CHAPTER ONE

INTRODUCTION

1.1 GENERAL

Industrial growth with increased automation has made electricity as the key resource for the modern society. In this scenario, the demand for electricity is growing each day. Electric power in one's life has assumed importance as basic necessity of life next to food, shelter and clothes. The per capita consumption in India has increased forty times from 15 kWH/yr in fifties to 600 kWH/yr at the moment. It is to be noted that, it is still lesser than per capita world consumption of 2700 kWH/yr [1]. Electricity consumption in United States for example has also been growing ten percent per year [2]. On the other side, there is a world over general belief, that supply of electric power could be met only through addition of generation capacity. However, a deeper look reflects that generation capacity alone cannot be only dimension. In fact, supply of electricity is akin to the functioning of a human body i.e. Heart (generation), Main arteries (main power grid), Sub-arteries (sub-transmission), Capillaries (distribution), Brain (load dispatch centers) and Nerves (dedicated communication). The two important functional parameters of human being are Blood Pressure (BP) and heart beat, which are nothing but voltage and frequency of the power system. Thus, all the organs of power sector, namely, Generation, Transmission, Distribution, Load Management and Communication; need to be balanced to ensure healthy system functioning[3].

The demand for electricity is growing each day, and on other side the gap between available electrical energy and demand is widening. In fact in the last few years, Indian economy has been growing at a rapid and impressive pace, averaging over 8%, with 2007 exhibiting 9% GDP growth. The manufacturing and service sector are growing even faster by logging double digit growth rates. Key ingredient in achieving these growth rates and sustaining them will be availability of adequate quantity and quality power at affordable prices. India has installed capacity of over 132110 MW. However, the country still has been witnessing peak shortages and energy shortages of about 13% and 10% respectively; implying capacity is short of the required levels [1]. Further, as the volume of power transmitted and distributed increases, the associated loss becomes an important issue of concern. Transmission & Distribution (T&D) losses in fact have been ranging between 30-45% in many states. It is to be noted that we have country goal "Electricity for all by 2012". Further, if the per capita consumption has to be brought at par with the world average, then country needs to install at least 5 times the existing installed capacity by the year end of 2012 [1].

Added to it is also the proliferation of sensitive electronics and critical processes, which impose need for high quality and reliable supply. Further, rising costs and growing environmental concerns make the process of building new power transmission and distribution lines increasingly complicated and time consuming. This has led people work on the alternative solutions. Considerable efforts are hence put in renewable sources of energy like wind, solar, bio-gas etc. In fact, as per the working group formed by Govt. of India on power for XI Plan, 13,500 MW are targeted from renewable energy sources and 22,000 MW from captive / merchant power plants [1, 4-6]. Organizations like Power Grid, have also been planning to adopt hybrid Ultra High Voltage (UHV) transmission system comprising of 800 kV/1200 kV AC Systems and ± 800 kV HVDC. On the other side, considerable efforts are being put in to make existing lines as well as new ones more efficient and economical. It is widely accepted fact, that improvement in energy efficiency has faster payback compared to the creation of fresh generation capacity.

From energy perspective, the present scenario can be best represented as shown in fig. 1.1

