Why and When Power Electronics Calls For Artificial Intelligence - From Hidden Past To Brightest Future

Power electronics is a field in constant evolution; power grids are becoming intelligent and flexible with power electronics, real-time control, and further data layers of communications and signal processing. Renewable energy, distribution and microgrids, automotive and shipboard power systems and wireless power transfer, will advance our society.


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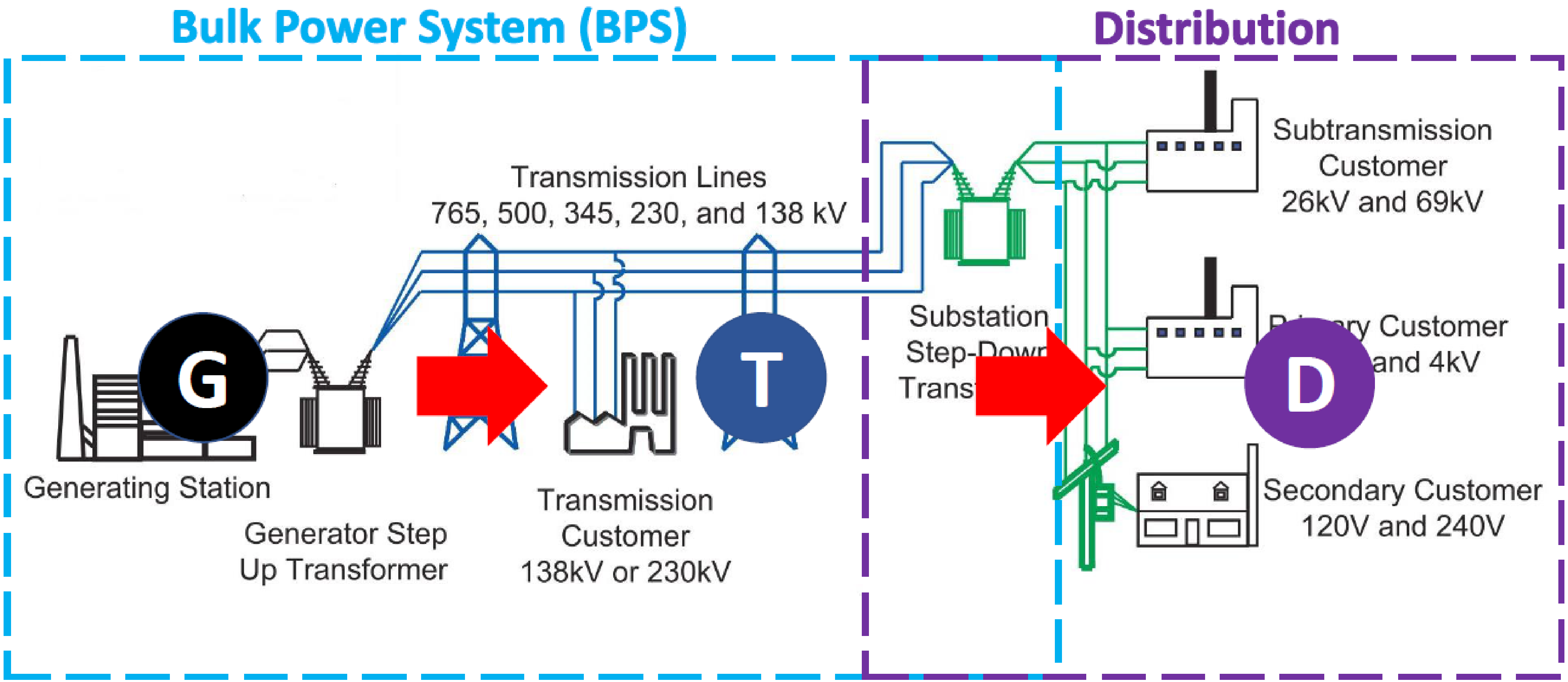
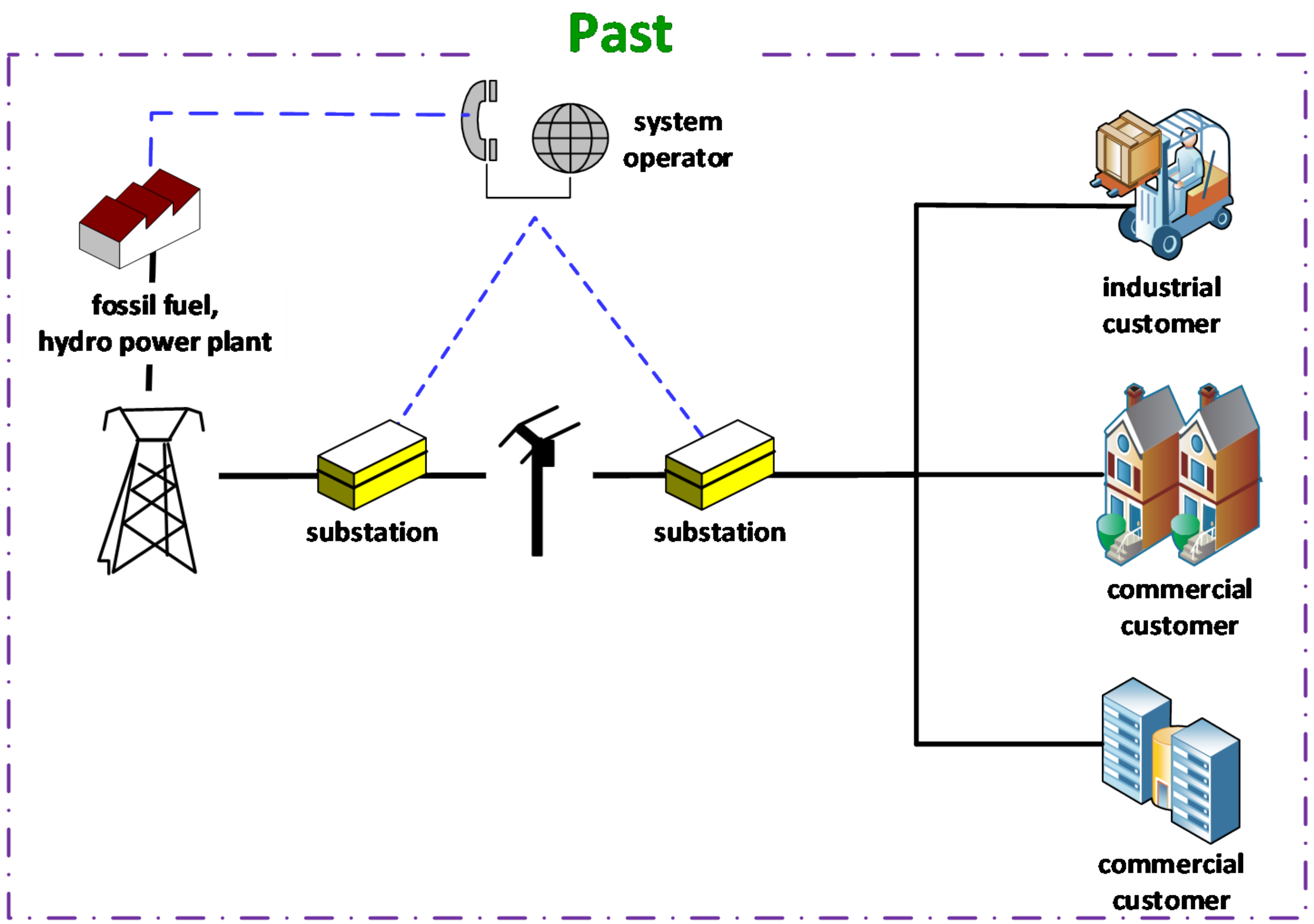
Overview – electrical engineering integrated power electronics with power systems for smart-grid applications

