CHAPTER 1

INTRODUCTION TO THE PROBLEMS OF ANALYSIS AND CONTROL OF ELECTRIC POWER SYSTEMS

1.1. PRELIMINARIES

1.1.1 Electric power can be easily and efficiently *transported* to locations far from production centers and *converted* into desired forms (e.g., mechanical, thermal, light, or chemical).

Therefore, electric power can satisfy the requirements of a variety of users (e.g., factories, houses, offices, public lighting, traction, agriculture), widely spread around the intended territory.

On the other hand, it is generally convenient to concentrate electric power generation into a few appropriately sized generating plants. Moreover, generating plants must be located according to both technical and economic considerations. For example, the availability of water is obviously of primary concern to hydroelectric power plants as well as the availability of fuels and cooling water to thermoelectric power plants. General requirements — about primary energy sources to be used, area development planning, and other constraints, e.g., of ecological type — must also be considered.

Consequently, the network for electric power transportation must present a branched configuration, and it can be required to cover large distances between generation and end-users. Moreover, the possible unavailability of some generating units or interconnection lines could force electric power flows to be routed through longer paths, possibly causing current overloads on interconnection lines.

These considerations make it preferable to have a network configuration sufficiently meshed to allow greater flexibility in system operation (as an adequate rerouting when encountering partial outages) thus avoiding excessive current flows in each line and limiting voltage dips and power losses to acceptable levels.

1.1.2 As it is widely known, electric power is produced, almost entirely, by means of synchronous three-phase generators (i.e., alternators) driven by steam or water turbines. Power is transported through a three-phase alternating current (ac) system operated by transformers at different voltage levels.

More precisely:

- Transportation that involves larger amounts of power and/or longer distances is carried out by the "transmission" system, which consists of a meshed network and operates at a very high voltage level (relative to generator and end-user voltages). This system ensures that at the same transmitted powers the corresponding currents are reduced, thereby reducing voltage dips and power losses(1).
- Power transportation is accomplished through the "distribution" system, which also includes small networks of radial configuration and voltages stepped down to end-user levels.

The use of ac, when compared with direct current (dc), offers several advantages, including:

- transformers that permit high-voltage transmission and drastically reduces losses;
- ac electrical machines that do not require rotating commutators;
- interruption of ac currents that can be accomplished in an easier way.

Moreover, the three-phase system is preferable when compared with the single-phase system because of its superior operating characteristics (rotating field) and possible savings of conductive materials at the same power and voltage levels.

For an ac three-phase system, reactive power flows become particularly important. Consequently, it is also important that transmission and distribution networks be equipped with devices to generate or absorb (predominantly) reactive power. These devices enable networks to adequately equalize the reactive power absorbed or generated by lines, transformers, and loads to a larger degree than synchronous machines are able.

These devices can be static (e.g., inductive reactors, capacitors, static compensators) or rotating (synchronous compensators, which can be viewed as

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(1) Moreover, an improvement in stability can be obtained, at the same transmitted powers, due to reduced angular shifts between synchronous machine emfs, resulting in a smoother synchronism between machines.

synchronous generators without their turbines or as synchronous motors without mechanical loads).

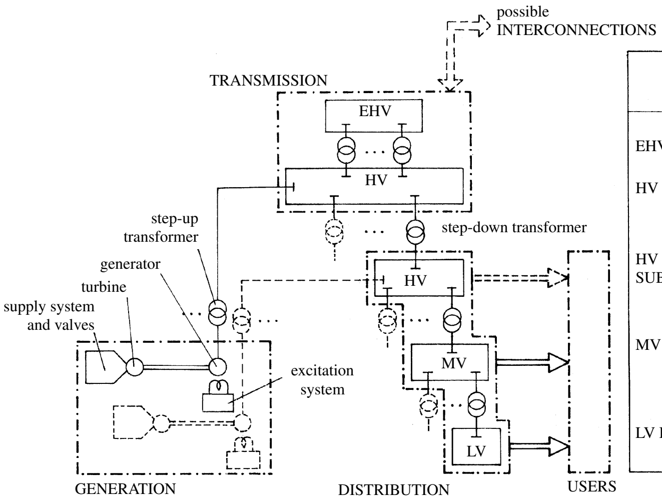
Furthermore, interconnection between different systems — each taking advantage of coordinated operation — is another important factor. The electrical network of the resulting system can become very extensive, possibly covering an entire continent.

1.1.3 The basic elements of a power system are shown in Figure 1.1. Each of the elements is equipped with devices for maneuvering, measurement, protection, and control.

The nominal frequency value is typically 50 Hz (in Europe) or 60 Hz (in the United States); the maximum nominal voltage ranges 20–25 kV (line-to-line voltage) at synchronous machine terminals; other voltage levels present much larger values (up to 1000 kV) for transmission networks, then decrease for distribution networks as depicted in Figure 1.1.

Generation is predominantly accomplished by thermal power plants equipped with steam turbines using “traditional” fuel (coal, oil, gas, etc.) or nuclear fuel, and/or hydroelectric plants (with reservoir or basin, or fluent-water type). Generation also can be accomplished by thermal plants with gas turbines or diesel engines, geothermal power plants (equipped with steam turbines), and other sources (e.g., wind, solar, tidal, chemical plants, etc.) whose actual capabilities are still under study or experimentation.

The *transmission* system includes an extensive, relatively meshed network. A single generic line can, for example, carry hundreds or even thousands of megawatts (possibly in both directions, according to its operating conditions),



examples of nominal line-to-line voltages	
EHV TRANSMISSION	...
HV TRANSMISSION	380 kV 220 kV
HV DISTRIBUTION (or SUBTRANSMISSION)	150 kV 132 kV 60 kV
MV DISTRIBUTION	30 kV 20 kV 15 kV 10 kV
LV DISTRIBUTION	380 kV 220 kV

Figure 1.1. Basic elements of an electric power system (EHV, HV, MV, LV mean, respectively, extra-high, high, medium, and low voltage).

covering a more or less great distance, e.g., from 10 km to 1500 km and over. The long lines might present large values of shunt capacitance and series inductance, which can be, at least partially, compensated by adding respectively shunt (inductive) reactors and series capacitors.

The task of each generic *distribution* network at high voltage (HV), often called a "subtransmission" network, is to carry power toward a single load area, more or less geographically extended according to its user density (e.g., a whole region or a large urban and/or industrial area). The power transmitted by each line may range from a few megawatts to tens of megawatts.

Electric power is then carried to each user by means of medium voltage (MV) distribution networks, each line capable of carrying, for example, about one megawatt of power, and by low voltage (LV) distribution networks. To reduce the total amount of reactive power absorbed, the addition of shunt capacitors might be helpful ("power factor correction").

Reactor and *capacitor* types can be fixed or adjustable (through the use of switching devices); the adjustment increases the networks' operation flexibility and may be realized before ("no-load") or even during operation ("under-load", or "on-load").

To further improve system behavior, *controlled compensators* (*synchronous* and/or *static* ones) may be added in a shunt configuration at proper busbars of HV (transmission and subtransmission) networks. *Tap-changing transformers*, which are controllable under load, are also adopted, mostly at the HV to MV transformation, sometimes between HV transformations. While at the MV/LV transformation, the use of tap-changing transformers, set up at no load, can be sufficient.

Moreover, some transmission lines are equipped with series *"regulating" transformers*, by which a range of voltage variations (both in magnitude and phase) — particularly useful to control line power flows — can be achieved.

More recently, the so-called FACTS (Flexible AC Transmission Systems) have also emerged; these equipments recall and integrate the above-cited functions, providing controlled injections of active and reactive powers, through the use of high-performance electronic devices.

The possibility of adopting *direct current links*, by using controlled converters (i.e., rectifiers and inverters) at line terminals, also must be discussed. This is particularly helpful with very long distances and/or with cable connections (e.g., sea-crossing connections); that is, when the ac option would prevent voltage variations within given ranges at the different locations or the synchronism between connected networks.

Finally, the *interconnections* between very large systems (e.g., neighboring countries) are generally developed between their transmission networks. Similar situations involving a smaller amount of power can occur, even at the distribution level, in the case of "self-generating users" (e.g., traction systems, large chemical or steel processing plants, etc.), which include not only loads in the strict sense but also generators and networks.

1.2. THE EQUILIBRIUM OPERATION

1.2.1 A proper definition of the generic steady-state (or equilibrium) operating condition (i.e., the "working point" at which the system may be required to operate) refers to a well-defined mathematical model of the system itself, as discussed in detail in the following chapters. The present section is limited to a general definition at this preliminary stage.

Let us assume that the "configuration"(2) and the system parameters are constant, as well as the external variables which define, together with parameters concerning users, each load requirement (e.g., braking torques externally applied to electromechanical users). Let us also assume that the three-phase electrical part of the system is "physically symmetrical." Moreover, we may assume that the electrical part of the system is linear with regard to the relationships between *phase* voltages and currents, thus allowing sinusoidal operations of *phase* variables without waveform distortions or production of harmonics.

Note however that, in this concern, the presence of nonlinearities also may be assumed, provided they can be simply translated into nonlinear *time-invariant* relationships between (voltage and current) *Park's vectors*, as specified in Section 5.6.1.

We will say that the system is in equilibrium operation if (and only if):

- excitation voltages of synchronous machines are constant;
- all synchronous machine shafts rotate at the same electrical speed (*"synchronous" operation*), so that electrical angular shifts among rotors are constant;
- such speed is constant.

Under the above-mentioned conditions, each three-phase set of the emfs applied to the electrical part of the system results in a positive sequence sinusoidal set, at a frequency equal to the electrical speed of the synchronous machines; the same applies for voltages and currents at any generic point inside the electrical network. More precisely, the frequency of these sets, which comes from the synchronous motion of the machines, can be given the name of *"network" frequency* because of its common value at every point of the network.

The following important consequences apply:

- by using the Park's transformation (see Appendix 2) with a "synchronous" reference (i.e., rotating at synchronous speed), both voltages and currents at any generic point of the network are represented by constant vectors;

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(2) By the term *configuration* we imply both the system "composition" (i.e., the whole set of operating components) and its "structure" (i.e., the connection among such components).

