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Understanding the power systems engineering

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Abstract

The basis of the industrialized world is the electrical power industry. This requires increasing number of engineering professionals; however, the industry loses many experienced engineers owing to their retirement. Therefore, the industry needs new engineers with high qualification. The area of study named power systems engineering is quite important for the electrical power industry and it necessitates undergraduate and postgraduate engineers to be able to plan and operate the power system efficiently. However, the choice of this study area is often not made by students because of the lack of knowledge of the tasks that a power system engineer performs and what knowledge he/she needs to perform these tasks. To help students to better understand the cited study area, this paper presents, in a didactic and objective way, the types of studies that are carried out by a power system engineer. Thus, students can understand how the power systems engineering area is interesting and, consequently, choose this area for their undergraduate and postgraduate studies.

Keywords

Power systems analysis, engineering education, educational technology

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Introduction

Electrical engineer has many study areas. However, despite several publications,[1–5] none of them described systemically the power systems engineering (PSE) area that is vital to the electric power industry worldwide.

This paper presents systemically the PSE area. Thus, students can understand how PSE area is interesting and, consequently, choose this area for their undergraduate and postgraduate studies.

This paper is organized as follows. Firstly, the electric power system is presented briefly. Secondly, the PSE area is presented. Concluding remarks are presented in the section.

Electric power system

An electric power system (EPS) mainly consists of power stations, substations, transmission lines, and distribution lines, as shown in Figure 1. An EPS is a set of equipment that operates with the purpose of providing electricity to consumers with quality standards, safety and costs with a minimum environmental impact. Therefore, it is extremely necessary for this system to be under control, to be kept in a stable operation, and that the faults be remedied quickly. Therefore, there is a need for qualified professionals to carry out this challenging task.

Unlike engineers and technicians who go to the field to perform scheduled and corrective maintenance on equipment, transmission, and distribution lines, a power system engineer is the brain behind planning the EPS expansion and operation efficiently. To do this, he/she needs to have a solid undergraduate and postgraduate training to realize the various studies related to PSE area as shown in Figure 1. These studies are described hereafter, in a didactic and summarized way, to teach students about the PSE area.

PSE area

The electricity sector planning can be divided into two main groups of activities: the EPS operation planning and the EPS expansion planning.

The EPS expansion planning has as basic objective to determine a strategy for the implementation of projects that meet the electricity consumption forecast, to minimize the sum of the investment costs and the expected values of the operating costs, also considering the reliability restrictions in the supply to the consumer market. Projects may include generating units (hydroelectric, thermoelectric, renewable energy sources), transmission lines, and even energy efficiency projects as shown in Figure 2(a). It is a short, medium, and long-term problem.

The EPS operation planning's objective is to evaluate the voltage and load control of the network, the impacts of contingencies on the system stability, the conditions of maneuvers of lines and transformers and the issuance of guidelines

