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A Review of Power Electronics Applications in Power Systems

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ABSTRACT: Power electronics and power system can provide utilities the ability to more effectively deliver power to their customers while providing increased reliability to the bulk power system. Utilities can strengthen the reliability of the bulk power system and supply power to their consumers more efficiently by utilizing power systems and power electronics. Power electronics is, in general, the process of controlling and converting electrical power flow from one form to another to satisfy a specific purpose through the use of semiconductor switching devices. Power systems are inevitably moving toward automation and intelligence as civilization grows, and power electronics is a crucial piece of modern science's technology. In order to guarantee the stability and safety of operation as well as enhance the power quality, advanced power electronics can fortify and optimize the power system. One key to building a robust smart grid and quickening the growth of the power system is to accelerate power electronics. This paper gives a review on the power electronic applications for power systems. Moreover, developments in semiconductors and their packaging technology will drive power electronics into distribution applications as device efficiency and reliability increases whilst the cost of the switched megawatt falls. Finally, different types of power electronic converters and applications are described and discussed.

Keywords: Power Electronics Converter, Power System appliance, Power Semiconductor Devices. Distributed generation (DG); micro grids; power electronics; renewable energies; smart grids; static converters

INTRODUCTION

Power electronics, in general, describes the application of semiconductor devices to regulate and transform electrical power in order to satisfy a particular requirement. Stated differently, power electronics allows for the regulation of both the direction and the magnitude of power flow (AC or DC). The field of power electronics includes control systems, electronics, and power (electric power). [1]. Power electronics may be defined as the application of solid- state power semiconductor devices for the control and conversion of electric power.

The primary impetus behind the growth of power electronics is the assessment and revolution of power electronic equipment. The first PE revolution began in 1947 when American Bell Laboratories invented the transistor. Because of the thyristor's excellent electrical and control capabilities, it was quickly used to a variety of industries, including steel, electrochemistry, power industries, and others. The process was continually refined through practice. Fully controlled gadgets quickly evolved in the late 1970s. [2] which were represented by GTO (Gate-Turn-Off Thyristor) [1], BJT (Bipolar Junction Transistor), Power-MOSFET, etc. These power electronic devices were applied to high frequency circuit, and its control mode changed from phase-controlled to chop-controlled (Pulse Width Modulation), which made power electronics take on a new look. In the late of 1980s, composite devices represented by IGBT (Insulated-Gate BipolarTransistor) thrived, improving the characteristics of former power electronics circuit. Composite devices had advantage of both Power MOSFET and BJT: smaller state voltage drop, stronger current carrying capability, higher voltage endurance, etc. Those all made a hit and were applied to our life widely. Afterwards, PIC (Power electronic integrated circuit) was born at the proper time in order to reduce the volume o f power electronic devices, which became an important direction of power electronics.

Power electronics can be found in many forms within the power system. Some examples are: high-voltage direct current (HVDC) converter stations, flexible AC transmission system (FACTS) devices that are used to control and regulate AC power grids, variable-speed drives for motors, interfaces with storage devicesof several types, interfacing of distributed energy resources with the grid, electric drive in transportation systems, fault current–limiting devices, solid-state distribution transformer and transfer switches[2,3].The main uses of power electronics for power systems are reviewed in this paper, which is structured as follows. A brief history of power electronics and some of its uses are presented in Section II. Next, semiconductor devices with power are demonstrated. Classification, fundamental characteristics, significant uses, and advancements in power semiconductor devices are covered in Section III. In the fourth section, power electronic converter topologies, applications, types, and pros and cons are discussed. Section V concludes with the conclusions and future tendencies presented.

I. BRIEF HISTORY AND SOME APPLICATIONS OF POWER ELECTRONICS IN POWER SYSYTEM

A. Brief History of Power Electronics

The Mercury Arc Rectifier, created in 1900, was the first power electronic gadget. Subsequently, until 1950, other power devices such as magnetic amplifiers, ignitrons, phantoms, thyratrons, and grid-controlled vacuum tube rectifiers were developed and employed progressively for power management applications. Bell Labs created the first SCR (silicon controlled rectifier), sometimes known as a thyristor, in 1956. This was the first transistor to use PNPN triggering. When the General Electric Company (GE) developed the commercial Thyristor in 1958, the second electronic revolution got underway. With that, a new age in power electronics began. Following then, a wide variety of power semiconductor devices and power conversion methods were introduced.

