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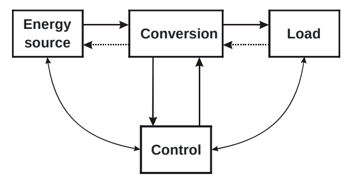
Lecture #12

Power Electronics and Converter Circuits

- Power electronics and control systems must interface energy sources with loads.
- The variable output from renewable energy devices also means that power conditioning and control equipment is required to transform this output into a form (voltage, current & frequency) that can be used by electrical appliances.

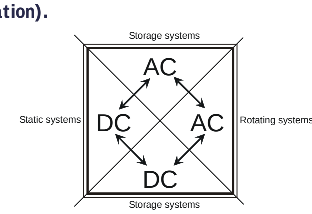


Classification of RE Systems

- Renewable energy systems can be classified in two types: **stationary and rotatory**.
- The stationary type usually provides direct current; photovoltaic (PV) arrays and fuel cells (FC) are the main renewable energy sources in this group.
- The rotatory type usually provides alternating current: induction, synchronous and permanent magnet generators are the main drivers for hydropower, wind and gas turbine energy sources.
- Of course, dc machines are the rotatory type, but not usually employed due to their high cost and maintenance needs.

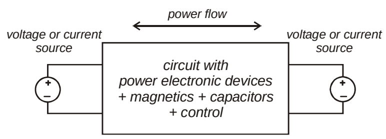
Matching the Electrical Characteristics

- **Static systems** appear as a DC input converted to a DC or AC output and unidirectional power flow.
- **Rotating systems** appear as an AC input converted to a DC or AC output and bi-directional power flow.
- **Storage systems** are necessarily bi-directional systems with requirements of AC and DC conversion (dependent on the application).



Power Electronic Circuits Connect Two Ports

- The inherent regenerative capabilities of renewable energy systems require restrictions for input/output or supply/load when connecting two sources.
- The links between a power converter and the outside world can be perceived as a possibility of power reversal.
- We have to define by either "voltage source" (VS) or "current source" (CS) when describing the immediate connection of converters to entry and exit ports.



Typical Power Electronics Systems

- There are different circuit topologies that can be used to handle variation in supply or change the electrical current into a form that can be used by industrial, rural or household loads.
- The following power electronic equipments are frequently used in renewable energy systems:
  - regulators for battery charge controllers
  - inverters for interfacing dc to ac
  - protection/monitoring units

Regulators

- A battery charge controller or regulator should be used to protect the battery bank from over-charging and over-discharging. There are three main types of regulators: Shunt, Series and Chopper regulators.
- Shunt regulators: once the batteries are fully charged the power from the renewable source is dissipated across a dump load. These are commonly used with wind turbines.
- Series regulators: once the batteries are fully charged the power from the renewable source will be switched off in the simplest series regulator.
- Chopper regulators: These regulators use a high frequency switching technique. The regulator switches the control device on and off quickly. When the batteries are discharged the unit will be switched fully on. As the battery is reaching a fully charged state the unit will start switching the control device on and off in proportion to the level of charging required. When the battery is fully charged no current will be allowed to flow to the battery.

Inverters

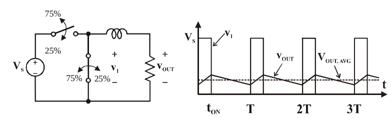
- Renewable energy systems often provide low voltage, direct current (DC) from batteries, solar panels or from wind generators with rectification.
- An inverter is an electrical device that changes direct current (DC) into alternating current (AC). Inverters often incorporate extra electronic circuits that control battery charging and load management.
- If inverters are used only to supply power from a generator to a load, they are unidirectional. On the other, hand if they need to transfer power to an electrical machine to operate in motoring mode (such as for start-up, braking and pumping), they need to be bidirectional.
- Inverters must produce power of a similar quality to that in the main electricity grids. They can operate in stand-alone mode or connected to the main grid. In the subsequent case, interconnection guidelines must be attained with the local public services company.

Protection and Monitoring Units

- In systems with a number of power sources, sophisticated system controllers are required. These controllers are usually computer controlled, monitoring the system operation.
- System controllers can measure energy demanded in the house and communicate with the utility company to achieve contracted load management for example water heaters and furnaces or to dispatch to a local generator.
- The functions performed by system controllers include:
  - Disconnecting or reconnecting renewable energy sources
  - Disconnecting or reconnecting loads
  - Implementing a load management strategy
  - Starting diesel generators if battery voltage is too low or if load becomes too heavy
  - Synchronizing AC power sources (e.g. inverters and diesel generators)
  - Shutting systems down if overload conditions occur
  - Monitoring and recording of key system parameters

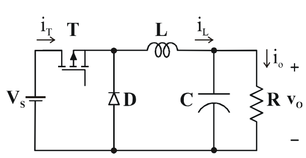
DC-DC Converters

- A very fundamental form of the dc-dc converter is the buck converter, sometimes called a chopper.
- A buck converter can create an average dc output less than or equal to its dc source. The switch used in a buck converter must be fully controllable, i.e. a MOSFET or an IGBT, so that the switch can forcibly turn off its current.
- Principle of PWM, by turning on and off the switches, a variable average voltage can be synthesized at the output.



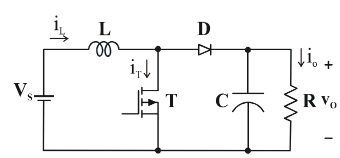
Buck Converter

- The output voltage is less than input voltage.



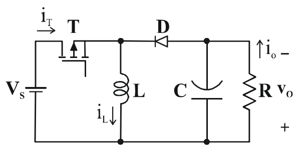
Boost Converter

- The output voltage is higher than input voltage.
- It is normally used with PV cells.



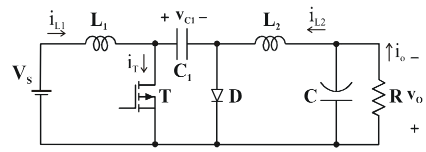
Buck-Boost Converter

- The output voltage can be higher or lower less than input voltage (depending on duty-cycle).
- The output voltage is negative.



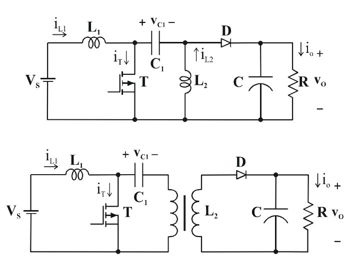
`Cuk Converter

- The output voltage can be higher or lower less than input voltage (depending on duty-cycle).
- The output voltage is negative.
- The input current is smooth.