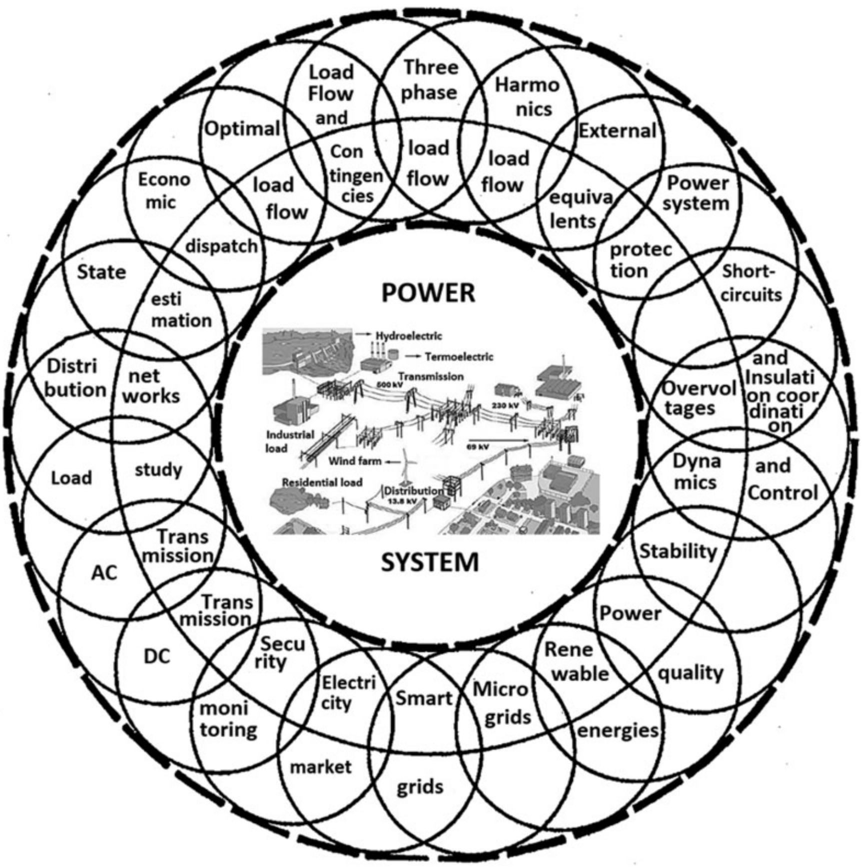

Figure 1. EPS and the PSE area.
Source: Figure 1 is drawn by the authors themselves.

for the operation of the system in normal condition, in contingencies, and for its restoration. It is a short-term problem.

The studies required for the planning and operation of an EPS are interconnected and they form the PSE area, which is presented in a didactic and summarized form in the following subtopics, inclusive of a typical design problem (TDP) that students can study in each subtopic.

Load flow

The purpose of the power flow calculation is to determine the magnitude and angle voltages for all the nodes or busbars of an EPS, given a configuration and a load condition. After the calculation of the voltages, the active and reactive power flows

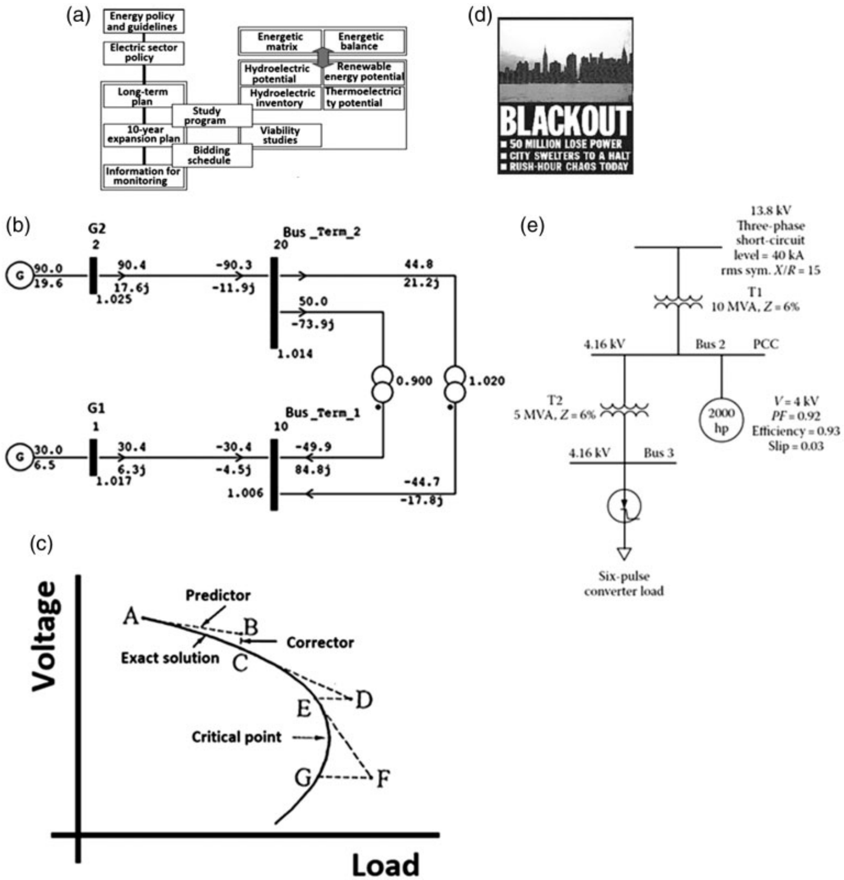

Figure 2. EPS studies block 1: (a) expansion planning; (b) load flow; (c) continuation power flow; (d) stability; (e) harmonic load flow.
Source: Figure 2(a), 2(b), 2(c) and 2(e) are drawn by the authors themselves. Figure 2(d) is sourced from the New York Times headline: In 2003, a blackout crippled area of the U.S. and Canada, leaving some 50 million people in the dark.

