POWER ELECTRONICS – PAST, PRESENT & FUTURE

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POWER ELECTRONICS (PE)

- **DEFINITION**

Technology associated with the efficient
- **Conversion** • **Control** • **Conditioning**

of electrical power / energy by static / solid state means from the available electrical input form into the desired electrical output form

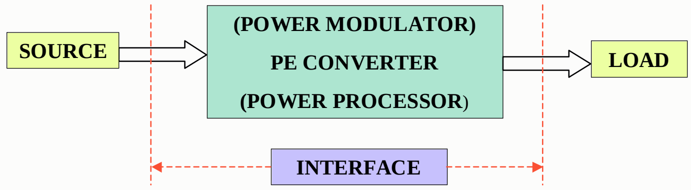
- **GOAL**

To control the flow of energy from an electrical source to an electrical load with

- **High efficiency**
- **High availability**
- **High reliability**
- **Small size**
- **Light weight and**
- **Low cost**

Source: Wilson, Trans. PE, May, 2000

- **FEATURES**
- **Provides an interface between the fixed voltage / frequency source and the diverse requirements of consumers' load**



▪Source: **Fixed Voltage / Fixed Frequency**

Small : Wind / Photovoltaic/ Battery / Fuel Cell
Medium : Diesel/ Gas Turbine Generator
Large : Hydro / Thermal / Nuclear
DC, 1-Phase/ 3-Phase AC (50 / 60 hz)

▪Load : **Diverse Requirements—Examples**

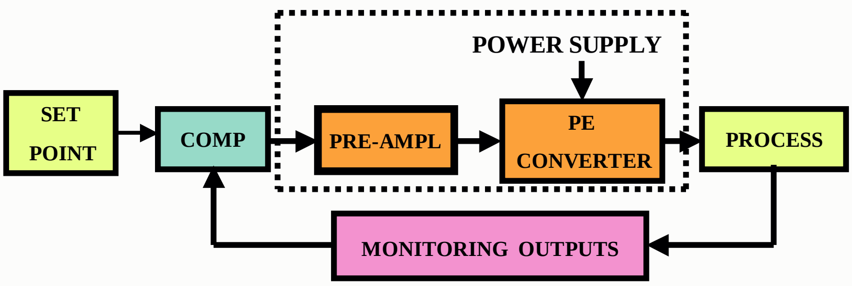
Electro Chem.Plants	:	**Low DC Voltage, High Current**
Induction Furnace	:	**1-phase , High Frequency AC >> 50hz**
Machine Tools	:	**Variable DC Voltage**
Plants with AC Motors	:	**Variable Voltage Variable Frequency (VVVF)**
Computer Loads	:	**Un-interrupted Power Supply (UPS)**
Aircraft Power Systems	:	**Variable Speed Constant Frequency (VSCF)**
HVDC Systems	:	**AC/ DC & DC / AC**

- **PE CONVERTER : Accepts electric power from the existing source and converts it in a controlled manner to a suitable form compatable with a particular load or process**

  AC / DC **DC / DC** **DC / AC** **AC / AC**

- **Provides an essential link between the micro- / milliwatt levels of the electronic controllers (now, computers) and the kilo-/megawatt levels of process.**

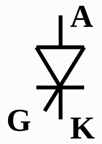
POWER ELECTRONIC CONTROLLER



A PROCESS CONTROL BLOCK DIAGRAM

- Gone through more than four and half decades of intense technological revolution (silent*?) since the development of SCR in 1957

- THYRISTOR (SCR)



- SILICON SEMICONDUCTOR
- CONTROLLED RECTIFIER
- LATCHING SWITCH
- AMPLIFIER (Power Gain Over 10^8)

- Emerged as **KEY TECHNOLGY** in all areas of

POWER PROCESSING

- GENERATION
- TRANSMISSION / DISTRBUTION
- UTILISATION

and SYSTEMS

- INDUSTRIAL
- COMMERCIAL
- RESIDENTIAL
- TRANSPORTATION
- UTILITY
- AEROSPACE
- TELECOMMUNICATION

- **MAJOR APPLICATION AREAS OF PE:**

- REGULATED POWER SUPPLIES (DC &AC),UPS, SMPS
- ELECTRO-CHEMICAL PROCESSES
- HEATING AND LIGHTING CONTROL
- INDUCTION HEATING
- ELECTRONIC WELDING
- PHOTO-VOLTAIC AND FUEL CELL CONVERSION
- HVDC SYSTEMS / FACTS
- POWER LINE VAR AND HARMONIC COMPENSATION (SVC) (APLC / APF)
- SOLID STATE CIRCUIT BREAKER
- MOTOR DRIVES (DC & AC)—INCLUDING ROBOTICS AND ACTUATORS (*MOTION CONTROL*)

POLARISATION IN TWO DIRECTIONS:

- LOW POWER HIGH FREQUENCY SUPPLIES (e.g. SMPS)
- MODERATE TO HIGH POWER LOW FREQUENCY (MOTOR DRIVES, UPS, APLC, ...

- **ACHIEVEMENTS WITH POWER ELECTRONICS**

- COST AND SPACE SAVING
- ENERGY SAVING *- INDUSTRIAL ECONOMY
- REDUCTION OF MAINTENANCE
- IMPROVEMENT OF RELIABILITY
- LONGER LIFE
- HIGH QUALITY OF PERFORMANCE
- COMPLETE CONTROLABILITY
- MAXIMUM FLEXIBILITY
- CLEAN ENVIRONMENT

(*Motor drives and lighting industries represent more than 75% of electrical power consumption .

Today more than 40% of electric power being processed pass through some form of PE equipment. Expected to be 80% by 2010. With use of PE, the energy is to be saved by 35%)

TABLE – 1
SIGNIFICANT EVENTS IN THE PAST HISTORY OF POWER ELECTRONICS (TILL 1960)

1783 CONCEPT OF 'SEMICONDUCTOR' (VOLTA)

1802 DISCOVERY OF 'UNIPOLAR CONDUCTOR' (ERMAN)

1803 RECTIFICATION EFFECT OF COPPER OXIDE (OHM)

1838 ROTATING CURRENT INTERRUPTER 'INVERSOR' (POGGENDROF), 'MUTATOR' (DOVE)

1876 SELENIUM RECTIFIER (SIEMENS / ADAMS)

1883 EDISON EFFECT- HEATED WIRE EMITS ELECTRONS

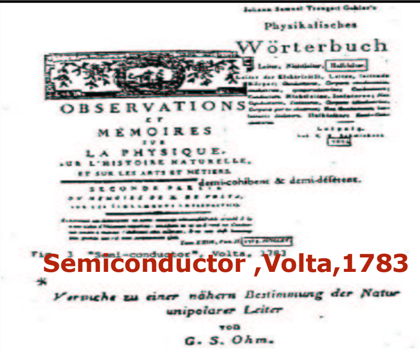
1896 SINGLE-- PHASE RECTIFIER BRIDGE CIRCUIT (POLLAK)

1897 GRAETZ CIRCUIT (THREE-- PHASE BRIDGE RECTIFIER)
DISCOVERY OF ELECTRON (THOMSON)

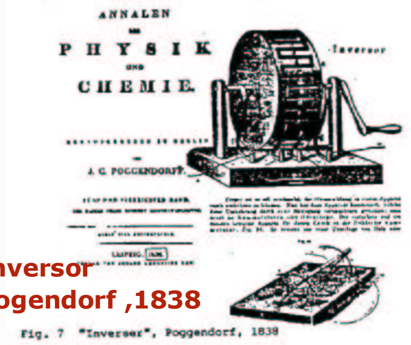
1902 COOPER- HEWITT PATENT ON MERCURY-ARC RECTIFIER

1903 PATENT ON PRINCIPLE OF PHASE ANGLE CONTROL (THOMAS)

....CONTD.



Semiconductor ,Volta,1783



Inversor
Pogendorf ,1838

Fig. 7 "Inverser", Poggendorf, 1838

Source: Kloss, EPE 1985

Bridge, Christie 1833
Rect.Bridge,Pollak,
1896; Graetz,1897

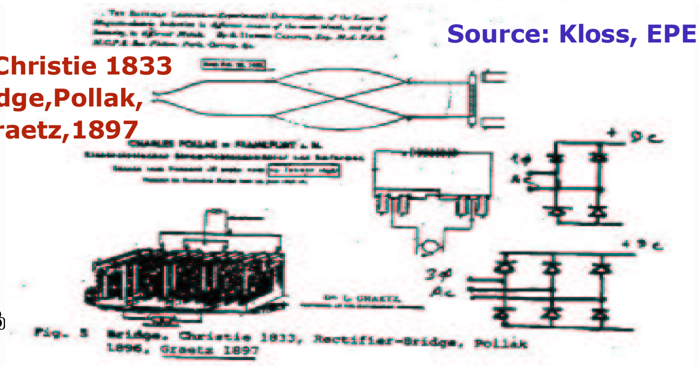


Fig. 5 Bridge, Christie 1833, Rectifier-Bridge, Pollak 1896, Graetz 1897

Mercury-arc Rectifier, Cooper-Hewitt 1902

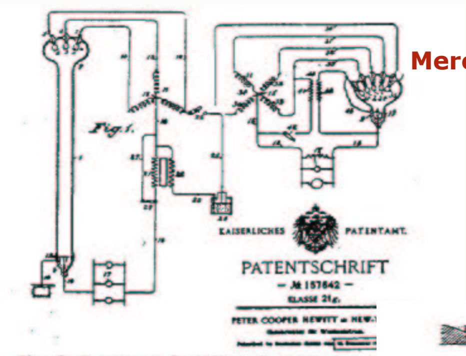


Fig. 8 Mercury-arc Rectifier, Cooper Hewitt, 1

Source: Kloss , EPE 1985

Phase Angle Control
Thomas 1903, Toulon 1923

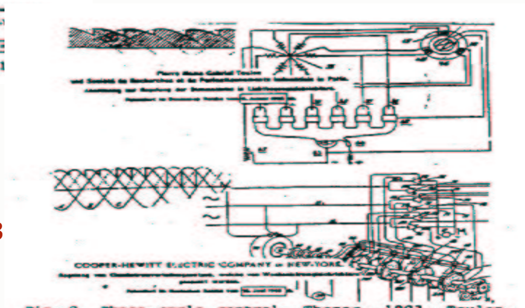


Fig. 9 Phase angle control, Thomas, 1903, Toulon, 1923

TABLE-1 (CONTD.)