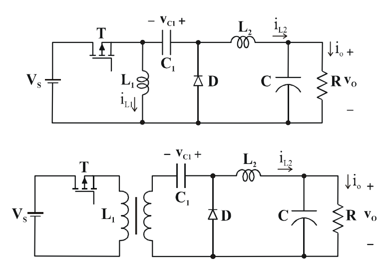
Sepic Converter

- Non-isolated and isolated topologies.
- Also used for smooth input current applications.



Zeta Converter

- Non-isolated and isolated topologies.
- Also used for smooth input current applications.

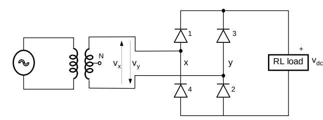


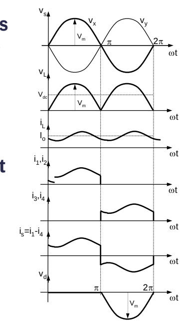
AC-DC Converters

- **For ac-dc conversion the following parameters are required to design the circuit:**
  - Evaluation of AC input limitations
  - Average output voltage
  - Output ripple voltage
  - Efficiency
  - Circuit load, output power
  - Regulation to input voltage variation
  - Regulation to output load variation
  - Power flow direction
    - if it is required ac => dc and dc => ac

Diode-Bridge Single-Phase Rectifier

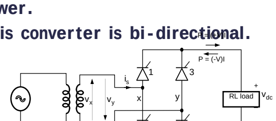
- **Uncontrollable converter, since the diodes turn-on as soon as the impressed voltage becomes positive.**
- **With pure resistive load the current waveform takes the same shape of the rectified semi-cycles.**
- **For light inductive load where the current is discontinuous the following solution for the load current can be used:**

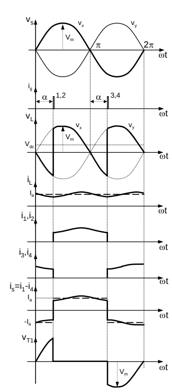




Full Controlled Single-Phase Converter

- **Thyristors T1 and T2 must be triggered at the same time, for example by using a pulse transformer with double secondary for the positive half-cycle and trigger T3 and T4 for the negative half-cycle.**
- **This type of converter is very typical for power up to 15 kW. However, the harmonic pollution at the utility side and consequent neutral loading inhibits its use for higher power.**
- **This converter is bi-directional.**

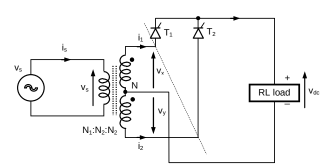




$$V_{dc} = \frac{2}{2\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\omega t\, d\omega t = \frac{2V_m}{2\pi}[-\cos\omega t]_{\alpha}^{\pi+\alpha} = \frac{2V_m}{\pi}\cos\alpha = V_{do}\cos\alpha$$

Center Tapped Single-Phase Rectifier

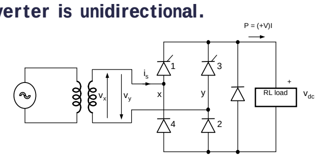
- **The center tap splits the voltage in out of phase voltages in respect to the neutral terminal N. Therefore, each diode conducts for each half-cycle of the input voltage.**
- **The circuit operation can be evaluated with thyristors (SCR's) where α is the firing angle for each SCR.**



$$V_{dc} = 2\times\frac{1}{2\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\theta\, d\theta = \frac{2V_m}{\pi}\cos\alpha$$

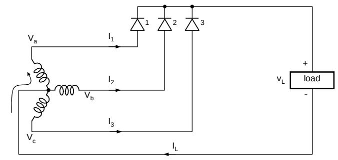
Single-Phase Semi-Converter

- A simplification of the full controlled converter is achieved by the half-converter.
- Only two controlled devices are used, the bottom devices are diodes and there is a free-wheeling diode across the load. The free-wheeling diode increases the average voltage across the load and improves the power factor at the input side.
- This converter is unidirectional.



Half-Wave Three Phase Bridge

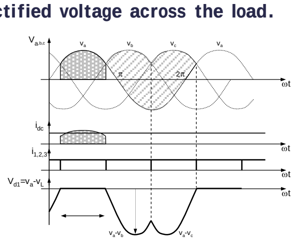
- The half-wave three-phase bridge is a basic circuit used for understanding most of the polyphase circuits.
- Balanced three-phase voltages are assumed to be available.



$$V_{dc} = \frac{1}{2\pi/3}\int_{\frac{\pi}{6}}^{\frac{5\pi}{6}} V_m \sin\theta \, d\theta = \frac{3\sqrt{3}}{2\pi} V_m$$

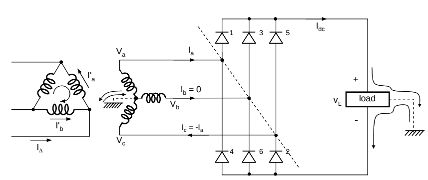
Half-Wave Three Phase Bridge – Cont.

- Every period of time that a phase voltage has the largest instantaneous voltage the correspondent diode is on as indicated by the period "a."
- For half-wave three-phase bridge there are three pulses at the rectified voltage across the load.



Three-Phase Full-Wave Bridge Rectifier

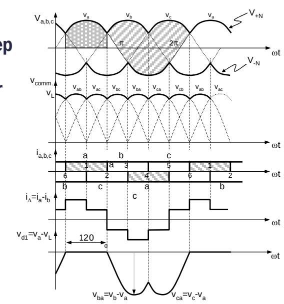
- The three-phase full-wave bridge rectifier shown in has a very wide use in industrial systems, it is also called Graetz converter.
- It can operate with or without a transformer and gives six-pulse-ripple waveform at the output. The output voltage is the subtraction of two half-wave three-phase voltages as in respect to the neutral N.



Three-Phase Full-Wave Bridge Rectifier – Cont.

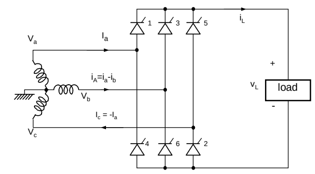
- The waveforms are shown on the side.
- The line current is a six-step waveform resembling a sinewave with improved power factor at the input side.
- The average voltage is given by:

$$V_{dc} = 2\frac{3\sqrt{3}}{2\pi}V_{m(phase)} = \frac{3}{\pi}V_{m(line)}$$



Three-Phase Controlled Full-Wave Bridge Rectifier

- The waveforms of the three-phase controlled full-wave bridge rectifier are similar to the Graetz bridge, shifted by α.
- The sequence of thyristors is indicated by their number.

