol. 41, pp. 248-260, September 2014.

[17] IEC Smart Grid Standards, www.iec.ch/smart grid/standards, 10.10.2015.

[18] Lu, L., Liu, J., Chu, C., Wu, Y., and Cheng, P., “Real-time simulations of a laboratory scale micro-grid system in Taiwan”, in Proc. 2012 IEEE 13th Workshop on Control and Model ing for Power Electronics, Kyoto, 10-13 June 2012, pp. 1-8.

[19] Hassan, M. A. and Abido, M. A., “Real time implementation and optimal design of auton omous microgrids”, Electric Power Systems Research, Elsevier, vol. 109, pp. 118-127, April 2014.

[20] Salehi, V., Mazloomzadeh, A., and Moham med, O., “Real-time analysis for developed laboratory-based smart micro grid”, in Proc. 2011 IEEE Power and Energy Society General Meeting, San Diego, 24-29 July 2011, pp. 1-8.

[21] Eghtedarpour, N., and Farjah, E., “Power con trol and management in a hybrid AC/DC mi crogrid”, IEEE Transactions on Smart Grid, vol. 5, no. 3, pp. 1494-1505, May 2014.

[22] Paquette, A., “Power quality and inverter-gen erator interactions in microgrids”, Georgia In stitute of Technology, Ph. D. Thesis in the School of Electrical and Computer Engineer ing, May 2014.