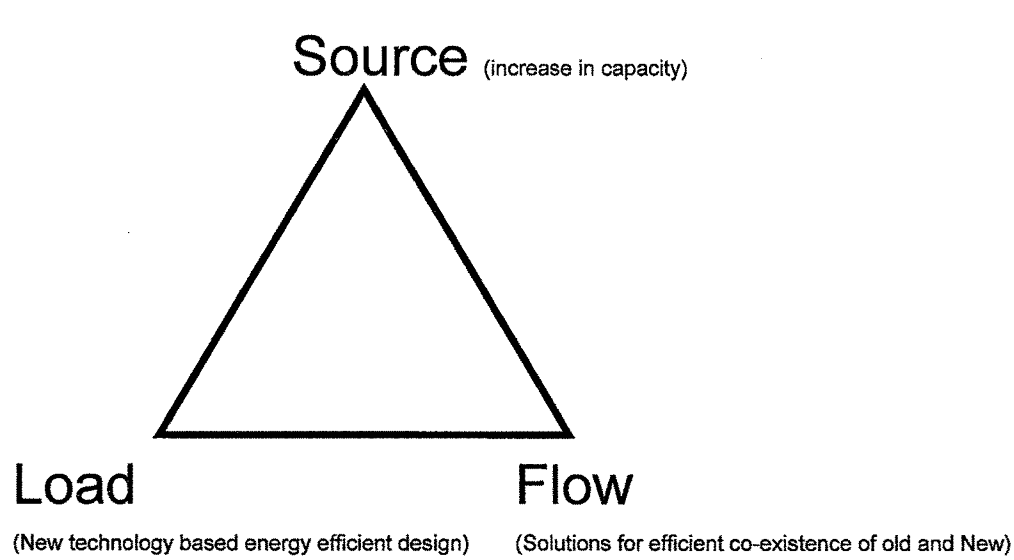


Fig. 1.1 Energy Perspective

This can be best explained as below:

I. Source :

- Efforts for increasing the sources of energy including the efforts for alternative and renewable sources of energy.

II. Load :

- Efforts for identifying newer and efficient technology so as to reduce the power consumption requirements

III. Flow :

- Efforts for exploring newer solutions to ensure co-existent of conventional and modern technologies in the most efficient way, to see highest conversion of generated power for eventual usage by load.

In this context, making the existing lines as well as new ones more efficient and economical becomes the most compelling alternative. Within the given constraints of power availability, transmission and distribution losses, economics, and supply of uninterrupted quality and reliable power to consumers, Power Quality (PQ) has assumed sustained concern in the present scenario [7-31].

Electrical power is an important raw material for all commercial operations and like any other raw material, the quality of supply is very important. Numerous industries, institutes, research organization, electricity boards and utilities have been doing extensive research to address power quality and associated challenges. Further to add, electrical power remains an unusual commodity because it is required as a continuous flow. It cannot be conveniently stored in quantity also cannot be subject to quality assurance checks before it is used. It is, in fact, the epitome of the 'Just in Time'(JIT) philosophy in which components are delivered to a production line at the point and time of use by a trusted and approved supplier with no requirement for incoming inspection. For 'Just in Time' (JIT) to be successful, it is necessary to have good control of the component specification, a high confidence that the supplier can produce and deliver it on time, and knowledge of overall product behavior with 'on limit' components. The situation with electricity is similar; the reliability of the supply must be known and the resilience of the process to variations must be understood. In reality, of course, electricity is very different from any other product. It is generated far away from the point of use, is fed to the grid together with the output of many other generators and delivered at the point of use via several transformers and many kilometers of overhead and possibly underground cabling. Further, with unbundling of state electricity boards/ privatization, these network assets are now being owned, managed and maintained by a number of different organizations. Assuring the quality of delivered power at the point of use hence is no easy task and there is no way that sub-standard electricity can be withdrawn from the supply chain or rejected by the customer [7].

It is important to note that, quality as well as economics is important for present day users. However, price and quality are complementary. Together, they define the value that customers derive from consuming electricity. In order to avoid the high cost of equipment failures, all customers have to make sure that they receive electricity supply of satisfactory quality, and that their electrical equipment is capable of functioning as required when disturbances occur.

1.2 POWER QUALITY PHENOMENA

The Power Quality relates to delivery of power at committed voltage and frequency without any deviation in sinusoidal nature of the voltage.

Deviations, however, could be as below.

- Voltage dips and swells
- Short and long interruptions
- Harmonics and inter harmonics
- Transients, Surges (switching, lightning)
- Power frequency variations : Flicker
- Unbalance
- Voltage value (long term under voltages and over voltages)

