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Dynamic stability of industrial electrical networks



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Glossary

H:

Inertia constant, homogeneous with a period of time, characterising the sensitivity of speed of a machine to variations in electrical power.

Internal angle (δ):

Angle between the vector representing the supply voltage of a machine and the vector representing its electromotive force.

Electrical distance:

Connection impedance. Two electrical connections of the same length may have very different electrical distances.

Load flow:

Balance of the active and reactive powers exchanged on the connections of a network.

Voltage plan:

Set of automatic and manual procedures scheduled to keep the network within its rated operating voltage limits.

Synchronising power:

Characterises the operating point of a generator: ratio of the variation in supplied power over the variation in internal angle. The lower this ratio, the greater the risk of loss of synchronism in overspeed.

Transient reactance:

Impedance of a machine in the first second after a disturbance.

Subtransient reactance:

Impedance of a machine in the first 100 milliseconds after a disturbance.

Redundancy:

Used in a technical context, this term no longer has its accepted meaning of « superfluous ». Redundancy in this case is the implementation of more than one channel to perform a function in order to prevent failure and/or to allow maintenance during operation without interruption of operation.

Primary, secondary adjustment:

For generator regulation, describes the frequency/active power characteristics or voltage/reactive power characteristics (see droop) and the correction (secondary) provided.

Dynamic stability:

Behaviour of networks subjected to disturbances: causes, consequences (instabilities) and solutions.

Droop characteristic:

Characterises the primary adjustment of generator regulation: frequency as a function of active power or voltage as a function of reactive power.

EDF: Electricité de France:

National electricity board.

Dynamic stability of industrial electrical networks

Given that electrical energy is very difficult to store, a permanent balance between production and consumption is vital.

Generators, loads and the electrical networks which connect them have mechanical and/or electrical inertias which complicate the maintaining of a balance guaranteeing relatively constant frequency and voltage.

When confronted with a power variation, the electrical system normally resumes a stable state after a few oscillations.

However in certain cases the oscillating state can diverge, and studies are then required to avoid this phenomenon and guarantee the stability of the electrical network.

These studies are of particular importance in the case of industrial networks which contain one or more generator sets and motors.

The purpose of this Cahier Technique is to understand why instability can appear and to define the main causes and effects of such instability.

It explains the precautions to be taken and, using a concrete example, describes how a typical study is conducted.

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1 General

1.1 Electrical networks

Since electrical energy is produced at the same time as it is consumed, production must constantly adapt to consumption. As a result, energy production, transmission and consumption form a complex system known as the electrical network stability of which is vital. An electrical network can vary considerably in power (according to the country where it is installed). In all cases its characteristics are expressed in terms of:

- electrical quantities,
- arrangement in space,
- time-related data.

Electrical quantities:

- Frequency: 50 or 60 Hz according to the country.
- Voltage: from a few hundred volts to a few hundred kV, depending on the part of the network in question.

These basic quantities are affected by the intensity of the current flowing in the lines and cables, which in turn is linked to the active and reactive powers generated, transmitted and consumed.

- Active power is produced by generators from thermal or mechanical energy, and also

consumed in thermal or mechanical form by loads.

- Reactive power is produced or consumed in all the components of the network.

Note that in dynamic conditions, active energy is « stored » by rotating machines (inertia), and that reactive energy is stored in magnetic (e.g. transformers or rotating machines) or capacitive (e.g. cables) form.

Arrangement in space:

The topological structure varies according to:

- the continent,
- the country and region,
- the industrial site (from hundreds of metres to dozens of kilometers),
- the service sector building.

In the first two cases there are three levels of energy transmission:

- transmission,
- subtransmission,
- distribution.

Time-related data:

Variations in the balance between energy offer and demand disturb frequency and voltage which must be kept within acceptable limits.

1.2 Quality of electrical energy

An electrical network normally has an overall stability revealed by large-scale balance of the production/transmission/consumption system in time and space.

However a finer analysis shows that in reality events occurring at all times and places cause fluctuations which, with the exception of disasters, will be compensated.

Thus the notion of quality of electricity appears in the form of (see [fig. 1](#)):

- Continuity of supply: availability of the electrical energy at a given point that may be interrupted by short (< 1 min.) or long (> 1 min.) power cuts.
- The voltage waveform (frequency, amplitude, duration): in this case disturbances are normally classed according to their frequency range:
 - high frequency phenomena (kHz -> MHz): fast front overvoltages due to lightning or to certain

switching operations (e.g. disconnectors, switches, some circuit-breakers),

□ low frequency phenomena (50 Hz -> kHz): switching overvoltages, harmonics.