- active and reactive powers at any point of the network are constant, as well as active powers generated by alternators; consequently, the driving powers also must be constant, otherwise a variation in machines' speeds would result(3).

The definition of the steady-state condition is both useful and appropriate, as it can be transformed, by means of the Park's transformation, into an operating condition characterized by constant values. The definition also has practical aspects, as the synchronous operation at a given speed can be viewed (at ideal operating conditions and once stability conditions(4) are satisfied) as a result of the "synchronizing" actions between the machines and the frequency regulation (see also Sections 1.3 and 1.6).

The generic equilibrium operation is determined by:

- system configuration and parameters,
- load requirements,
- network frequency,
- synchronous machine excitation voltages,
- synchronous machine (electrical) angular shifts.

Note that, once all the N excitation voltages and the $(N-1)$ angular shifts are known (where N is the number of synchronous machines), the N vectors corresponding, through the Park's transformation, to the synchronous machine emfs in equilibrium conditions, can be directly deduced, both in magnitude and phase, by assuming an arbitrary reference phase.

However, for a better characterization of the steady-state, one could specify the value of other $(2N-1)$ scalar variables, as detailed in Chapter 2.

For example, instead of excitation voltages, it is usually preferable to specify the terminal voltage values (magnitude) of all synchronous machines, as these values are of paramount importance for the system operation (and are under the so-called "v/Q control"; see Section 1.3).

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(3) The driving power of each generating unit is obviously limited between minimum and maximum values, which are dependent (at the given speed) upon the characteristics of the supply system and the turbine. At the steady-state, each generated active power matches the corresponding net driving power and is subjected to the same limitations. The maximum real power made available by all the operating plants at the steady-state, which is called "*rotating power*," must be large enough to supply — with an adequate margin, named "rotating reserve" or "*spinning reserve*" — the total active load and network losses (we obviously imply that possible powers generated by nonmechanical sources have been previously subtracted from the total load).

(4) The stability properties can vary according to the considered operating point, due to nonlinearities in the equations relating active and reactive powers, magnitude and phase of voltage vectors, etc. Moreover, stability is particularly related to synchronizing phenomena which govern the relative motion between the machines, and to actions (possibly having stabilizing effects) through the control devices; as a consequence, the stability analysis may use some schematic approaches, such as those presented in Section 1.8.

Similarly, it is preferable to specify, instead of angular shifts:

- all active powers of generating plants except one, that is, the active power generation dispatching: this distribution is, in fact, important for system operation (and is related, with frequency regulation, to the "f/P control"; see Section 1.3);
- mechanical powers generated by synchronous motors and compensators; powers can be considered known for motors based on actual loading conditions, whereas powers for compensators can be neglected, as their value is only equal to mechanical losses at the given speed.

1.2.2 Nevertheless, the equilibrium operation previously defined corresponds to, with regard to voltage and current behavior, an ideal situation which in practice can be only approximately achieved.

Regarding the above-mentioned hypotheses (and assuming that stability holds), the most important reasons for deviation from the ideal behavior are:

- *network configuration variations, in proximity to loads*: for example, frequent inserting and disconnecting operations of loads, or opening and closing operations of distribution networks due to local requirements or operation of protection systems (e.g., with stormy weather);
- *load variations*: for example, those caused by intermittent operating cycles (traction systems, rolling mills, tooling machines, excavators, welding machines, etc.);
- the *physical dissymmetries* of the electrical part of the system: for example, in lines, transformers, and mostly in loads (as single-phase loads), which can be amplified by anomalous connections (e.g., the disconnection of a phase or an unsymmetrical short-circuit);
- the *nonlinearities* of the electrical part, with reference to the instantaneous values of voltages, currents, magnetic fluxes, etc.: for example, saturations and magnetic hystereses, and "granular" effects due to winding distribution and slots in the machines; electrical characteristics of arc furnaces, fluorescent lights, thyristor controlled converters, static compensators, etc.

As far as network configuration variations and/or load variations are concerned, they can be treated, in terms of a real quasi-steady-state operating condition, similar to small, random "load fluctuations" (both active and reactive) with a zero mean value, whose fastest variations can only be partially compensated by control devices(5). In practice, these fluctuations can significantly affect voltage and current behavior, particularly in proximity of loads, where filtering actions

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(5) Here, we are not considering significant and typically deterministic perturbations (e.g., the opening of a major connection in the transmission network, the outage of a generator or a significant load rejection, etc.), in which case the role of control actions becomes essential; see Section 1.7.

might be recommended. On the contrary, the effects on machines' speeds and network frequency are generally modest, because of the filtering actions of the machines' inertias.

Physical dissymmetries generate voltage and current components of negative or zero sequence; however, such components usually can be kept within acceptable limits by properly equalizing loads connected at each phase (see Section 6.1) and by avoiding (with the help of protective devices) permanent anomalous connections. Furthermore, the presence of zero-sequence components can be limited to a particular section of the network near the element that caused them, by proper transformer winding connections (delta or wye) and neutral conductor connection of the wye windings.

Nonlinearities, instead, are responsible for current and voltage waveform distortion and can generate harmonic components that might produce undesired disturbances to telephonic and data transmission systems. Harmonic effects can be reduced by introducing filtering actions close to those components responsible for harmonic generation. Often, a significant filtering is already provided by the same reactive elements adopted to equalize reactive power flows in the network.

In the following — except when differently specified — all previously mentioned phenomena will be considered within acceptable limits. Consequently, at the considered operating condition (synchronous and at constant speed), both voltage and current Park's vectors and active and reactive powers will be considered constant as above specified.

1.3. OPERATING REQUIREMENTS

1.3.1 Different operating requirements can be classified according to the following fundamental aspects: quality, economy, and security.

Quality of operation must be evaluated by considering:

- load supply conditions, which should not be much different from contractual ones;
- operating conditions of each system's equipment, which should not deviate much from optimal design conditions, in both performances or life duration.

Economy implies evaluation of the overall operating cost necessary to provide service to users, with specific reference to:

- availability and costs of energy sources;
- maintenance costs, personnel costs, and so forth, which are relatively dependent on the "operational scheduling" of each equipment.

Security of operation(6) implies the warranty, from a probabilistic point of view, of continuity in system operation (particularly of continuity in supplying

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(6) Obviously, here reference is not made to equipment or human safety, which is rather demanded of protection devices, according to considerations developed in Section 1.4.

load), when faced with significant perturbations. The equilibrium stability, for "small" variations, can be viewed as requirement for both quality and security aspects.

Fundamental requirements concerning the quality of the generic equilibrium operation are(7):

- network *frequency* should be at its "nominal" value (the choice of the nominal value is a technical and economic compromise among design and operating characteristics of main components, with specific regard to generators, transformers, lines, and motors);
- *voltage magnitudes* (positive sequence) should match their nominal values, within a range, e.g., of ±5% or ±10% at each network busbar, particularly at some given load busbars.

One should note that, in a pure transmission line, the *voltage support* at values near nominal voltage also may be important to guarantee satisfactory voltages at the line terminals and avoid a reduction in transmittable active power (see Section 1.5.).

The fulfillment of these requirements should comply with "admissibility" limits of each equipment piece (see Section 1.4): for example, it is necessary to avoid, at any network location, excessive *current amplitudes* which may cause tripping of protective devices.

Moreover, the agreed *power supply to users* should be respected as well as the agreed *exchanges of power* (or energy) with other utilities, in the case of interconnected systems.

As far as the quasi–steady-state operating condition described in Section 1.2 is concerned, voltage waveform deviations, nonpositive sequence components, and effects of small and unavoidable zero-mean random load fluctuations are required to be negligible. For instance, voltage *flicker* on lighting and on television apparatus must be limited to avoid disturbances to human eyes (e.g., for voltage variations greater than approximately 1.5% at a frequency of 10 Hz).

Problems related to system operation economy will be discussed in Chapter 2. One can anticipate that, once the system configuration and load demand are given(8) (as well as possible interconnection power exchanges), economy

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(7) There are exceptions to these requirements, such as the case of a small system temporarily operating in island conditions, for which out-of-range frequency deviations may be accepted, or a system with lack of sufficient generating capacity (for technical, human, or other reasons) for which the requirements of spinning reserve may suggest reduction of active power absorbed by loads by lowering the voltage profile of the network.

(8) One should note that if load voltages are imposed, load currents — and consequently active and reactive powers — are only related to parameters and external variables which define the loads themselves. For instance, the knowledge of the resistance and reactance values of a generic user which can be represented by an equivalent shunt branch allows the definition of load demand directly in terms of absorbed active and reactive powers.

requirements dictate the most adequate dispatching of total power generated among plants in steady-state conditions.

Finally, security requirements have a strong effect (detailed later in Chapter 2) on the system configuration choice and can suggest further limitations on electrical line currents. If, for instance, the spinning reserve is increased and adequately distributed throughout the system, and if power flows and network voltages are adjusted, there can be a reduced risk that perturbations might cause (see Section 1.7):

- instability conditions;
- unacceptable current redistributions that might cause line tripping (due to overcurrent protective devices) leading to a nonsecure network configuration.

1.3.2 To match all operating requirements, the system configuration and working point must be adequately scheduled.

Scheduling is performed by considering situations preevaluated (*"previsional" scheduling*) or measured during system operation (*"real-time" scheduling*), with emphasis on load demand and equipment availability.

According to Section 1.2.1 and Chapter 2, we can assume that the degrees of freedom in choosing the working point for any system configuration are given by:

- the excitation voltages (or the terminal voltages) of the synchronous machines;
- the dispatching of generated active power (whose amount matches the total load demand and system losses);
- the values of adjustable parameters of system devices, such as reactors, capacitors, static compensators, tap-changing transformers, regulating transformers (some of these values are actually adjusted by control systems, whereas the other ones are chosen before the device operation and kept constant).