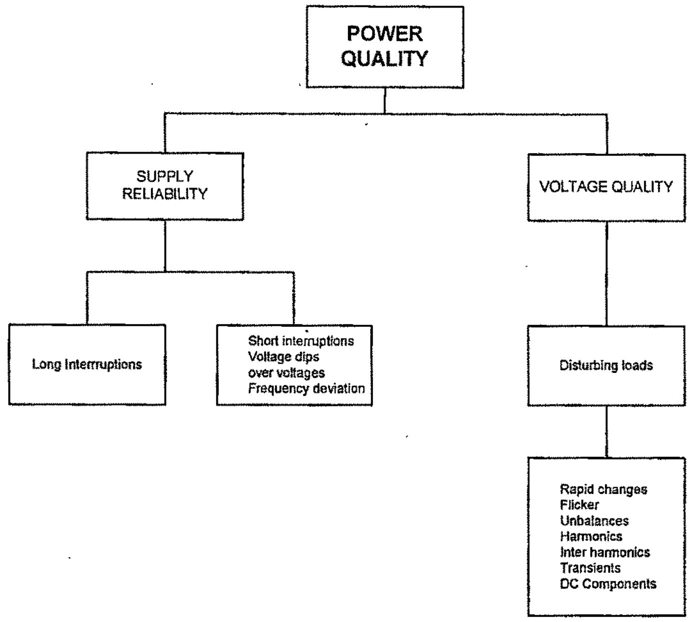


Fig. 1.2 Simplified Characterization of Power Quality

Just how much deviation from perfection can be tolerated depends on the user's application, the type of equipment installed and his assessment of his requirements. Also, each of the power quality problems listed above has a different cause. Some problems are a result of the shared infrastructure. For example, a fault on the network may cause a dip that will affect some customers and the higher the level of the fault, the greater the number affected. Similarly, a problem on one customer's site may cause a transient that affects all other customers on the same subsystem. Sudden inrush currents with weak network conditions also further intensify such problems. Poor power factor of operation can also be conceived as potential culprit in aggravating the power quality issues linked with voltage and current profiles. Other problems such as harmonics, arise within the customer's own installation and may or may not propagate into the network and so affect other customers. Harmonic problems can be dealt with by a combination of good design practice and well proven reduction equipment [32-34].

Thus, in brief power quality can be quantified as:

- Constant sine-wave shape; no harmonics
- Constant frequency; unchanged nominal value
- Symmetrical three-phase voltages with phases shifted by 120°

- Constant RMS voltage value; nominal power system voltage value unchanged over time
- Fixed voltage; power system voltage unaffected by load changes
- Reliability; energy in the required amounts available at all times

The report [8] describes a desk survey of power quality related studies performed in various countries of Europe, with a view to identify the problems that adverse power quality creates for various groups of end users. Report covers in detail the survey conducted by,

a) European Copper institute survey

b) Dutch DNO Survey

c) UK Survey

d) Schneider Electric Survey

The survey involving several types of customer, especially in Europe, indicates that reliability is the critical consideration for all customers. Some reports for other countries are also covered in publications [21, 23-27, 30]. No such dedicated report is available for Power Quality (PQ) problems and impacts in India. However, different publications in trade magazines and growth of usage of Power Quality based products (with ever increasing demands facing shortfall of the available cost optimal solutions) do highlight the needs. A paper [9] in Electrical India does give a brief overview of the Power Quality scenario in India.

1.3 POWER QUALITY CONCERNS

The Power Quality from Transmission and Distribution point of view revolves mainly around power factor of operation, supply voltage distortion, and harmonics getting introduced in the supply networks. From the researchers point of view the problem is even more difficult. There is some limited statistics available on the quality of delivered power. However, the acceptable quality level as perceived by the supplier (and the industry regulator) may be very different from that required, or perhaps desired, by the consumer. The most obvious Power Quality problems are complete interruption (which may last from a few seconds to several hours) and voltage dips/sags where the voltage drops to a lower value for a short duration. Naturally, long power interruptions are a problem for all users. However, many operations are very sensitive to even very short interruptions. There are international standards, from Institution of Electrical and Electronics Engineers (IEEE), International Electro technical Commission (IEC), European Norms (EN), American National Standards Institute (ANSI) etc. which set limits of voltage variation and harmonic voltage distortion below which equipment should function without error. Similarly there are also standard limits for voltage deviation and harmonic voltage distortion of the supply. Examples of sensitive operation are: continuous process operations, where short interruptions can disrupt the synchronization of the machinery and result in large volumes of semi-processed product.

Typical examples are,

- Paper making industry, petrochemical plants, refineries where the clean-up operation is long and expensive.
- Multi-stage batch operations, where an interruption during one process can destroy the value of previous operations. For example, semiconductor industry, where the production of a wafer requires a few dozen processes over several days and the failure of a single process is catastrophic.
- Data processing, where the value of the transaction is high but the cost of processing is low, such as share and foreign exchange dealing can also see serious impact in such scenario. The inability to trade can result in large losses that far exceed the cost of the operation.
- Certain operations, in common man day to day life, which though appear mundane, have quite critical power supply requirements. Examples include hospitals, shopping malls - large retail units with computerized point of sale and stock control equipment and manufacturing plant with distributed control or railway reservation system, core banking institutions involving Automatic Transaction systems (ATMs).