Traditional Way to Teach, Model, and Analyze the T&D Power System




Past
system
operator
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hydro power plant
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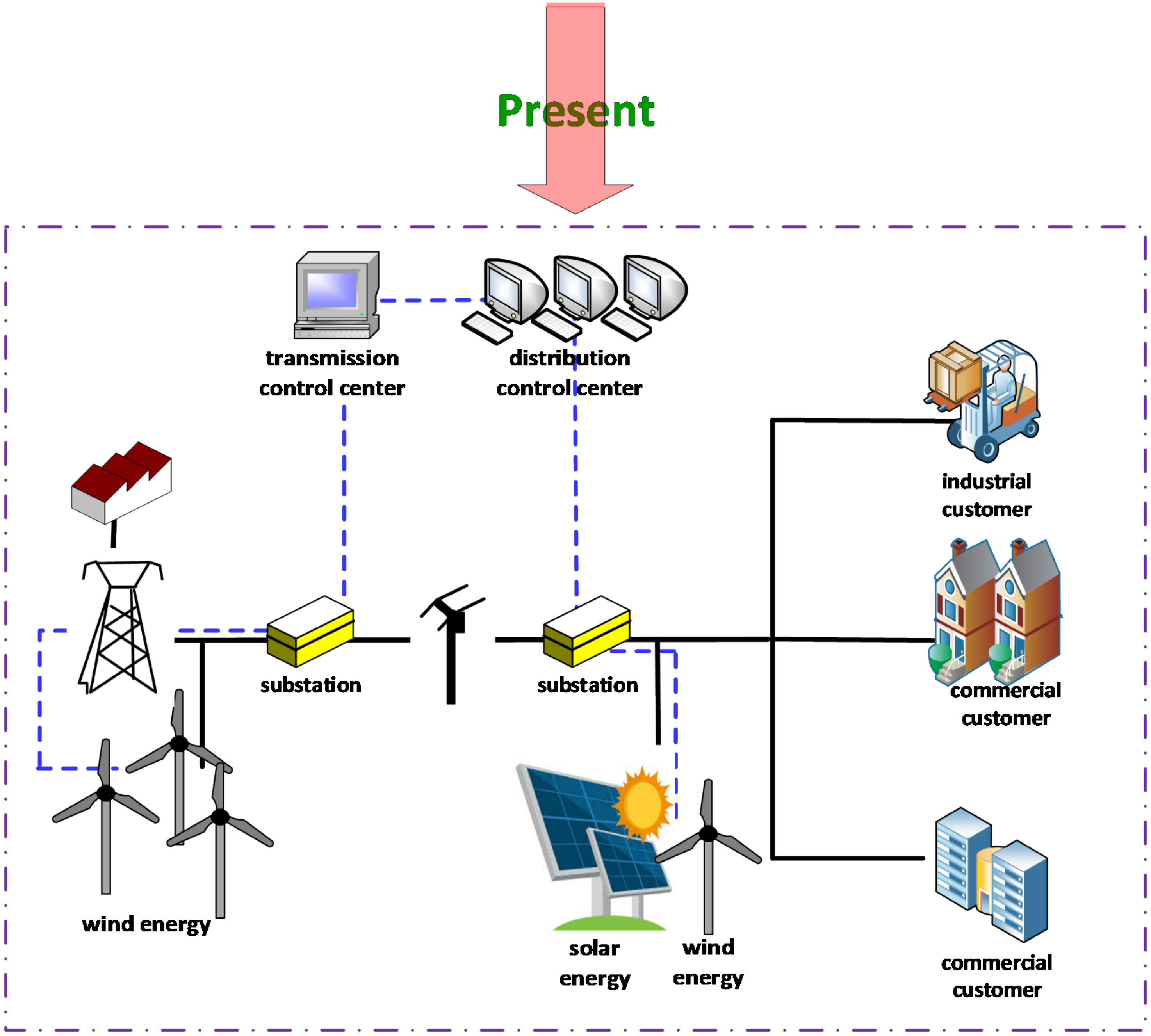
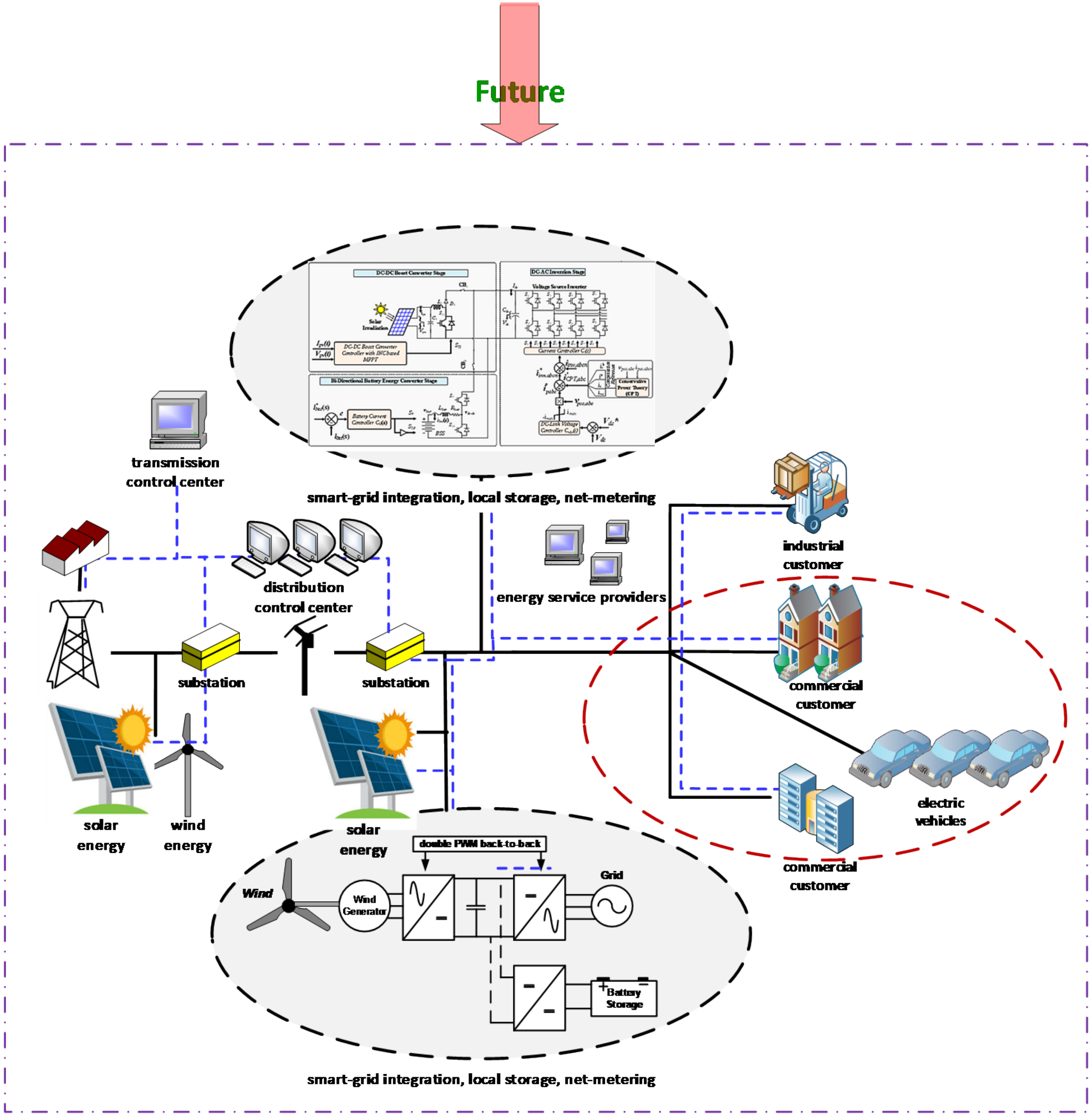


Present
transmission control center
distribution control center
industrial customer
commercial customer
substation
substation
wind energy
solar energy
wind energy
commercial customer


Future
transmission control center
smart-grid integration, local storage, net-metering
distribution control center
energy service providers
industrial customer
commercial customer
substation
substation
solar energy
wind energy
solar energy
electric vehicles
commercial customer
double PWM back-to-back
Wind
Wind Generator
Grid
Battery Storage
smart-grid integration, local storage, net-metering

- The power system and electricity needs were simpler in the last 100 years.
- The grid was designed to deliver unidirectional electricity.
- The original structure is difficult for the rising demand ever changing needs of 21st century.
- The smart-grid is a two way dialogue of electricity and information exchanged between the customers and the utility.
- Network of communications, controls, computers, automation, with new technologies and tools.
- The future grid must be efficient, more reliable, more secure and greener.
- A smart-grid enables new technologies to be integrated. Further wind and solar energy production. Plug-in electric vehicle charging. The smart-grid is the new infrastructure of today's grid.

