Designing Energy Conversion Systems for the Next Decade

Slobodan N. Vukosavić

Abstract—**Sustainable growth in energy consumption requires transition to clean and green energy sources and energy systems. Environment friendly and renewable energy systems deal with electrical energy and rely on efficient electrical power converters. High power electronics is the key technology to deal with the next generation of electrical energy systems. The door to future breakthroughs in high power electronics is opened by major improvement in semiconductor power devices and their packaging technologies. New materials allow for much higher junction temperatures and higher operating voltages. Most importantly, advanced power semiconductor devices and novel converter topology open the possibility to increase the energy efficiency of power conversion and reduce the amount of heat. Although the waste heat created by high power converters can be put to use by adding on to heating systems, this option is not always available and the conversion losses are mostly wasted. At the same time, wasted heat is a form of pollution that threatens the environment. Another task for high power converters is efficient harvesting of renewable energy sources, such as the wind energy and the sun. Intermittent in nature, they pose a difficult task to power converter topology and controls. Eventually, high power converters are entering power distribution and transmission networks. With their quick reaction, with fast communication between the grid nodes and with advanced controllability of high power converters, a number of innovations can be introduced, facilitating the power system control and allowing for optimizations and loss reduction. Coined smart grid, this solution comprises two key elements, and these are intelligent controls and large static power converters. At virtually no cost, smart grids allow for a better utilization of available resources and it enlarges the stable operating range of the transmission systems. Therefore, it is of interest to review the future trends in designing high power converters.**

Index Terms—**Energy efficiency, high power electronics, high power converters, renewables.**

I. Introduction

POWER converters include electric motors and generators, which perform electromechanical conversion, and also static power converters, power electronic devices that perform DC/DC Conversion (chopper), DC/AC conversion (inverters), AC/DC conversion (rectifiers) and AC/AC conversion (cycloconverters). Recent demands increase the required voltage level, rated power, efficiency and functionality of static power converters. From the consumer side, there are requirements for electronic speed control of electric motors in consumer devices, with the goal to achieve savings in energy, copper and iron, as well as to increase functionality and introduce advances diagnostics and sensing. Power converters are used to control power in lighting, heat sources, fans and other consumer devices. From the power source side, new topologies of power converters and new types of electric machines are used in production, transmission and distribution of electrical energy. Power inverters rated hundreds of kilowatts or several megawatts are used to facilitate the grid connection of generators and sources that use tidal, wave, wind, solar, geothermal energy and other forms of renewable energy.

New applications of electrical machines and static power converters require a different approach to conceiving and designing conversion systems and its components. A word on electrical machines, where conventional use of motors and generators was to establish grid connection and engage the operation at line frequency. Most recent applications of electrical machines involves the connection to the primary source (grid) through a static power converter that serves as the energy interface and fine-tunes the voltage and current waveforms supplied to electrical machine. The static power converter placed between the grid and the machine adapts the nature and form of voltages and currents in a way that increases energy efficiency and allows usage of motor (generator) with less copper and iron. This new approach to interfacing the grid and electrical machines opened the door to designing novel kinds and types of electric machines that cannot operate from the mains, such as the SR motors. The converter systems for use of tidal energy, wave and wind power require generators designed for a very low speed and high values of electromagnetic torque. On the other hand, generators connected to the gas turbines, as well as the motors in some electrical vehicles are spinning faster than 20,000 rpm. In these applications, it is necessary to design and apply the static power converters that provide the interface between low speed (or high speed) machine and the mains or grid. With electrical machines operating at extremely high speed, it is necessary to use new types of ferromagnetic materials that

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can operate in regimes B>1 T f> 1 kHz. In addition, it is necessary to find new forms of magnetic circuits to achieve the desired characteristics and to reduce losses in the conversion. Finally, the applications with low-speed generators should be designed for a reduced volume and reduced inertia of the rotor.