In brief, Power Quality problems can be listed as below [10, 14]

- Loss of energy and poor efficiency of transmission, distribution of power
- Circuit breakers nuisance tripping
- Computers lock up
- Damage to electronics gadgets
- Data loss
- Lights flicker, blink, or dim
- Loss of synchronization of processing equipment

- Malfunctions/Damages of process equipment (PLC, motors etc.)
- Noise interference to telecommunication lines
- Relays and contactors nuisance tripping
- Transformers and cables overheating

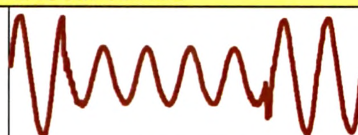
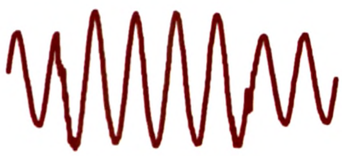
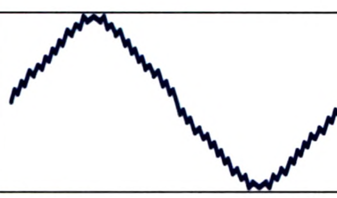
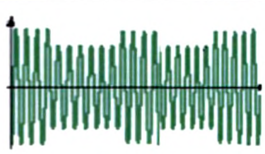
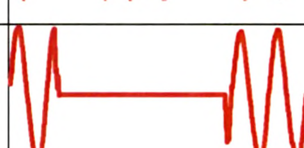
Disturbance		Possible Causes	Consequences
Voltage Dip		• Successfully cleared faults resulting from lightning, insulation failure etc • Start up of large motors	• Shutdown of certain equipment particularly electronic devices
Over voltages		• Fault in another phase • Lightning strike on network structure • Incorrect setting in substation (Sustained over voltages)	• May harm equipment with inadequate design margins
Harmonic distortion		• Non linear load • Resonance • Transformer saturation	• Voltage distortion causing additional heating in motors • Disturbed operation of electronic equipment
Flicker or fluctuations		• Start up of large motors • Electric arc furnaces • Repetitive large loads (eg. arc welding)	• Weakening of components • Malfunctions
Transient over voltages		• Lightning strike • Switching event	• Insulation failure • Reduced life of transformers, motors etc
Interruption		• Close faults • False tripping • Load shedding	• Shutdown of equipment
Phase unbalance		• Single phase loads	• Machine overheating

Fig. 1.3 Power Quality Concerns

Thus, it is evident that Power quality has become a very important issue for electricity companies, the operating, maintenance and management personnel of service sector and industrial sites, as well as for equipment manufacturers due to following reasons,

- Economic necessity of business to increase competitiveness
- Widespread use of equipment, sensitive to voltage disturbance and/or generates disturbance itself
- Opening of electricity market

1.4 POWER QUALITY SOLUTIONS

The products offered for the Power Quality improvements also need to address the issues related to speed, accuracy, controllability and dynamic response, apart from the economics. Utilities too have been imposing restrictions and penalties in respect of the voltage and current distortion, maximum or peak reactive power, maximum kVA, low power factor of operation, and excess kW drawn by the consumer. For an end user, what matters is availability of high quality reliable power within constraints of economics, though "price and quality" are complementary. End user also has an expectation of high returns on investment.

With this as the Power Quality scenario, an optimal solution having right technology for proper operation of applied sub-systems has become the important need of the hour. Designers across the globe hence have been putting efforts to evolve novel power electronics based solutions, which can satisfy both the consumer as well as the utility while making use of state of art power electronic devices and the controllers. Report [8, 10, and 14] also describes the current equipment available/ needed to mitigate the identified problems and presents estimates of the associated costs.

Based on current technology, these solutions can be classified as below.