It should be noted that actual ranges for the preceding degrees of freedom are limited.

Furthermore, facing the effects of perturbations, particularly of those lasting longer, and keeping the system at satisfactory steady-state conditions can be done with two fundamental controls:

- frequency and active power control (in short named *f/P control*), which acts on control valves of prime movers (except for plants generating power at fixed rate), to regulate frequency (and exchanged active powers in case of interconnected operation) and dispatch active powers generated by each plant(9).

- voltages and reactive power control (v/Q *control*), which acts on the excitation circuit of synchronous machines and on adjustable devices (e.g., reactors, capacitors, static compensators, underload tap-changing transformers), to achieve acceptable voltage profiles with adequate power flows in the network.

It should be noted that f/P and v/Q control problems substantially differ for the following reasons:

- Regulated frequency is common to the whole system and can be affected by all the driving powers. Therefore, the f/P control must be considered with respect to the whole system, as the result of different contributions (to be suitably shared between generating plants). In other words, the f/P control must present a "hierarchical" structure in which local controls (also named "primary" controls) on each turbine are coordinated through a control at the system level (named "secondary" control).
- Regulated voltages are instead distinct from each other (as they are related to different network points), and each control predominantly acts on voltages of the nearest nodes. Consequently, the v/Q control problem can be divided into more primary control problems (of the local type), which may be coordinated by a secondary control (at the system level) or simply coordinated at the scheduling stage.

The control systems should also be provided (see Section 1.5) with sufficient margin for actions. This can be accomplished during real-time scheduling by performing "adaptive"-type actions on system configuration, adjustable parameters, parameters and "set-points" of the f/P and v/Q controls, etc. Adaptive actions

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(9) Frequency regulation implies the modulation of driving powers which must match, at steady-state conditions, the total active load (apart from some deviations due to mechanical and electrical losses, or contributions from nonmechanical energy sources). One should note that, after a perturbation, the task of frequency regulation is not only to make net driving powers and generated active powers coincide but, moreover, to return frequency to the desired value. Therefore, even the regulation itself must cause transient unbalances between the powers until the frequency error returns to zero.

As a final remark, transient frequency errors, integrated over the time, cause a "phase error" which affects time keeping by electric clocks operating on the basis of network frequency; such an error can be reset to zero by forcing the system — using the f/P control, for instance, at night — to operate with frequency errors of the opposite sign for an adequate time duration (*"phase" regulation*). In an analogous way, one may compensate the transient errors which arise in the exchanged power regulation, thus returning to agreed values of the energy exchange at interconnections (*"energy" regulation*).

can also be suggested by a timely "diagnosis" of the perturbed system operation (see Section 1.7.2.).

1.3.3 Before concluding, it is worth emphasizing the advantages that may be offered by *interconnections*, with reference to quality, economy, and security. The following observations can be made:

- *Quality*. The voltage profile in the transmission network is better supported and distribution networks benefit because more generators provide their contribution to it, with an increased total capability (more specifically, an increased "short-circuit power" is obtained, at the busbars which are influenced by interconnections; see also Section 5.7.2). The same considerations apply to improved frequency behavior, with respect to any deterministic active power perturbation of given amplitude and to random perturbations. Random perturbations increase but, due to a partial statistical compensation, to an extent less than proportional to the total active power (i.e., in practice, to the total inertia of units and to the total driving power available for regulation purposes), so their relative influence is reduced.
- *Economy*. Different from isolated systems, it is possible to reduce the total set of generating plants and, consequently, operational and investment costs. This can result from the diminished influence of load perturbations and (for analogous reasons) errors on total load forecasting (thus allowing the reduction of the total spinning reserve), and time "compensation" of individual system load diagrams. Moreover, operational (including plant start-ups and shutdowns) and generation scheduling of units can be more economically coordinated by exploiting the flexibility offered by interconnections and by optimizing the scheduling of exchanged powers.
- *Security*. The chances of rerouting transmitted power flows in response to perturbations are increased and, more specifically, each system can benefit from the help of others even when spinning reserves were not sufficient for isolated operation.

1.4. ADMISSIBILITY LIMITS FOR SINGLE COMPONENTS

1.4.1 Each equipment of the power system (including generation, transmission, distribution, and utilization) is required to operate within limits expressed in terms of related variable ranges.

Some limits are *intrinsic*, as they are directly derived from the physical characteristics of the equipment. Examples are limits on excitation voltages of synchronous machines or the maximum allowable opening limit of turbine valves, which may be translated (at given conditions of the motive fluid and of speed) into a limit for the available motive power (see Section 1.2, footnote(3)).

On the contrary, other limits are related to operating ranges(10), according to different requirements, specifically:

(1) necessity of avoiding, for each equipment, *anomalous or nonacceptable operations* from the technical and economical points of view (then also considering efficiencies, duty, etc.); corresponding limits are: minimum and maximum values of voltage (and frequency) for the electrical auxiliary systems of power plants and, more generally, for users; the minimum technical value of generated power for steam units; maximum load currents related to contractual agreements; and so on;
(2) necessity of avoiding *equipment damage and any possible consequent damage*: for example, insulation damage due to excessive voltage; mechanical damage due to overspeed or to electrodynamic stresses between conductors by overcurrents; damage to insulating and conducting materials due to overtemperatures (which are, in turn, related to overcurrents);
(3) necessity of avoiding *situations which do not respect quality and security requirements*, also reducing instability risks (by limiting, for instance, the generator underexcitation to avoid unstable operating points)(11).

The fulfillment of requirements (1), (2), and (3) can be made easier through an appropriate system configuration and steady-state operating point. Control and, if necessary, protection actions are then integrative during operation.

1.4.2 Without much detail about functional requirements of *protection devices* (e.g., response speed, reliability, selectivity, etc.), the following remarks can be made:

- Many protective devices refer to local variables that are not directly under control or on which no significant effect may be expected through control actions (especially in short times). The case of short-circuit currents and fast overvoltages caused by external perturbations at a generic network location (usually with dissymmetric effects) is one such example. In fact, these situations are particularly vulnerable, and protection actions may be the only way to address them. On the other hand, the role of control actions becomes

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(10) Such limits may depend on particular conditions and on the duration of the considered phenomena. For instance, limits on currents set to avoid excessive overtemperatures can vary according to local temperature and must account for overcurrent duration.

(11) For given values of voltage and frequency, the operating limits of a generator (see Section 2.2.1) can be expressed, in terms of delivered active power P and reactive power Q, by the maximum and minimum values for P, and by two curves that define the over- and underexcitation limits (i.e., the maximum and minimum Q values, at each value of P). Curiously, these four limits can be viewed as excellent examples of the four above-mentioned motivations, respectively; in fact, the maximum limit on P can be considered an intrinsic limit, and the minimum limit on P can be considered as a type (1) limit, whereas the overexcitation limit is type (2) and the underexcitation limit is often related to stability constraints, and hence a type (3).

essential to overcome even more severe phenomena, such as relatively slow voltages and frequency variations, due to large generator tripping or other causes. In these cases, the protection system is required to operate only "in extremis", i.e., once the control has not succeeded in its action.

- Some protective equipment (e.g., surge arresters) consists of limiting devices that address external cause by eliminating its undesired effect through a nonlinear behavior which does not alter the system structure. Many other protections, as in the typical case of short-circuit current protection, disconnect the faulted equipment (connecting it again in case of temporary fault), causing a structural change. Therefore, in this occasion (and apart from cases of extreme intervention, when control action is too late), the control also must address the subsequent (and sometimes severe) effects of structural changes caused by the protection system itself.

Setting protection devices is usually done according to "local" criteria, which are not strictly related to control requirements of the whole system(12).

Therefore, the interaction between control and protection systems can be seen as quite a critical problem (which can be made worse, for example, by protection out-of-settings); some examples will be given (see Sections 1.7 and 7.3), with reference to typical situations in the dynamic behavior of the system.

1.5. TYPICAL EXAMPLES OF NONEXISTENCE OF THE EQUILIBRIUM OPERATION

The system configuration must particularly:

(1) allow the set-up of the desired steady-state condition or, at least, of a condition meeting the operating requirements;
(2) guarantee a sufficient margin for control actions.

Even to fulfill condition (1) at the adopted configuration, it may be not enough to have several variables available. In fact, their limitations in variation ranges, and the nonlinearities of the system equations may be prohibitive.

More precisely, let us assume that some system variables properly chosen (e.g., voltages at specific busbars of the network), are set at the desired values, and their number is as large as possible. If the system configuration is not properly chosen, it may result that the "static" model of the system, and particularly the equations relating active and reactive powers, voltages, etc.:

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(12) On the other hand, network protection coordination implies specific difficulties, in both selectivity requirements (in order to correctly identify the location of the original fault) and convenience of arranging the most appropriate intervention sequences, even if device settings are choosen independent of the system's general operating conditions.

- admit one solution (or more than one, because of nonlinearities), but with some variables assuming undesired (e.g., voltage far from nominal value at some location) or unacceptable values, i.e., so as to cause protection device intervention (e.g., excessive current flow in a line);
- admit no solution at all.

These considerations also involve condition (2), which states that control systems must work with a sufficient margin of action. In fact, if control systems were programmed to work around a steady-state point close to the limits of solution existence (or to the limits of protection intervention), they might be ineffective or even cause instability, even in response to relatively small perturbations.

The following are meaningful, although simple(13), examples that illustrate:

- typical operating limits that are dependent on system configuration and can be responsible for the nonexistence of the desired solution (such limits can be considered intrinsic, in addition to those related to each equipment, as mentioned in Section 1.4.1);
- different instability situations that may occur when conditions cannot produce the desired solution.

Example 1

Let us consider the system illustrated by obvious notations in Figure 1.2a,b, where(14):

- the block (G) includes the generating system, constituted by more plants and represented by a single equivalent unit, with emf $\overline{e}_a$ (vector) behind a series reactance X_a; more precisely, the amplitude e_a of the emf depends on the excitation voltage of the equivalent generating unit, whereas its phase is the (electrical) angular position of the rotor, apart from a difference by a constant value depending on the Park's transformation angular reference;
- the block (M) includes a static compensator of adjustable susceptance B;
- the block (L) represents a connection link of reactance X, given by more parallel lines; therefore, the value of X depends on the actual set of operating lines;
- finally, the block (U) represents the utilization system, defined as a resistance R, the value of which depends on the actual set of users.