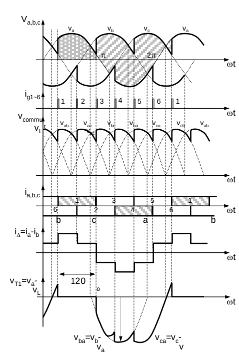


Three-Phase Controlled Full-Wave Bridge Rectifier – Cont.

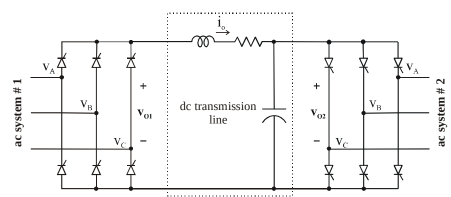
- This converter is bidirectional.
- The average voltage is computed by:

$$V_{dc} = \frac{3}{\pi}V_{m(line)}\cos\alpha = \frac{3\sqrt{2}}{\pi}V_{(line,RMS)}\cos\alpha =$$
$$= \frac{3\sqrt{6}}{\pi}V_{rms(phase)}\cos\alpha = V_{do}\cos\alpha$$

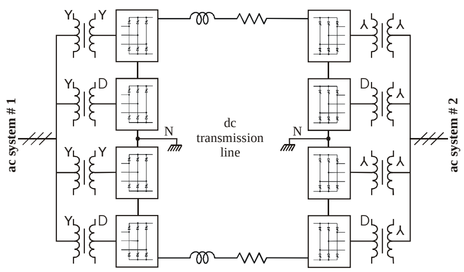
- This converter is used for medium to high power installations.
- Drawback : low power factor at the utility side.



DC-Link Interconnection of Two AC Grids

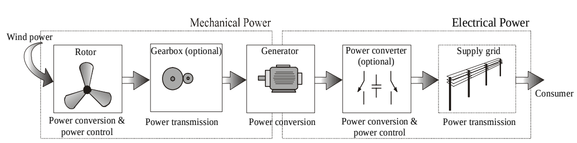


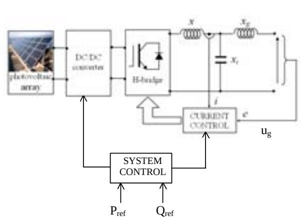
Very High Power DC-Link Interconnection



DC-AC Converters : Inverters

Where do We Use Inverters ?



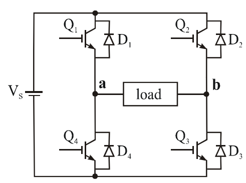


DC-AC Converters

- The conversion from dc to ac is performed by inverters.
- The general description of operation of inverter topologies is valid for any power electronic device; the difference will be in the hardware implementation, switching frequency, gate drivers and of course power ratings.
- Inverters require electronic control of the pulses applied to their gates.
- Such control needs a prescribed pulse train that will command the frequency and voltage of the output voltage.
- There are several pulse-width modulation techniques and space vector techniques to synthesize the output voltage.

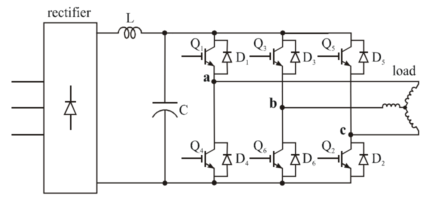
Single-Phase H-bridge Inverter

- The inverter contains four switches Q1 – Q4 comprising a power device with an anti-parallel diode. The inverter is supplied by a dc source. The load, which in this case is assumed to be a passive RL load, is connected between the two legs of the inverter.
- When the switches Q1and Q2 are on, Q3 and Q4 are off. Similarly, when Q3 and Q4 are on, Q1, and Q2 are off.
- A small time delay is provided between the turning off an upper device with the correspondent lower one.



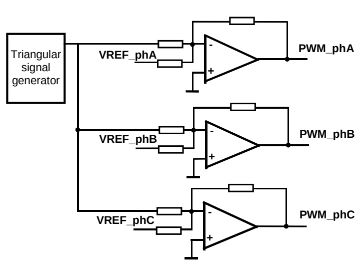
Three-Phase Inverter

- It contains six switches Q1 - Q6 each of which is made of a power semiconductor device and an anti-parallel diode. The switches of each leg are complementary, i.e. when Q1 is on, Q4 is off and vice versa. The inverter is connected to a dc-link and a three-phase load is connected at the output of the inverter.
- For a floating neutral point the phase currents will add to zero and no triple harmonic current will flow in the load.

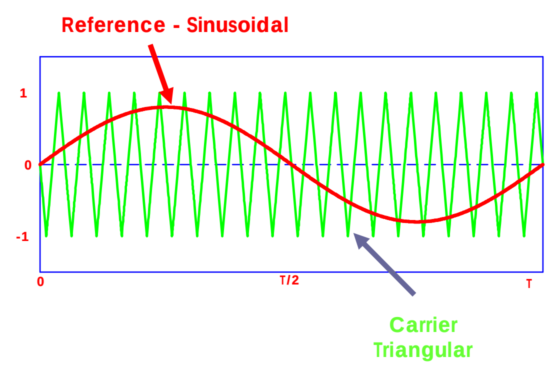


Three Phase SPWM Inverters

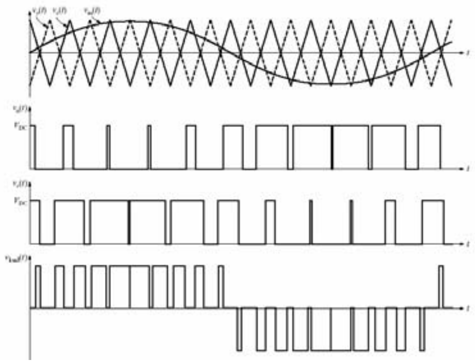
- Three phase SPWM inverters are controlled with three sinusoidal modulating signals at the frequency of the desired output are compared with the triangular carrier waveform of suitably high frequency.



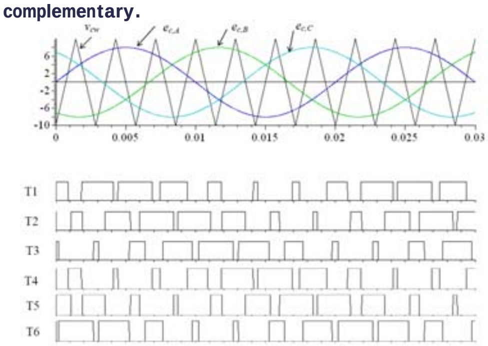
Sinusoidal PWM



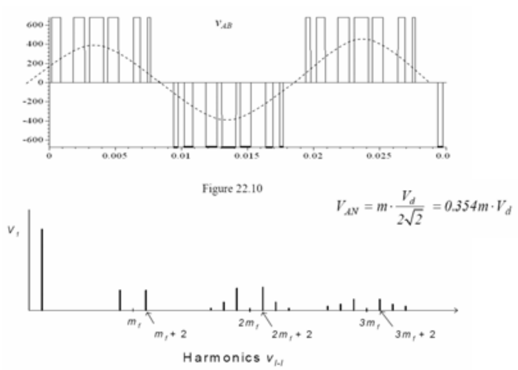
Phase Voltage is Modulated by Frequency and Amplitude of Reference



- The resulting switching signals from each comparator are used to drive the inverter switches of the corresponding leg. The switching signals for each inverter leg are complementary.