in the branches are determined, as well as the active and reactive powers generated, consumed, and lost in the EPS. Figure 2(b) shows the result of a load flow in an EPS, where the bus voltage magnitudes and the active and reactive power flow in the lines can be observed.[6]

Power flow analysis is one of the most important studies currently carried out on power systems operating on a permanent basis. It is extensively used in the design, planning, and operation phases of the electrical systems, constituting the study itself, or being part of more complex studies of optimization, stability, contingencies, short circuits, and others.

Mathematically, the EPS model for the load flow, according to de Moura and de Moura,[6] is denoted by

$$[g]\big([\mu],\ [x],\ [p]\big) = [0] \tag{1}$$

where $[g]$ is the nonlinear system of equations; $[\mu]$ is the unknown variables voltage magnitude and voltage angle for the reference bus, active power generated and voltage angle for the PV buses, and active and reactive power consumed for the PQ buses; $[x]$ is the unknown variables voltage magnitude and voltage angle for the buses of the PQ type, generated reactive powers and voltage angles for the PV buses, and the generated active and reactive powers for the reference bus; $[p]$ is the active and reactive loads and the elements of the admittance matrix.

TDP: The data from the transmission lines of two interconnected systems are known. Thus, students should allocate the load total without violating voltage limits and loading lines.

Stability

It is the "ability" of the EPS to maintain or return to normal operating balance after undergoing disturbances.[7] The variables subject to the changes are voltage, frequency, and angular deviation.

Angular stability is the "ability" of an EPS machine to keep in synchronism after a disturbance caused by increased rotation and oscillation of synchronous generators, coming out of synchronism with the rest of the system. This can lead to the cascade exit of several power stations, causing a blackout, as already occurred in Brazil, Sweden, and United States as shown in Figure 2(c).

Voltage stability is the "ability" of the EPS to maintain voltages on all buses, after a disturbance has occurred, for the given initial operating conditions.

Frequency stability is the "ability" of the EPS to maintain frequency following a severe incident, resulting in an imbalance between generations, loads, and losses.

TDP: A large metropolitan system has several lines operating under low load. Students should do a study to determine the maximum angles at the sending end of the lines for short circuits and at the receiving end these lines for the system to remain stable.

Continuation power flow

The conventional power flow algorithms present convergence problems for operating conditions close to the voltage stability limit. The continuous power flow solves this problem by reformulating the power flow equations such that the equation system remains well-conditioned for all possible charging conditions. This allows the power flow to be solved for points with stable and unstable equilibria.[8]

Continuous power flow analysis uses an iterative process involving the predictor and corrector steps, as shown in Figure 2(d).

TDP: Students should determine the PV, QV, and PQ curves for a specific EPS at busbars with wind generation and without wind generation and compare the results.

Harmonic power flow

It allows to analyze and investigate the generation and propagation of harmonic components of voltage and current through the EPS operating in steady state.[9] In Figure 2(e), a system with a harmonic load is illustrated.

TDP: To apply phase shifting to mitigate local harmonic, if large single-phase nonlinear load is present in the three-phase distribution system.

Load study

It is the determination of voltage, current, power, and power factor at various points of the EPS under normal conditions. The load study is essential for EPS expansion planning, since its satisfactory operation depends on the prior knowledge of the effects of the interconnection with other EPSs, the connection of new loads and new power plants, as well as new transmission lines and distribution.[10]

TDP: Students can do a 10-year load study on a real EPS.

Three-phase power flow

The main objective of an unbalanced three-phase power-flow study is to obtain the individual phase voltages at each bus corresponding to the network-specified conditions.[10,11] The balanced three-phase power-flow studies assume that the system unbalances may be neglected. However, there are many cases in which the unbalances of loads and untransposed transmission lines cannot be ignored. Besides, in distribution systems, there are several examples in which the balanced conditions hypothesis cannot be applied. A typical case would be mixed single-phase, two-phase, and three-phase systems as shown in Figure 3(a) in which it is obviously impossible to use a balanced model hypothesis.