- There is increasing high penetration of solar and wind power in the electric grid, with evolving bidirectional power, mobile prosumers (such as HEVs), integrated communications, and advanced infrastructure

- Scheduling and operation of smarter power systems are compromised with challenges of uncertainty, random generation, and mobile flexible loads.

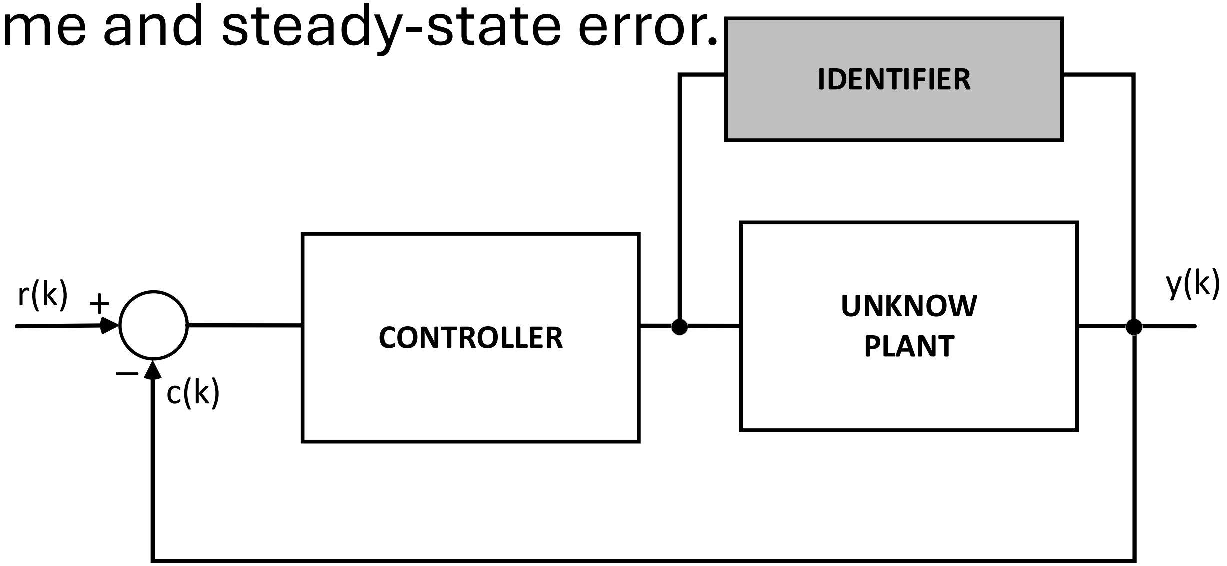
- Accurate forecasting of energy demands at different echelons in an integrated power system is very important for reliability and resilience.

- Future smart-meters and cognitive-meters will provide a tremendous opportunity with pervasive and massive data that useful for deep learning algorithms.

What is the difference between conventional and intelligent systems ?

CONTROL SYSTEMS – SYSID VERSUS OPERID

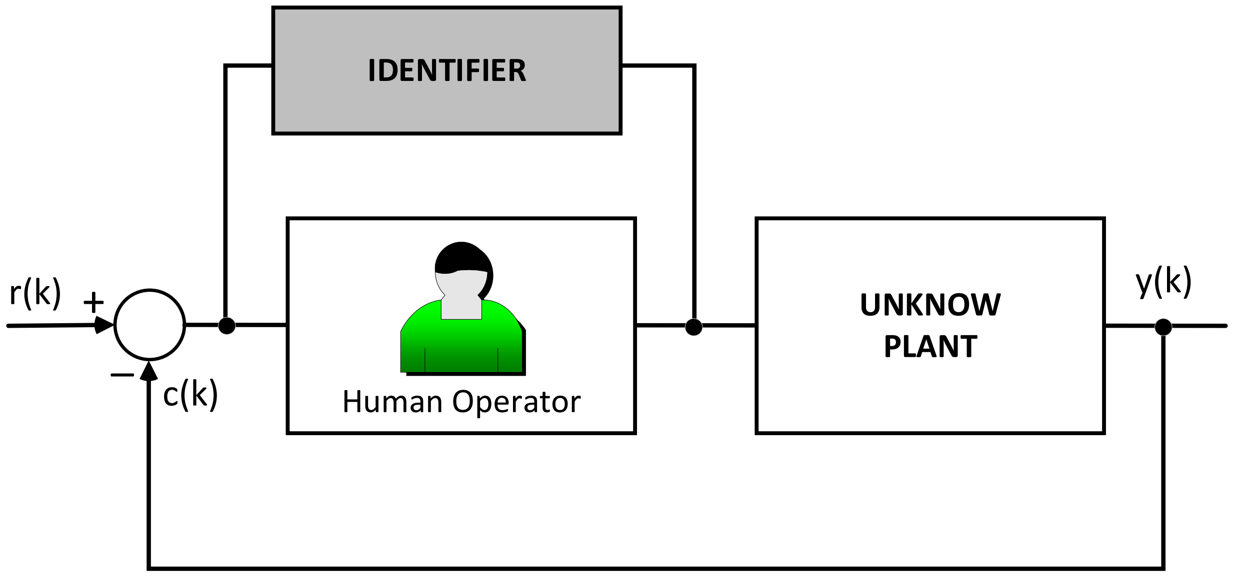
- The conventional methodology in designing control systems: what is modelled is the plant or process that will be controlled.
  - ✓ This procedure is called system identification **(SysID),** where the plant or process is assumed to be linear, or approximately linear, characterized with differential equations, if those can be solved an analytical transfer function can be derived, and then parameters of a controller, or regulator, in a closed-loop will have to be adjusted for an adequate behavior, such as maximum overshoot, damping, velocity response, accommodation time and steady-state error.



Identification of process or plant dynamics

CONTROL SYSTEMS – SYSID VERSUS OPERID

- There are several systems that are not attained on traditional automatic control, particularly when human operators are employed and the methodology is focused in how those operators observe the system, adjust set-points and control the quality in a heuristic way (**OperID**).
  - ✓ In a bakery, or in a sauce factory, or maybe in a beer production plant, the behavior of the operator is what matters, how they will adjust parameters, temperatures, mixing strength, humidity for a given set of circumstances.



Identification of control operator behavior

Control Systems – SysID versus OperID

- **There are several systems that are not attained on traditional automatic control**
- **Particularly when human operators are employed and the methodology is focused in how those operators observe the system, adjust set-points and control the quality in a heuristic way.**
- **In a bakery, or in a sauce factory, or maybe in a beer production plant, the behavior of the operator is what matters, how they will adjust parameters, temperatures, mixing strength, humidity for a given set of circumstances.**

"As complexity rises, precise statements lose meaning and meaningful statements lose precision" — Lotfi A. Zadeh

- Supervisory control systems are very important, because they allow decoupling of complex systems into feasible smaller tasks.
- A brewing company, or an alcohol production for sugar cane, or a cement and concrete factory production, or sewer treatment, or a wind farm, a large PV array, a fuel cell, all of those systems can be controlled and managed with supervisory control systems that allow experts to look at variables, instrumentation, closed loop control error responses, change to set-points, and make real-time fine tuning.
- Their expertise can be captured with fuzzy control rules, by modeling the operators, instead of the process. Fuzzy parametric relational (TSK) can be implemented by fuzzy evaluation of input data and multi-parametric linear expansion of equations to be implemented in fuzzy control rules.