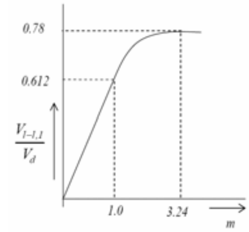


Linear Modulation (m < 1)



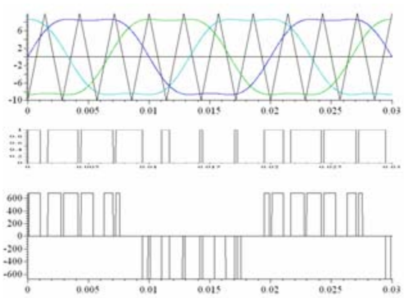
Overmodulation m > 1

- Overmodulation is a means of increasing the output voltage range of a SPWM inverter. When over-modulation is used, more sideband harmonics and its multiples will exist. However, the dominant harmonics will not be as large in amplitude as with operation in the linear range.



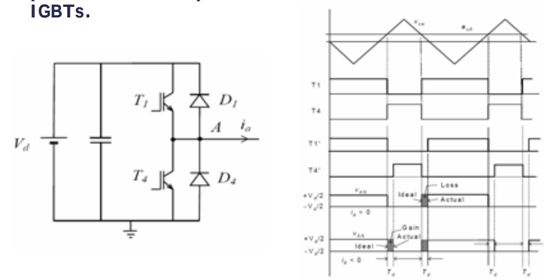
Modulating Signal with 3rd Harmonic

- The amplitude of the fundamental can be increased further by adding a third harmonic to the modulating waveform.



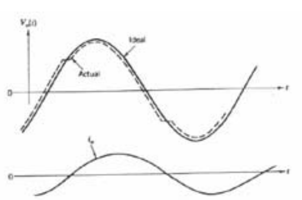
Dead-Time

- To prevent overlap of conduction, dead-time is interposed into the switching signals as indicated. The dead-time can be of the order of a few microseconds for fast devices (such as MOSFETs) to a few tens of microseconds for IGBTs.



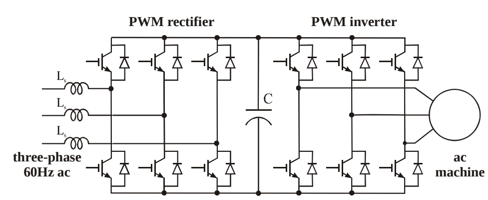
Dead-time Distortion

- The figure shows the effect of dead-time on the fundamental output voltage waveform of a full-bridge single-phase SPWM inverter. Note that output voltage level changes at the zero crossings of the load currents imply that there is now a low order harmonic voltage in the output which is at twice the output frequency.



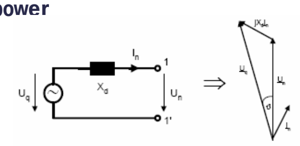
Back to Back Converters

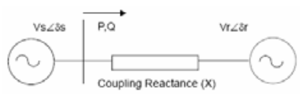
- Double PWM converters connected back to back have been used for ac-ac conversion with an intermediate dc-link voltage that must be boosted to a higher voltage level, capable of imposing linear operation to both converters.
- Double PWM converters have been used for bi-directional power controllers and in applications denominated by electronic transformers.



Grid Connected Inverters

- The inverter must be controlled to impose active or reactive power



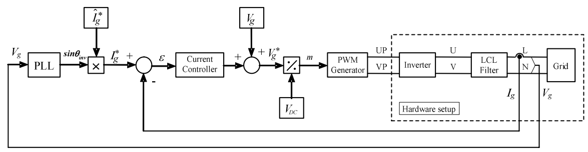


$$P = \frac{VsVr}{X}\sin(\delta s - \delta r)$$

$$Q = \frac{Vs^2}{X} - \frac{VsVr}{X}\cos(\delta s - \delta r)$$

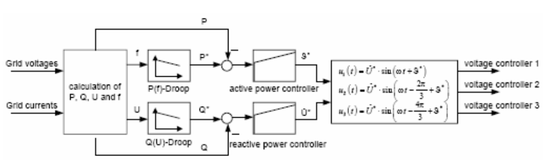
Grid Connected Inverters – Cont.

- A PLL must synchronize the inverter with grid voltage



Grid Connected Inverters – Cont.

- Feedback control of active and reactive power set-points as related to frequency and voltage will command the SPWM modulating signals



Temperature Concerns

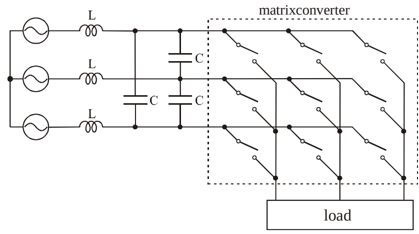
- Inverters usually have to operate in rather harsh environmental conditions, but regardless of the location, each of the inverter manufacturers specifies the operating temperature ranges its product will operate in.
- The inverters are designed to take necessary measures to regulate the temperature of heat sensitive components. This includes scaling back the power available to the utility or momentarily shutting down to maintain a safe operating temperature.

Some Interactive Inverters

- SMA Technologie AG (Sunny Boy Inverters)
  http://www.sma-america.com/
- Outback Power Systems (Trace Engineering R&D)
  http://www.outbackpower.com/
- Beacon Power : http://www.beaconpower.com/
- Xantrex : http://www.xantrex.com/
- PV Powered: http://www.pvpowered.com/
- Fronius Inverters : http://www.fronius.com/

AC-AC Conversion

- Direct ac-ac conversion was a strong solution using thyristor for phase-controlled regulation and phase-controlled cycloconverter during 1960's.
- The current matrix converter offers an all silicon solution for AC-AC power conversion, removing all the needs for the reactive energy storage components used in conventional inverter based converters such as capacitors and inductors.