TDP: The task is to calculate the losses in a real three-phase feeder and verify their accuracy through border measurements.

Power system security

Power systems are often interconnected to improve reliability and quality of power supply to consumers, to reduce the spinning reserve requirements of individual systems, and for similar other advantages. The operating state of a power system can be divided into four modes: normal mode; preventive mode; emergency mode; and restorative mode.[12] In the normal mode of operation, the system must maintain scheduled voltages, frequency, and load flow profile maintaining the scheduled tie line power flows. This mode of operation control is required to maintain scheduled voltages and frequency, maintain scheduled tie-line flows, and obtain economic generation. In the emergency mode of operation, i.e. when the contingency

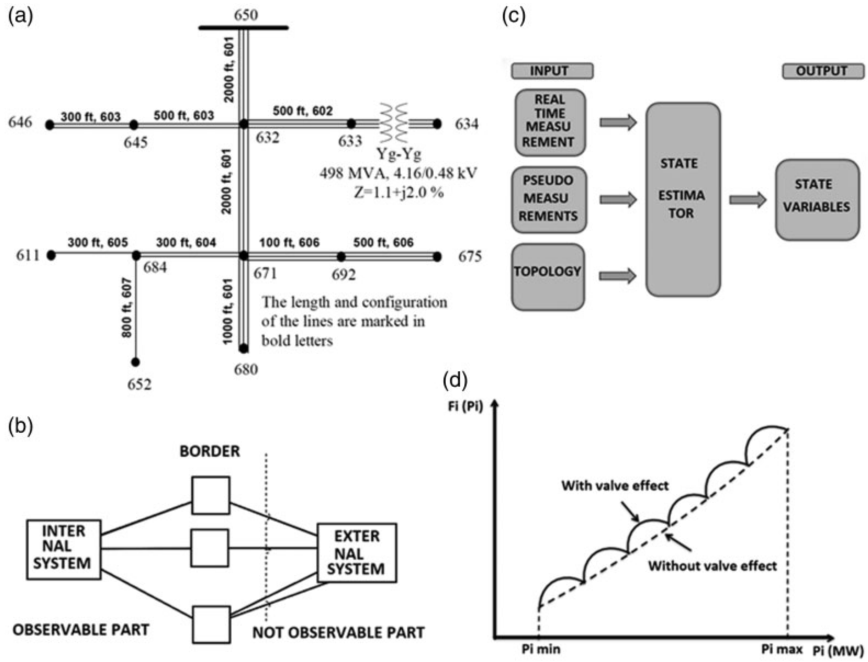

Figure 3. EPS studies block 2: (a) three-phase system; (b) external equivalent; (c) state estimator; (d) economic dispatch.
Source: Figure 3(a), (b), and (c) are drawn by the authors themselves. Figure 3(d) is sourced from Chiang.[17]

has occurred, control is required to maintain the specified frequency, and maximize the amount of load demand being met. During the restorative mode of operation, the system is brought from the emergency mode of operation into either normal mode or preventive mode.

TDP: Students should perform computational simulations, using the new England system, for the normal mode, the preventive mode, the emergency mode, and the restorative mode.

External equivalents

In EPS expansion planning and operation studies, parts of the grid can be represented by external equivalents, as shown in Figure 3(b), aiming at reducing the dimensions of the problems (power flow, short-circuit, stability) and computational effort.[13]

TDP: Students can choose 10 busbars from the new England system and obtain the external equivalents.

State estimation

It models the network in real-time guaranteeing the safe EPS operation through the tele-measures, which are provided by the Supervisory Control and Data Acquisition (SCADA), processes redundant information, contaminated by noise (errors), providing the best estimate for complex EPS bus voltages.[14]

There are traditionally four steps in the state estimation process, as illustrated in Figure 3(c), which are: topology processing, where the information is represented at the bus section level; analysis and restoration of observability, in which it is verified if it is possible to determine the complex voltages in all the system buses from the available analog and virtual measurements, according to the bus-branch model obtained in the previous step and, otherwise, verifies the possibility of supplying the lack of real-time measurement with pseudo-measurements in order to make the system operable; the state estimation that determines the estimation that best represents the EPS and the processing of gross errors, where the state estimator eliminates the errors and estimates the state of the EPS again.