"As complexity rises, precise statements lose meaning and meaningful statements lose precision" — Lotfi A. Zadeh

- In several industrial processes, such as extrusion, rubber, elastomers, tires, Banbury mixer, fermentation, distillation, ceramics, ferrites, permanent magnets, food mills, there are no mathematical functions describing their input/output transfer functions
- There are complex reactions, dynamics not formalized, inter-related multi-disciplinary complex models, unknow parameters, and expert people still work with those processes.
- There are empirical recipes, accepted procedures, adopted parameters, to produce acceptable results. Such recipes could be taken as input/output functions
- Input variables are sometimes in different domains, desired outputs might be dimensionless variables, such as rubber composition, the system would relate origin of the rubber tree with thickness of tire and life-time warranty
- Maybe a historical data set of production, or project management data (such as hardness of rock for tunnel boring machines), would be useful for training parametric linear relationships modeling and control approach.

What is the main difference in designing a control system based on deductive reasoning versus inductive reasoning ?

Traditional control approach requires formal modeling of the physical reality. Here we show two methods that may be used to describe a system’s behavior:

- 1. **Experimental Method**
  - ✓By experimenting and determining how the process reacts to various inputs.
- 2. **Mathematical Modeling**
  - ✓Mathematical model of the controlled process, usually in the form of differential or difference equations. Laplace transforms and and z-transforms are respectively used.
  - ✓Problems that can arise: – Model complexity
  - ✓Inaccurate values of various parameters

Alternative Approach: Heuristic Method

- The heuristic method consists of modeling and understanding in accordance with previous experience, rules-of-thumb and often-used strategies.
- Heuristic rule: It is a logical implication of the form:
  - If <condition> then <consequence>, or in a typical control situation:
    If <condition> then <action>

Rules associate conclusions with conditions.

- The heuristic method is actually similar to the experimental method infused with the control strategies of human operators.

Intelligent control strategies may be implemented by other means. However, fuzzy implementations are very efficient for several reasons.

Fuzzy Logic Deductive versus Inductive Reasoning

- Fuzzy Logic is a technique to incorporate the human nature in thinking in a control system

- A typical fuzzy logic controller could be designed to behave in accordance with **the deductive reasoning**
    - process in which people use to infer conclusions based on information know with previous experience. For example, human operators can control industrial processes and complex manufacturing plants, which could even have non-linear mathematical models and not completely defined dynamics, based on experience, inference, training with more experienced tutors. Fuzzy Logic can capture such knowledge in a fuzzy controller, allowing the computational implementation of an algorithm that has equivalent performance of the human operator.

Fuzzy Logic Deductive versus Inductive Reasoning – Cont.

- Another possibility is with **inductive reasoning.**
- Approach in learning to generalize from unique examples fed by data and observation of dynamic process behavior, with time varying conditions, in order to design a fuzzy controller.
- In such an implementation the fuzzy system is taught, and the fuzzy controller adapts to a given performance,
  - i.e. an adaptive fuzzy control system will learn from experience, when tasks are performed in a repetitive way, and a management layer will make the fuzzy controller to adapt and improve, based on a performance index or optimization function. Therefore, learning by example associated to encoding human expertise, make fuzzy systems very robust, extensible to being applied in a wide variety of engineering systems.

Why is fuzzy logic control considered as intelligent ?

Why Fuzzy Logic

- Fuzzy Logic is a technique to incorporate human nature in thinking in a control system
- A typical fuzzy logic controller could be designed to behave in accordance to the deductive reasoning, i.e. the process in which people use to infer conclusions based on information know with previous experience.
- **For example, human operators can control industrial processes and complex manufacturing plants, which may have non-linear mathematical models and not completely defined dynamics, humans do this control based on experience, inference, training with more experienced tutors.**
- Fuzzy Logic can capture such knowledge in a fuzzy controller, allowing the computational implementation of an algorithm that has equivalent performance of the human operator.
- **Artificial Intelligence (AI) is a discipline for studying how people solve problems and how machines (computers) may emulate such human behavior on "problem solving", in other words, how to make machines to have further and deeper attributes of human intelligence.**

- **Fuzzy logic controllers** have ability to cope with knowledge represented in a linguistic form instead of the conventional mathematical framework. Although, control systems engineers have traditionally relied on mathematical models for their designs, it has been observed that as further complex becomes a system, the less effective is their mathematical model. Real-world problems can be very complex. Therefore, fuzzy logic controllers can be useful in incorporating human experience, intuition and heuristics into the system controllers, instead of relying on in-depth mathematical models. Fuzzy logic control can be very effective in applications where existing models are ill- defined and not reliable, but there is human understanding about them.
- **Neural Networks, on the other hand,** are algorithms to learn representations of data, such as input/output, or sequence of data, or features represented in a database with numerical ranges, or to find patterns in data, their clustering and so on.
- There are hybrid approaches of Fuzzy Logic with Neural Networks where semantics become part of the NN topology.

Use of Fuzzy Control

- Fuzzy control incorporates ambiguous human logic into computer programs. It suits control problems that cannot be easily represented by mathematical models :
  - ✓Weak model
  - ✓Parameter variation problem
  - ✓Unavailable or incomplete data
  - ✓Very complex plants
  - ✓Good qualitative understanding of plant or process operation
- Because of its unconventional approach, design of such controllers leads to faster development / implementation cycles

Reason to study, understand and design intelligent systems

What are the main characteristics and features of intelligent control ?

Intelligent Control

- Sometimes in conventional control, useful heuristics are ignored because they do not fit into the proper mathematical framework, for example how the hot-spot of a transformer or an inductor will affect the parameter sensitivity of a PI closed-loop control ?

- Fuzzy logic and neural networks approach exactly these lack of real-life understanding by heavily math-oriented control designers, by allowing heuristics and learning from past case studies or numerical data, retrofitting usually an excellent performance controller which most of the time excel when compared to heavily mathematical control design approaches.

HOW DOES INTELLIGENT CONTROL WORK ?

- **Importance**
  - In the last few years, the applications of artificial intelligence techniques have been opening doors to convert human experience into a form understandable by computers. Advanced control based on artificial intelligence techniques is called intelligent control.
- **Fuzzy Logic**
  - Fuzzy logic is a technique to embody human-like thinking into a control system.
  - A fuzzy controller can be designed to emulate human deductive thinking, that is, the process people use to infer conclusions from what they know.
- **Neural Networks** have been adopted for a wide variety of scientific, engineering, and business problems. Capable of complex functions, noise cancellation, adaptive filtering, pattern recognition, non-linear controls, and forecasting.

Control of Systems Towards Intelligence

- **"Intelligent Systems (IS)"** are capable to supply answers that solve problems.
- Such answers may fit specific situations of those problems, also new or unexpected circumstances
- **IS** approaches unique solutions, very often to mimic nature and biological systems, for example: (i) observing how a person implement some pre-defined control functions, (ii) looking for patterns on data or behavior, (iii) taking decisions based on historical experience.
- There is still a lapse in how human beings think and act in a creative way when compared to how computational machines implement their decision making.
- In such a perspective, a human being is capable of holding two opposite concepts in their mind and still come up with an attitude that might be completely different to them.
- People may think in uncertain ways, with imprecise data, with facts that are blurred, and computers will be moved by an algorithm written in a precise workflow defined by yes/no paths, and true/false statement evaluations. When a human will make a decision if a bakery is good, bad, or wonderful, the evaluation will be made in what could be considered uncertain, imprecise, or what has been defined in the past few decades as a "fuzzy way".

What would be the main characteristics of a fuzzy logic-based control versus an artificial neural network-based control ?