1. Equipment specification changes
2. Intra-System level equipment protection (controls protection)
3. Site wide protection (overall protection inside plant)
4. Grid/Utility solutions

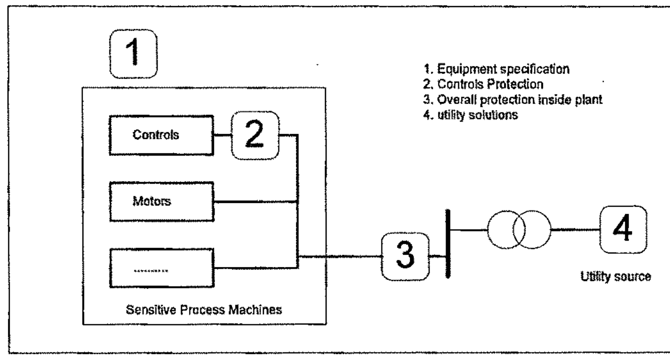


Fig.1.4 Levels of protection for Power Quality mitigation

The choice of solution depends on

1. The nature of the disturbance generated and/or to be prevented
2. The required level of performance
3. The financial consequences of malfunction
4. The time required for a return on the investment
5. Practices, regulations and limits on disturbance set by the grid operator

Power Quality Solutions which have evolved and in use during last decade can now be listed as below:

- Static VAR compensators
- Harmonic filters
- Dynamic voltage restorers
- Backup generators
- Isolation transformers
- Multiple independent feeders
- over sizing of equipments (Transformers, motors) and cables (line and especially neutral conductors)
- Static transfer switches,
- Surge protectors
- Uninterruptible power supply
- Voltage stabilizers etc

More details for this solution are covered in ref. [8, 10, and 14].

Narrowing down further in respect of power quality, reactive power control and voltage distortion (caused due to weak networks and associated current harmonics) can be considered to be the most important aspects. The mitigation solutions for reactive power therefore have seen changes over the past few decades from fixed capacitors to present day dynamic reactive power compensators. These solutions are in detailed covered in Chapter 3. Similarly, the harmonic mitigation also has seen change from passive filters to present day active filters [32, 34]. Further, Flexible AC Transmission Systems (FACTS) also cover number of technologies that enhance the security, capacity and control of many parameters in power transmission systems [35-36]. These solutions raise dynamic stability limits and provide better power flow control and thereby helping power grid owners to increase existing transmission network capacity while maintaining or improving the operating margins necessary for grid stability. Voltage Source Converters (VSC) based FACT controllers for transmission and distribution systems are given in fig. 1.5.

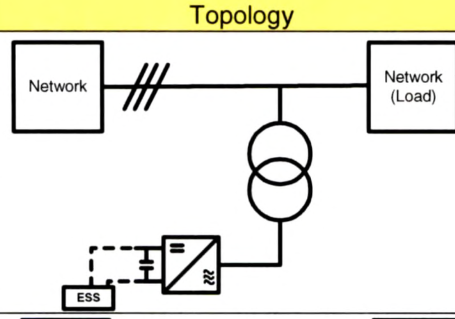
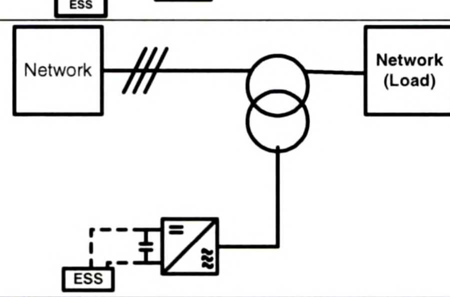
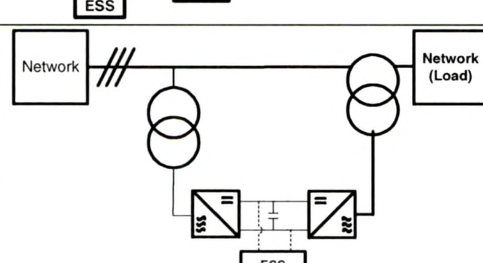
Name	Topology	Preferred Tasks	
		Transmission	Distribution
STATCOM (DSTATCOM) Static Synchronous Compensator		• Voltage Control • Oscillation Damping • Reactive Power regulation	• Flicker Compensa tion • Reactive Power Compensa tion • Harmonic Filter
S^3C (DVR) Static Synchronous Series Compensator (Dynamic Voltage Restorer)		• Power Flow • Transient Stability • Oscillation Damping	• Sag/Swell Compensa tion
UPFC Unified Power Flow Controller		• Power Flow • Transient Stability • Oscillation Damping • Voltage Control	• Sag/Swell Compensa tion • Under Voltage/ Over Voltage Compensa tion