1904 THERMIONIC DIODE (PAWLOWOSKI / FLEMING)

1905 STEINMETZ HIGH VOLTAGE RECTIFIER FOR STREET LIGHTING

1907 THREE ELEMENT THERMIONIC VACUUM TUBE, *AUDION* TRIODE (DE FOREST)

1911 METAL TANK MERCURY RECTIFIER FOR SREET LIGHTING (SCHAFER)

1912 MAGNETIC AMPLIFIER FOR RADIO TELEPHONY (ALEXANDERSON, GE)

1913 DISCOVERY OF GRID CONTROL PRINCIPLE (LANGMUIR / PIERCE)

1922 CYCLOCONVERTER PRINCIPLE (MEYER / HAZELTINE)
GRID CONTROL APPLICATION (TOULON)
INVERTED RECTIFICATION (ALEXANDERSON)

1923 POOLED CATHODE THYRATRON *(LANGMUIR)

-- contd.

*(Thyratron- Greek derivative meaning 'a door that can be opened')

TABLE – 1 (CONTD.)

1924 CHOPPER PRINCIPLE (BURNSTEIN)

1925 PARALLEL INVERTER COMMUTATION (PRINCE)

1926 HOT CATHODE THYRATRON (HULL)

1931 CYCLOCONVERTER FOR RAILWAYS (SCHENKEL & ISSENDORF)

1933 SINGLE ANODE LIQUID MERCURY CATHODE IGNITRON (SEPIAN, WESTINGHOUSE)

1934 THYRATRON MOTOR BUILT AND TESTED (ALEXANDERSON, GE) Mittag Patent on ASCI principle

1935 HVDC TRANSMISSION BETWEEN MECHANICVILLE AND SHENECTADY, NY, USA

1939 AMPLIDYNE INTRODUCED (ALEXANDERSON)
ELECTRONIC KRAMER /SCHERBIUS DRIVE (ALEXANDERSON / STOHR)
LCI-SYN. MOTOR DRIVE CONCEPT (STOHR)

1942 20 MW FREQUENCY CHANGER, 25/60 Hz

… CONTD.

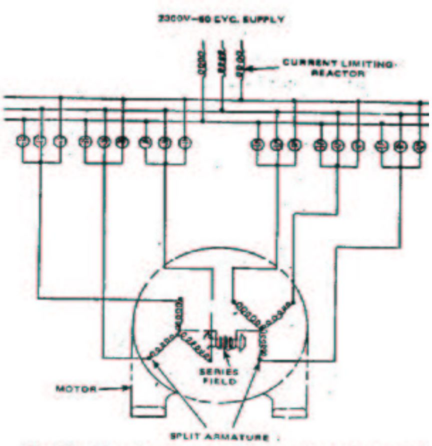


Fig. 12. Thyratron motor elementary power circuit

Thyratron Motor Power Circuit
Alexenderson, 1934

Source:Kloss, EPE 1985

Power Rectifier
Syb-Syn.Cascade
Schafer,1912

Fig. 10 Power-Rectifier, Sub-Synchron Cascade, Schäfer, 1912

TABLE – 1 (CONTD.)

1948 **INVENTION OF TRANSISTOR (*POINT CONTACT*) (BARDEEN, BRATTAIN, SHOCKLEY, BELL LAB), Nobel Prize in 1956**

1951 **JUNCTION TRANSISTOR (SHOCKLEY)**

1953 **GERMANIUM POWER DIODE, 100 A**

1954 **SILICON POWER DIODE;**
FIRST TRANSISTOR RADIO

1957 **THYRISTOR (SCR) ANNOUNCED (BELL LAB, USA)**
(p-n-p-n switches, MOLL et al, 1956)

1958 **COMMERCIALISATION OF THYRISTOR (GE , USA)**
FIRST TRANSISTORISED COMPUTER (CDC 1604)

1959 **DEVELOPMENT OF INTEGRATED CIRCUIT (IC)**
(KILBY/NOYCE), Kilby, Nobel Prize in 2000
(FIRST RADIO WITH IC –1967)

PE --- A MULTIDISCIPLINARY TECHNOLOGY

***Synthesis* of multiple *diverse* technological disciplines**

- **Power Electronic Devices, Components and Materials**
- **Converter Circuit Topologies**
- **Electrical Machines and Power Systems**
- **Alternate Energy Sources and Conversion Processes**
- **Control Theory – Analysis and Implementation**
- **Analog / Digital electronics**
- **Computer-aided Design and Simulation Tools**
- **Microprocessors / Microcomputers / DSP**
- **Microelectronics (VLSI/ ULSI / ASIC)**
- **Instrumentation and Transducer Technology**
- **Motion Control (Mechatronics)**
- **Expert Systems / Fuzzy logic / Neural networks**

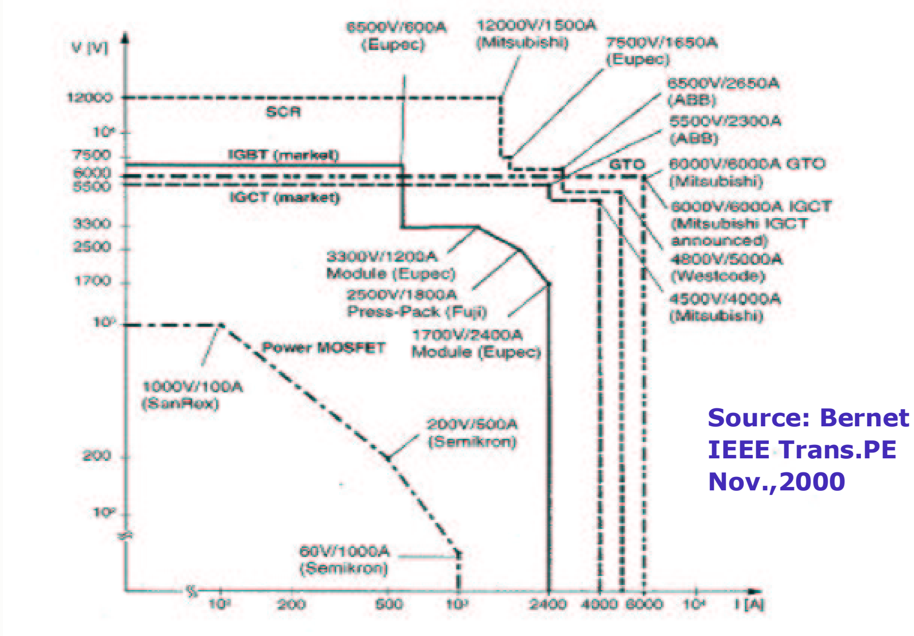
Each component discipline has developed rapidly and provided a challenge to the research and development of PE

Essentially two types of digital elements involved in marriage

- **Power Semiconductors -- Muscle of Equipments Gw**
- **Micro-Electronics -- Brain or Nerves mw**

POWER SEMICONDUCTOR DEVICE EVOLUTION ---- (SILICON)

- **POWER DIODES: SCHOTTKEY/ EPITAXIAL (P-I-N) / MPS (1992) / EmCon(2000)**
- **THYRISTORS :**
  - **SCR (1958)**
  - **TRIAC (1964) / BCT(1998)**
  - **ASCR / RCT / GATT (1970)**
  - **LASCR (1965) / LTT (1980)**
  - **GTO (1961 / 1981)**
- **POWER TRANSISTORS:**
  - **BJT (1970)**
    - **DARLINGTON**
  - **POWER MOSFET (1979)**
    - **S-FET (1996)**
    - **Cool MOS (1998)**
- **HYBRID:**
  - **IGBT (1983/1988)**
    - **NPT/PT/SPT/LPT/CSTBT**
    - **TRENCH-GATE / HVIGBT**
    - **RBIGBT (2000)**
    - **BLIGBT (1998 Patent)**
  - **SIT/ SITH (1987)**
  - **MCT (1988) / BRT / EST (1992)**
  - **IGCT / MTO / ETO (1996)**
- **PIC:**
  - **"SMART" / IPM (1990) / HVIPM**
  - **ASPIC / PEBB / IPEM (1996)**



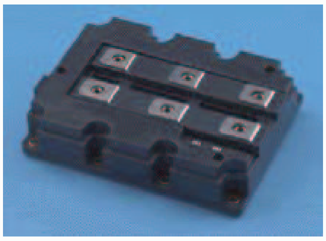
Power range of commercially available power semiconductors

6 kV, 6 kA GTO (Mitsubishi)

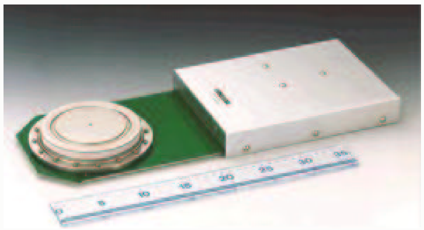
1995

1999

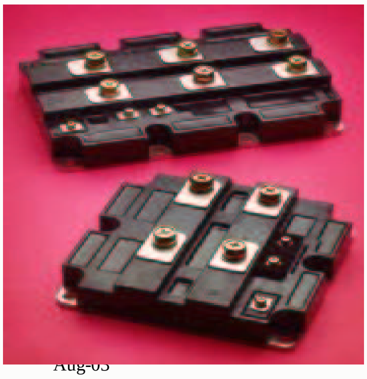
12 kV, 1500A High Voltage Thyristor (Powerex)