Application of Power Electronics

Power electronics is widely used in power systems and encourages their evolution in the direction of greater intelligence and sustainability. According to research, power electronic converters process at least 60% of the final electric energy utilized in developed nations. In other words, power electronics helps with power generation, transmission, stabilization of the power supply, control of power system harmonics, etc.

Power Generation. The natural state allows for the dynamic operation of wind and hydroelectric power. The relationship between the pressure and current velocity and the power generated by water and wind, respectively, is the third power of the wind velocity. Power electronic devices enable variable-speed constant-frequency excitation, or the ability to modify the rotor excitation current speed so that it can operate at its maximum effective power when the rotor excitation current speed added with its own speed is consistent with the stator frequency. This enhances the quality and efficiency of power generation.

Power Transmission. Originally, power electronics was used for high voltage DC transmission [3]. As the power system evolved, the need for transmission capacity and distance increased dramatically, and the power structure also became more sophisticated. If we were to keep using AC transmission, the cost of the transmission line and facilities would be very high. Demand drives output. HVDC surfaced. The thyristor rectifier, which converts alternating current to direct current after being stepped up by a boost converter, receives power energy from the alternating-current generator. After inversion, power energy will finally be distributed to users and scaled down via a step-down transformer. HVDC transmission is more advantageous than AC transmission for long-distance, high-capacity power energy transmission, submarine or subterranean cable transmission, power grid connection, and other applications.

Power Quality. With the constant development of technology and society, power quality leads more and more people to pay attention to. Large-scale wind power station, photovoltaic, micro grid, electric vehicle, etc, these facility's parallel operation would have some influence on power quality. The application of SVC (Static Var Compensator) in power system could improve power supply stability and power quality, control voltage flicker and compensate var according to load variation to achieve the high-quality operation. FACTS(Flexible AC Transmission System) [4] is based on power electronic devices, combined with modern control theory to control former power system key parameter and grid topology, which changes the status that relying on inaccurate facility fundamentally and improves strong control and transmission ability of system. Typical FACTS devices are SVC (Static Var

Compensator), STATCOM (Static Compensator), TCPST (Thyristor Control Phase Shifter), etc [5].

Electrical applications:

Power electronics can be used to design AC and DC regulated power supplies for various electronic equipment, including consumer electronics, instrumentation devices, computers, and Uninterruptable Power Supply (UPS) applications. Power electronics is also used in the design of distributed power systems, electric heating and lighting control, power factor correction and Static Var Compensation (SVC).

Electromechanical applications:

Electromechanical conversion systems are widely used in industrial, residential, and commercial applications. These applications include AC and DC machine tools, robotic drives, pumps, textile and paper mills, peripheral drives, rolling mill drives and induction heating.

Electrochemical applications:

Electrochemical applications include chemical processing, electroplating, welding, metal refining, production of chemical gases and fluorescent lamp ballasts. Table (I) gives several power electronics applications in industrial, commercial, transportation, residential, utility systems, and telecommunication fields.

B. Power Semiconductor Devices

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Power semiconductor devices represent the heart of modern power electronics, with two major desirable characteristics guiding their development:

1. Switching speed (turn-on and turn-off times).
2. Power handling capabilities (voltage-blocking capability and current-carrying capability).

Improvements in semiconductor processing technology as well as in manufacturing and packaging techniques have allowed the development of power semiconductor devices for high voltage and high current ratings and fast turn-on and turn-off Characteristics. The availability of different devices with different switching speeds, power handling capabilities, sizes, costs, and other factors makes it possible to cover many power electronic applications, so that trade-offs must be made when it comes to selecting power devices.