In a set of measurements provided by the SCADA, the system state variables and measurement errors are related through the following measurement model, according to Monticelli[14]

$$[z] = [h(x)] + [\aleph] \tag{2}$$

where $[z]$ is the vector containing the measured quantities; $[h(x)]$ is the vector that contains the true values of the quantities measured and that are nonlinear state functions; $[\aleph]$ is the vector whose values model the measuring random errors such as imprecision of meters, measurement transformers errors, and analog–digital conversion effects of quantities.

TDP: To study the observability of a large system whenever necessary, students should use the meter placement algorithm to make the system observable.

Electricity market

Each electric utility generally operates in a geographic area not served by other companies. An advantageous rate is a stimulating factor for the location of industries. Electricity companies compete vigorously to attract industrial consumers to their action zone. This competition forces companies to keep their rates as low as possible. The regulation of government commission rates also serves as a pressure on these companies to operate economically and profitably.[15]

TDP: Students should examine, at European level, the following issues: the functioning of energy exchanges with respect to the characteristics of electricity, market design, and regulatory framework.

Economic dispatch

It can be defined as a process of assigning levels of production to the units of energy production in operation, so that the system load is fully satisfied in the most economical way possible. Therefore, the objective of this problem is to minimize the energy generation costs associated with fuel consumption.[16]

The formulation of the problem of economic dispatch can be aggregated to the objective function innumerable goals such as, reduction of thermal cost, reduction of emission cost, reduction of losses, voltage control, control of reactive, among others. The objective functions of the economic dispatch are usually represented by a smooth quadratic function disregarding several characteristics/constraints. However, in other situations the inputs and outputs have characteristics of non-linearities and discontinuities due to punctual loads of the valve, as shown in Figure 3(d) and equation (3), according to Chiang[17]

$$F_i(P_i) = a_i P_i^2 + b_i P_i + c_i + |e_i sin(f_i(P_i^{min} - P_i))| \quad (3)$$

where $F_i(P_i)$ is the quadratic function; P_i is the active power generation; a_i, b_i, c_i are the coefficients of the fuel cost of the unit "I"; e_i, f_i describe the effect of the valve point.

TDP: Two generator units with two specific piecewise linear incremental cost functions have known data. Students should find the optimum schedule for a total power active delivery.

Optimal power flow

It can be defined as the determination of the EPS state that optimizes a given objective function $f(x, u)$, satisfying a set of physical constraints $g(x, u)$ and operating $h(x, u)$.

According to Das,[10] the optimal power flow problem is mathematically expressed by

Minimize

$$f(x, u)$$

while satisfying

$$g(x, u) = 0$$
$$h(x, u) \leq 0$$

where $g(x, u)$ are the set of nonlinear equality constraints (power flow equations); $h(x, u)$ are the set of inequality constraints of vector arguments x and u; x is the vector of dependent variables consisting of bus voltage magnitudes and phase angles, as well as MVAr loads, fixed bus voltages, line parameters, and so on; u is the vector of control variables.