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(13) Generally, to keep the examples related to practical cases, the block (U) in Figure 1.2a can include a reactance in series to the resistance R; nevertheless, the resulting conclusions are analogous to those presented afterward (see also Chapter 6).

(14) Vectors are defined according to the Park's transformation (see Appendix 2), and impedances are intended as evaluated at nominal frequency. (See Chapters 4 and 5 for more details and to evaluate the adopted approximations.)

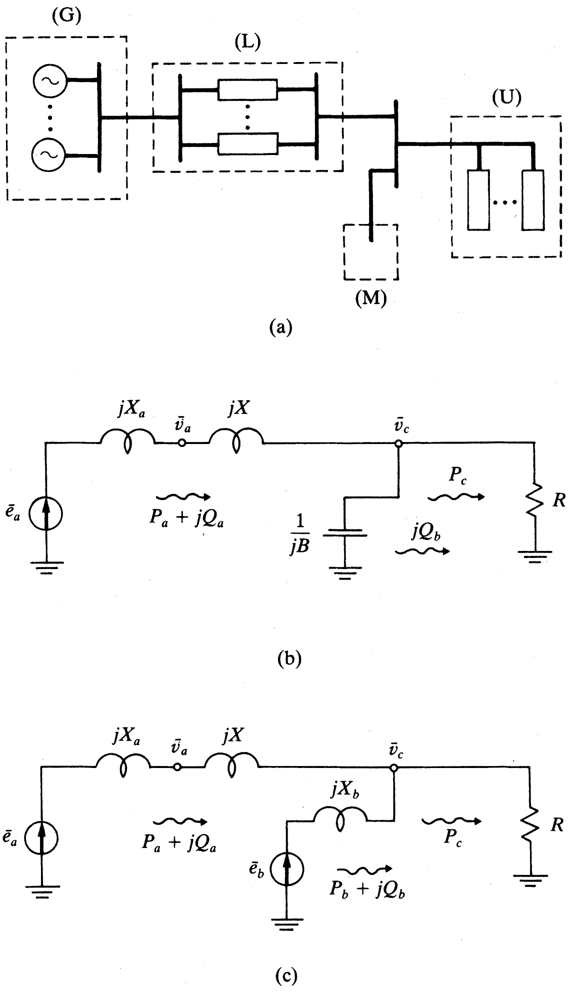

Figure 1.2. Some elementary examples (see text): (a) Reference diagram; (b) Example 1, with static compensator; (c) Example 2, with synchronous compensator (or generator).

(For the sake of simplicity, no transformer is included, although one could account for it in an obvious way).

To achieve the desired values of the voltages v_a and v_c (amplitudes), let us assume that the control of v_a is performed by means of e_a, and the control of v_c through the adjustment of B.

It should be specifically noted that, by imposing $v_a = v_c$, it results $Q_a = Q_b$, which is to say that a reactive power equal to half of what is absorbed by the link (L) (and varying in accordance to the P_a to be transmitted) must be injected at each end of the line. This condition is obviously not related to the rest of the system and therefore can be extended to the following Example 2.

It should be noted that:

- at each given B, both voltages v_a and v_c are proportional to e_a;
- on the other hand, the ratio v_c/v_a depends only on B, according to the equation:

$$\left(\frac{v_c}{v_a}\right)^2 = \frac{R^2}{R^2(1 - BX)^2 + X^2}$$

  and cannot be larger than R/X (see Fig. 1.3); consequently, the desired voltage profile can be obtained only if the ratio R/X is large enough.

In other words (and not considering the variation limits for e_a and B) the desired value for v_a can always be achieved by acting on e_a, while the desired value of v_c can be achieved only if it is not larger than Rv_a/X, which can then be defined as *"supportability limit" of the voltage* v_c; the considered case also implies a limitation on the power P_c that can be transmitted to the load, as given by:

$$P_c = \frac{v_c^2}{R} \leq \frac{Rv_a^2}{X^2}$$

By assuming that the regulation of v_c is of the "integral" type, with $\mathrm{d}B/\mathrm{d}t$ proportional to the regulation error ($v_{c\mathrm{des}} - v_c$) (so that B and v_c may vary according to the arrows reported in Fig. 1.3), the value $v_c = v_{c\mathrm{des}}$ can be achieved only if $v_{c\mathrm{des}}$ is below the supportability limit. Otherwise, the regulation error remains

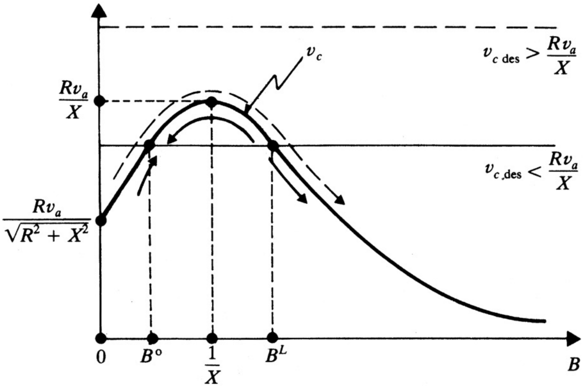

Figure 1.3. Dependence of voltage v_c (amplitude) on susceptance B, and variations due to control actions as per Figure 1.2b.

positive and B continues to increase, leading to an instability phenomenon, *voltage instability*, which results in the "collapse" of voltage v_c(15).

It is therefore necessary to guarantee relatively large values of R/X, which is equivalent to maintaining a sufficient set of lines in the link (L), so to have a reactance X small enough, and to reduce the risk of R/X below its critical value, in case of line tripping (resulting in larger X) and/or load increase (resulting in smaller R)(16).

Moreover, if the desired voltage profile can be achieved ($v_{c\text{des}} < Rv_a/X$), it is also necessary that the turbines can supply the driving power required to operate at the given constant value of frequency. Specifically, it is necessary to maintain an adequate number of units to guarantee a sufficient "spinning reserve", reducing the risk that a tripped generating unit would cause *frequency instability* and collapse of the frequency itself.

Example 2

Consider the system of Figure 1.2a and c, which differ from that in the previous example only in block (M), which now includes a synchronous compensator (or other generators, still considered an equivalent unit) with an emf $\overline{e}_b$ (vector) behind a series reactance X_b. The magnitude and phase of $\overline{e}_b$ have analogous meanings as per $\overline{e}_a$; in particular, the phase difference between vectors $\overline{e}_a$ and $\overline{e}_b$ is the (electrical) angular shift between the rotors of the equivalent machines in (G) and (M).

By not limiting the variability of e_a and e_b, both the desired values of v_a and v_c can be achieved (by just acting on e_a and e_b), so that no limitation on P_c applies (contrary to the previous example).

However, opposite to this, a limit on P_a arises since, if α is the angular shift between $\overline{v}_a$ and $\overline{v}_c$:

$$P_a = \frac{v_a v_c}{X} \sin\alpha$$

so that P_a cannot be larger than $v_a v_c/X$, which is the *"transmissibility limit" of the active power* through the link (L); while the power P_b, given by $P_b = P_c - P_a$, cannot be lower than $P_c - v_a v_c/X$.

Therefore, if the reactance X is not small enough, the link (L) might become an unacceptable "bottleneck" for active power transmission.

To run the operation at the desired frequency, it is not enough that the total rotating power matches the load demand P_c with an acceptable margin. In fact, it is now necessary to consider the above-mentioned limits on P_a and P_b:

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(15) The regulation of v_c is then coresponsible for the described phenomenon. In real cases, B is increased up to its maximum value, i.e., the regulation is upper limited, and the voltage collapse may be avoided. Similar situations can be reached even with nonintegral regulation, provided the "static gain" of the regulator is large enough, as generally required by the v_c regulation. The phenomenon can be more complex because of interactions with the regulation of v_a (more specifically: v_a can also decrease if e_a reaches its maximum limit and/or its regulation is not fast enough), protection intervention (due to low voltage or increased line and generator currents), and other factors.

(16) Similar results are obtained in a system with no capacitor and in which block (L) presents at its terminal, at the load side, a tap-changing transformer used to regulate v_c.

- by properly sharing the rotating power between (G) and (M);
- by maintaining an acceptable line set in the link (L), thus providing a sufficiently high transmissibility limit, also considering the risk of line outages.

This last measure can become essential when the units in (M) are of small or even zero rotating power, with the latter being the case of a synchronous compensator.

In fact, in the opposite case (i.e., if the total rotating power is enough but the rotating power in (M) is below $P_c - v_a v_c / X$), the generating set (M) lacks driving power and slows down, so that the desired steady-state cannot be achieved. Particularly, it can be seen that at specific conditions concerning driving powers the synchronism between (G) and (M) might be achieved but at a frequency progressively lower (collapse); otherwise, if the total driving powers in (G) and (M) were equal to P_c, according to the power balance necessary for frequency regulation, the lack of power for the unit (M) would result in a surplus of power for the unit (G), causing the latter to accelerate. The final consequence would be another instability, known as *loss of synchronism* between (G) and (M) (see also Section 1.6).

1.6. SYNCHRONIZING ACTIONS BETWEEN MACHINES

Synchronous machines have the property, which is fundamentally important to the steady-state operation of the system, of spontaneously synchronizing with one another under proper operating conditions. In other words, if these machines present initial (electrical) speeds different from one another, the variations in their reciprocal angular shifts cause subsequent variations in active generated powers. These variations usually slow down the faster rotors and speed up the slower rotors, until — obviously if no further perturbation is applied — the speed deviations are reduced to zero.

This synchronizing phenomenon is generally characterized by damped oscillations (called *"electromechanical" oscillations*). However, the oscillations might degenerate into the so-called "loss of synchronism" between one or more machines and the remaining ones, following particular perturbations of relative severity.