Power semiconductors are essential components of most power electronics devices and systems. Silicon is by far the most widely used semiconductor material. With the advance of power semiconductor devices, more and more power electronics systems are used in high-power utility and industry applications. Power semiconductor device has played an essential role in the development of power electronics as a key component in system topologies [10]. Compared to normal electronic devices, power semiconductor devices require to stand large voltages in the off state and to carry high currents in the on state, which demand geometry differences from the low-power devices

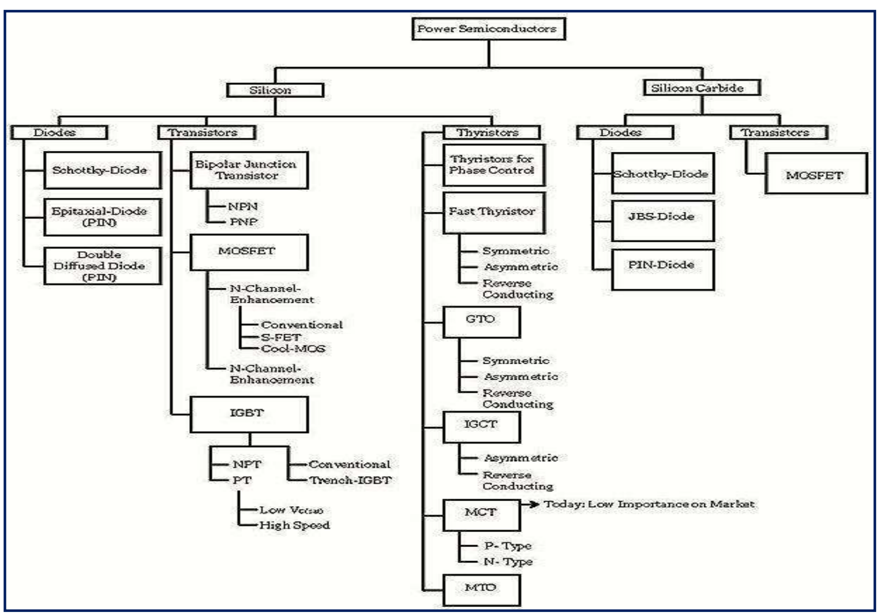


Figure 1: Classification of Power Semiconductor Devices

CLASSIFICATION, APPLICATIONS AND DEVELOPMENT OF POWERSEMICONDUCTOR DEVICES

A. Some Devices and Applications of Power Semiconductors

Controllable power semiconductor devices have made significant strides in power electronics technology recently. The most significant power semiconductors available today, along with their rated voltages and currents, are compiled in Figures (2) and (3) [14], [15]. Table (II) [16] displays the device characteristics for medium voltage power semiconductors. Bipolar Junction Transistors (BJT) have nearly entirely been superseded by IGBTs and Metal Oxide Semiconductor Field Effect Transistors (MOSFET). For traction and industrial converters, conventional GTOs are offered with a maximum device voltage of 6 kV. [16]. Among these devices' many benefits are their high on-state current density, high blocking voltages, and ability to combine an inverse diode. In 1988, IGBTs were released onto the market. Commercially accessible IGBTs with DC current ratings of up to 3kA and voltage ranges from 1.7kV to 6.5kV Table (II) [15], [16]. They have been optimized to satisfy the specifications of the high-power motor drives for industrial and traction applications.
In [17], the main advantages of the IGBT over a Power MOSFET and a BJT are explained as follows:

1. It has a very low on-state voltage drop due to conductivity modulation and has superior on-state currentdensity. So smaller chip size is possible and the cost can be reduced.
2. Low driving power and a simple drive circuit due to the input MOS gate structure. It can be easily controlled as compared to current controlled devices (thyristor, BJT) in high voltage and high current applications.
3. Wide Safe Operating Area (SOA). It has superior current conduction capability compared with the bipolar transistor. It also has excellent forward and reverse blocking capabilities.

The main drawbacks are:

1. Switching speed is inferior to that of a Power MOSFET and superior to that of a BJT. The collector current tailing due to the minority carrier causes the turn-off speed to be slow.
2. There is a possibility of latch up due to the internal PNPN thyristor structure.