Fuzzy Logic and Neural Network Based Controller Design

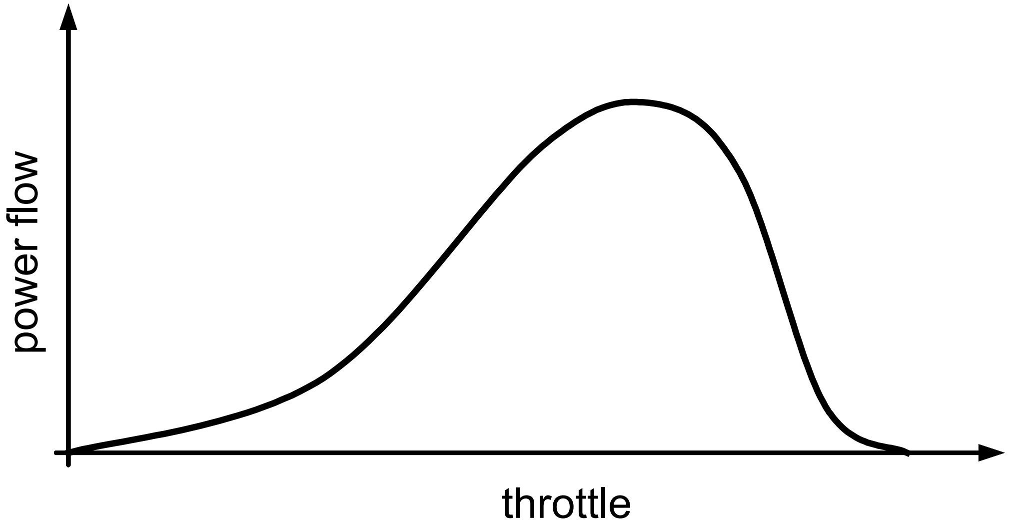
Conventional control has provided a mathematical formulation for the system to be controlled, approaching a design for closed-loop control. Some of those methods are:

- **Proportional-integral-derivative (PID) control: Over 90% of the controllers in operation today are PID controllers (or at least some form of PID controller like a P or PI or a I+P controller). This approach is often viewed as simple, reliable, and easy to understand. Sometimes fuzzy controllers are used to replace PID, but it is not clear yet if there are real advantages.**
- **Classical control: Lead-lag compensation, Bode and Nyquist methods, root-locus design.**
- **State-space methods: State feedback, observers.**
- **Optimal control: Linear quadratic regulator, use of Pontryagin´s minimum principle or dynamic programming.**
- **Robust control: H2 or H∞ methods, quantitative feedback theory, loop shaping.**
- **Nonlinear methods: Feedback linearization, Lyapunov redesign, sliding mode control, backstepping.**
- **Adaptive control: Model reference adaptive control, self-tuning regulators, nonlinear adaptive control.**
- **Stochastic control: Minimum variance control, linear quadratic gaussian (LQG) control, stochastic adaptive control.**
- **Discrete event systems: Petri nets, supervisory control, infinitesimal perturbation analysis.**

Where exactly intelligent control systems improve and enhance power electronics enabled power systems, smart-grid systems and integration 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:

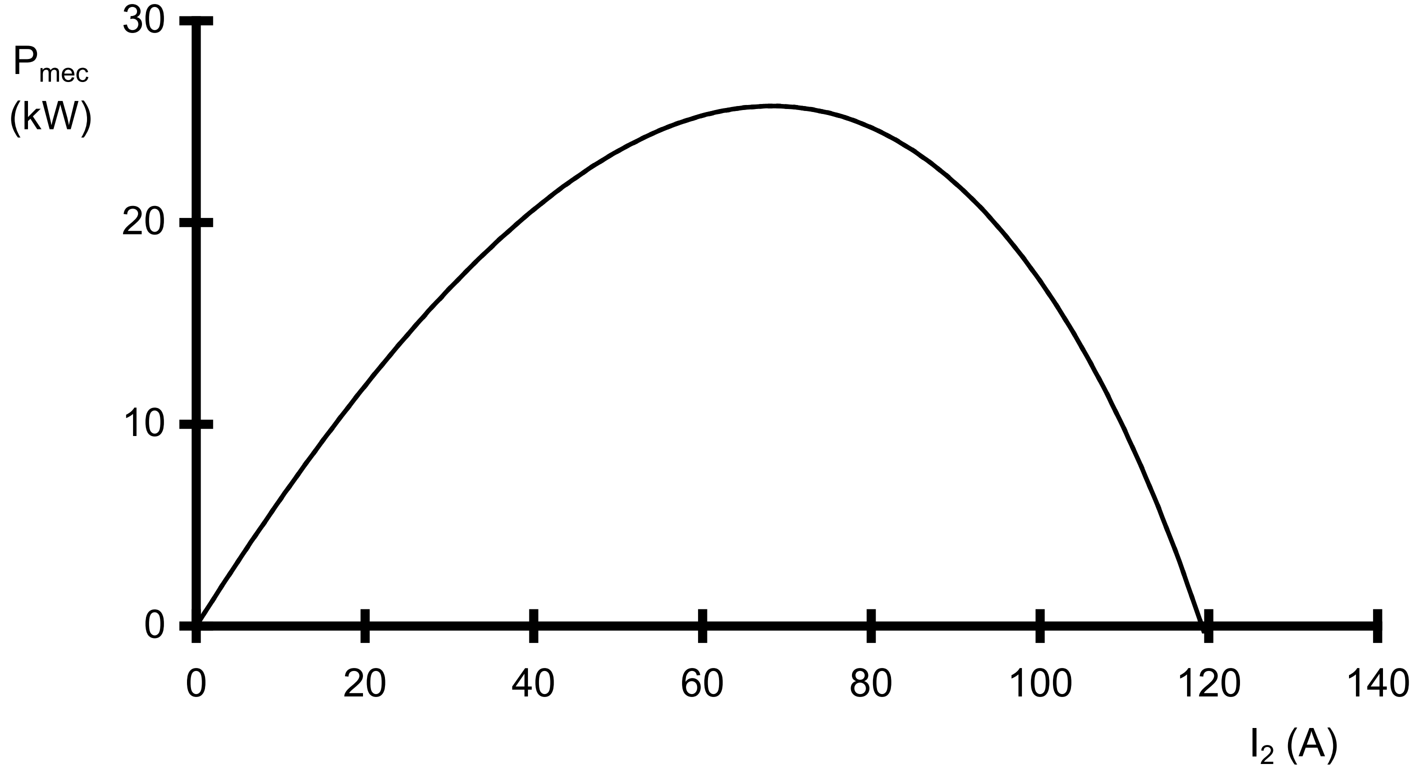
> "If the last change in the input variable (x) has caused the output variable (y) to increase, keep moving the input variable in the same direction; if it has caused the output variable to drop, move it in the opposite direction."

Optimization of Renewable Energy Sources

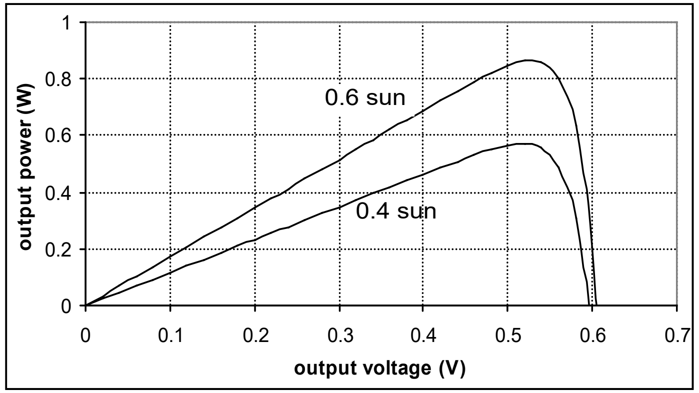
- Power is the product of two variables, one related to strength (force, torque, sun intensity) and another related to its flow (velocity, speed, temperature).
- Energy is the integral of this product, and bounded to the physical resource. Therefore, the derivative of the energy (power) will be constrained.
- 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

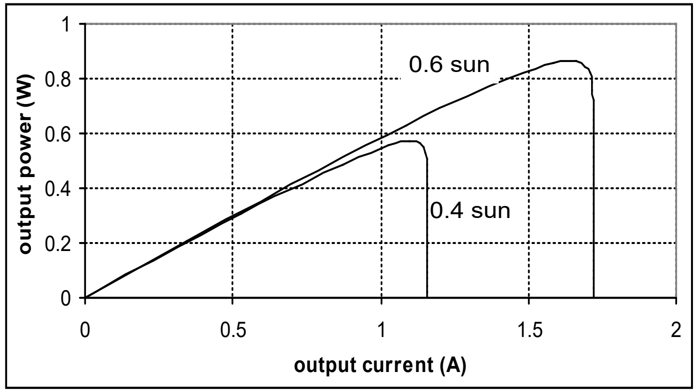
Typical power curve for an electrical generator