To qualitatively ascertain these phenomena, consider the simple system in Figure 1.2c, which includes only two machines.

By denoting P_{ma} and P_{mb} as the driving powers of the two units and Ω_a and Ω_b as the electrical speeds of their rotors, the motion of the units (considering only their inertias) can be estimated with the following equations:

$$\begin{cases} P_{ma} - P_a = M_a \dfrac{\mathrm{d}\Omega_a}{\mathrm{d}t} \\[2ex] P_{mb} - P_b = M_b \dfrac{\mathrm{d}\Omega_b}{\mathrm{d}t} \end{cases}$$

with M_a and M_b constant.

If a "static" model for the electrical part[17] of the system is assumed, the electrical powers P_a and P_b are only dependent on the magnitudes e_a and e_b of the emfs and on the angular shift δ_{ab} between the emfs themselves.

Specifically, by developing the relations between emfs and currents, the following equations can be derived:

$$\begin{cases} P_a = A \sin \delta_{ab} + B \cos \delta_{ab} + C_a \\ P_b = -A \sin \delta_{ab} + B \cos \delta_{ab} + C_b \end{cases}$$

where A, B, C_a and C_b are functions of e_a and e_b, according to[18]:

$$\begin{cases} A \triangleq \dfrac{R^2}{R^2 + X'^2} \dfrac{e_a e_b}{X_a + X + X_b} \\ B \triangleq \dfrac{R X'}{R^2 + X'^2} \dfrac{e_a e_b}{X_a + X + X_b} \\ C_a \triangleq \dfrac{R}{R^2 + X'^2} \left(\dfrac{e_a X_b}{X_a + X + X_b} \right)^2 \\ C_b \triangleq \dfrac{R}{R^2 + X'^2} \left(\dfrac{e_b (X_a + X)}{X_a + X + X_b} \right)^2 \end{cases}$$

where, for the sake of simplicity,

$$X' \triangleq \frac{(X_a + X) X_b}{X_a + X + X_b}$$

Moreover, the angular shift δ_{ab} is equal to the electrical angular shift between the rotors of the two units, so that the following equation holds:

$$\frac{\mathrm{d}\delta_{ab}}{\mathrm{d}t} = \Omega_a - \Omega_b \triangleq \Omega_{ab}$$

The previous equations can be depicted by Figure 1.4a. Specifically, the relative motion of the rotors is defined, according to the block diagram of

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[17] More precisely (see Section 3.1.1), M_a and M_b should be considered respectively proportional to Ω_a and Ω_b, but the assumption of constant M_a and M_b may be accepted due to the negligible speed variations that can occur. Besides that, a more rigorous description of the system should account for the dependence of e_a and e_b on speeds and more generally for the actual dynamic behavior of the electrical part of the machines and network. In particular, the reactances X_a, X, X_b are calculated at the nominal frequency as if the speeds Ω_a and Ω_b were equal to each other and to the nominal network frequency; for more details, see Chapters 4 and 5.

[18] Other network variables, particularly v_a and v_b, are related to e_a, e_b, δ_{ab}. If "ideal" voltage regulations are assumed (i.e., with e_a and e_b to keep v_a and v_b exactly constant), e_a and e_b would become functions of δ_{ab}. The same would happen for A, B, C_a, C_b, and the dependence of P_a, P_b on δ_{ab} would no longer be sinusoidal.

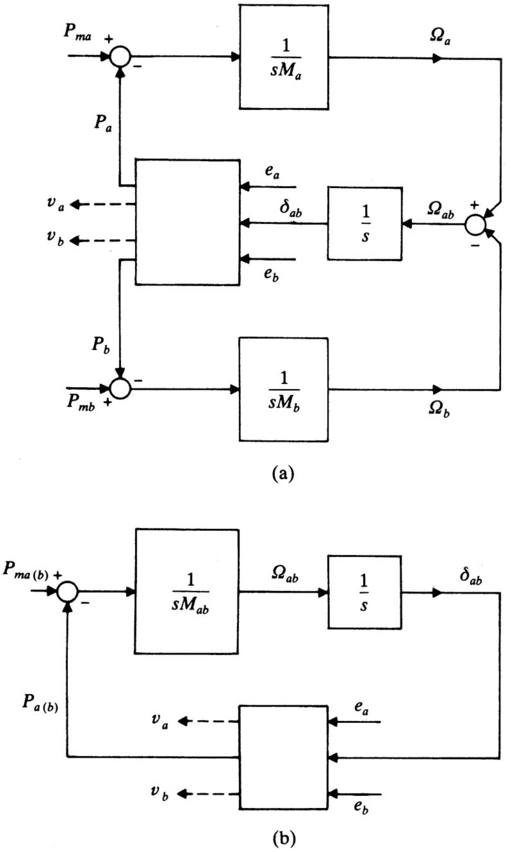

Figure 1.4. Block diagram for the system of Figure 1.2c: (a) motion of the two machines; (b) relative motion between the two machines.

Figure 1.4b, by:

$$\begin{cases} \dfrac{\mathrm{d}\delta_{ab}}{\mathrm{d}t} = \Omega_{ab} \\ \dfrac{\mathrm{d}\Omega_{ab}}{\mathrm{d}t} = \dfrac{P_{ma} - P_a}{M_a} - \dfrac{P_{mb} - P_b}{M_b} = \dfrac{P_{ma(b)} - P_{a(b)}}{M_{ab}} \end{cases} \qquad [1.6.1]$$

in which:

$$\begin{cases} P_{ma(b)} \triangleq P_{ma} - \dfrac{M_a(P_{ma} + P_{mb})}{M_a + M_b} \\ P_{a(b)} \triangleq P_a - \dfrac{M_a(P_a + P_b)}{M_a + M_b} \\ M_{ab} \triangleq \dfrac{M_a M_b}{M_a + M_b} \end{cases}$$

where, in accordance to the above:

$$P_{a(b)} = A\sin\delta_{ab} + \frac{M_b - M_a}{M_a + M_b} B\cos\delta_{ab} + \frac{M_b C_a - M_a C_b}{M_a + M_b}$$

Let us now assume, for simplicity, that $P_{ma(b)}$ remains constant (because, for instance, P_{ma} and P_{mb} are constant, or even variable due to the f/P control but proportionally to M_a and M_b, respectively). Let us also assume that e_a and e_b are constant (not considering the regulation of v_a and v_c), so that the power $P_{a(b)}$ is dependent only on δ_{ab} as shown in Figure 1.5(19).

The equilibrium of the relative motion (i.e., the synchronous operation) is defined by the following conditions:

$$\begin{cases} 0 = \dfrac{\mathrm{d}\delta_{ab}}{\mathrm{d}t} \\ 0 = \dfrac{\mathrm{d}\Omega_{ab}}{\mathrm{d}t} \end{cases}$$

from which the steady-state values of δ_{ab} and Ω_{ab} can be deduced.

Specifically, $\Omega_{ab} = 0$, i.e. $\Omega_a = \Omega_b$, can be deduced from the first condition, while the second condition gives $P_{a(b)} = P_{ma(b)}$ from which the two solutions δ^o_{ab}, δ^L_{ab} result, as generically shown in Figure 1.5, apart from the periodical repetition every 360° with respect to δ_{ab}(20).

The solution $\delta_{ab} = \delta^o_{ab}$, where P_{ab} is an increasing function of δ_{ab}, corresponds to a stable equilibrium point around which electromechanical oscillations may occur. The solution $\delta_{ab} = \delta^L_{ab}$ corresponds to an unstable equilibrium point.

To verify this, let us assume that the shift δ_{ab} and the slip Ω_{ab} had the initial values $\delta^i_{ab} = \delta'_{ab}$, $\Omega^i_{ab} = 0$ (the superscript "i" stands for initial value), with

---

(19) One should note that if one of the two units had an infinite inertia (e.g., $M_b = \infty$), it would simply result $\Omega_b =$ constant. Moreover, $P_{ma(b)} = P_{ma}$, $P_{a(b)} = P_a$, $M_{ab} = M_a$. Furthermore, if $M_b = \infty$ and $X_b = 0$, which is equivalent to considering the node at voltage v_c as an "infinite busbar," the following (simpler) result would be obtained:

$$B = Ca = 0, \qquad P_{a(b)} = P_a = A\sin\delta_{ab} = \frac{e_a e_b}{X_a + X}\sin\delta_{ab}$$

The treatment can be viewed as a generalization of such simple cases, nevertheless with no formal difference. It could be also extended in an analogous way to the case of "ideal" voltage regulations, by considering the dependence (again of the "static" type) of $P_{a(b)}$ on δ_{ab}, according to what is stated in footnote(18). However, this is not recommended for practical purposes, because the actual behavior of regulations increases the system dynamic order and might lead to instabilities not revealed by this analysis (see Section 7.2.2).

(20) It is assumed that $P_{ma(b)}$ is within the minimum and maximum values of $P_{a(b)}$, otherwise no solution would exist and the "loss of synchronism" between the two units would certainly result (see Section 1.5, Example 2).

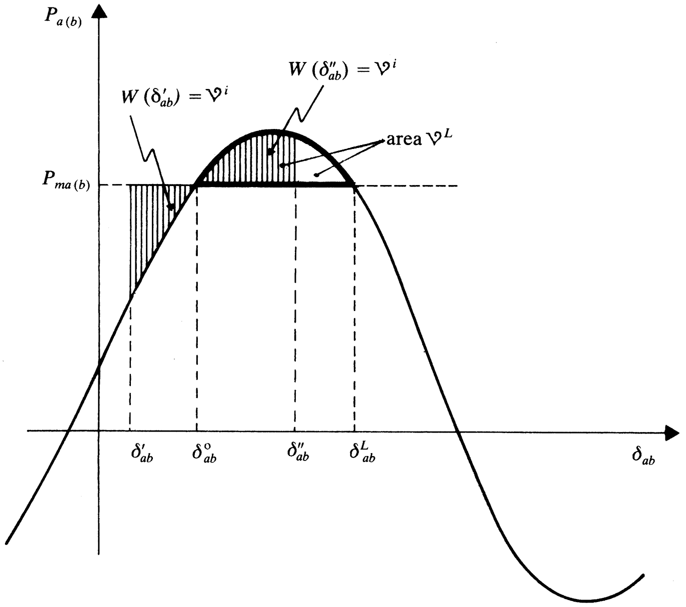

Figure 1.5. Active power versus angular shift curve, used to analyze the relative motion between machines, as in Figure 1.2c.