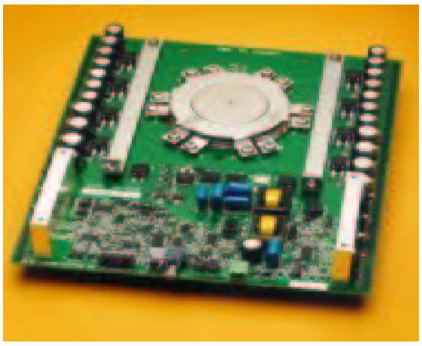
3.3kV HVIPM (Powerex / Mitsubishi)



6.5kV, 6kA IGCT (Powerex / Mitsubishi / ABB)



4.5 kV HVIGBT (Powerex / Mitsubishi)



6.5 kV, 1.5 kA SGCT(Powerex / Mitsubishi)

NEXT GENERATION POWER SEMICONDUCTOR MATERIALS

- Galium Arsenide (GaAs) / Galium Nitride (GaN)
- Silicon Carbide(SiC)
- Diamond (Thin Film)
- Superconducting

Properties:

- Large band Gap
- High Carrier Mobility
- High Electrical Conductivity
- high Thermal Conductivity

Results:

- High Power Capability
- High Frequency
- Low Conduction Drop
- High Junction Temperature
- Good Radiation Hardness

Ideal switch requirements :

High input impedance	Integrated Gate Drive
Low on-state drop	Minimize Conduction Loss
Infinite 'off' resistance	Zero Leakage
Fast turn-off and turn-on	Minimize Switching Loss
Ability to withstand high V & I (Good SOA)	Snubber-less Operation
High current density	Low Die Cost
Low cost	Reduced Size
High temp.Capability	Reduced Heat-sink
Bilateral /Bi-directional	Less Device Count

Ideal switch is still a dream!

Comparison of material properties of Silicon (Si) , Silicon Carbide (4H-SIC) and Diamond for high-power devices

		Si	4H-SiC	Diamond
Band-gap	eV	1.1	3	5
Breakdown field	MV/cm	0.3	3	10
Max.Electron velocity	10^7cm/s	1.0	2	3
Thermal conductivity	W/cmK	1.5	5	20

Technical potential of SiC power devices , compared with the limits of Si

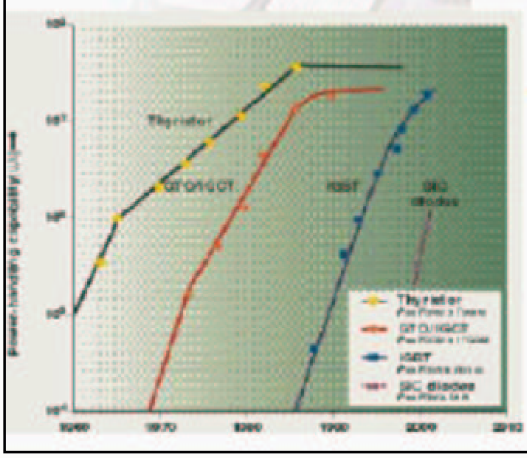
Device voltage	5 to 10 times higher
Current densities	10 to 100 times higher
Switching losses	1/10th to 1/100th of today's
Working temperature	up to 500^{o}C

Status of SiC Power Devices (2001)

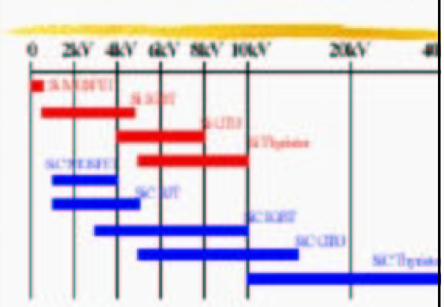
- 19 kV 4H-SiC p-i-n Diodes
- Power MOSFETs
- 1800V n-p-n BJTs , performance 100 times higher than silicon
  - 3.1 kV,12 A GTOs
- Hybrid Modules: Si-IGBT/SiC Diodes, SiC IGBT Modules (GE, 2000)

Post Silicon Development

- Higher voltage and current ratings
- Higher junction temperature = Much simpler cooling



Si vs. SiC Switches



IGBT SCENARIO

- Device that takes advantage of the high voltage bipolar transistor with MOS gate
- Fast evolution since the introduction in 1983 (marketed in 1988)
- Can be designed with or without snubber
- Improved characteristics like reduced loss, high speed, high blocking capability etc., with PT (Punch Through) NPT (Non-Punch-Through), SPT (Soft Punch Through, ABB), Field-Stop(FS-IGBT, Infineon),LPT,CSTBT (Mitsubishi) technologies.
- State-of-the-art high power device (HVIGBT): 3.3kV 1.2kA, 5kV 0.9kA,(6.5kV, 600A Module reported), EUPEC
- 4th generation device with Trench gate (low on-state voltage and on-state loss (30% less) and 50% higher speed than 3rd generation Planar gate device

Contd

IGBT Scenario (Contd.)

•Press-pack type package for applications with a redundant series connection (acts as short circuit and thus the operation not affected by failure of one/two devices)

•Best option for low and medium power applications (e.g. Traction where IGBT's have replaced GTO's)

•Intelligent power modules (IPM) up to 1200 V 800A (200 hp motor), "Smart power " capability, 3.3kV 1200A (Powerex)

•3 MW power level with 3-Level inverter

•HVIGBT offers interesting features: Active control of dv/dt and di/dt, Active clamping, short circuit limitation and active protection, however, higher on-state and total losses, substantially smaller utilization of silicon area, etc. are some of the disadvantages.

•First Reverse Blocking IGBT (RBIGBT) announced, IXYS, 2000

New Switching Devices

- IGBTs *(Insulated Gate Bipolar Transistors)*
- IGCTs *(Integrated Gate-Commutated Thyristors)*
  - *lower cost, volume and weight*
  - *higher efficiency*
  - *much higher reliability*

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IGCT=GTO+IGBT Advantages

- **Switching technology**
  - **Switches at high frequency**
  - **Low switching losses**
  - **Low on-state losses**
  - **Suitable for medium voltage**
  - **Snubberless (Unity Gain)**
  - **Short-circuit failure mode**
- **Power circuitry**
  - **Integrated diode and gate unit for low parts count**
  - **Suitable for parallel and series connection**
- **Equipment design**
  - **Allows compact, modular equipment design**
  - **Application-ready modules**
  - **Reduced cabling and interconnection**

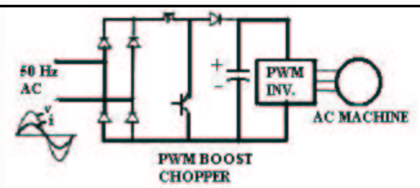
POWER ELECTRONIC CONVERTERS

- **General:** •AC/DC- Rectifier •DC/DC- Chopper •DC/AC–Inverter •AC/AC– Regulator/Cycloconverter
- **AC/DC:**
  - Phase controlled rectifier
  - 1-phase/ 3-phase Rectifier Boost Chopper (SMR)
  - PWM Rectifier
- **DC/ DC:**
  - PWM(Buck/ Boost/ Buck-Boost)
  - C'uk Converter
  - Transformer Coupled-Flyback/ Forward
  - Resonant high frequency AC link
  - Quasi-Resonant link-ZVS & ZCS
- **DC/ AC:**

- VSI	-CSI
- Square wave / 6-step	- LCI
- PWM (Hard/Soft switching)	-ASCI
- Double PWM	- PWM
- Resonant DC /AC link	- Double PWM
- Multi level	-Series Resonant AC Link

- **AC/ AC:**
  - Phase- controlled Regulator
  - Phase-controlled Cycloconverter
  - High frequency / DC link cascaded
  - Matrix converter

Moromito 1989



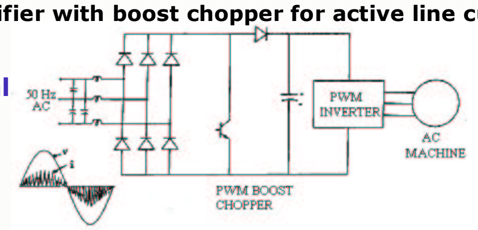
AC/DC/AC

SMR

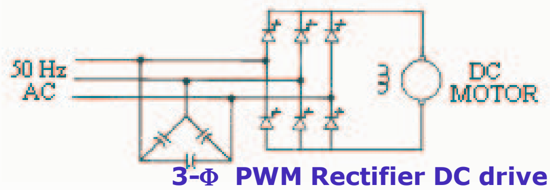
1-Φ diode rectifier with boost chopper for active line current wave shaping

PROSAD et al 1989

UPF



3-Φ diode rectifier with boost chopper for active line current wave shaping



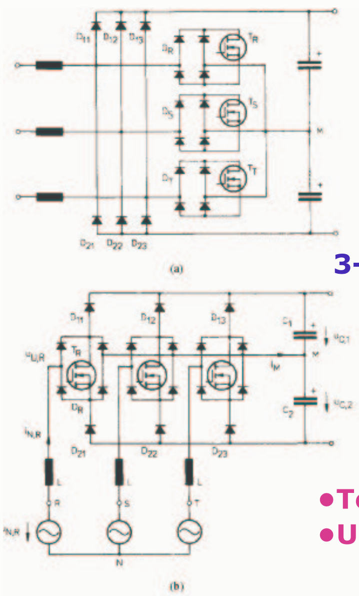
AC/DC PWM

3-Φ PWM Rectifier DC drive

AC/DC

VIENNA RECTIFIER

(KOLAR , 1994)



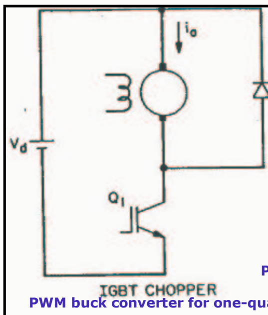
3-Phase / 3-Level / 3-Switch PWM

Sinusoidal Input Current
Unity Power Factor

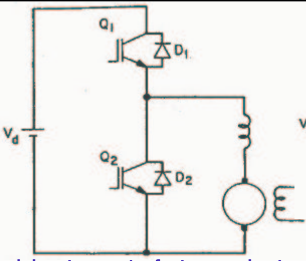
Applications:

- Telecommunications Power Supply
- UPS

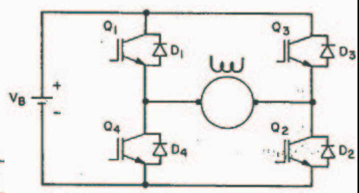
DC / DC



PWM buck converter for one-quadrant control

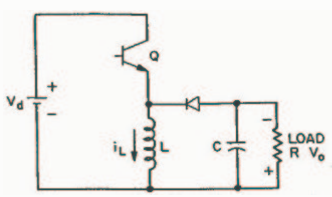


PWM buck-boost converter for two-quadrant control

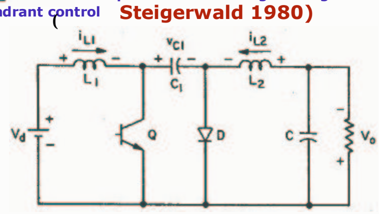


Four quadrant drive using H-bridge

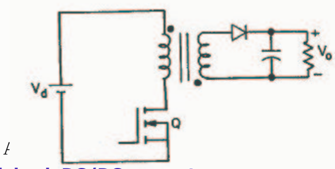
Steigerwald 1980)



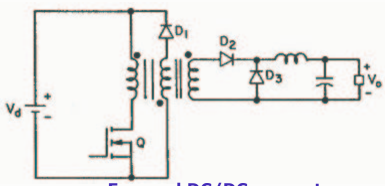
Duty-cycle modulated buck-boost converter



C'uk converter (1982)

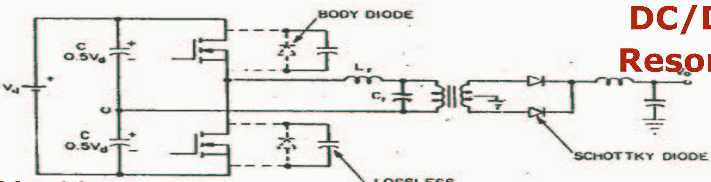


Flyback DC/DC converter



Forward DC/DC converter

DC/DC Resonant



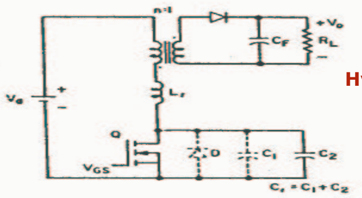
Steigerwald 1984

For power supply to computers, telecom, instrumentation

Half bridge inverter (VSI) (ZVS)

Resonant link dc-dc converter

Lee (1989)

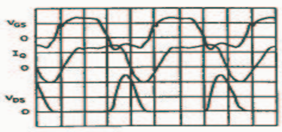


Hybrid (PWM + Resonant)

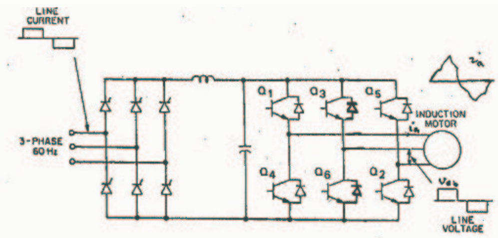
(ZVS)

Quasi-resonant flyback converter with zero voltage switching

Res. Freq. higher than Switching freq.

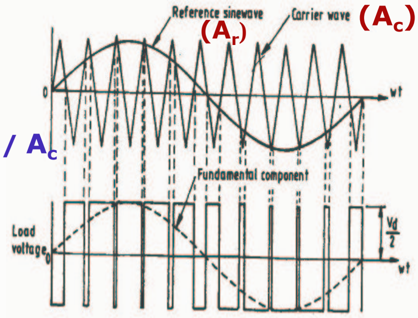


DC / AC VSI

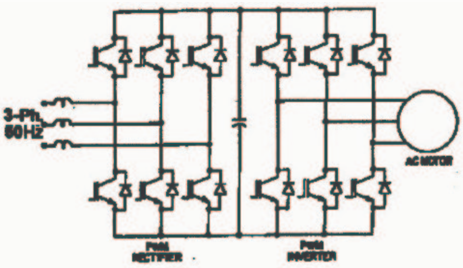


Three –phase square wave inverter with phase-controlled

$M = A_r / A_c$



2-level Sinusoidal Pulse Width Modulation (SPWM)



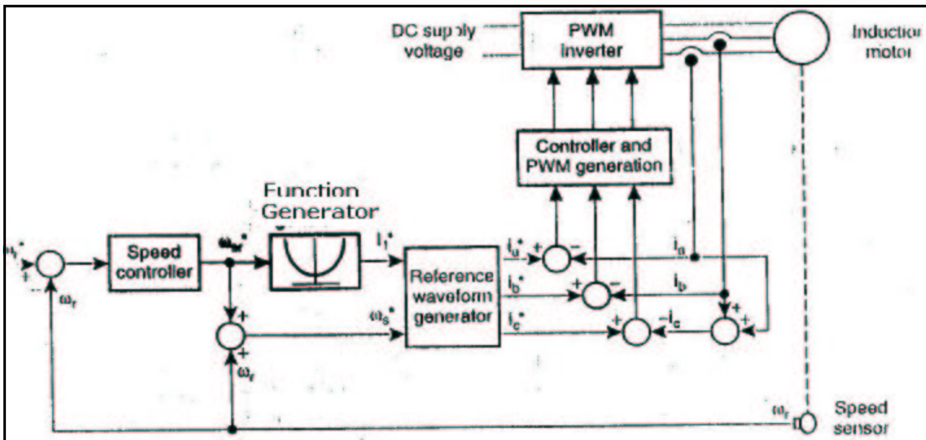
Double PWM VSI rectifier-PWM inverter configuration

1987

INVERTER PWM METHODS

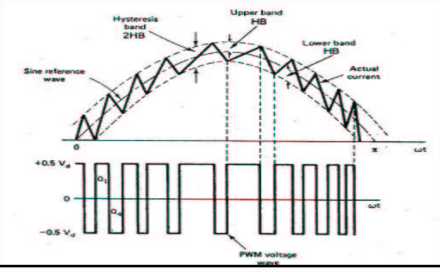
- Sinusoidal PWM (SPWM)
- Selected Harmonic Elimination (SHE)
- Hysteresis Band (HB) Current Control
- Delta Modulation (DM)
- Sigma Delta Modulation (SDM)
- Random PWM (RPWM)
- Space Vector PWM (SVM) :Features

- Advanced , computation intensive for VF Drives for superior performance
- Based on the concept of rotating space vector theory
- Better DC Bus Utilization, 15% higher output voltage than that of SPM
- Considers the interaction of the phase and optimizes the harmonic component of the 3-phase isolated neutral load
- Power switching frequency limited. Can be increased by simplifying computations and using Look-up table. ANN-based proposed (Bose)

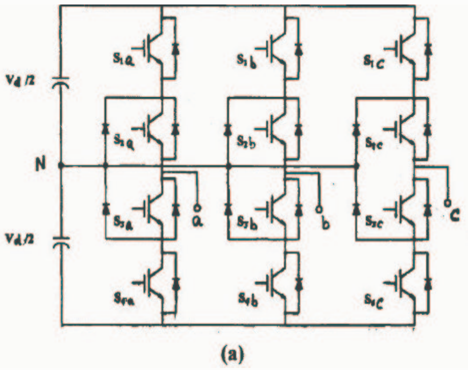


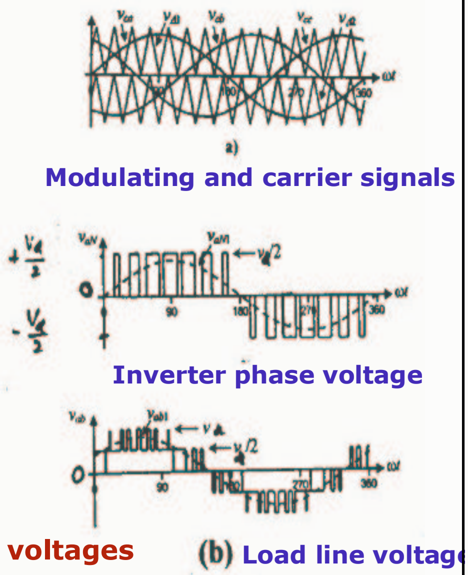
Current Controlled PWM (CRPWM) Inverter Drive With Slip-Frequency Control

Hysteresis Band Current Control⇒



DC / AC VSI



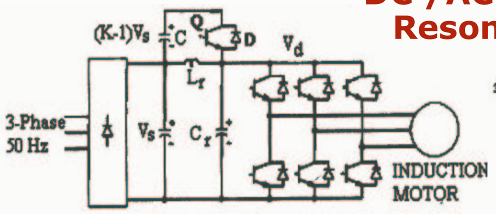


Nabae , 1987

3-Level (NPC) PWM Inverter

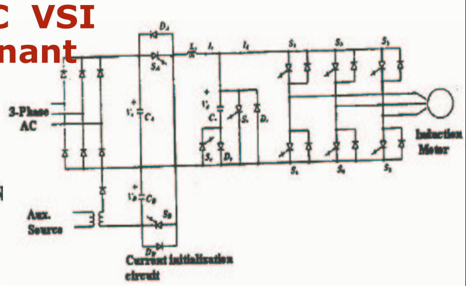
(a) Circuit diagram (b) Output voltages

DC /AC VSI Resonant



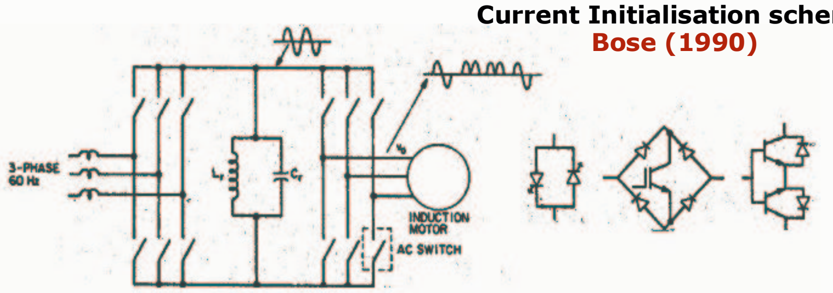
Resonant dc-link inverter with active voltage clamping