Fig. 1.5 VSC based FACTs controllers for Transmission and Distribution systems

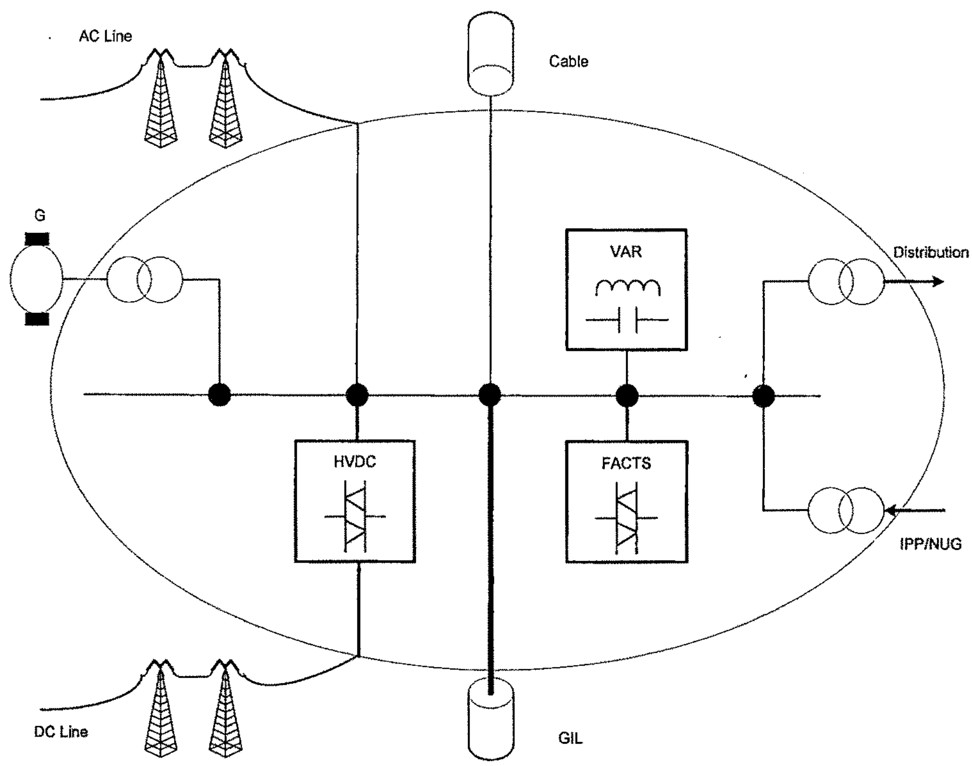


Fig. 1.6 Network node considerations with power electronic systems and / or modules

The next generation(s) of semiconductors will enhance capabilities of FACTs devices. It is also fuelling research on the new concepts for connection of dispersed generation, DC/AC and AC/AC conversion as well as new power quality applications [37]. Fig 1.6 gives view of network node considerations with usage of power electronic systems and / or modules, while fig 1.7 shows trends in power electronic applications driven by new generation of power semiconductors.

On power conversion side, the rectifier / converter technology has moved from diode rectifiers to thyristor converters and now to present day four quadrant converters using self commutated devices such as Gate Turn off Thyristors (GTO's), Insulated Gate Bipolar Transistors (IGBT's), and Integrated Gate Commutated Thyristors (IGCT's) etc. Development of power semiconductors has been mainly with respect of reducing switching losses, so that devices can operate at higher switching frequencies. This development has enabled many AC applications exploiting new generation of power semiconductors in almost all areas of transmission and distribution systems. Major two areas to be noted are i) power electronic devices used for substituting mechanical switches and contacts and ii) power electronic modules and systems comprising valves and / or converters for controlling network parameters by producing / consuming reactive power and / or injecting voltages or currents in parallel and / or in series with a network branch[38, 39].