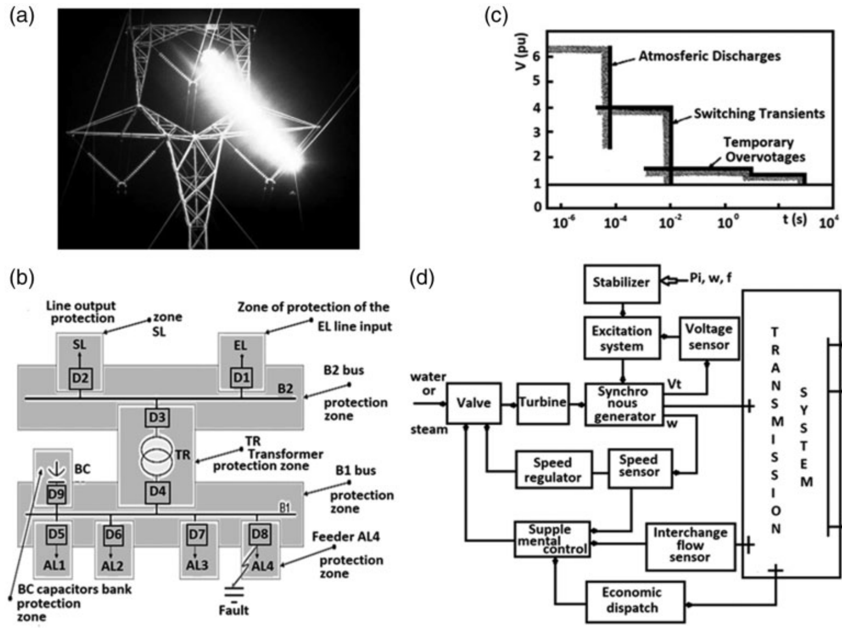

Figure 4. EPS studies block 3: (a) transmission line fault; (b) protection zones; (c) overvoltage types; (d) main control meshes associated to a synchronous generator.
Source: Figure 4(b), (c), and (d) are drawn by the authors themselves. Figure 4(a) is from authors' personal archive.

The vector u includes the following: real and reactive power generation; phase-shifter angles; net interchange; load MW and MVAr (load shedding); DC transmission line flows; control voltage settings; load tap changer (LTC) transformer tap settings.

TDP: Students should find the correct setting of the open and closed circuit-breakers that minimize the sum of all losses in a distribution system.

AC transmission and DC transmission

The transmission lines have the function of transporting energy from generating centers to consumer centers (loads). The AC line basically consists of conductors, towers, cables, and lightning arrests.[18]

An engineer should determine all parameters of the AC lines and study the transients and the operation on steady-state of AC and DC lines.

TDP: To study the compensation of a line with a thyristor-controlled series capacitor-type compensator with a stabilizing signal.

Short circuit

The American Institute of Electrical Engineers defines a fault in a wire or cable as a total or partial failure in its insulation or continuity. Therefore, a short circuit may occur in a contact between conductors under different potentials, as shown in Figure 4(a). Such contact may be direct (through or through impedance) or indirect (through an arc). Its calculation is extremely important in the planning and operation of EPS and its equipment and installations, because it is used to dimension circuit-breakers and fuses, to regulate and coordinate the protection, and to predict thermal and electrodynamic efforts.[19]

TDP: The task is to calculate the phase-to-ground, the three-phase fault currents, and the short-circuit power for all busbars in the new England system.

Protection

The purpose of EPS protection is to detect and eliminate anomalies in the electrical system, which can cause deterioration of the installations for a long time and can lead to instability, possibly causing loss of large blocks of supply.[20]

The protection system has agents such as circuit breakers, relays, reclosers, fuses, and lightning arresters, which divide the EPS into primary protection zones (Figure 4(b)), where the agent is responsible by the zone, and adjacent zones, when another agent is activated if the principal agent is defective.

TDP: Design protection coordination for the IEEE 34 test feeder.

Overvoltage and insulation coordination

An overvoltage can be defined as any phase-to-ground or phase-to-phase voltage whose crest value exceeds the crest value deducted from the maximum equipment voltage. The study of this phenomenon provides subsidies for the coordination of the isolation of distribution networks, transmission lines and substations, as well as for the equipment specification.[21]

Briefly, the overvoltage can be classified into two groups:

- Overvoltage of external origin: from external causes to the system in question, such as atmospheric discharges.
- Overvoltage of internal origin: caused by events within the system under consideration, such as short circuits or equipment maneuvers.

The classes and forms of the stress solicitations are shown in Figure 4(c).

The coordination of the insulation is a set of procedures used in the selection of electrical equipment, considering the voltages of the EPS and considering the characteristics of the protection devices, to reduce to economic and operationally acceptable levels, the probability of damages to the equipment, and/or interruptions in power supply caused by such voltages.

TDP: Students should study the surges caused by atmospheric discharges in the equipment of a substation using the ATP program.

Dynamics and control

The dynamics and control of the generation system refers to the constant load variation in the EPS, representing the dynamicity and the control that must be made for the generation to remain uniform during this variation, maintaining the voltage, frequency, and demand parameters of power consumed by loads.[16]

There are three main control systems that act on the synchronous generator: primary speed control, supplementary load–frequency control or automatic generation control, and excitation control (Figure 4(d)).