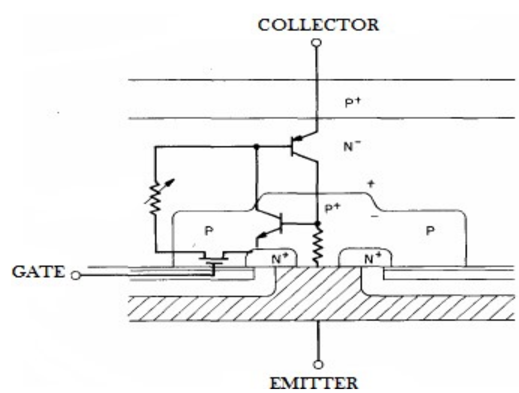
An overview of the main AC & DC systems and semiconductor components used in power systems applications are provided in order to enhance the distribution and transmission of electrical power. Power semiconductors are quite versatile, thus the best kind for a particular function depends on a number of variables, including amplification, switching speed, and power class. Applications in industry, the consumer sector, and transportation show trends in certain categories. [18][19]. The Integrated Gate Commutated Thyristor (IGCT) was developed to be a new high-power semiconductor based on the developing experience of SCR and GTO which combines the advantage of IGBT and GTO [20]. IGCT has these characteristic such as high current, high voltage, high frequency, high reliability, compact structure and low consumption. It is a strong candidate to be the power semiconductor of choice in Medium Voltage Industrial Applications. Nowadays, IGCT is increasingly applied in Static Var Generator (SVG), Static Var Compensation (SVC) Equipment, Management Energy of Super conduction Storage System and DC High Voltage Power Transmission [21], [22].

B. Future Developments of Power Semiconductors

For future power conversion applications, new structures or semiconductor materials can be investigated for prospective power semiconductor devices [23], [24].

1. Structure Improvement:

Insulated gate bipolar transistors (IGBT), Integrated Gate Commutated Thyristor (IGCT) and MOS- controlled thyristor (MCT) [10] are three new structures of power devices. IGBT is most common



An IGBT is basically a hybrid MOS-gated turn on/off bipolar transistor that combines the attributes of a MOSFET, BJT and thyristor.

2. Materials Improvement:

Silicon based power switching devices are reaching fundamental limits imposed by the low breakdown field of the material. Silicon carbide, with a higher field characteristic, is a promising choice for high power, high temperature and high frequency applications [25], [26], [27] due to the reasons below:

1) Sic has a high electric breakdown property, which will support a very high voltage across a thin layer.

2) Sic has a high carrier drift velocity, which is essential for high frequency operation particularly for minority carrier driven bipolar devices.

3) Sic has a high thermal conductivity realizing high temperature operation and better thermal management of power control applications. Due to the superior material properties, Sic power devices can give a much better performance than silicon power devices, e.g., the on-resistance of Sic can be 700 times lower than similar silicon devices.

POWER CONVERTER TOPOLOGIES

Power converters are used in many applications in power systems, both in the power delivery system and as part of the end user applications. Power delivery applications include HVDC transmission, flexible AC transmission system (FACTS) devices at the transmission level and custom power devices at the distribution level. Many distributed generation and storage devices also incorporate power electronic interfaces. Load-based applications include motor drives and reactive compensators.

Multi-level voltage source converters have been studied intensively for high-power applications . Depending on the application, different topologies of power electronic converters are used in renewable energy generation systems. New converters are developed to increase efficiency of power conversion stage,improve its reliability or decrease initial cost.
In new control method for balancing the DC buses of cascaded H-bridge rectifier has been introduced. The cascaded H-bridge converter is extremely modular and makes possibility for connecting to medium voltage levels directly. Using this structure together with the series-parallel connection of isolated DC/DC converters and a voltage source inverter, the power electronic transformer (PET) structure is achieved. Currently, there is an increasing interest in multilevel power converters especially for medium to high-power, high-voltage wind turbine applications [33] and [34].

Active Power Filter. There are two main methods to suppressing the power system harmonics caused by power electronic devices and other harmonic sources. One is to improve the device itself, eliminating harmonics fundamentally. The other is to detect harmonics, then install compensation devices to compensate [7]. Compared to LC passive filter, AFC (Active Power Filter) has more superior performance, it can be used to compensate for the dynamic harmonics, and the compensation performance will not be affected by the frequency and impedance of the power grid, so it is widely used [8].