Divan (1989)



Resonant DC link Inverter with Current Initialisation scheme

Bose (1990)

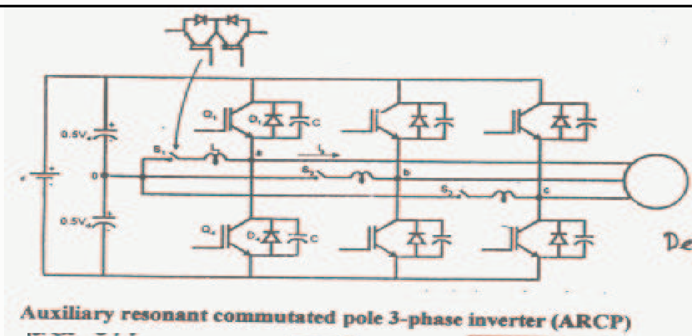


Resonant AC link converter showing configuration of AC switches Lipo (1990)

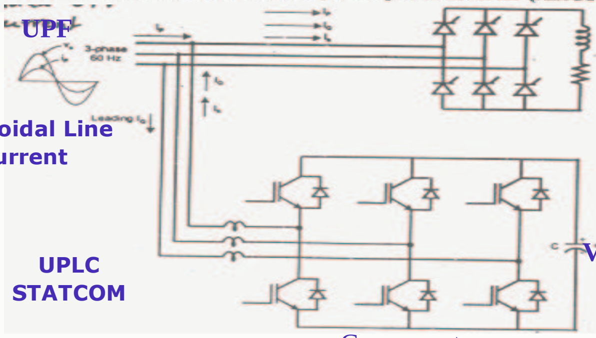
SOFT SWITCHED CONVERTERS

- Reduced switching loss at both turn-on and turn-off; Higher inverter efficiency; Less cooling requirement
- Softened EMI
- Reduced snubber size or snubber-less operation
- Reduced *dv/dt* on machine insulation
- Less acoustic noise because of high frequency
- Elimination of Machine bearing current
- Elimination of Machine voltage boost with long cable
- Less device stress ; Improved reliability
- Higher conduction loss and higher V and I ratings for the power devices
- Need of extra high frequency components
- Complex control
- Hardly any industrial drive so far

DC / AC

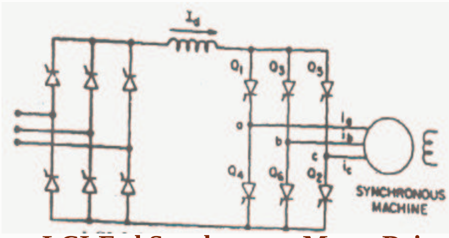


De Donker(1990)

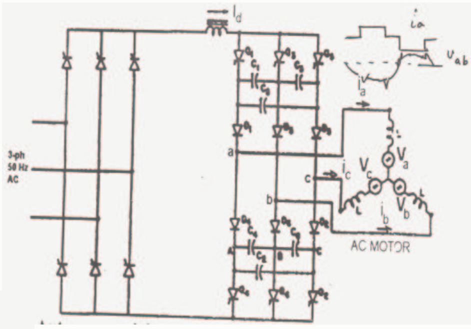


Static VAR Compensator (Active Filter) for Electric Railways (1995)

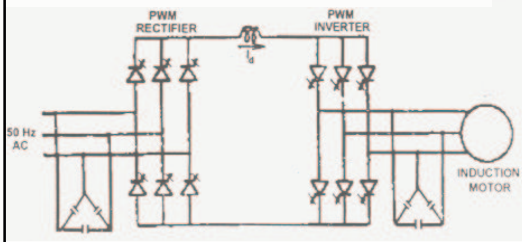
DC / AC
CSI



LCI-Fed Synchronous Motor Drive



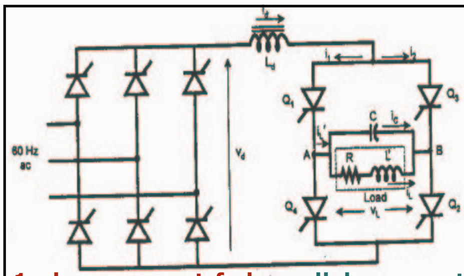
ASCI-Fed Induction Motor Drive



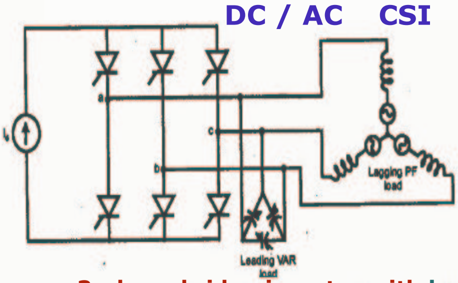
CSI-PWM Rectifier-PWM Inverter-Fed Drive

Hombu (1985)

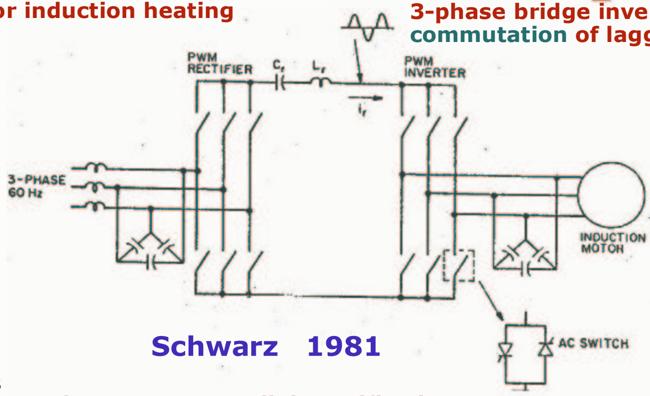
DC / AC CSI



1-phase current-fed parallel resonant inverter for induction heating



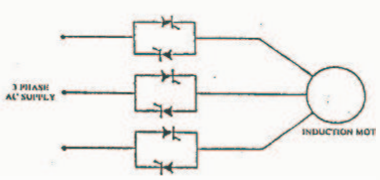
3-phase bridge inverter with load commutation of lagging p.f. load



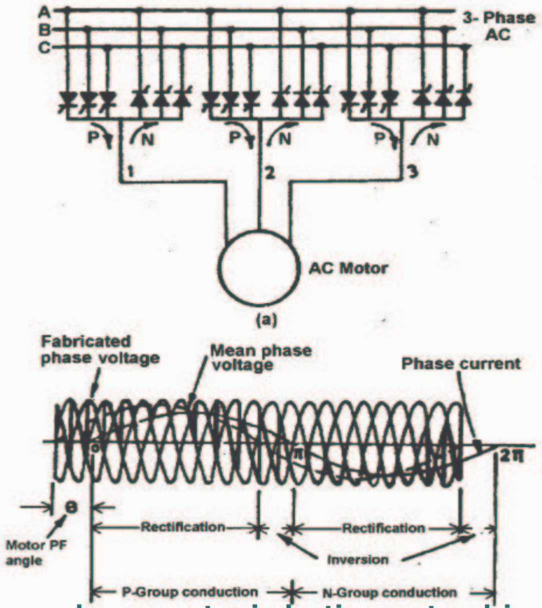
Schwarz 1981

Series resonant AC-link rectifier-inverter system

AC / AC

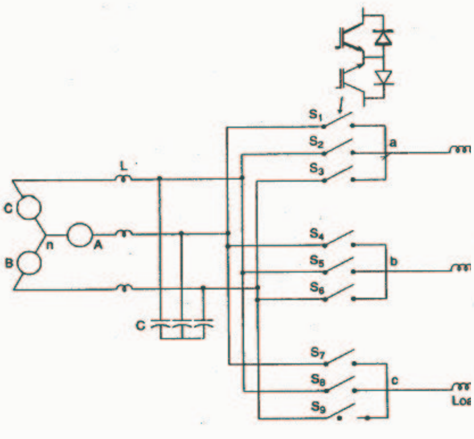


3-phase AC voltage control with anti-parallel Thyristors

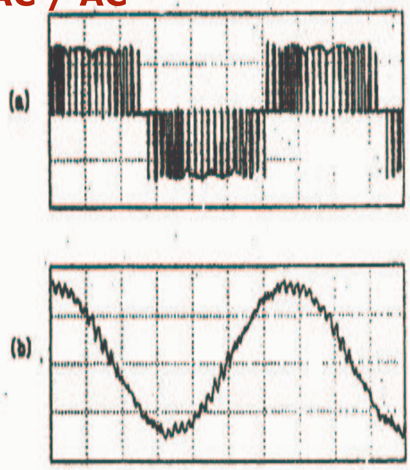


3-phase 3-pulse cyclo-converter induction motor drive
(a) Power circuit (b) wave forms

AC / AC



3-phase to 3-phase matrix converter
(Venturini 1980)



Experimental waveforms for a matrix converter at 30 Hz form a 50 Hz input
(a) Output line voltage (b) Output line current

❑ Motors in Drives

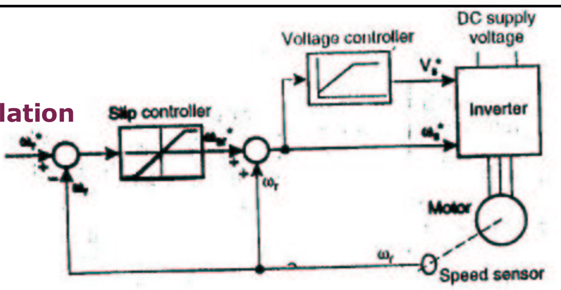
- DC, Induction & Synchronous Motors
- Commutator-less Motors (CLM)/ECM : •AC-CLM •DC-CLM
- Synchronous Reluctance Motor (SyRM)
- Brushless DC Motors (BLDM)
- Permanent Magnet SM (PMSM), SPM / IPM
- Stepper Motor
- Switched Reluctance Motor (SRM)