Parallel to the development of new types of electric machines, it is necessary to make a breakthrough in the field of power converters. Most current controlled PWM inverters, rectifiers, choppers and AC/AC converters with conventional topologies have relatively high dV/dt and di/dt, which leads to isolation stress, accelerated aging, reduced reliability, high losses and problems with EMI and EMC. It is therefore necessary to develop converter topologies that mitigate the stresses, reduce losses and prolong life expectancy. In the power transmission systems and distribution there is a need for new power semiconductor switches and converter topologies ready to work with power levels in excess to several tens of MW and with voltages of several tens of kV. These characteristics are required from grid-side converters that provide interface to wind generators and solar power plants. The same characteristics are also required from static compensators of reactive power. Even larger power and voltage ratings are encountered in high voltage DC power transmission.

This paper discusses the need for develop advanced electromechanical and static converters and discusses the features and solutions that should be reached. The arguments that go in favor of intensifying scientific research in this area and increasing investments are numerous. Amongst them, rapid depletion of resources, problems with pollution and degradation of the environment, and, indirectly, growing problems of health, education and security. There are also issues that could negatively affect the pace of further development, such as the tendency of governments, regulatory bodies and companies to focus on short-term goals.

II. Immediate Challenges

Several applications require novel approach to designing static power converters and electrical machines. In the field of electrical vehicles, it is necessary to design electronically controlled speed controlled and position controlled systems for electrically assisted vehicles and their main and auxiliary functions. The operation involves elevated temperatures, large mechanical stress, increase reliability and long life expectancy. What is also required is a compact, low cost, low weigh, high efficiency traction system for hybrid electric vehicles and zero emission vehicles. The traction system comprises power electronic devices, advanced traction motors, energy storage devices, and endotermic devices hooked to electrical generators. One of hot applications is KERS, Kinetic Energy Recovery System, device that assists the vehicles with endotermic motors. The role of KERS is to get enabled during braking intervals. It should acquire the kinetic energy of the braking vehicle and convert it into electrical energy by means of a high speed generator. The energy should be stored in super capacitor or in a battery back. Later on, during acceleration periods, the acquired energy can be advantageously used to boost the acceleration. At first used only in sports vehicles, KERS system enters the arena of commercial vehicles. Proper design requires an advanced electrical machine and high efficiency static power converter.

The concept that nowadays catches attention of investors is V2G-G2V. It has to do with hybrid and electrical vehicles with battery pack aboard. The use of V2G concept is in providing a low cost energy accumulation alternative to electric power transmission and distribution utilities. Namely, one of main problems in efficient use of renewable energy today is a feeble capability of the grid to accumulate the energy. It is well known that the energy production has to meet the demand without exception. Any imbalance of the two can be alleviated only by means of energy accumulation. With excessive production that cannot be put down quickly, the energy can be stored for future use. A sudden step of the demand that cannot be followed by an adequate increase in production is a problem that can be solved by drawing