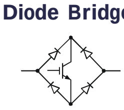


Advantages of Matrix Converters

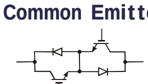
- No dc-link capacitor or inductor. Therefore, noise, EMI, size and weight are greatly reduced.
- Less maintenance, more durable
- Inherently bi-directional, so it can regenerate energy back to utility.
- High efficiency as the number of devices connected in series is less.
- Four quadrant of operation.
- Depending on modulation technique, sinusoidal input/output waveforms.
- Controllable input displacement factor independent of output load current.
- No electrolytic capacitors, hence can be used in high temperature surroundings. So it is an ideal topology to utilize future technologies such as high temperature silicon carbide (SiC) devices.

AC-AC Bipolar Switches

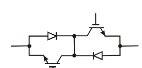
- Diode Bridge Bi-directional Switch



- Common Emitter Anti-parallel IGBT Diode Pair



- Common Collector Anti-parallel IGBT Diode Pair



Grid Interconnection of Alternative Energy Systems

- Initial interconnection requirements were established in early “PURPA” days.
- Many utilities were using rotating machinery requirements for PV systems.
- Special (and costly) engineering were needed for each specific utility requirements.
- The interconnection of AES to the distribution system is currently regulated by codes and standards put in place to address performance, safety and power quality issues.

Grid Interconnection of AES – Cont.

- Regulatory Agency Interconnection Rules : FERC, State Public Utility Commissions (PUCs), Municipal Boards
- Some organizations are major players in the interconnection codes and standards arena.

Institute of Electrical and Electronics Engineers (IEEE),
- IEEE 929, IEEE 1547, IEEE P1547.1, IEEE 1547.2

Underwriters Laboratories (UL)
- UL1741, UL2200

National Fire Protection Association (NFPA)
- National Electric Code (NEC)

Power Quality Issues

- Service Voltage
- Voltage Flicker
- Frequency
- Waveform Distortion (IEEE 519)
- Power Factor

Safety and Protection Issues

- Response to Abnormal Utility Conditions
- Voltage Disturbances
- Frequency Disturbances
- Islanding Protection
- Reconnect After a Utility Disturbance
- Direct Current Isolation
- Grounding
- Manual Disconnect

Islanding

- Islanding is when a distributed source continues to operate, feeding power into a portion of the grid when the utility source is no longer present. This situation presents many hazards including lethal electric shock to utility service personnel that think that the load side of the utility transmission line is "electrically dead."

Fire and Hazards

- The NFPA publishes the National Electrical Code (NEC) (NFPA-70), which covers electrical equipment wiring and safety on the customer's side of the point of common coupling. The NFPA also publishes other standards relating to AES interconnection.
- NFPA 70 – National Electrical Code: It covers electric conductors and equipment installed within or on public and private buildings or other structures, including mobile homes and recreational vehicles, floating buildings, and other premises such as yards, carnivals, parking and other lots, and industrial substations; conductors that connect the installations to a supply of electricity and other outside conductors and equipment on the premises; optical fiber cable; and buildings used by the electric utility, such as office buildings, warehouses, garages, machine shops, and recreational buildings that are not an integral part of a generating plant, substation, or control center.

Fire and Hazards – Cont.

- Some NEC Articles related to interconnection are described below.
- Article 230 – Services. Includes provisions and requirements for electric service to a building, including emergency, backup, and parallel power production.
- Article 690 – Solar Photovoltaic Systems. Mentions interconnection to the grid but focuses on descriptions of components and proper system wiring.
- Article 692 – Fuel Cells. Covers stationary fuel cells for power production.
- Article 700 – Emergency Systems. Includes provisions that apply to emergency power systems together with information on interconnection such as references to transfer switches.

Fire and Hazards – Cont.

- Article 701 – Legally Required Standby Systems. Includes provisions that apply to standby power systems. Has some information on interconnection such as references to transfer switches, UPSs, generators, etc.
- Article 702 – Optional Standby Systems. Includes provisions that apply to standby systems that are not legally required. Has some information on interconnection such as references to transfer switches, grounding, circuit wiring, etc.
- Article 705 – Interconnected Electrical Power Production Systems. Broadly covers AES interconnection other than PV systems and fuel cells.

Fire and Hazards – Cont.

- NFPA 853 – Standard for the Installation of Stationary Fuel Cell Power Plants. Applies to the design and installation of the following stationary fuel cell power plant applications:

  (a) a singular prepackaged self-contained power plant unit,

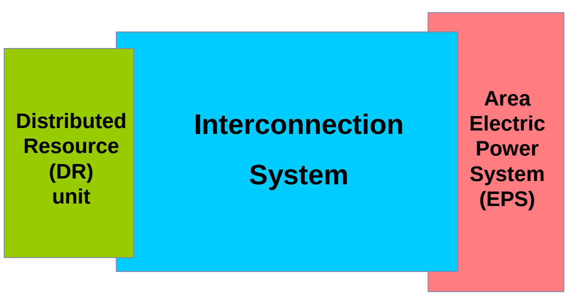
  (b) a combination of prepackaged self-contained units, and

  (c) power plant units composed of two or more factory matched modular components intended to be assembled in the field.

UL Certification

- Underwriters Laboratories, Inc. (UL) is an independent, not-for-profit product safety testing and certification organization. UL has tested products for public safety for more than a century and is the leader in US electrical product safety and certification. UL has a number of certifications that apply to AES interconnection equipment.
- UL 1741 – Inverters, Converters, and Controllers for Use in Independent Power Systems. These requirements cover inverters, converters, charge controllers, and output controllers intended for use in stand-alone (not grid-connected) or utility-interactive (grid-connected) power systems. Utility-interactive inverters and converters are intended to be installed in parallel with an Area EPS or for an electric utility to supply common loads. This standard is harmonized with the IEEE 1547 interconnection requirements and IEEE P1547.1 test procedures

IEEE 1547 Standard



IEEE 1547 Standard – Cont.

- This document provides a uniform standard for interconnection of distributed resources with electric power systems. It provides requirements relevant to the performance, operation, testing, safety considerations, and maintenance of the interconnection.
- The requirements shall be met at the point of common coupling (PCC), although the devices used to meet these requirements can be located elsewhere. This standard applies to interconnection based on the aggregate rating of all the DR units that are within the Local EPS. The functions of the interconnection system hardware and software that affect the Area EPS are required to meet this standard regardless of their location on the EPS.
- The stated specifications and requirements, both technical and testing, are universally needed for interconnection of DR, including synchronous machines, induction machines,

IEEE 1547 Standard – Cont.

- The requirements are applicable to all AES technologies with aggregate capacity of 10 MVA or less at the point of common coupling that are interconnected with EPSs at typical primary or secondary distribution voltages.
- The installation of AES on radial primary and secondary distribution systems is the emphasis of the 1547 standard, but installation on primary and secondary network distribution systems is also considered.
- IEEE Standards Coordinating Committee (SCC) 21 is also developing a series of standards within the 1547 family.