❑AC Drive Control

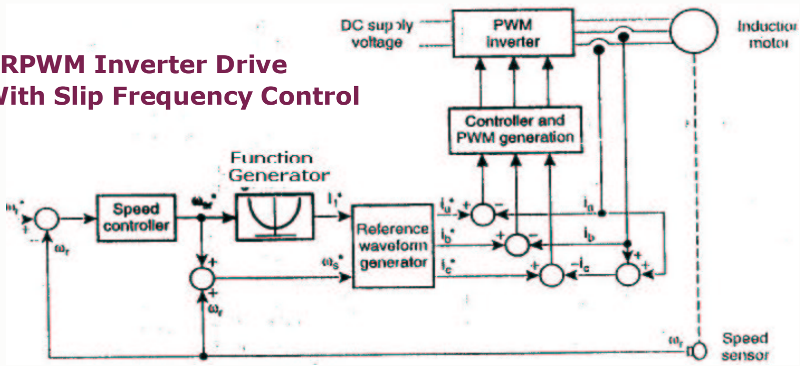
- Open Loop / Closed Loop
- Volts / Hz; Scalar Control
- Vector or Field Oriented Control
  - Direct/Indirect/Universal
  - Stator Flux /Rotor Flux/ Air-gap Flux
- Direct Torque Control (DTC)
- Sensor-less Control
- Modern Control Theory Applications:
  - State Feedback / Feed-Forward Control
  - Self –Tuning Control
  - Adaptive (MRAC) / Optimal Control
  - H-Infinity (Robust) Control
  - Sliding Mode(Variable Structure) Control
  - AI (Fuzzy/ANN) based Control
  - Parameter Estimation / Identification / Self Commissioning Methods

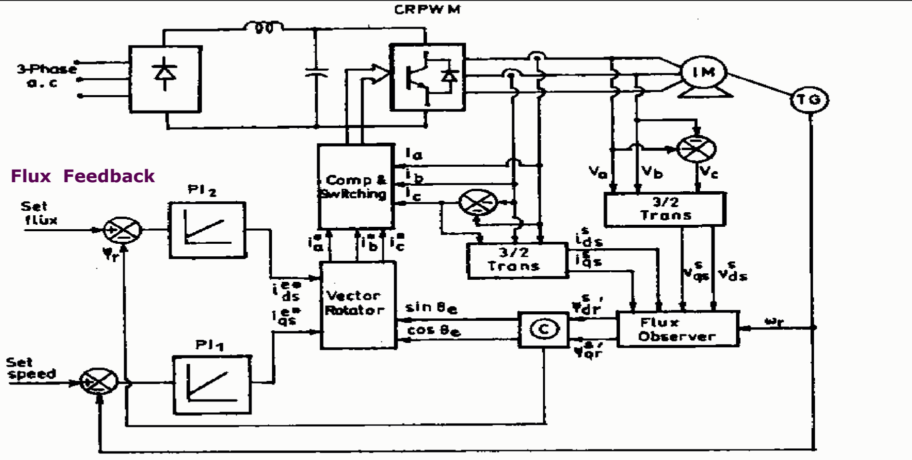
Constant V/Hz Speed Control with Slip Regulation

SCALAR



CRPWM Inverter Drive With Slip Frequency Control





$$|\hat{\psi}_r| = \sqrt{(\hat{\psi}^{s\prime}_{dr})^2 + (\hat{\psi}^{s\prime}_{qr})^2}$$

$$\cos\theta_e = \frac{\hat{\psi}^{s\prime}_{dr}}{|\hat{\psi}_r|}, \quad \sin\theta_e = \frac{\hat{\psi}^{s\prime}_{qr}}{|\hat{\psi}_r|}$$

Direct Vector Control Scheme for a CRPWM-fed Induction Motor with a Rotor Flux Observer

VR Equations: R/S

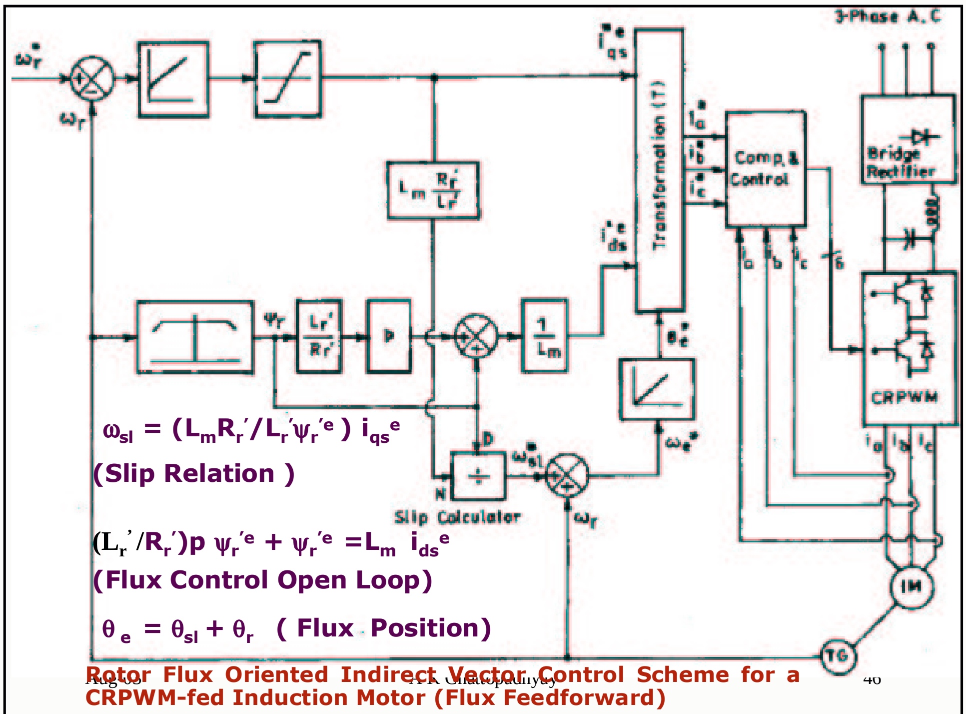
2/3 Transformation

$i_a^* = i_{qs}^{*e}\cos\theta_e + i_{ds}^{*e}\sin\theta_e$;

$i_b^* = (-\tfrac{1}{2}\, i_{qs}^{*e} - \sqrt{3}/2\, i_{ds}^{*e})\cos\theta_e + (\sqrt{3}/2\, i_{qs}^{*e} - \tfrac{1}{2}\, i_{ds}^{*e})\, i_{ds}^{*e}\sin\theta$;

$i_c^* = (-\tfrac{1}{2}\, i_{qs}^{*e} + \sqrt{3}/2\, i_{ds}^{*e})\cos\theta_e - (\sqrt{3}/2\, i_{qs}^{*e} + \tfrac{1}{2}\, i_{ds}^{*e})\, i_{ds}^{*e}\sin\theta_e$

Aug-03 A K Chattopadhyay 45



$\omega_{sl} = (L_m R_r'/L_r'\psi_r'^e)\, i_{qs}^e$

(Slip Relation)

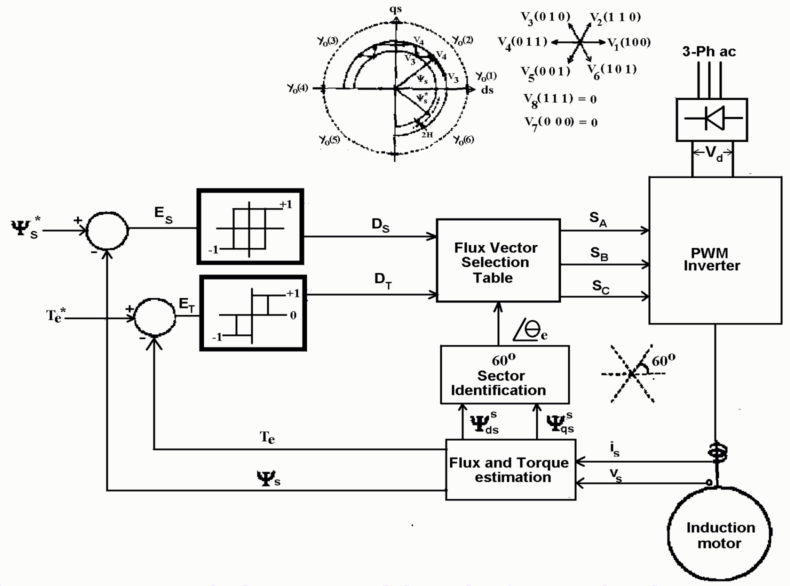
$(L_r'/R_r')p\,\psi_r'^e + \psi_r'^e = L_m\, i_{ds}^e$

(Flux Control Open Loop)

$\theta_e = \theta_{sl} + \theta_r$ **(Flux Position)**

Rotor Flux Oriented Indirect Vector Control Scheme for a CRPWM-fed Induction Motor (Flux Feedforward)

Aug-03 A K Chattopadhyay 46



Direct Torque and Flux Control (DTC) of an Induction Motor

TABLE-2

SIGNIFICANT DEVELOPMENTS IN PE (SINCE 1960)

1961 SMALL POWER GTO (GENERAL ELECTRIC)
PRACTICAL ELECTRONIC CHOPPER CONTROL (JONES)
FIRST UPS

1964 TRIAC (GE) (GENTRY ET AL) THYRISTOR -CONTROLLED DC DRIVE (10-MW)

1965 LASCR (G E)

1967 THYRISTORS FOR HVDC APPLICATIONS

1969 MOS IC (INTEGRATED CIRCUIT)

1970 SILICON BIPOLAR JUNCTION TRANSISTOR (BJT) 500 V, 20 A (IR)

1971 PRINCIPLE OF FIELD ORIENTATION (VECTOR CONTROL) (BLASCHKE /HASSE)

1972 4-BIT MICROPROCESSOR (INTEL)

1973 GEARLESS BALL MILL DRIVE WITH CYCLOCONVERTERS (SIEMENS)

(CONTD).