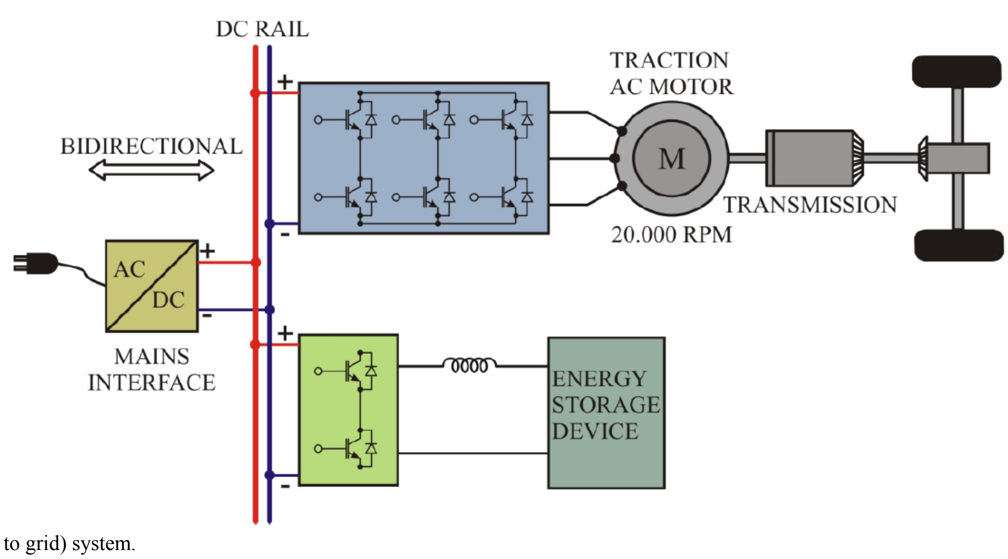

Fig. 1. V2G (Vehicle to grid) system.

accumulated energy from the energy storage device or system. Traditional storage solutions involve reversible hydro power plants and these are rather costly. The use of renewables such as the wind or sun power plants introduce another source of variable power, uncorrelated to the demand. This emphasizes the need for energy accumulation in the system. V2G concept provides a low cost accumulator.

In return for a lower cost of electrical energy or other benefits, power utilities can straighten a number of contracts with owners of electrical vehicles that employ battery packs on board. What is technically required is that chargers of these traction batteries have a communication device that receives remote commands from power utility control center. Most of such vehicles stay parked and connected to the grid for extended periods of time, said periods being considerably longer than the time needed to charge the battery. In most cases, expected time when the user will have the need to use the vehicle is known in advance. Therefore, in the case of an immediate energy demand, the power utility controls can issue a remote command that puts a required number of battery chargers in "discharge" mode. In this mode, accumulated energy is going to be pumped into the grid. Later on, having dealt with the demand, the batteries can be recharged again.

Another requirement imposed on power electronic devices is the need to increase the bandwidth of high performance servo drives. This can be done by reducing the control cycle time and, therefore, reducing the PWM period. An increase PWM frequency contributes to commutation power losses in power semiconductor switches. Therefore, a number of topologies is been under consideration, aiming to provide commutations with reduced losses, such as the resonant or quasi-resonant DC link topologies and similar.

Grid-interface power converters are mostly three phase inverters that interface the mains and deliver the power obtained from the intermediate DC link circuit. Depending on the power rating, grid inverters can be conventional three-phase two-level IGBT bridges, or, for larger voltage and power ratings, multilevel inverters which provide quasi-sinusoidal waveforms with reduced switching frequency. The DC-link power is obtained by exploiting tidal energy, wind energy, solar energy, geothermal energy and similar. With tidal and wind energy, the source is mechanical power which is converter to electrical energy by means of a electrical machine. Another inverter is used between the electrical machine terminals and the DC-link circuit (see Fig. 2) to provide the power interface. Namely, the current waveforms of the generator are shaped so as to reach the operation point with maximum efficiency. Rather stringent regulations when it comes to total harmonic distortion of the line current and parasitic DC component of the line current pose a difficult task to designers.

III. Long Term Challenges

Considering the fact that energy related problems becomes the key issue worldwide, it is likely that the importance of power conversion and power electronics will grow further. Energy issues are closely related to environmental issues. Besides notorious air pollution problems related to coal-fired thermal power plants, radiation leakage coming from nuclear power plants and side effects of hydro power, it is widely accepted that the waste heat itself presents one of major pollution constituents. Considering electrical power, the heat arises from power losses in electrical generators, transformers, transmission lines, as well as from consumer devices that run on electrical power. Even nowadays, a vast majority of electrical motors in use are single phase AC motors, renown for their low efficiency. At the same time, almost any kind of consumption of electrical energy ends in heat. Considering lighting, a large part of input power is turned into heat due to a low efficiency of light sources. Eventually, even the most of light produced by electrical light sources eventually turns into heat. Apparently, electrical motors do not produce heat but mechanical work. Yet, all of this mechanical work is eventually dissipated into heat due to motion resistances. As a consequence, the average temperature of heavily inhabited places, such as the large cities, goes well above the ambient. Satellite IR images of EU countries show warm spots above all the major cities. Due to thermal pollution, in most of Germany, these warm spots are merging.