  IEEE P1547.1
  IEEE P1547.2
  IEEE P1547.3
  IEEE P1547.4

IEEE 1547 Standard – Cont.

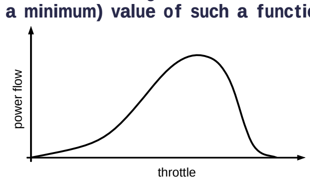
- IEEE P1547.1 which will provide the detailed test procedures to prove or validate that interconnection specifications and equipment conform to the functional and test requirements of IEEE 1547.
- IEEE P1547.2, which will provide technical background and application details to make IEEE 1547 easier to use. It will characterize various distributed resource technologies and their associated interconnection issues.
- IEEE P1547.3, which will aid interoperability by offering guidelines for monitoring, information exchange and control among fuel cells, photovoltaics, wind turbines and other distributed generators interconnected with an electrical power system.
- IEEE P1547.4, which will address engineering aspects of how local facilities could function as "an electrical island" providing power when utility grid power is not available.

Marcelo Godoy Simões

Optimized Control of Renewable Energy Systems

Optimization Principles
Optimize Benefit or Minimize Effort

- When someone plans a trip on a map the roads that go towards the right direction are observed. Then, the ones that reduce the distance at the fastest rate are selected.
- Other considerations may come into the decision, such as scenery, facilities along the way and weather conditions.
- The effort required or the benefit desired in any practical situation can be expressed as a function of certain decision variables (i.e. the ***objective or cost function***), and optimization is defined finding the conditions that generate a maximum (or a minimum) value of such a function.



Optimization Principles
Optimize Benefit or Minimize Effort – Cont.

- In the previous optimization function the x-axis may represent any physical variable such as power, force, velocity, voltage, current, resistance, while the y-axis might indicate the amplitude of the physical variable to be maximized.
- For example, a throttle controlling a water-pump system versus the amplitude of the physical variable to be maximized, for example, input power to the pump.
- As the throttle opens, the water flow increases but the pressure decreases, and the power (y-axis) initially goes up, reaching a maximum and decreasing as the throttle continues opening.

Optimization Principles
Optimize Benefit or Minimize Effort – Cont.

- The maximum might change under some conditions such as: parameter variations as temperature, density, ageing, part replacement, impedance, non-linearities like dead-band and time delays, and cross-dependence of input and output variables.
- The typical way of dealing with so many interdependencies would be by utilizing sensors to improve parameter robustness, analytical and experimental preparation of look-up tables, and mathematical feedforward de-coupling.
- The heuristic way of searching the maximum could be based on the following meta-rule:

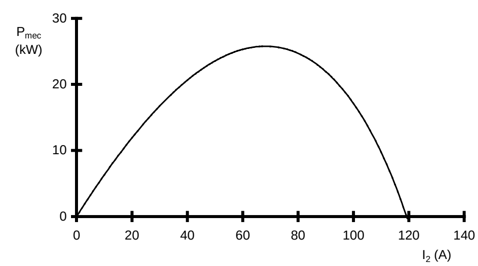
  "If the last change in the input variable (x) has caused the output variable (y) to increase, keep moving the input variable in the same direction; if it has caused the output variable to drop, move it in the opposite direction."

Optimization of Renewable Energy Sources

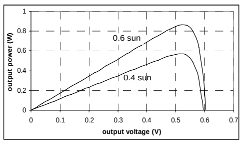
- Power is the product of two variables, one related to strength (force, torque, sun intensity) and another related to its flow (velocity, speed, temperature).
- Energy is the integral of this product, and bounded to the physical resource. Therefore, the derivative of the energy (power) will be constrained.
- Therefore, renewable energy resources will typically be a convex curve with a maximum point.
- The locus of the strength versus the flow will define the peak power operating point.

Wind and Hydro with Electrical Generator

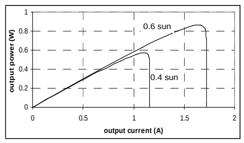
- Typical power curve for an electrical generator :



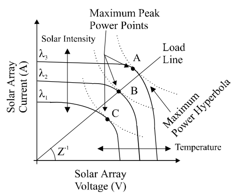
Photovoltaic Systems



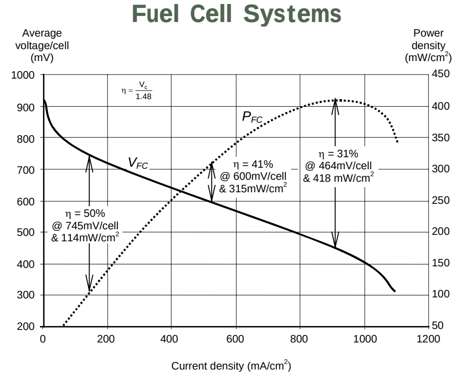
Power x Current



Power x Voltage



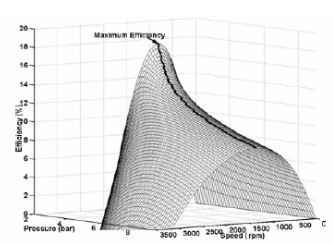
Fuel Cell Systems



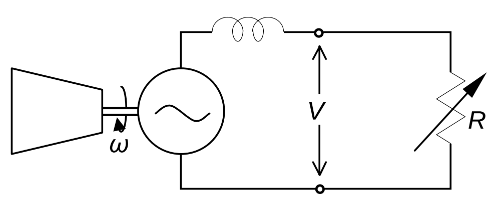
Power x Current and Efficiency x Current

Air Based Systems, Microturbines, HVAC

- The peak power operating point will depend on operating speed, as well on pressure :

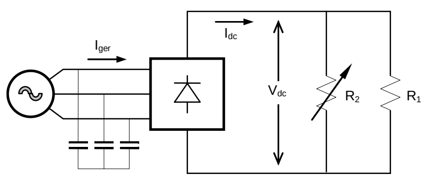


Electronic Control by the Load (ECL)

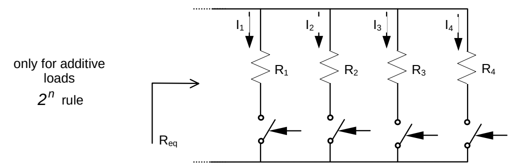


Example of ECL Implementation

- **Wind or hydro turbine with a fixed load plus a deferrable load.**

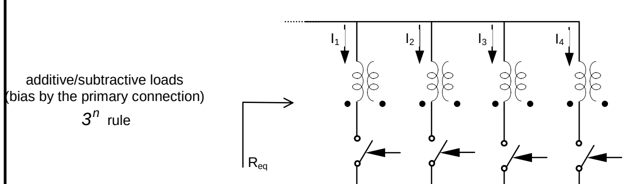


Variable Power Resistor

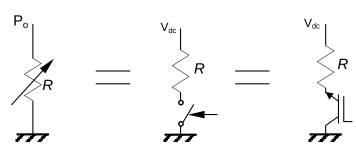


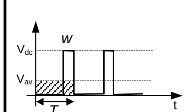
Variable Power Resistor – Cont.