A. Types of Power Electronic Converters and its Applications [1, 15, 16, 35]

A power electronic system consists of one or more power electronic converters. A power electronic converter is made up of some power semiconductor devices controlled by integrated circuits. The switching characteristics of power semiconductor devices permit a power electronic converter to shape the input power of one form to output power of some other form. Static power converters perform these functions of power conversion very efficiently. Broadly speaking, power electronic converters (or circuits) for power systems canbe classified into:

1. ***AC to DC converters (phase-controlled rectifiers)***

These convert constant AC voltage to variable dc output voltage. These rectifiers use line voltage for their commutation and therefore they are also called line-commutated or naturally-commutated AC to DC converters. Phase-controlled converters may be fed from a 1-phase or 3-phase source. They are seen by the grid as current sources. These are used in DC drives, chemical industries and excitation systems for synchronous machines etc.

2. DC to AC converters (Inverters)

An inverter convert's fixed DC voltage to a variable AC voltage. The output may be a variable voltage and variable frequency. These converters use line, load or forced commutation for turning-off the switches. They can be seen as voltage sources or as current sources. The former are the latest candidates for most power systemapplications. Inverters find wide use in induction-motor, synchronous-motor drives, induction heating, UPS and HVDC transmission etc.

3. AC to AC converters

These convert fixed AC input voltage into variable AC output voltage. These are of two types as under:

I. AC voltage controllers (AC voltage regulators)

These converter circuits convert fixed AC voltage directly to a variable AC voltage at the same frequency. ACvoltage controllers are widely used for lighting control, speed control of fans and pumps etc.

4.Cycloconverters

These circuits convert input power at one frequency to output power at a different frequency through one-stage conversion. Line commutation is more common in these converters, though forced and load commutated cycloconverters are also employed. These are primarily used for slow-speed large AC drives like rotary kiln etc.

5 DC to DC converters

Converts input DC to variable magnitude DC, e.g., voltage regulators. Like (DC Chopper-Buck/Boost/Buck- Boost Converter).

B. **Advantages and Disadvantages of Power Electronic Converters [1]**

(i) High efficiency due to low loss in power-semiconductor devices.
(ii) High reliability of power-electronic converter systems.
(iii) Long life and less maintenance due to the absence of any moving parts.

(iv) Fast dynamic response of the power-electronic systems as compared to electromechanical convertersystems.
(v) Small size and less weight result in less floor space and therefore lower installation cost.
(vi) Mass production of power-semiconductor devices has resulted in lower Cost of the converter equipment.

Systems based on power electronics, however, suffer from the following disadvantages

(a) Power-electronic converter circuits have a tendency to generate harmonics in the supply system, as well asin the load circuit. In the load circuit, the performance of the load is influenced, for example, a high harmonic content in the load circuit causes commutation problems in DC machines, increased motor heating and more acoustical noise in both DC and AC machines. So steps must be taken to filter these out from the output side ofa converter. In the supply system, the harmonics distort the voltage waveform and seriously influence the performance of other equipment connected to the same supply line. In addition, the harmonics in the supply line can also cause interference with communication lines. It is, therefore necessary to insert filters at the input side of a converter.
(b) AC to DC and AC to AC converters operate at a low input power factor under certain operating conditions. In order to avoid a low pf, some special measures have to be adopted.
(c) Power-electronic controllers have low overload capacity. These converters must, therefore, be rated to take momentary overloads. As such, cost of power electronic controller may increase.
(d) Regeneration of power is difficult in power electronic converter systems.

CONCLUSIONS

This paper has reviewed Power electronic devices are the primary method of system control, ensuring the security, stability, dependability, and economy of the power system's operation. They can also be used to modify the distribution of the power load on the grid, improve the grid's structure, and enable the grid to self-heal under a range of conditions. Electricity electronics help ensures that the electricity system continues to play a vital part in the country's economy. Power electronic devices are widely used in energy storage, power transmission, and power generating, among other applications. Power electronics which has become a inseparable part of power system helps to improve power quality, power system performance, and promote the gradual transformation of intelligent power system. The most important thing is that advanced power electronics lays substantial foundation for the long-term development of power systems in the future.

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