One of the tools at the disposal of engineers eager to reduce the waste heat generation by improving efficiency is distributed power generation. This future trend provides the ability to accommodate a number of renewable energy sources, and it has potential to improve the energy efficiency in transmission and distribution of electrical power, offering at the same time increased levels of power system capability, reliability and security. Distributed power generation is essentially based on disseminated a vast number of efficient, remotely controllable power converters. Power converters are the key element as they provide an interface to many

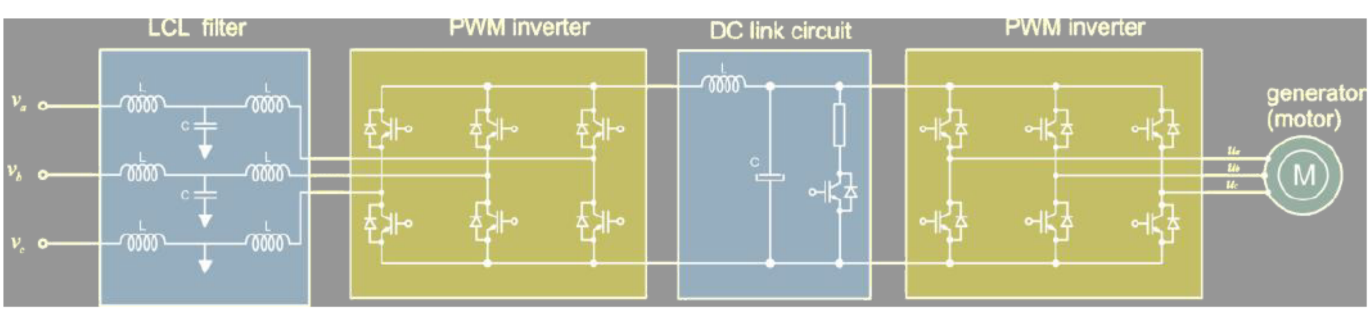

Fig. 2. Grid side inverter.

distributed energy sources such as solar and wind power, tidal and geothermal, fuel cell units and micro turbines.

Up to now, development of large power, high voltage power converters for distributed power systems has been rather sluggish. The reasons for that are numerous. Amongst others, most key governments are favoring near term goals over long term goals. Therefore, they tend to give a lower priority to the energy issues and environmental issues. The consequences of inactivity in solving these issues have the time constants that are (have been) longer than the time interval of 4-5 years being in focus of decision makers. At the same time, there has been lots of confusion regarding the climate changes and whether we are experiencing global warming or global cooling. Yet, large amounts of exact measurements and conditions are rather disturbing. East Russia is 3-4 degrees warmer on an average, boosting the snow and ice melting, increasing the fresh water income into northern seas and decreasing salinity. This weakens the "motor" that moves the north Atlantic current. With reduced heat transfer from Mexican gulf to northern Europe, the former gets warmer and generates more devastating storms, while the later gets colder. Exact satellite measurements show the peak recorded loss in Arctic ice, reaching three times the surface of Serbia per week. It has to be noted at this point that eventual melting of Greenland and West Arctic shelf would increase the see level by 12m. There are numerous indicators of adverse environmental changes spread around the globe. Large lakes, such as Aral, have virtually disappeared. Mighty rivers such as Colorado get consumed by water supply needs to such an extent that in critical months they virtually do not get to the sea. On an average, there is more rain and less snow, leading to periodic flooding and fresh water shortages. Augmented flood and draught extremes degrade the Earth surface. The overall surface of fertile soil has been in permanent increase, only to experience a decline in past decades. As a consequence, there are less crops and less forests. With disappearing forests, CO2 absorption is reduced, making the greenhouse effect more severe. Elevated temperatures contribute to crops failures and forests decline. Namely, the key process of photo-syntheses descend at 35 degrees centigrade and stops at 40 degrees. Therefore, in many regions, many plants, bacteria and animals are disappearing. In 10 years, crop reduction of 15% in 10 years is registered in China, notwithstanding advances in crops cultivation measures. With an increased request for crops used in bio-diesel production, humans and cars virtually compete for grain.