TABLE-2 (CONTD.)

1974 8-BIT MICROPROCESSOR
1975 GIANT TRANSISTOR, 300 V, 400A
1976 16-BIT MICROPROCESSOR (INTEL)
1978 POWER MOSFET, 100V, 25A

1979 MICROPROCESSOR IMPLEMENTATION OF VECTOR CONTROL WITH TRANSISTOR INVERTER (LEONHARD)

1980 MATRIX CONVERTER CONCEPT (VENTURINI)
LIGHT TRIGGERED THYRISTOR (LTT), 4kV, 1.5kA
SWITCHED RELUCTANCE MOTOR (LAWRENSON)
10,000 HP LCI DRIVE

1981 2500V,1000A GTO (HITACHI / MITSUBISHI / TOSHIBA)
CYCLOCONVERTER-FED ROLLING MILL DRIVE

1982 C'UK CONVERTER
1983 IGBT DEVELOPED (BALIGA)
1983 RESONANT LINK DC-DC CONVERTER (STEIGARWALD)

TABLE-2 (CONTD.)

1986 RESONANT DC LINK INVERTER (DIVAN)
FLEXIBLE AC TRANSMISSION (FACTS) PROPOSED (HINGORANI)

1987 DOUBLE-SIDED PWM RECTIFIER-INVERTER

1987 MOS-CONTROLLED THYRISTOR (MCT) (TEMPLE)
ACTIVE POWER LINE CONDITIONER (APLC)
SIT/ SITH (JAPAN)
CONCEPT OF DIRECT TORQUE CONTROL (DTC), (DEPENBROCK / TAKAHASI)

1989 85 MW VARIABLE-SPEED PUMPED STORAGE SYSTEM
QUASI-RESONANT INVERTER (LEE)

1990 "SMART" POWER DEVICES

1991 80 MVA STATIC VAR COMPENSATOR (SVC), (MITSUBISHI)

TABLE-2 (CONTD.)

1992 300 MW HVDC LINK WITH 6kV, 2.5kA LTT VALVES (TOSHIBA)
EXPT. WITH SILICON CARBIDE DEVICES

1993 FUZZY LOGIC / NEURAL NETWORK APPLICATIONS TO PE & DRIVES (BOSE)

1994 1-MVA IGBT UPS (TOSHIBA)
38-MVA GTO INVERTER FOR "MAGLEV" RAILWAY LINE (TOSHIBA)
400-MW VARIABLE SPEED PUMPED STORAGE (JAPAN)

1995 3-LEVEL GTO / IGBT INVERTER FOR ROLLING MILLS (15 /1.5 MV
100 MVAr STATCOM (TVA, EPRI, SIEMENS)

1997 IGCT INTRODUCED AND COMMERCIALISED (ABB)
ETO / MTO DEVELOPED (Virginia Tech / SPCO)

1998 5-MW 3-LEVEL CONVERTER WITH DTC CONTROL (AC 1000, ABB)
1 MW 50 kHZ CURRENT-FED INVERTER FOR INDUCTION HEATING (MITSUI ENGG)

 ----- CONTD.

TABLE-2 (CONTD)

1998 300 MW GTO CONVERTER SYSTEM FOR HVDC INTER-TIE (TOKYO ELECTRIC POWER CO.)
6.5 kV BIDIRECTIONAL THYRISTOR (BCT) (ABB)
IMPROVED Cool MOS (INFINEON)
FIRST UPFC (±160 MVAr) at AEP'S INEZ, (SIEMENS)
BILATERAL IGBT (BLIGBT) PATENT (LI)
DIRECT POWER CONTROL (DPC) IN PWM RECTIFIER

1999 6.5 kV, 600 A IGBT MODULES TO REPLACE 6.5kV GTO's in 3kV DC MAINS
MOS BILATERAL SWITCH (MBS) (ST Microelectronics)

2000 REVERSE BLOCKING IGBT (RBIGBT) ANOUNCED (IXYS)
45 MVA DYNAMIC VOLTAGE RESTORER (DVR) WITH 3-LEVEL IGCT INVERTER (ABB)

2001 ECONOMAC MATRIX CONVERTER POWER MODULE (EUPEC/SIEMENS)

Emerging Applications in PE

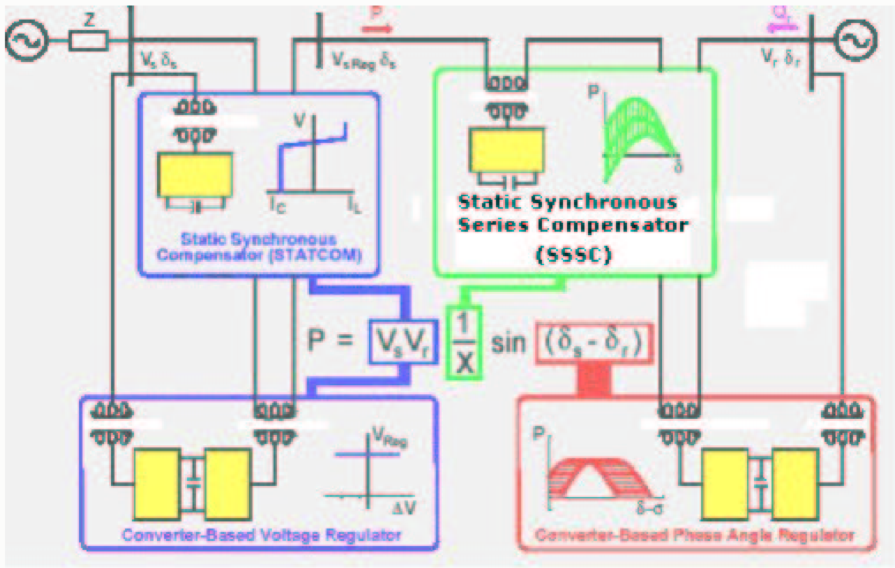
Application	Description	Typ. Power(MW)	Segment
STATCOM	Static Syn. Compensator (SHUNT) (Voltage control, VAR compensation)	100	T&D Industry
SSSC	Static Syn. Series Compensator	100	T &D
UPFC	Unified Power Flow Controller (Shunt-series, Power flow, voltage and PF control)	200	T&D
IPFC	Interline Power Flow Controller (Series-series linking multiple transmission lines)		T&D
DVR	Dynamic Voltage Restorer (Corrects the voltage dip instantly)	2-100	Power quality
SSTS	Solid State Transfer Switch (to alternative lines)	5-30	-do-
Static Breaker	Interrupts faults with sub-cycle response	5-30	-do-
Intertie	Allows energy exchange between asynchronous 3-ph and/ or 1-ph. systems	2-300	Utility Traction
VAR Speed	Syn. Motor / Gen. Excitation control	30	Generation

(Contdd.)

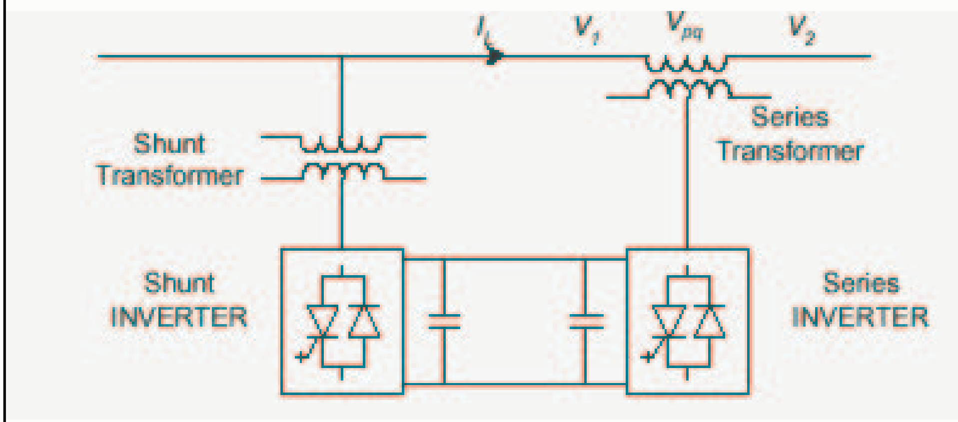
Emerging Applications in PE (Contd.)

Application	Description	Typ. Power(MW)	Segment
Local/Dist. Generation	Fuel Cells or small Turbo-Gen. (Distributed Generation)	2	Generation
Energy Storage / UPS	Short term energy storage with batteries, flywheels, SMES etc.	1-100	PQ, T&D Traction
Active Filter	Harmonic distortion compensation	1-30	PQ
Short DC Link	Short distance HVDC(100kV) from utility to load and from alt. Sources to grid	50	T&D
DC Distribution	Local network to DC processes or PE systems with a DC link on the customer's site		Distribution
EV/HEV	Electric Vehicles / Hybrid Electric Vehicles		Industry
MEMS	Micro-electro-mechanical systems, actuators		

Power Source for the Information age (Computers, Telecom, Instrumentation…..)