$\delta'_{ab} < \delta^o_{ab}$ as in Figure 1.5(21). Under such assumptions, it follows that $P^i_{a(b)} < P_{ma(b)}$ and $(\mathrm{d}\Omega_{ab}/\mathrm{d}t)^i > 0$, so that the slip $\Omega_{ab} = \mathrm{d}\delta_{ab}/\mathrm{d}t$ becomes positive and the shift δ_{ab} increases. Then $P_{a(b)}$ becomes larger, $\mathrm{d}\Omega_{ab}/\mathrm{d}t$ diminishes (it goes to zero at $\delta_{ab} = \delta^o_{ab}$ and becomes negative for $\delta_{ab} > \delta^o_{ab}$), and Ω_{ab} reaches its maximum value (Ω_{abM}) at $\delta_{ab} = \delta^o_{ab}$ and subsequently decreases by again crossing zero (under the following conditions) at a given value $\delta_{ab} = \delta''_{ab}$.

Specifically, from Equations [1.6.1] it follows that:

$$(P_{a(b)} - P_{ma(b)})\mathrm{d}\delta_{ab} + M_{ab}\Omega_{ab}\mathrm{d}\Omega_{ab} = 0$$

and consequently:

$$\mathcal{V}(\delta_{ab}, \Omega_{ab}) \triangleq W(\delta_{ab}) + \frac{M_{ab}\Omega^2_{ab}}{2} = \text{constant} = W(\delta^i_{ab}) + \frac{M_{ab}(\Omega^i_{ab})^2}{2} = \mathcal{V}^i \qquad [1.6.2]$$

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(21) Such a situation may occur if, for example, the system is initially in equilibrium condition with $P_{ma(b)} = P_{a(b)}$, $\Omega_{ab} = 0$ and one of the lines connecting the two units is tripped, causing a sudden variation of the curve $(P_{a(b)}, \delta_{ab})$ to that in Figure 1.5. On the contrary, generic values of δ^i_{ab}, $\Omega^i_{ab} \neq 0$ can be the consequence of a multiple perturbation, such as an opening-closing after a short-circuit fault or other situations.

in which(22):

$$W(\delta_{ab}) \triangleq \int_{\delta_{ab}^{o}}^{\delta_{ab}} (P_{a(b)} - P_{ma(b)})\mathrm{d}\delta_{ab}$$

Therefore, the values Ω_{abM}, δ''_{ab} must satisfy the following conditions:

$$\begin{cases} \dfrac{M_{ab}\Omega^2_{abM}}{2} = \mathcal{V}^i \\ W(\delta''_{ab}) = \mathcal{V}^i \end{cases}$$

where $\mathcal{V}^i = W(\delta'_{ab})$ is known.

The equation $\Omega_{abM} = \sqrt{2\mathcal{V}^i/M_{ab}}$ can be derived, while δ''_{ab} can be obtained according to Figure 1.5, where the two dotted areas — respectively equal to $W(\delta'_{ab})$ and $W(\delta''_{ab})$ — are both equal to $\mathcal{V}^i$ with $\delta''_{ab} \in (\delta^0_{ab}, \delta^L_{ab})$ (*"equal area" criterion*). It should be noted that $W(\delta''_{ab})$ cannot be larger than the "limiting" value $\mathcal{V}^L$ as defined in Figure 1.6 (the area limited by the bold line). Consequently, the solution at δ''_{ab} exists if and only if $\mathcal{V}^i \leq \mathcal{V}^L$, where $\mathcal{V}^L$ is the value of the function $\mathcal{V}(\delta_{ab}, \Omega_{ab})$ at the second equilibrium point ($\delta_{ab} = \delta^L_{ab}$, $\Omega_{ab} = 0$), i.e., $\mathcal{V}^L \triangleq \mathcal{V}(\delta^L_{ab}, 0)$.

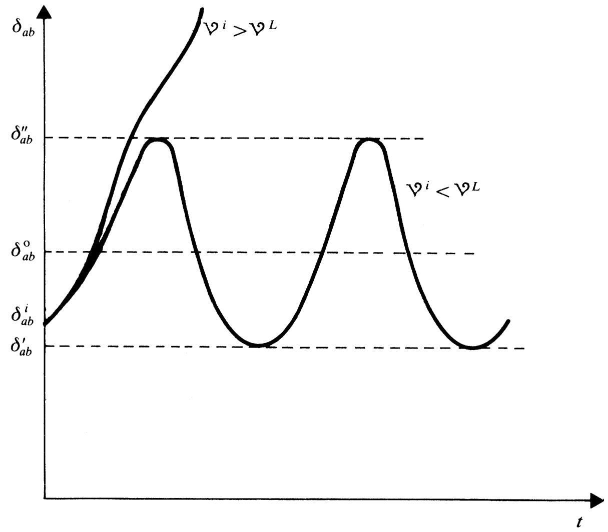

Figure 1.6. Typical behaviors of angular shift between machines for the system of Figure 1.2c.

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(22) Actually, in the definition of $W(\delta_{ab})$, the lower integration limit may be arbitrarily chosen or even different from δ^o_{ab}. One should note that the function $\mathcal{V}(\delta_{ab}, \Omega_{ab})$ is (independent from the possibility of assigning to it any particular physical meaning in terms of energy) a *Lyapunov function*, used to analyze stability properties of the system (see Section 8.3).

At the limit case $\mathcal{V}^i = \mathcal{V}^L$, it is easy to see that the system would settle itself at the second equilibrium point, indefinitely.

When $\mathcal{V}^i < \mathcal{V}^L$ (obviously is the most interesting case from the practical point of view), the transient of Ω_{ab}, δ_{ab} continues to oscillate. Starting from the point at which $\delta_{ab} = \delta''_{ab}$, the system behaves similarly to what is described above, but with Ω_{ab} negative and δ_{ab} decreasing, until Ω_{ab} (after having reached its minimum $-\Omega_{abM}$ at $\delta_{ab} = \delta^o_{ab}$) again crosses zero at $\delta_{ab} = \delta'_{ab}$. Then Ω_{ab} and δ_{ab} again vary as described above, through persistent oscillations around the equilibrium point $\delta_{ab} = \delta^o_{ab}$, $\Omega_{ab} = 0$. One should note that, contrary to possible expectations, the resistance R in Figure 1.2c has effect only on the function $P_{a(b)}(\delta_{ab})$, without leading to any damping of oscillations.(23)

On the other hand, if $\mathcal{V}^i > \mathcal{V}^L$, Ω_{ab} remains positive and δ_{ab} always increases, leading to a loss of synchronism because of the lack of synchronizing actions. *The loss of synchronism then can happen not only because of the lack of equilibrium points* (see footnote(20) and Section 1.5), *but also in the presence of a stable equilibrium point*, if the initial point is "too far," i.e., with $\mathcal{V}^i > \mathcal{V}^L$, from it.

During the increase of δ_{ab} at the loss of synchronism, currents and voltages in Figure 1.2c experience unacceptable transients, which actually cause the intervention of protective actions, with the disconnection of the two units. By simply assuming, for instance, $X_b = 0$, $\overline{v}_c = \overline{e}_b$, one can say that, for $\delta_{ab} = 180°$:

- the current in the link between the two units reaches its maximum value $(e_a + e_b)/(X_a + X)$;
- the voltage v_a (amplitude) reaches its minimum value $(X_a e_b - X e_a)/(X_a + X)$;
- the voltage becomes zero (as if a short-circuit occurred) at an intermediate point of the branch connecting $\overline{e}_a$ and $\overline{e}_b$ (this point, also named "electrical center," is defined by the pair of reactances X_1 (from the $\overline{e}_a$ side) and X_2 (from the $\overline{e}_b$ side), with $X_1 + X_2 = X_a + X$, $e_a/X_1 = e_b/X_2$).

In conclusion, the oscillations discussed above depend only on the value $\mathcal{V}^i$ of the function $\mathcal{V}(\delta_{ab}, \Omega_{ab})$ at the initial instant. Therefore, they also may occur starting from $\delta^i_{ab} = \delta''_{ab}$, $\Omega^i_{ab} = 0$ or, more generally, from any pair of initial values $\delta^i_{ab} \in (\delta'_{ab}, \delta''_{ab})$, $\Omega^i_{ab} \neq 0$ that provides the same value of $\mathcal{V}^i$.(24)

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(23) Under the adopted assumptions, the oscillations are persistent and the equilibrium is "weakly" stable. Nevertheless, in a real two-machine system, oscillations are generally damped because of the dynamic behavior of different components (particularly because of the effect of rotor circuits of machines). However, such *damping* may be negative (e.g., because of dynamic interactions with voltage regulators; see also footnote(19)), if proper stabilizing actions are not provided through control systems (see Section 7.2.2).

(24) For "small" variations (i.e., when $\delta^i_{ab} \to \delta^o_{ab}$, $\Omega^i_{ab} \to 0$) the oscillations of δ_{ab}, Ω_{ab} tend to become sinusoidal, with amplitudes $(\delta''_{ab} - \delta'_{ab})/2 \to \sqrt{2\mathcal{V}^i/K}$ (where $K \triangleq (\mathrm{d}P_{a(b)}/\mathrm{d}\delta_{ab})^o$) and $\Omega_{abM} = \sqrt{2\mathcal{V}^i/M_{ab}}$ respectively, and at frequency $\Omega_{abM}/((\delta''_{ab} - \delta'_{ab})/2) \to \sqrt{K/M_{ab}}$, as it also can be deduced by "linearizing" the system of Figure 1.4b.