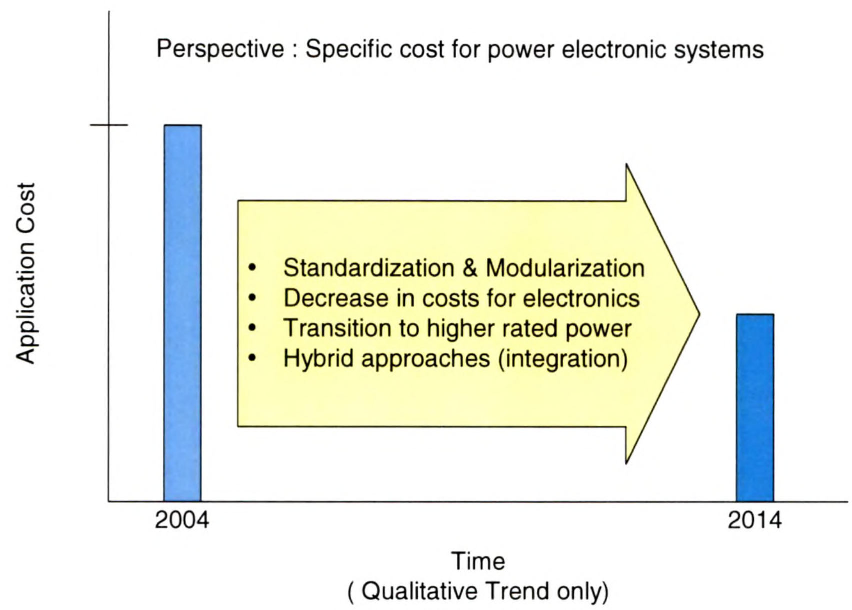


Fig 1.7 Major trends in power electronic applications driven by new generation of power semiconductors

Similarly, the Control Electronics or Control Electronic Regulator design also has undergone substantial change from analog to digital controls with 8/16/32 bit Microcontrollers and Digital Signal Processors, making use of embedded software with operating speeds from few MHz to GHz and offering sub cycle control responses [40]. While the solutions in early sixties have been based on hardwired Analog and Digital circuits, with the emergence of Microprocessor/Microcontrollers in early 1970s, the embedded firmware based control electronics became more acceptable. With every decade, new and new generation of controllers inclusive of Mixed Signal Logic and on chip multiple processors integrated with high speed Analog to Digital Converter (ADC) and Digital to Analog Converters (DAC) along-with special functions blocks have evolved. On chip hardware integrated with algorithms for power device controls have changed the philosophy of control electronics realizations. Higher operating speeds of digital processors and combination of fast switching devices also has led to usage of fiber optics interface between the Gate drive circuit of power devices and Control Electronics. On the other side, it is also important to note that these devices also are becoming more sensitive to power irregularities; also they make circuits more susceptible to Electro-Magnetic Interference (EMI). Technology also has led to the circuits being miniaturized with less space between adjacent conductors and increasing susceptibility to the over-voltage and increasing adjacent channel interference. The integrated circuits including the core controllers have also become smaller and densely packed which on one side decreases the heat dissipation and makes them less robust. Further, the operating voltage have been falling from logic levels of 15V in 70's to 1.5V in 2008, which makes them equally more susceptible to the smaller over-voltages from transient conditions leading to operating errors.

Conducted research across the globe as represented in fig 1.8, however, still continues to address power quality mitigating solutions, especially for weak networks. Thus, the research continues on mitigation of reactive power (more so dynamically varying) and current harmonics / distortion caused by them [41-46]. In line with this scenario, work presented in this thesis deals with new methods / techniques for reactive power control using Pulse Width Modulation (PWM) based Voltage Source Converters (VSCs). As a part of power quality the work presented also includes economical technique for controlling sudden voltage dips/rises in the industry networks and unity power factor based Electronic Transformer.