Water and crops shortages increase the health problems and produce political stress. There is an increased risk of conflicts for resources. Principal world powers are aware of an imminent exhaustion of resources such as water, air, food, oil and coal. Developed countries tend to alleviate the problem temporarily by increased exploitation of the resources in the third world countries. To secure the availability and control the prices of key resources, developed countries need to get or force a formal consent of local authorities. This goal is easier to achieve with a decreased awareness of local population. On the long run, this approach leads to an increased gap between poor and reach, between north and south, between east and west. Failing health and education in poor countries leads to unrest and terrorism, impeding eventually the exploitation of resources and their secure transfer to developed countries. Increased number of conflicts and reduced standard of living gives a rise to a lack of tolerance between racial, ethnical and religious groups, narrowing the space for discussions and agreements, and worsening the original problems. Recent phenomena of massive market failures and even failing states can be attributed to problems mentioned above. A number of economic specialists identify the failure of existing "invisible hand" economical model as the key factor to current hardships. Yet, it is reasonable to conclude that no economic model can resolve the energy and environmental problems without a strenuous technical effort with practical solutions. Power electronic is not the key to all the problems, but it can surely serve as one of important tools for dealing with such problems.

The goals that can be achieved by devising advances in power electronics are numerous. They include energy saving in efficient appliances, efficient electrical loads and devices in commercial sector and residential sector, such as "banning the bulb" and low voltage DC house installations. At the same time, power electronics helps adopting and implementing energy efficient production technologies, the use of lighter and quicker industrial robots and manipulators, and advanced use of electrical drives in vehicles and transportation systems. The goals are also reducing the losses in power generation, transmission and distribution, redesigning power distribution at home & office, and reducing the losses in electrical drives, which consume more than 2/3 of electrical energy in developed countries. Reducing consumption of fossil fuels is achieved by harvesting green and renewable energy sources, such as solar, geothermal, tidal, hydro, wind, wave and others. In areas where natural gas is readily available and fed to consumers, distributed generation comprising micro turbines provides an alternative, distributed and well controlled source of electrical energy, increasing in such way the overall efficiency and reducing the power losses.

Another challenge is design of 21th century electrical machines. Unlike conventional, line frequency machines, modern generators and motors are fed from static power converters and they cover a very wide range of speeds and operating frequencies. Their design requires the use of new ferromagnetic materials that operate with low losses even at $B = 1$ T and $f = 20$ kHz. The operation at elevated frequencies requires new ways of designing and manufacturing the windings. Vast number of applications require new types of machines, such as SRM, BPM, SunREl and linear machines. New machine designs require new cooling methods and systems. The key factor appears to be the machine-converter integration and an integrated machine-converter design and optimization.

IV. Conclusion

Environment friendly and renewable energy systems deal with electrical energy and rely on efficient electrical power converters. High power electronics is the key technology to deal with the next generation of electrical energy systems. New materials allow for much higher junction temperatures and higher operating voltages. Advanced power semiconductor devices and novel converter topology open the possibility to increase the energy efficiency of power conversion and reduce the amount of heat. Important task for high power converters is efficient harvesting of new energy sources, such as the wind energy and the sun. Intermittent in nature, they pose a difficult task to power converter topology and controls. Eventually, high power converters are entering power distribution and transmission networks. Smart grid solution comprises two key elements, and these are intelligent controls and large static power converters. At virtually no cost, smart grids allow for a better utilization of available resources and it enlarges the stable operating range of the transmission systems. This review of future trends in designing high power converters indicates the principal direction and goals for research, development and design in power electronics.

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