The only condition for the existence of oscillations (for generic initial conditions δ^i_{ab}, Ω^i_{ab}) is then:

$$\mathcal{V}^i < \mathcal{V}^L$$

whereas, when $\mathcal{V}^i > \mathcal{V}^L$, the loss of synchronism results, as shown in Figure 1.6. Additionally, it is easy to determine, under analogous considerations, that the equilibrium point $(\delta^L_{ab}, 0)$ is unstable, because any generic deviation from it would cause oscillations around $(\delta^o_{ab}, 0)$ or loss of synchronism.

All the phenomena described here can be accounted for more concisely by considering (see Fig. 1.7) the possible "trajectories" on the $(\delta_{ab}, \Omega_{ab})$ plane. Each trajectory is, as shown, characterized by a constant value of $\mathcal{V}(\delta_{ab}, \Omega_{ab})$ and is described in the direction indicated by arrows. Then, the knowledge of the initial point $(\delta^i_{ab}, \Omega^i_{ab})$ immediately permits the subsequent evolution of the angular shift δ_{ab} and slip Ω_{ab}, thus confirming what is stated above.

Finally, similar phenomena occur in the more general (and more realistic) case of n machines, with $n > 2$. In such situations, $(n - 1)$ angular shifts and $(n - 1)$ slips must be considered, i.e., $(n - 1)$ possible oscillatory modes, which interact according to system nonlinearities. Unstable situations may occur both "in the small" (e.g., due to negative damping) and "in the large" (with loss of synchronism), or because of the lack of equilibrium points (and subsequent loss of synchronism).(25)

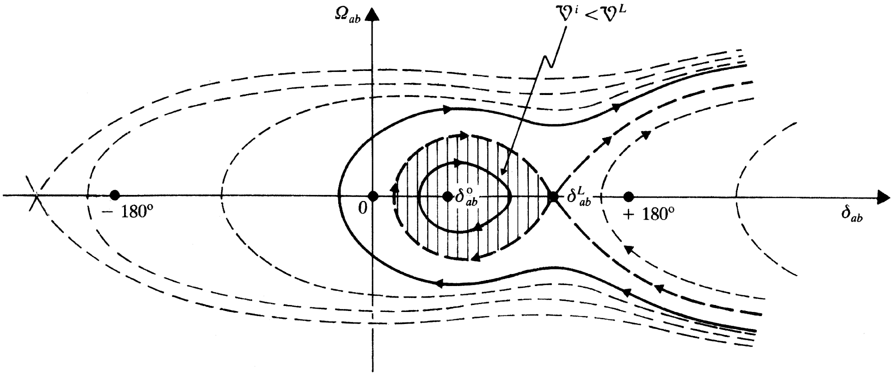

Figure 1.7. Trajectories on the $(\delta_{ab}, \Omega_{ab})$ plane, for the system of Figure 1.2c.

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(25) In the usual practice, with a more or less "formal" correctness, these three types of instability are named, respectively, "*dynamic*," "*transient*," and *"static" instability*. The transient instability is also called "first swing" instability, with a clear reference to the undamped two-machine case considered above (on the contrary, when considering more general cases, loss of synchronism also may occur after some oscillations).

The analysis of such phenomena generally requires the use of simulations, except with indicative analyses (see Section 8.3) based upon a simplified dynamic model similar to that considered here(26).

1.7. THE PERTURBED OPERATION

1.7.1 As in Section 1.2, the steady-state is actually a limit situation with superimposed unavoidable small, zero average, "load fluctuations," whose effects can be considered predominantly local and, consequently, moderately important to the whole system. In this section, such fluctuations will not be addressed; instead, more relevant perturbations (see also Section 1.2, footnote(5)) will be considered because of their influence on the whole system with possible risk for its operation.

With these problems, the combination of cases is complex but can be summarized as follows (under the hypothesis of significant perturbations):

(1) perturbations altering only the system configuration and only in a transient way: for instance, a short-circuit from a nonpersistent cause, cleared by protective devices temporarily disconnecting the faulty equipment;
(2) perturbations not altering the system configuration (with regard to generation, transmission, and the most important distribution links), but forcing the system to leave its original steady-state: for instance, a "gradual" load variation;
(3) perturbations permanently altering the system configuration: for instance, a short-circuit from a permanent cause and subsequent disconnection of the affected equipment by protective devices; with more detail, it can happen that:
    (3a) the resulting system is still connected: for instance, because of a tripped network with alternative routings (Fig. 1.8a), a generating plant outage (Fig. 1.8b), or the loss of a user group (Fig. 1.8c)(27);
    (3b) the system is separated into two parts, each including generators, transmission, and distribution systems, and loads: for instance, as a result of a tripped (single) interconnection line (Fig. 1.8d).

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(26) In the above example, due to the adopted assumptions, the loss of synchronism phenomenon occurs in a definitive way, i.e., without any chance to restore synchronism.

In real systems, the combined effects of the different damping actions — due, for instance, to machine rotor circuits and control systems — also might permit this restoration (cases of temporary loss of synchronism), provided that the links between the units are not disconnected by tripping from overcurrent protections.

(27) Actually, the cases of Figures 1.8b,c also imply a disconnection of the original system and might be treated as limit cases of type (3b).

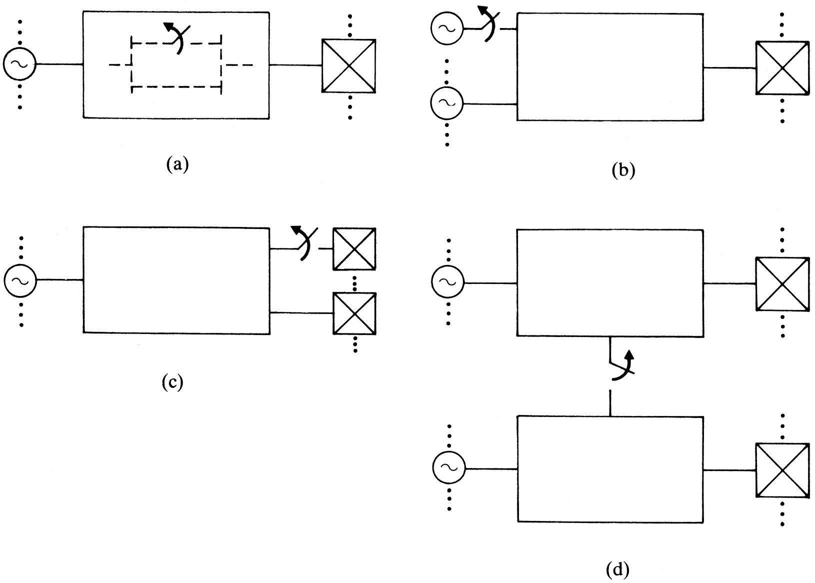

Figure 1.8. Examples of perturbations that permanently alter the system configuration: (a) internal line trip; (b) generating plant outage; (c) loss of a user group; (d) (single) interconnection line trip.

In addition, other perturbations, such as the outage of control system parts, cannot be excluded.

In case (1), the system is required to return to its original (stable) steady-state. In the other cases, above all, the system — or each of the two resulting parts in the case (3b) — is required to settle in a stable steady-state. Furthermore, when this occurs, it should meet all operating requirements. To verify all requirements are satisfied, a telemetering data report must be collected about the system's steady-state.

An accurate estimation of the operating state can be evaluated by using system equations (termed "*state estimation*"; see Section 2.5).

In fact, based on collected data and verification, the steady-state could be modified using available variables and acting on control parameters and "setpoints."

Additionally, it might be worth modifying the system configuration: adjusting it to the new load conditions in case (2), and restoring the original configuration, or achieving a new one, in cases (3a) and (3b). However, *"restoration" of the original configuration* is not possible if the outaged equipment is affected by permanent faults. The change to a new configuration must involve rectifying any critical situations; for example, adding generators or connecting new links.

Nevertheless, the operations required to put into service an equipment also may require special attention and/or long times, particularly with long lines, specific users, and steam-turbine power plants (the case is much easier for hydroelectric or gas-turbine power plants, which can be seen as a type of “quick reserve”; see also Section 2.4.2a).

1.7.2 The perturbed operation may become more complex and critical because of one of the following reasons:

(1) during the transient itself (approaching the stable steady-state condition), protection system action (e.g., due to excessive transient overcurrent in some line) causes new perturbations;

(2) instability situations arise, specifically:
   - equilibrium points exist but are unstable⁽²⁸⁾: for instance, with unstable electromechanical oscillations;
   - the final configuration (as in cases (3a), (3b)) does not permit equilibrium points, thus leading, e.g., to voltage or frequency instability or loss of synchronism (see Section 1.5);
   - stable equilibrium points exist but are not reachable from the initial system “state”: see the simple system in Figure 1.2b, when (even assuming $v_{c\text{des}} < Rv_a/X$) the susceptance B is initially larger than the value B^L reported in Figure 1.3, so that the result is again voltage instability; alternatively, refer to cases of loss of synchronism illustrated in Section 1.6 with $\mathcal{V}^i > \mathcal{V}^L$.

Instability situations also may result in protective actions of generator or load disconnections, or line tripping, which could be due to excessive currents and/or voltage or frequency dips.

Therefore, the subsequent behavior of the system, eventually split into more parts, must be examined in its new operating conditions.

In most real cases, system operation might not be disrupted, with the exception of local outages: for example, the trip of a load with a voltage instability (to remove the instability itself) or the disconnection of a relatively small unit with a loss of synchronism.

Nevertheless, much more severe situations may occur, i.e., *emergency* situations capable of leading the system to a total outage (*blackout*). This may happen in case of a cascade tripping caused by overcurrent protections because of the progressive weakening of the network configuration. It also can occur when the rotating power becomes insufficient, causing a frequency collapse; this can be

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(28) This might happen even when considering the case (2), for which the configuration is not altered. One should not be surprised because, due to the nonlinearities of the system, the stability properties can change with the equilibrium point.

worsened by further power plant disconnections because of protective actions in auxiliary systems.