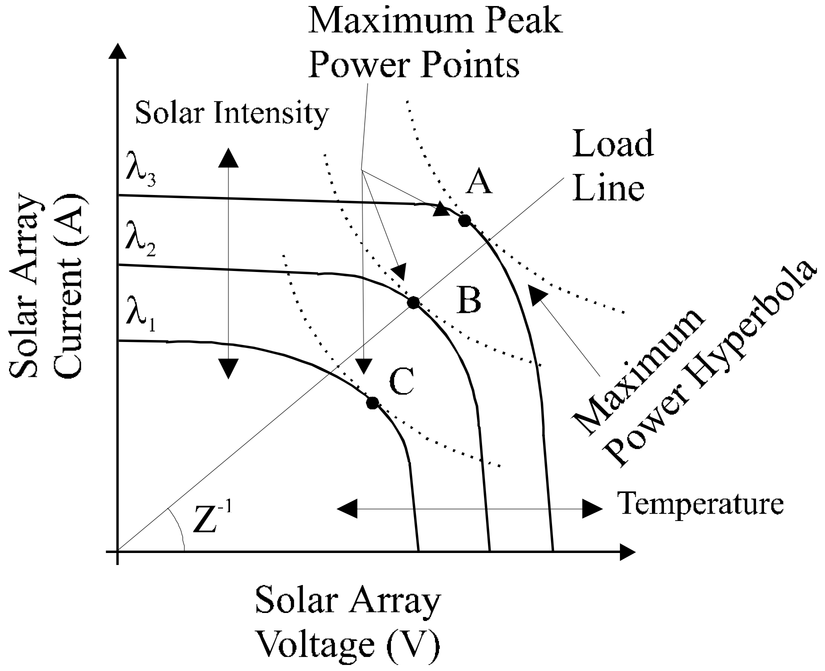
Photovoltaic Systems



Power vs Voltage

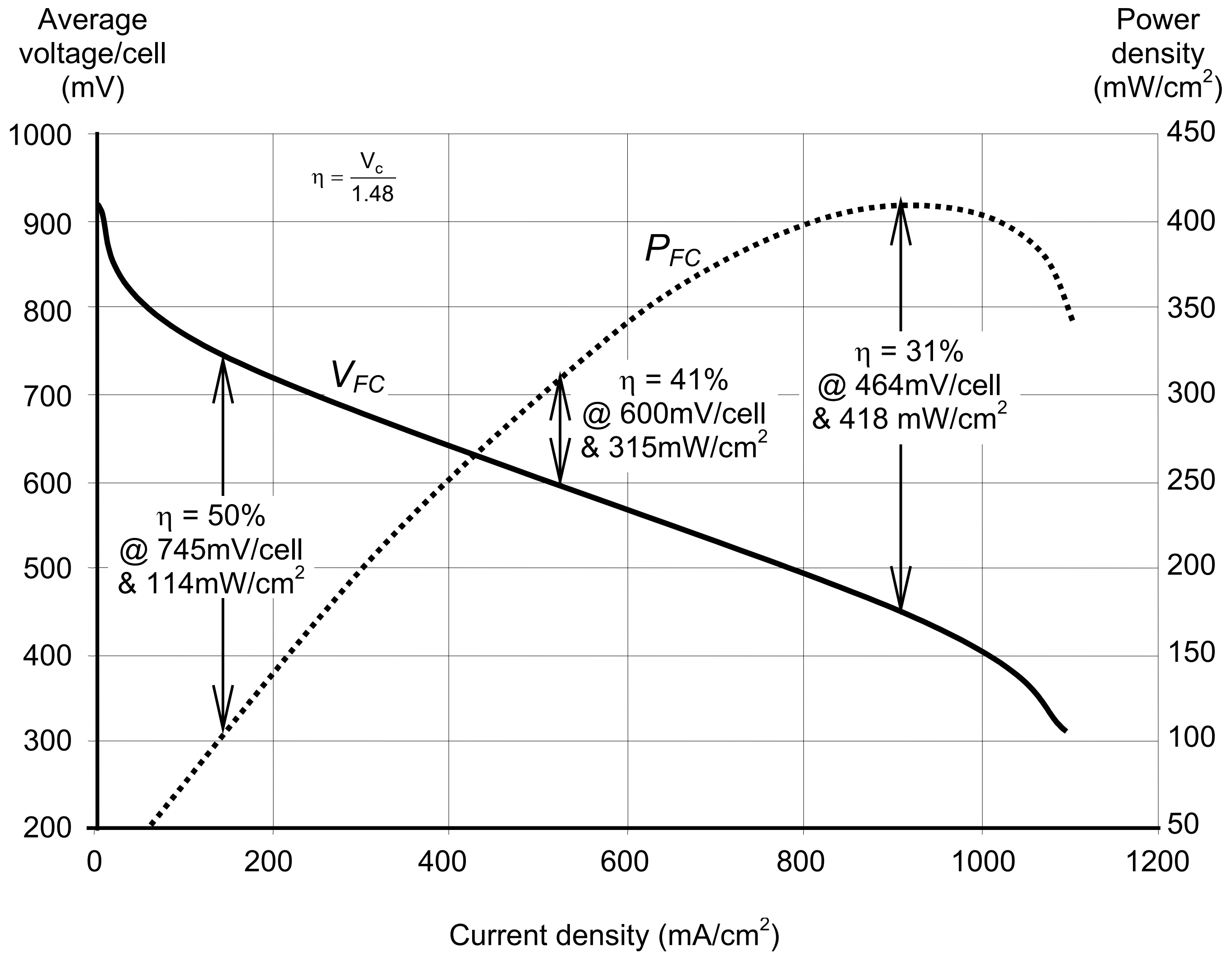


Power vs Current



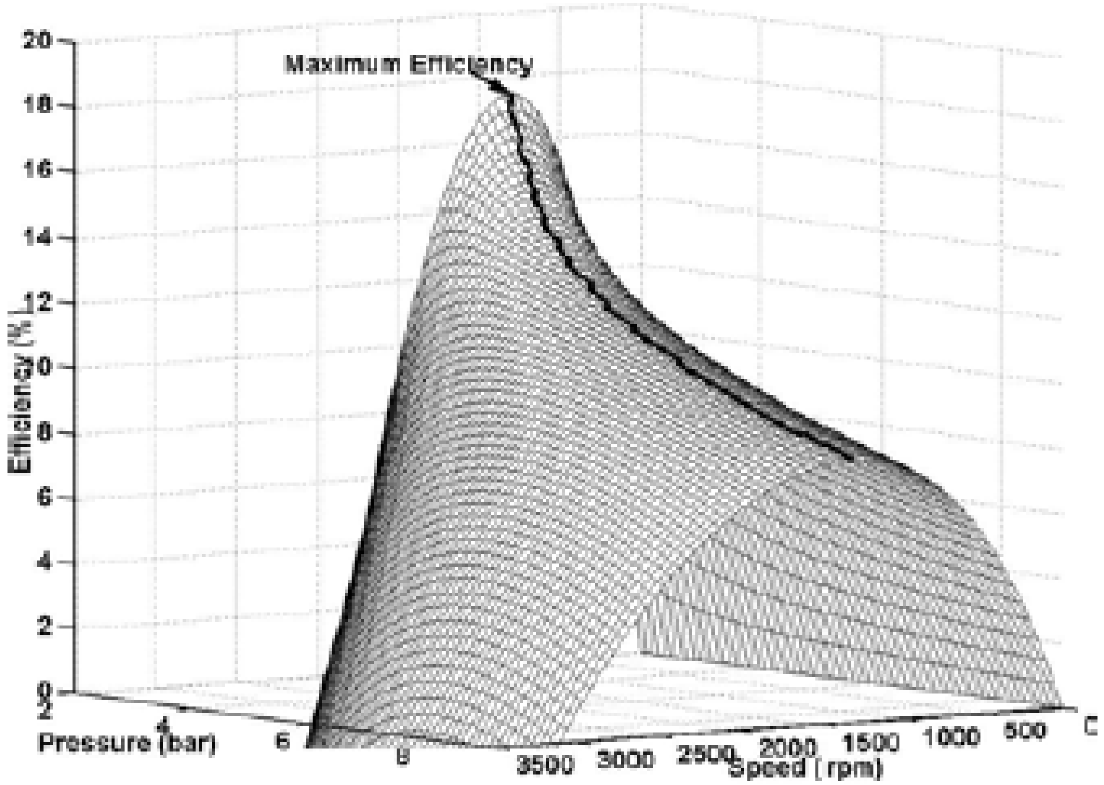
MPPT vs Solar Irradiation and Temperature Changes

Fuel Cell Systems



Power vs Current and Efficiency vs Current

Air Based Systems, Microturbines, HVAC



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

Impedance Based Controls

- The ECL – Electronic Control by Load is 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: 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.