Discrete control by additive/subtractive loads



Variable Power Resistor – Cont.





$V_{av}T = V_{dc}w$

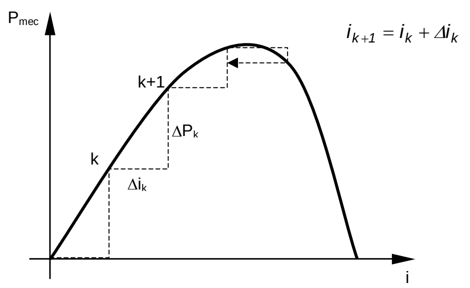
$\frac{V_{dc}}{R_{eff}} = I_{eff}$

$R_{eff} = \frac{R}{D}$

$D = \frac{V_{av}}{V_{dc}} = \frac{I_{av}}{I_{dc}} = \frac{w}{T}$

$\frac{V_{dc}}{R} = I_{dc}$

Hill Climbing Peak Power Searching



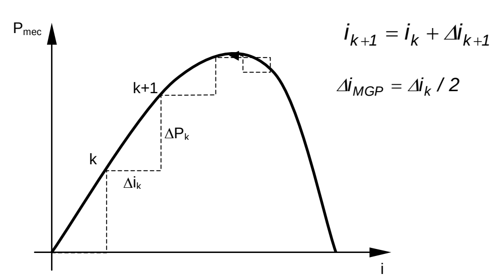
MODULATION BY FIXED STEPS

Fixed Steps

Features:

- causes oscillations around the MGP;
- may cause voltage flickering;
- electro mechanic stresses;
- in the case there is some resonance present, it will sustain oscillations;
- too slow / too fast response.

Peak Power Searching: Modulation by Divided Steps



Divided Steps

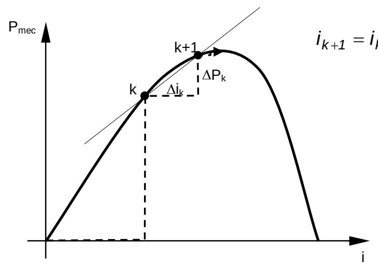
Features:

- similar to that of the fixed step except that it causes less oscillations around the MGP.

Peak Power Searching: Modulation by Adaptive Steps

$$k_{ak+1} = \frac{\Delta P_{k+1}}{\Delta i_{k+1}}$$

$$i_{k+1} = i_k + k_{ak+1} \Delta i$$

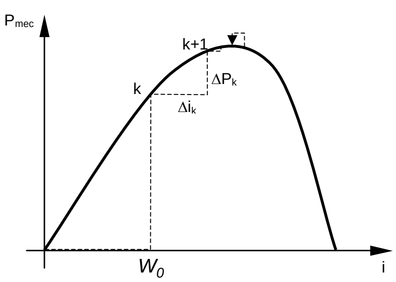


Adaptive Steps

Features:

- practically eliminates power oscillations around the MGP;
- acceleration factor proportional to the power variations;
- it goes smoothly to the maximum generated power;
- possible instability when there are fast generation transients.

Modulation by Exponential Steps



W_0 = initial step;
ξ_n = approaching gap;
Δ_i = incremental factor;
k = constant.

$$f_i = 1 - \xi_i = 1 - e^{-ki}$$

$$k = -ln(1 - W_o)$$

$$n = -\frac{1}{k} * ln(\xi_n)$$

$$\Delta_i = e^{-k*i} \cdot (e^k - 1)$$

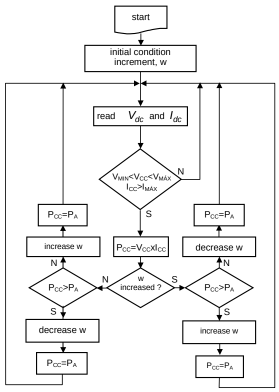
$$\Delta i = f_i - f_{i-1} = (1 - e^{-ki}) - [1 - e^{-k(i-1)}] = e^{-ki}(e^k - 1)$$

Exponential Steps

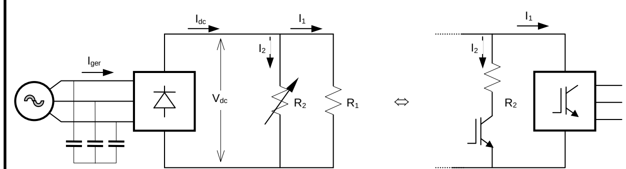
Features:

- fast transient response;
- soft approach of the MGP .

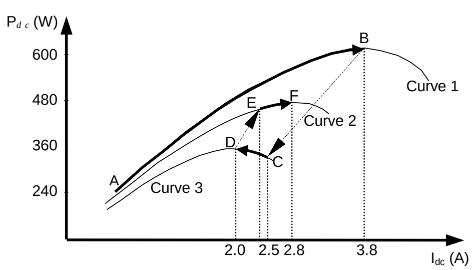
HCC Flowchart



ECL



ECL – Cont.



R_s	40 Ω	rated voltage	220/380 V
R_p	80 Ω	generator winding connection	Δ
W_0 (initial step)	10%	excitation capacitance	15 kVA
ξ	2%	IGBT	IRG4BC40U
generator output power	10 hp	switching frequency	20 kHz

Impedance Based Controls

- The ECL – Electronic Control by the Load is actually matching the best impedance for optimum power transference.
- Therefore, other impedance based controls can be implemented by directly adjusting a feature of the energy conversion device :
- Wind turbines: pitch, yaw, generator reference speed set-point
- Photovoltaic systems: variable impedance on the dc-dc converter by imposing the duty-cycle
- Water turbines : regulators for water flow and pressure
- Microturbines: variable air-flow restriction the inlet air chamber, variable generator reference speed-set point, variable load

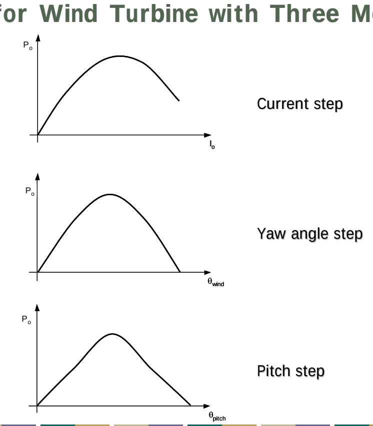
Wind Turbine Pitch Control

- In a pitch controlled wind turbine the turbine's electronic controller checks the power output of the turbine several times per second. When the power output becomes too high, it sends an order to the blade pitch mechanism which immediately pitches (turns) the rotor blades slightly out of the wind. Conversely, the blades are turned back into the wind whenever the wind drops again.
- The rotor blades thus have to be able to turn around their longitudinal axis (to pitch) as shown in the picture.
- During normal operation the blades will pitch a fraction of a degree at a time - and the rotor will be turning at the same time.
- Designing a pitch controlled wind turbine requires some clever engineering to make sure that the rotor blades pitch exactly the amount required. On a pitch controlled wind turbine, the computer will generally pitch the blades a few degrees every time the wind changes in order to keep the rotor blades at the optimum angle in order to maximise output for all wind speeds.