The primary speed control basically monitors the turbine-generator set shaft speed and controls the mechanical torque of the turbine to make the electrical power generated by the unit adapt to the load variations. The time constants of the primary control are of the order of a few seconds.

Since the operation of the primary control usually results in frequency deviations, it is necessary to rely on the operation of another control system to restore the frequency to its nominal value. This system is called supplementary control (automatic generation control) which, in the case of interconnected systems, also has the task of maintaining the power exchange between neighboring utilities as close as possible to the previously programmed values. The time constants are in the order of minutes.

Finally, the excitation control objectives are: (a) to maintain the terminal voltage of the generator within specified tolerances; (b) to regulate the reactive flow between machines; and (c) to cushion the machine rotor oscillations when disturbances occur in the system. The time constants of the excitation control system are in the order of milliseconds.

TDP: Students should analyze the results of the dynamic simulations of a specific EPS and propose changes in previously established adjustments.

Power quality

An electrical system with excellent power quality is characterized by the supply of energy at voltage with pure sine wave form, without changes in amplitude and frequency, as if it emanated from an infinite power source.

Figure 5(a) illustrates the various problems that may occur regarding power quality, where “a” represents the sinusoidal voltage; “b” an impulsive transient; “c” an oscillatory transient; “d” a voltage dip; “e” interruption in supply; “f” overvoltage; “g” harmonic; “h” voltage cut-off; “i” noises; and “j” inter-harmonics.[22]

TDP: The task is to calculate the voltage variation in the connexion point, the continuous operation flicker, and the short-term and the long-term flicker switching from a site data using the IEC 61400-21 standard.