Energy conversion systems have two possible classes that help define the requirement of advanced control systems:

(i) unconstrained energy systems vs. (ii) constrained energy systems

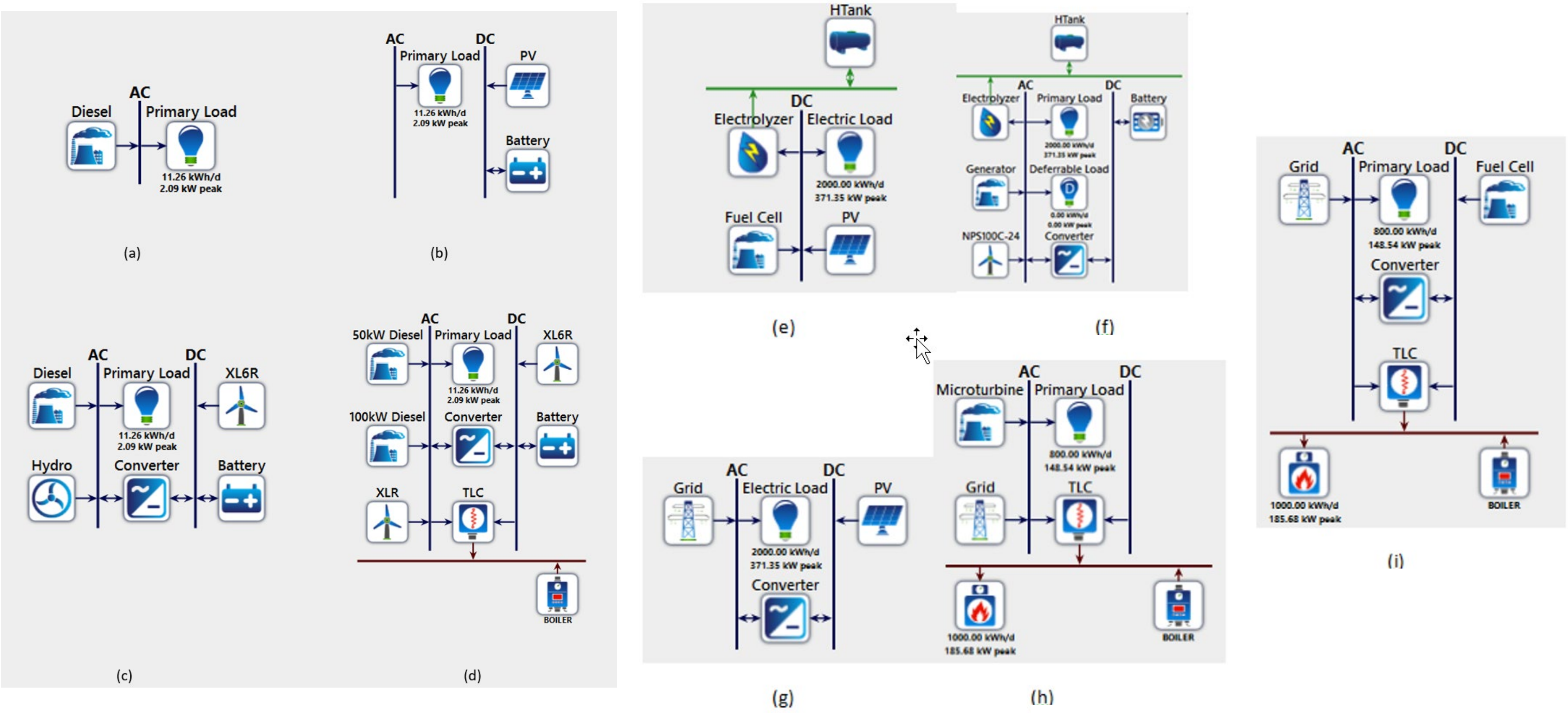
- **The constrained energy systems have a finite energy and most often a finite maximum power (which means finite maximum derivative of energy).**
- **Renewable energy systems can be sustainable, as long as the amount of energy conversion is less than the recovery of that energy by the environment.**
- **They are constrained because their derivative of energy should be optimized, which means there is a convex function that will define an amount of power conversion, dependent on the usage.**
- **For example, a wind turbine will have a peak power that depends on the tip-speed ratio and the output load, or a photovoltaic system will have a peak power that depends on the solar irradiation, temperature and the equivalent impedance across its terminals.**

- The optimal system performance depends on coherent operation of components.

- For example, an engineer will understand that a compressor with heat exchangers and a throttle will make-up a heat pump. But the operation of a thermodynamic system such as a heat pump requires information, measurement and control of the compressor, that depends on refrigerant pressure, a temperature measurement taken by a controller to evaluate how much heat is required,

  and a very intricate understanding of Physics, Chemistry, Electrical and Mechanical Engineering to make such a heat pump to operate on its maximum efficiency.

- Therefore, several issues will have to be taken in consideration, and efficient energy conversion for electrical power systems can be advanced by Artificial Intelligence.



Micropower Systems Diagrams: (a) a diesel system; (b) a PV-battery; (c) a hybrid hydro-wind-diesel system; (d) a wind-diesel system; (e) a PV-hydrogen system; (f) a wind-powered system; (g) a grid-connected PV system; (h) a grid-connected combined heat and power (CHP) system; (i) a grid-connected CHP system.

There are typically three frameworks with some generalization of functionalities, i.e. three paradigms, that can be used for energy conversion systems, with artificial based intelligence computation:

i. **a function approximation or input/output mapping,**
ii. **a negative feedback control, or**
iii. **a system optimization.**

i. **This is the construction of a model, using either heuristics or numerical data**
ii. **There is a comparison of a set-point with an output that can be either measured or estimated with a function that minimizes the error of the set-point with the output**
iii. **Online search for parameters and system conditions, that will maximize or minimized a given function.**

Fuzzy logic and neural network techniques make the implementation of such three paradigms possible, robust and reliable in practical cases.

- **Most of real-life control approaches will have a variety of ways to utilize information from mathematical models.**
- **Sometimes they do not take into account certain heuristic information early in the design process, but use heuristics when the controller is implemented to tune it (tuning is invariably needed since the model used for the controller development is not perfectly accurate).**
- **Very often when using some approaches to conventional control, some engineers become somewhat removed from the control problem itself and become more involved in the mathematics, this usually allows the development of unrealistic control laws.**

Fuzzy Logic and Neural Networks to Advance Electrical Systems
–improving power electronics enabled power systems–

FeedForward Neural Networks

The field of Neural Networks (NN) has a history of some decades, starting just after WW II, but has sounding application for industrial systems in the past 40+ years, and recently in deep learning paradigms.

Chapters 6 of my book covers FeedForward, Chapter 7 covers FeedBack, Competitive, and Associate Networks.

- Backpropagation algorithm revitalized the field of neural networks in 1985 and became a solid training technique. The field of NN became saturated with applications by the end of the 90's, with a diversity of paradigms, and learning methods. Many successful approaches have been categorized as their paradigm of neural network topology versus their industrial applications (Meireles, Almeida, e Simoes 2003).