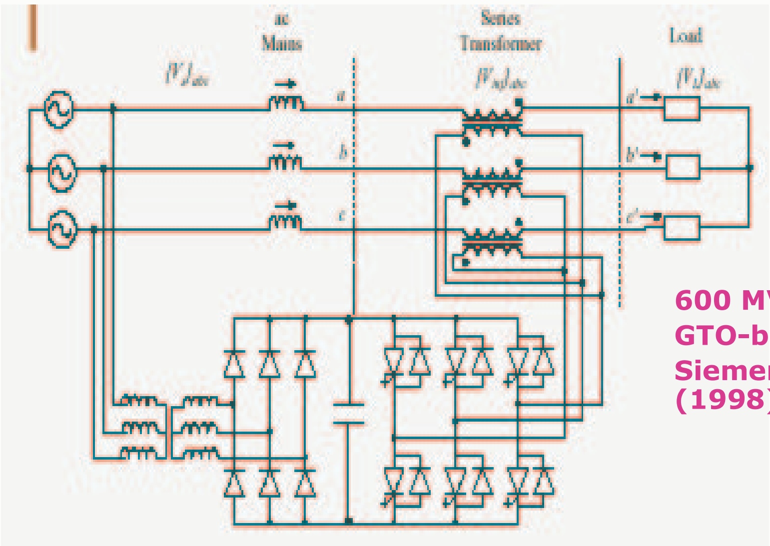


Voltage Source Converter-Based Transmission Controllers



UPFC (Unified Power Flow Controller)

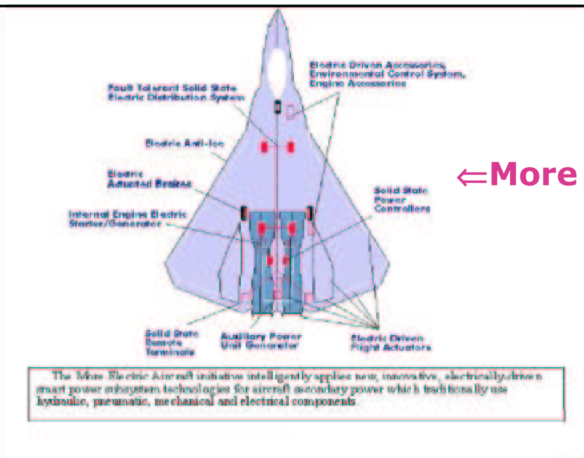
45 MVA
IGCT-Based
ABB (2000)



600 MVA
GTO-based
Siemens
(1998)

Dynamic Voltage Restorer (DVR)

Thyristor Valves: 300 MW,250 kV, 1200A,6kV,2500 A LTT (Toshiba), 1992



⇐More Electric Aircraft

Conventional vs EV ⇒

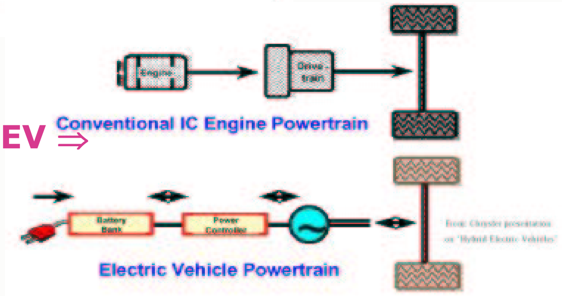


TABLE 3
PE-FUTURE PERSPECTIVE

- Power Electronics applications everywhere
- Thrust on energy saving, better environment, system integration and packaging technology
- Performance improvement and cost reduction in every process:drives, transport, consumer products, power system
- Devices with new materials (e.g. SiC) extending the frequency, power level, and temperature range with size and cost reduction
- IGCTs with snubberless turn-off capability, small turn-off delay, ease of series operation are the choice of high power electronics
- ETOs and MTOs have promise to compete with IGCTs for every high power applications
- "SMART" machines with IPEM—remotely controlled room computer will improve productivity and product quality

(Contd.)

TABLE 3 (Contd.)

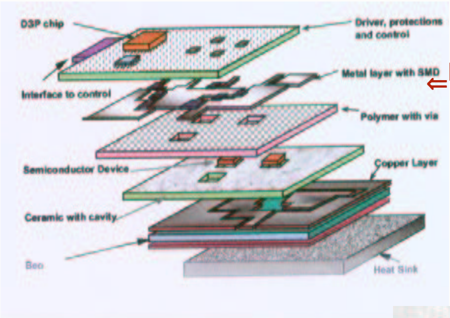
- Multilevel converters and modularized PEBB for high power converters
- Achieving fully silicon design (Matrix converter)with reduced passive components resulting in smaller size and weight and less cost
- Sensorless vector controlled drives with neural network and fuzzy logic chips
- Cheap high energy Magnet-PMSM drives with sensorless control
- Expert system applications to achieve real time performance optimization and fault tolerant controlDrive self-commissioning with auto-tuning of controller will become an integral part of the future drive system
- Efficient and light weight electric vehicles
- Automated active power line conditioners and increased applications of 'FACTS' equipment in transmission and distribution to improve power quality and power utility

Contd.

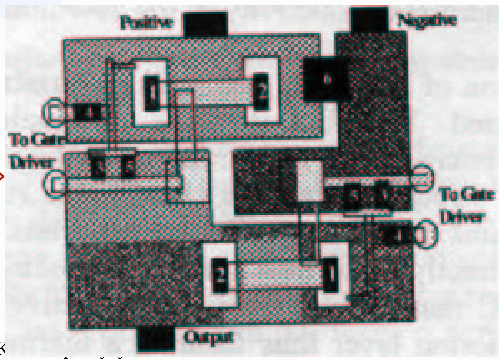
TABLE 3 (Contd.)

- Increasing clean energy applications with photovoltaic system, fuel cell power plants, battery, super-conducting magnetic storage (SMES) and wind energy systems (Distributed generation)
- DC distribution links with super-conducting DC loops for direct power supply to digital devices at the customer center
- Application of new PEBB processing concept (MPIPPS*) for development of PE modules for superior electrical, thermal and mechanical performance
- UPS substation (20-MW) providing instantaneous and continuous power at a transmission substation when the grid is down
- Innovative energy efficient consumer products
- Improved packaging maximizing integration efficiency and reliability

*Metal Posts interconnected Parallel Plate Structure

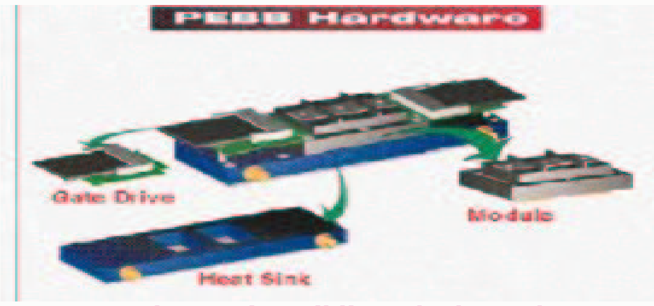


⇐Packaging of IPEM using laminated multichip Module cored ceramic (Van Wyk &Lee, 1999)



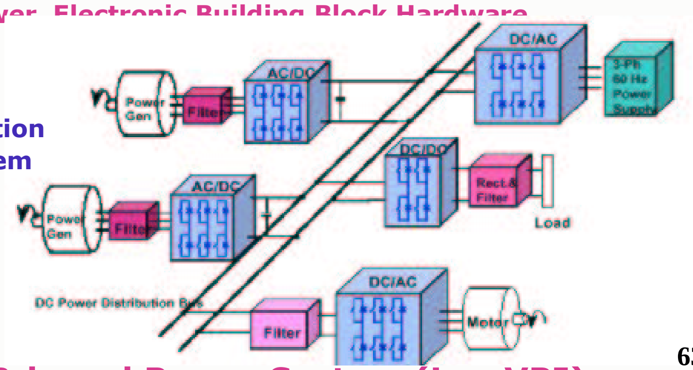
MPIPPS* Circuit Layout (1-IGBT, 2-Diode 3- Varistor 4&5-Resistor ⇒ 6-Capacitor (S.Haque et al, 1998)

- Metal Post Interconnected Parallel Plate Structure



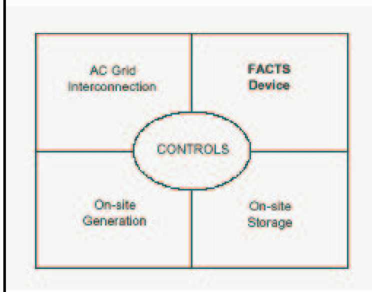
Power Electronic Building Block Hardware

DC Distribution Power System (Navy Ship)



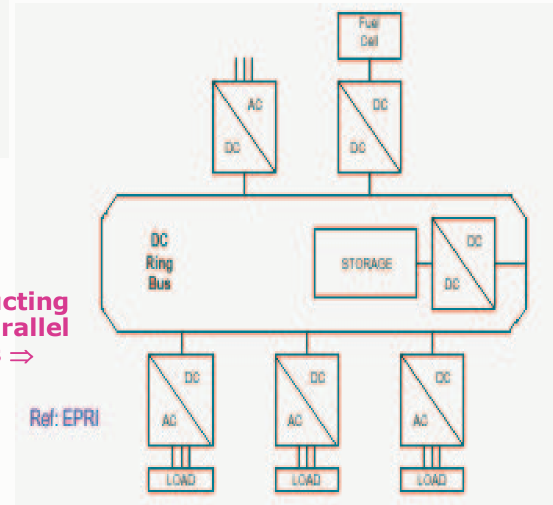
PEBB-based Power System (Lee,VPI)

20 MW Level



⇐ EPRI's UPS Substation Module Concept

High Temp. Superconducting DC Loop Bus with parallel converters & DC Choppers ⇒



DC Ring Distribution System (2010)

SUMMARY CONCLUSIONS

▪**Power Electronics is a multidisciplinary area synthesizing rapid developments in**

- **Electronics—low and high power**
- **Control (Theory and Implementation) and Automation**
- **Energy Conversion Systems and available Energy Sources**

•**Developments are dictated by the progress in**

- **Power Semiconductor Devices and VLSI Technologies**
- **Power Converter Topologies**
- **Digital Control and Modern Control Theory**
- **Applications / Market**

Applications are increasing in all areas including

- **Very low power applications : MEMS**
- **Very high power applications : T&D, Pulse Power, Traction, Electric Drives…**
- **Power supplies for the information age: Computers, Telecom……**
- **Industrial Power Conversion Systems**

▪**Challenges in the reduction of cost need :**

•**New Wide-Band Semiconductor Materials (GaAs, SiC…)**
•**Better integration of power and control with improved packaging**

CONCLUDING REMARKS

In the highly automated industrial front with economic competitiveness of nations in future ,

the importance of power electronics cannot be overemphasized

In the 21st Century, two technologies will dominate:

- **Computers (coupled with Communication and Information Technology) providing the intelligence as what-to-do**
- **Power Electronics (coupled with Microelectronics) providing the means to do it**

Let us wish them best.

THANKS!