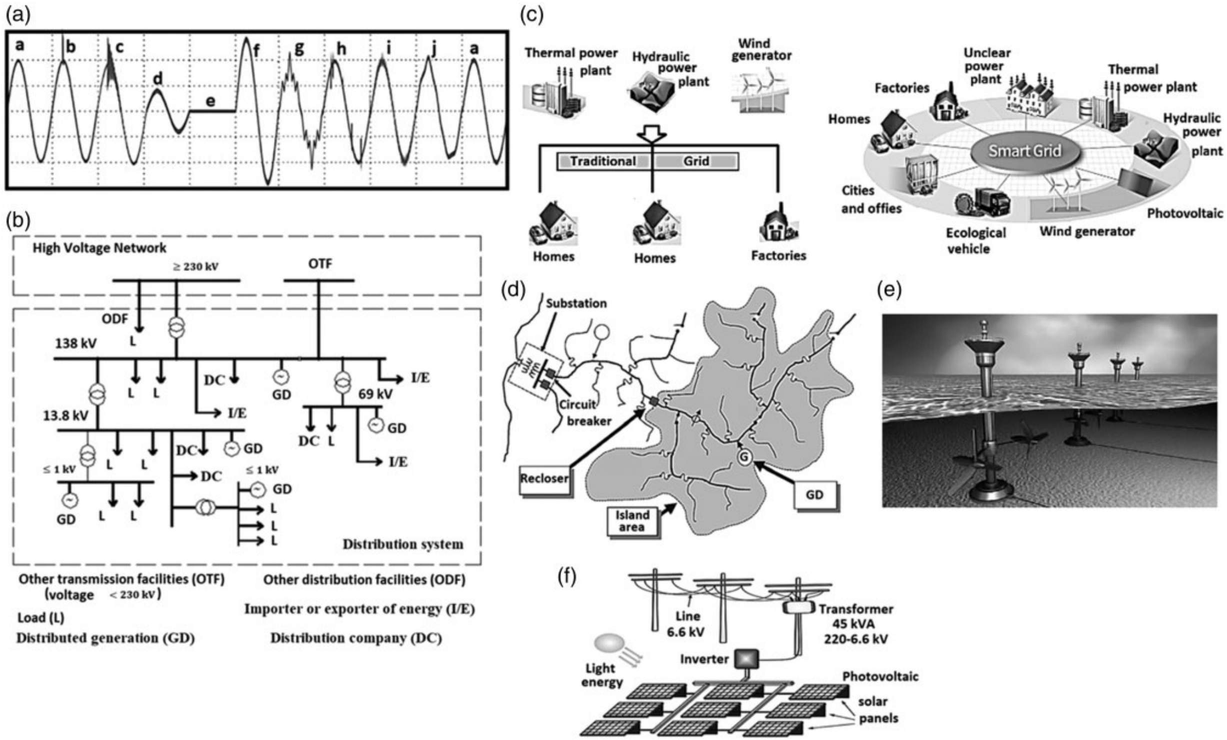

Figure 5. EPS studies block 4: (a) problems associated with power quality; (b) distribution system; (c) traditional grid × Smart grid; (d) microgrid; (e) generation of energy through tides and waves; (f) photovoltaic generation.
Source: Figure 5(a), (b), (c), (d), and (f) are drawn by the authors themselves. Figure 5(e) is sourced from https://www.woodharbinger.com/tidal-energy-sustainable-resource/

Distribution system

It is characterized as the segment of the electric sector dedicated to the lowering of the voltage coming from the transmission system, the connection of generating stations, and the electricity supply to the consumer. The energy distribution system is one that is confused with the city's own topography, branching along streets and avenues to physically connect the transmission system, or even medium- and small-sized generating units, to the final consumers of electric power.[11]

The simplified diagram of a distribution system (Figure 5(b)) shows the integration of the distribution system with the high-voltage network, the usual levels of distribution voltage, and the agents involved.

TDP: The task is to compute the secondary voltages on all transformers of a feeder using the diversity factors.

Smart grid

It is characterized by a bidirectional flow of electricity and information obtained by integrating the EPS with information and communication technologies and using demand response management that coordinates pluggable electric vehicles, renewable energy sources, and electrical loads. Real-time active operations such as self-healing and plug-and-play support are also expected characteristics of the smart-grid, which enables active end-customer participation in electricity markets and the creation of new services and products to maximize reliability, quality, and energy efficiency.[23]

Traditional grid: Centralized generation; unidirectional power flow; passive consumer and foreseeable behavior (Figure 5(c)).

Smart grid: Distributed generation; bi-directional power flow; active consumer and more complex behavior (Figure 5(c)).

TDP: Students should regulate efficiently the voltage in smart grid platforms using a multi-agent-based approach where each agent is equipped with a fuzzy inference engine.

Microgrids

They are defined by the integration of various distributed generation resources, energy, and load stores into a small system capable of operating by connected to a main network and, in cases of emergency or programmed events, operating in an islanded way, controlling the frequency and voltage and providing conditions for recompositing and black-start actions (Figure 5(d)).[24]

Ideally, the microgrids have the capacity to supply all the energy demand locally. In the island mode, there are some important aspects that increase the difficulty of the elaboration of the protection system: the protection for the lack in the distribution system, distributed generation (GD) resources, and the requirements for the distribution transformers.

TDP: Students should compare short-circuit currents of type IV turbines with the total fault currents and design the microgrid protection.

Renewable energies

They represent the sources in which the raw material, in theory, is inexhaustible, i.e. it is in constant production.[25] The main renewable sources in the market are: wind energy – it uses the force promoted by the winds for the production of energy; wave energy – waves are used in environments where they are the most intense for the generation of energy, as shown in Figure 5(e); solar energy: consists of the use of the solar radiation emitted on the Earth, as shown in Figure 5(f); water energy – it consists of the use of the water movement of the rivers for the production of electricity; biomass energy – corresponds to any and all nonfossil organic matter; geothermal energy – represents the use of the Earth's internal heat; tidal energy – the operation resembles that of hydroelectric plant, because a dam is created that captures tidal water during its floods, and this water is released when the tides decrease. During this release, the water turns on the turbines that activate the generators.

TDP: The task is to simulate, at permanent regime, a photovoltaic solar plant with 4680 panels and determine the power of each panel, the number of houses supplied, and if there is any voltage violation at the connection point.

Concluding remarks

In this educative paper, the PSE area was presented systematically. The study developed in this paper is a masterful contribution in the educational domain for students and lecturers of electrical engineering worldwide. The authors' experience in teaching PSE shows that students have some difficulties in carrying out their understanding and motivation properly. To overcome this, the authors propose this paper to increase the understanding and motivation of the students by PSE area and, consequently, choose this area for their undergraduate and postgraduate studies.

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