Fuzzy logic is mainly associated to imprecision, approximate reasoning and computing with words, neurocomputing to learning and curve fitting (also to classification), and probabilistic reasoning to uncertainty and belief propagation (belief networks).
These methods have in common that they:

1. are nonlinear,
2. have ability to deal with non-linearities,
3. follow more human-like reasoning paths than classical methods,
4. utilize self-learning,
5. utilize yet-to-be-proven theorems,
6. are robust in the presence of noise or errors.

Those are the following similarities between fuzzy logic systems and neural networks:

1. estimate functions from sample data
2. do not require mathematical model
3. are dynamic systems
4. can be expressed as a graph which is made up of nodes and edges convert numerical inputs to numerical outputs
5. process inexact information inexactly
6. have the same state space
7. produce bounded signals
8. a set of n neurons defines n-dimensional fuzzy sets
9. learn some unknown probability function p(x)
10. can act as associative memories
11. diagnostics and information security
12. can model any system provided the number of nodes is sufficient.

The main dissimilarity of fuzzy logic systems versus neural network are:

1. FLS uses heuristic knowledge to form rules and tunes these rules using sample data, whereas ANN forms “rules” based entirely on data.
2. Soft computing methods have been applied to many real-world problems. Applications can be found in signal processing, pattern recognition, quality assurance and industrial inspection, business forecasting, speech processing, credit rating, adaptive process control, robotics control, natural-language understanding, etc. Possible new application areas are programming languages, user-friendly application interfaces, automatized programming, computer networks, database management, fault
3. ANN has the power to solve many complex problems; it can be used for function fitting, approximation, pattern recognition, clustering, image matching, classification, feature extraction, noise reduction, extrapolation (based on historical data), and dynamic modeling and prediction.
4. ANN-based model building process including system analysis, data acquisition and preparation, network architecture, as well as network training and validation is explained. Different challenges in using ANN-based methodologies for industrial systems and their applications, advantages, and limitations are discussed in these lectures.

It is possible to design a fuzzy logic only with "understanding", while neural networks always "need data"

Computers have power to perform simulations and there is specialized hardware to implement neural networks. Neural network technology has been adopted for a wide variety of scientific, engineering, and business problems. Capable of complex functions, noise cancellation, adaptive filtering, pattern recognition, non-linear controls, and econometric forecasting. The characteristics that make neural networks so valuable:

- ✓ They can learn relationships between input and output data. Such learning does not depend on the programmer's prior knowledge of rules. They can infer solutions from presented data, often capturing subtle relationships.
- ✓ Neural networks can generalize and handle noisy, imperfect or incomplete data. Such generalization features provide a measure of fault tolerance and is useful when examining real-world data.
- ✓ They can capture complex, higher-order-functions, and non-linear interactions among the input variables in a system.
- ✓ Neural networks are highly parallel; their numerous operations can be executed simultaneously in most of the topologies. Parallel hardware can execute hundreds or thousands of times faster than conventional microprocessors, making many applications practical for the first time.

- From 1990 to 2010 the Neural Network Research was described as CONNECTIONISM, i.e. hundreds of topologies based on biological functions, and understanding of nature, but in fact, the Backpropagation Algorithm was the main one to be used for Industrial Signal Processing and Control, for most of 90% of applications
- For very complex non-linear relationships, more hidden layers were considered, but typically causing lack of convergence, and catastrophic forgetting and poor generalization
- As BP moves backwards and further layers, the derivative of the Error in Respect to the Transfer Function is less and less and small and smaller than 1, because the activation functions are based on exponential functions

Vanishing Gradient Problem

Feedforward Neural Networks with More than 2 Hidden Layers always had convergence problems, "vanishing gradient problem", until ReLUs were used as activation functions

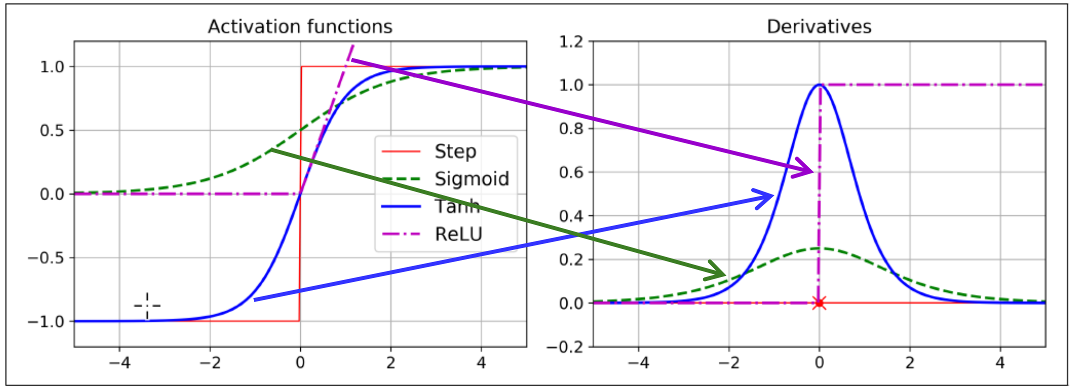
Sigmoid, TANH, ATAN, they all are based on <u>exponentials</u>

Vanishing Gradient: In a NN during the backpropagation stage, the weight(w) are updated as:

$$w_{new} = w_{old} - \alpha * \frac{\partial L}{\partial w_{old}}$$

where, α *is the learning rate*

$\frac{\partial L}{\partial w_{old}}$ *is derivative of loss with repect to weight*



- **The graphs shows the derivatives of activation functions.**
- **For example, the sigmoid is bounded from 0 to 0.25.**
  Due to chain rule of differentiation, the derivative can be so low that weight might not change or update significantly.
- **This leads to problem of updating weights during the backpropagation stage and no noteworthy information is passed to the following layers. This is called vanishing gradient.**

- **ReLU overcomes the problem of vanishing gradient as the derivative is 1 for z>0**
- **Due to its simple equation, it is computationally faster compared to the Sigmoid and Tanh**
- **Disadvantage (Dying ReLU): The derivative is 0 for negative inputs, so update is w(new) = w(old). That means, the neurons which go into that state will stop responding to variations in error/ input (because gradient is 0, so nothing changes). This is also a *ReLu problem*. This leads to dead neurons which are not able to update the weights anymore in backpropagation. To overcome this problem, we can use Leaky ReLU or other variants.**

Conclusion

- Intelligent and flexible grids: Power grids are becoming more complex due to the integration of renewable energy sources, distributed generation, and increased demand. AI helps manage this complexity by enabling real-time control, data analysis, and predictive capabilities.
- Optimal energy management: AI optimizes energy distribution, balances supply and demand, enhances grid stability, and integrates renewable sources like wind and solar more seamlessly.
- Predictive Maintenance: AI analyzes data to predict potential equipment failures before they happen, reducing downtime and ensuring optimal performance.
- Enhanced control in complex systems: AI provides efficient procedures for controlling complex systems even with incomplete information, by using learning and adaptation.

Conclusion – Cont.

- Conventional vs. Intelligent Systems: Conventional systems rely on predefined models and equations, while intelligent systems can learn, adapt, and make decisions based on data and experience
- Fuzzy Logic Control: Fuzzy logic is considered intelligent because it uses linguistic variables and approximate reasoning to handle uncertainty and imprecision, similar to human thinking, which makes it suitable for complex and non-linear systems where precise mathematical models are difficult to create.
- Fuzzy Logic vs. Artificial Neural Networks (ANN): Fuzzy logic controllers are based on expert knowledge and rules, while ANNs learn from data and can identify complex patterns without explicit programming. Both approaches can be combined for enhanced performance.

Conclusion – Cont.

- Deductive vs. Inductive Reasoning: Deductive reasoning starts with general principles and draws specific conclusions, while inductive reasoning observes specific patterns to form broader generalizations.; deductive reasoning for testing hypotheses derived from theories and inductive reasoning for identifying trends and forming new hypotheses from data.
- Improvements in power electronics and smart grids: Intelligent control systems improve power electronics and smart grids by providing real-time monitoring and automation, demand response, predictive analytics, integration of renewable energy, energy storage optimization, grid resilience, and cybersecurity.

end

do you have questions ?