To some extent, all these risks may be considered in operation scheduling, by imposing security checks on the generic steady-state. However, it is important to conduct an up-to-date *diagnosis* of the system during the perturbed operation itself, considering the results of preventive analyses, possibly synthesized in terms of stability "indices" or similar measures which can be quickly evaluated in real-time.(29)

If the diagnosis reveals an emergency situation as described above, then it is necessary to modify the system with new controls to avoid possible outages. An example would be operating the forced disconnection of some loads (*load-shedding*) to eliminate rotating power deficiencies (see Section 3.5) or prevent, or stop, cascade protection interventions ("cascading outages"). When outages are unavoidable it is also important to initiate actions that make easier and quicker the subsequent restoring operations: for instance, "isolating" thermal power plants from the network before a unit trip occurs, allowing operation via their auxiliary systems (*load-rejection*) and local loads, to be ready for reconnection to the network.

1.8. DYNAMIC PHENOMENA AND THEIR CLASSIFICATION

1.8.1 Dynamic relations among variables that characterize the generic system can be summarized as in the block diagram of Figure 1.9, where it can be seen:

- subsystem (a) of a predominantly mechanical type, consisting of generating unit rotating parts (specifically, inertias) and supply systems (thermal, hydraulic, etc.);
- subsystem (b) of a predominantly electrical type(30), consisting of the remaining parts, i.e., generator electrical circuits, transmission, and distribution systems, and users (and possible energy sources of the nonmechanical type), with the latter possibly assimilated with electrical equivalent circuits(31).

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(29) In particular, the diagnosis may be organized by considering the above-described cases, specifically the type of perturbations and the possible phenomena of the type (a) or (b).

(30) Subsystem (b) includes mechanical rotating parts of synchronous compensators and electromechanical loads. The mechanical parts of synchronous compensators and of synchronous motors — the latter including their loads — can be considered, if worthy, in subsystem (a) without any particular difficulties (but see footnote(31)).

(31) The equivalence must account for the dynamic behavior of loads, as "seen" from the network. However, with regard to the overall system behavior, strong approximations, which are unavoidable during the analysis stage, can be accepted (above all in the case of loads composed, in an aggregation difficult to determine, by a number of users different in type and with modest unitary power). Equivalent circuits may be used for whole load areas, including in them the MV and LV distribution networks or even subtransmission networks (see Fig. 1.1).

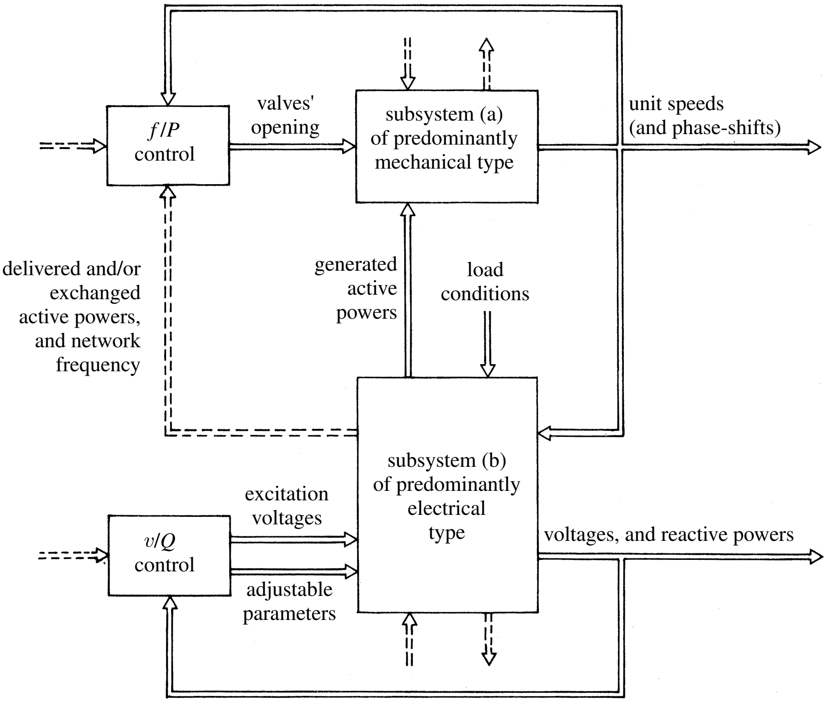

Figure 1.9. Broad block diagram of a generic system.

The input variables of the system composed by (a) and (b) are essentially (apart from structural perturbations):

- openings of prime mover valves, which "enter" into subsystem (a), affecting driving powers (at given operating conditions of the supply systems, e.g., set points of the boiler controls, water stored in reservoirs);
- excitation voltages of synchronous machines, which "enter" into subsystem (b), affecting the amplitude of emfs applied to the three-phase electrical system;
- different parameters that can be adjusted for control purposes (specifically, for the v/Q control): capacitances and inductances of reactive components (of the static type), transformer ratios of underload tap-changing transformers, etc.;
- load conditions dictated by users, which are further inputs for the subsystem (b), in terms of equivalent resistances (and inductances) or in terms of absorbed mechanical powers, etc.(32).

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(32) The power produced by nonmechanical sources can be accounted for in an analogous way as a further input to subsystem (b). For simplicity, the modulation of these powers for the f/P control is not considered here.

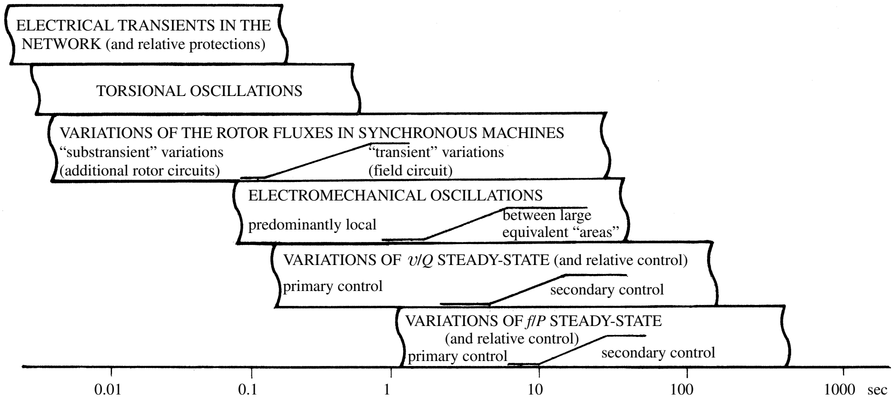

Figure 1.10. Typical time intervals for analysis and control of the most important dynamic phenomena.

According to Figure 1.9, the f/P control is achieved by acting on valves' opening, while the v/Q control is achieved by acting on excitation voltages and the adjustable parameters mentioned above. The load conditions instead constitute "disturbance" inputs for both types of control.

Subsystems (a) and (b) interact with each other, specifically through:

- generated active powers;
- electrical speeds of generating units (or, more generally, of synchronous machines; see footnote(30)) and (electrical) shifts between their rotors.

In fact, generated active powers clearly behave as resistant powers (opposed to driving powers) on each unit shaft. Consequently, they affect rotor speeds and relative angular shifts; the speed and angular shifts, vice versa, influence the emf vectors and thus the active powers produced by generating units (besides the other variables of the three-phase electrical system). These phenomena cause, under normal operating conditions, the previously mentioned synchronizing actions. Through electromechanically damped oscillations these actions usually permit the recovery of synchronism; only in the presence of large disturbances, might they be unsuccessful in preventing loss of synchronism.

1.8.2 Regarding response times (see Fig. 1.10), it is important to emphasize that subsystem (a) generally presents much slower "dynamics" than subsystem (b)(33), primarily because of the effects of rotor inertias, limits on driving power rate of change, and delay times by which (because of the dynamic characteristics of supply systems) driving powers match opening variations of the valves.

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(33) Except with torsional phenomena on turbine-generator shafts, which are quite fast (see Section 4.1.4).

This fact supports many simplifications, which are particularly useful in identifying the most significant and characterizing factors of phenomena, performing dynamic analyses with reasonable approximation, and selecting the criteria and implementing the significant variables on which the real-time system operation (control, protection, supervision, etc.) should be based.

According to this order of reasoning, dynamic phenomena can be structured into one of the following categories:

- *"predominantly mechanical" phenomena*, caused by perturbations in subsystem (a) and in f/P control, which are slow enough to allow rough estimates on the transient response of subsystem (b), up to the adoption of a purely "static" model (an example is the case of phenomena related to frequency regulation);
- *"predominantly electrical" phenomena*, caused by perturbations in subsystem (b) and in v/Q control, which are fast enough that machine speeds can be assumed constant (for instance, the initial part of voltage and current transients following a sudden perturbation in the network) or which are such to produce negligible variations in active powers, again without involving the response of subsystem (a) (for instance, phenomena related to voltage regulation, in case of almost purely reactive load);
- *"strictly electromechanical" phenomena*, for which interaction between subsystems (a) and (b) is essential, but it looks acceptable to simplify the dynamic models of components according to the frequencies of the most important electromechanical oscillations (e.g., phenomena related to a single-machine oscillation against the rest of the system, when the latter may be represented as an equivalent connection line and an "infinite power" network; see Chapter 7).

However, when analyzing more complex cases for which simplifications may not seem acceptable, computer simulations can become necessary.

ANNOTATED REFERENCES

Among the works of more general interest, the following may be quoted: 5, 11, 21, 25, 30, 37, 46, 50, 53, 54, 231, 337.

Moreover, as far as dynamic and control problems are concerned: 6, 28, 32, 38, 39, 40, 48, 57, 104, 210, 234, 246, 323, 330, and more specifically:

- with reference to terminology: 227, 263;
- with reference to voltage instability: 55, 59, 229, 259, 286;
- with reference to the perturbed (and emergency) operation: 199, 207, 226, 250, 308.

As far as the most peculiar aspects of power engineering are concerned: 24 (especially for what concerns harmonics), 60.