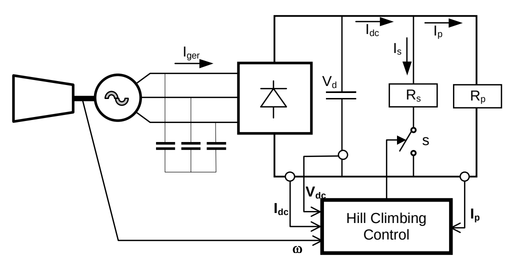
Wind Turbine Yaw Control

- Yaw control is used only for very small wind turbines.
- A wind turbine is said to have a yaw error, if the rotor is not perpendicular to the wind. A yaw error implies that a lower share of the energy in the wind will be running through the rotor area. (The share will drop to the cosine of the yaw error).
- The blades will be bending back and forth in a flapwise direction for each turn of the rotor. Wind turbines which are running with a yaw error are therefore subject to larger fatigue loads than wind turbines which are yawed in a perpendicular direction against the wind

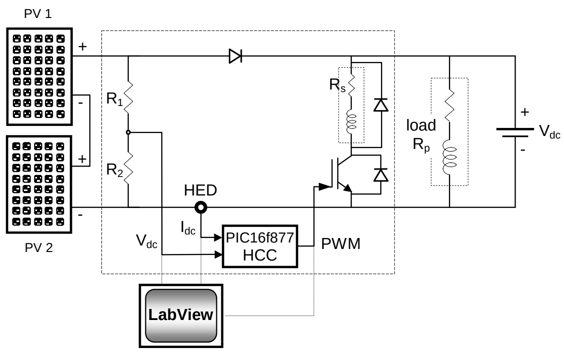
HCC for Wind Turbine with Three Methods



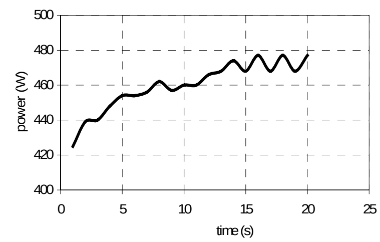
Practical Implementation of ECL Based HCC for IG



Practical Implementation of an ECL with Solar Panels

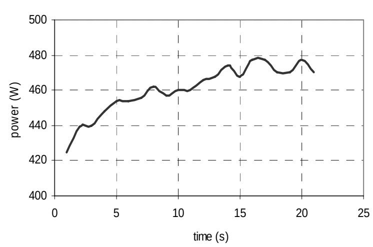


HCC Based Hydropower System



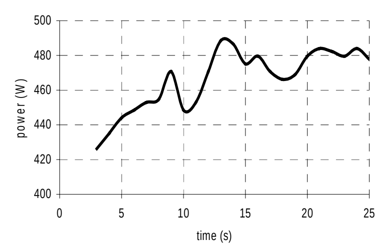
HCC with fixed step

HCC Based Hydropower System – Cont.



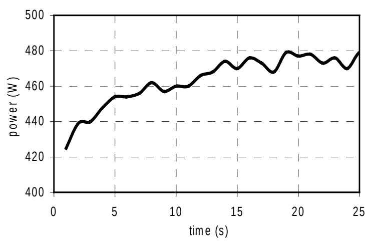
HCC with divided step

HCC Based Hydropower System – Cont.



HCC with adaptive step

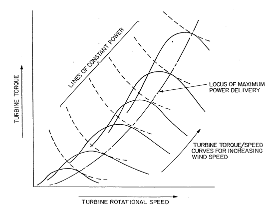
HCC Based Hydropower System – Cont.



HCC with exponential step

Fuzzy Logic Based Search Control

- Fuzzy logic has been applied for peak power tracking control of wind turbines and photovoltaic systems.
- Fuzzy logic allows a mathematical representation of rules that govern the system.
- For example, the rules for searching the best operating speed of a wind turbine generator can be derived from the family of curves below :

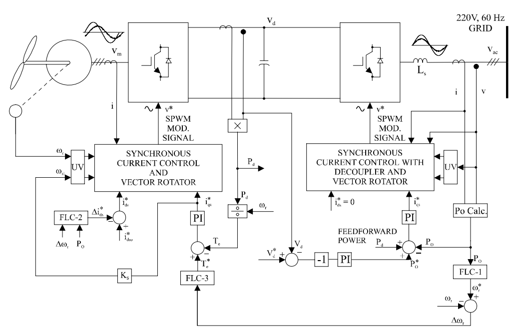


Set of Rules for Search Best Reference Speed

variation (Δ) of power and last speed

P_o \ Last Speed	P	ZE	N
PVB	PVB	PVB	NVB
PBIG	PBIG	PVB	NBIG
PMED	PMED	PBIG	NMED
PSMA	PSMA	PMED	NSMA
ZE	ZE	ZE	ZE
NSMA	NSMA	NMED	PSMA
NMED	NMED	NBIG	PMED
NBIG	NBIG	NVB	PBIG
NVB	NVB	NVB	PVB

Fuzzy Logic Based Search Control



Fuzzy Logic Based Search Control – Cont.

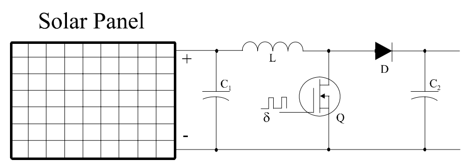
- The figure shows the control block diagram of an induction generator with a double PWM converter fed wind energy system.
- Three fuzzy logic based vector control are used to enhance three characteristics in this system:

(i) search of best generator speed (FLC-1) command to track the maximum power in the wind,

(ii) search of best flux intensity in the machine (FLC-2) to optimize inverter and induction generator losses, and

(iii) robust control of speed loop (FLC-3) to overcome possible shaft resonances due wind gusts and vortex.

Fuzzy Logic Based Photovoltaic PPT



Fuzzy Logic Based Photovoltaic PPT – Cont.