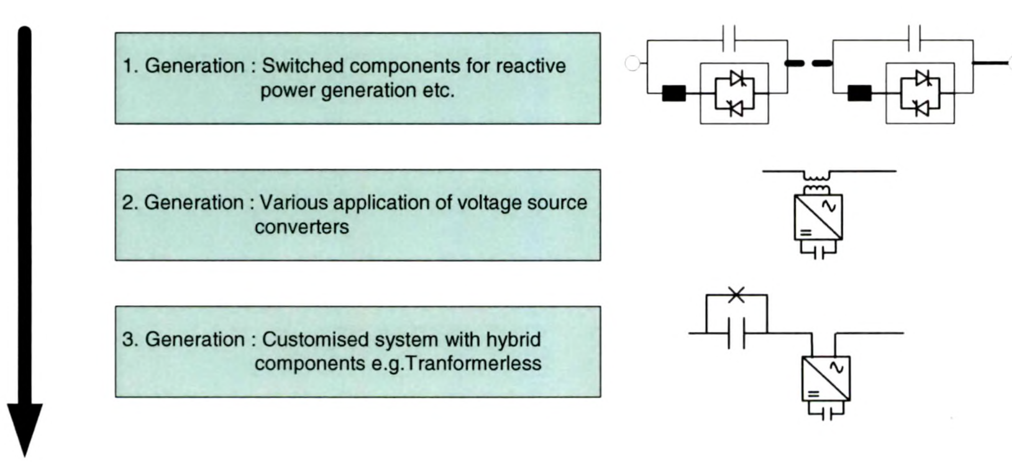


Fig. 1.8 Evolution of Power Electronic systems for controlling the parameters of power transmission and distribution system

Specific areas covered are,

1. Design, implementation and working of single phase dynamic reactive power compensator
2. Design, implementation and working of three phase dynamic reactive power compensator
3. New concepts extending the use of the above dynamic reactive power compensators to achieve improvements in system installations
4. New concepts in dynamic reactive power compensation, especially in Low Voltage (LV) distribution and Power Quality improvements.

1.5 OUTLINE OF THESIS

The work in this thesis is arranged as given below.

Chapter 2 gives review of development with focus on dynamic reactive power compensation, particularly in low voltage distribution. Survey, based on leading Journals (IEEE, IEE and others), draft publications by manufacturers and latest information as available from the Internet, are then compiled. These include available converter topologies, control techniques, power devices and power range covered in terms of kW/kVAR/kVA. It then highlights few case studies and covers the challenges for application like Railway, Automobile, and Windmill having dynamic load conditions.

Detailed design of dynamic reactive power compensator (termed here as STATCON) for single-phase and three-phase low voltage applications is covered in Chapter 3. Fundamentals of reactive power compensation are described in initial part followed with detail performance tradeoffs of traditional and current generation solutions. This is then followed by detail design description of single-phase and three-phase dynamic reactive power compensator (STATCON). At the end, highlights of the design innovations implemented for achieving the optimal dynamic reactive power compensation in terms of single-phase and three-phase STATCON are presented.

Chapter 4 then describes the issues related with digital controller design. It highlights the designs integration-implementation approaches with new generation of micro-controller, micro-processor and digital signal processors. Case studies of installation in automobile plant spot welding application and railway traction substation along with field performance results of designed STATCON are also then supported. Later, it gives insight to Electro Magnetic Interference and Compatibility (EMI/EMC) aspects and the advancements, which help highly reliable Control Electronics regulator design while working with power devices. Some of the software and hardware features and fallouts are also included, as experienced in the process of design evolution and converter installations.

Chapter 5 introduces a concept of dynamic reactive power compensation with source side active power balancing, against unbalanced load side currents. Simulation results on MATLAB platform are supported along with control algorithms to demonstrate a unity power factor operation with equal active power loading.

Chapter 6 presents another concept of dynamic reactive power compensation in three-phase application using single-phase STATCON in power multiplexed mode. Simulation results on MATLAB platform, with fuzzy logic based controller design and experimental results are also highlighted to support the concept.

Chapter 7 discusses an economical approach for dynamic reactive power compensation by having STATCON operation around steps produced by an integrated Thyristors Switched Capacitor (TSC) banks. Simulation results on MATLAB platform highlighting the advantages are also presented in support towards utility of the concept.

Chapter 8 considers a concept of Electronic Transformer in low voltage distribution system. Potential for this concept, especially for meeting quality power demands, is also illustrated. Simulation results are also covered to support the proposed approach.

Transformer based economical approach to compensate severe voltage dips / rises in networks is then introduced in Chapter 9. Analysis, simulation results, and experimental results are also included.

Overall conclusion, based on work presented in the thesis is given in Chapter 10 along with future scope of the work.