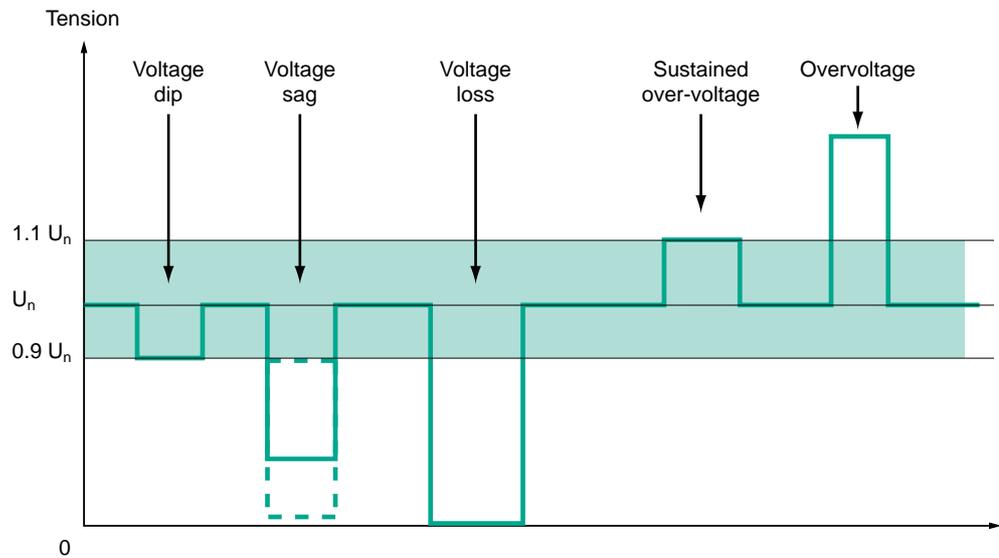
□ Power frequency phenomena (0 -> 100 Hz): rapid (20 ms -> 1s) or slow (more than one second) fluctuations such as unbalance, voltage sags due to implementation of powerful loads or to a short-circuit in the distribution network.

Variation in frequency may result from:

- a short-circuit near a source,
- a very large variation in source power,
- transfer to a replacement or standby source.

Such is the context in which the dynamic stability dealt with in this Cahier Technique studies the changes in frequency, voltage and power resulting from serious disturbances.

a - Amplitude



b - Duration



fig. 1: voltage disturbances in networks.

1.3 Stability of networks

Network stability is characterised by the fluctuations in the powers flowing in the network and is measured by the variations in time of the associated voltages and frequencies.

A distinction must be made between:

- **Stability in steady state:** the network has a stable behaviour, i.e., when subjected to small disturbances it returns to its initial point of operation with, possibly, damped oscillations until balance is restored.
- **Stability in transient state:** on moving from one steady stable state to another as a result of a voluntary or accidental durable disturbance, the change in balance is accompanied by a damped oscillating variable state considered to be acceptable with respect to the predefined limits of ΔU , Δf , Δt .
- **Instability in the transient state** is observed when, further to a serious disturbance, the oscillating state is divergent. Either a loss of power supply or a new unacceptable

stable state is induced (e.g. a « crawling » motor).

- **Stability in dynamic state:** the network is able to avoid all divergent oscillating states and to return to an acceptable stable state. This includes tripping of protection and automatic devices according to the disturbance under consideration.

The dynamic stability studies consist of:

- considering the main critical scenarios such as short-circuit, loss of mechanical power, loss of electrical supply, load fluctuations, process constraints,
- predicting network reactions to these disturbances,
- recommending the appropriate operating measures such as type of protection device, relay setting, load shedding, configurations... in order to avoid undesirable operating modes. Such studies therefore enable the reactions of the network considered (public or private, HV or LV) to be mastered.

1.4 Industrial networks

At this point we shall mention a few characteristics specific to industrial electrical networks:

- geographical size of sites of up to several dozen hectares,
- length of connections, lines and cables, of up to several kilometers for the various voltage levels,
- energy sources: external electricity boards, autonomous energy production (isolated network) and mixed solutions,
- voltages: several levels in a range varying from 380 V to 90 kV or more,

- powers: 250 kVA to 100 MVA or more,
- loads: dominated by the presence of asynchronous motors. Also note special loads linked to the process (e.g. electrolysis, furnaces...),
- complexity of the network architecture which must be able to supply priority loads, possess supply backup sources and have reconfiguration abilities,
- stability time constants: normally one to ten seconds.

2 Behaviour of an industrial electrical network

The behaviour of an electrical network during transient phenomena depends on the behaviour of each of its components.

These components, starting from a stable state, will affect the transient behaviour of the network as a whole. When the disturbance has passed, they will either be in the same stable state as

before the disturbance, in another stable state or in an unstable state which normally results in loss of one or more components due to tripping of the protection devices. Knowledge of the behaviour of each component is thus vital in determining the overall behaviour of the electrical network under consideration.

2.1 Passive loads

These are loads such as lighting and heating, whose electrical variation rules are of the type:

$$P = \left[\frac{V}{V_n} \right]^\alpha P_n \quad \text{and} \quad Q = \left[\frac{V}{V_n} \right]^\beta Q_n$$

where α and β are load characteristics.

2.2 « Power electronic » loads

A large number of loads: electrolysis tanks, variable speed drive, heating using a.c. voltage controller, etc. belong to this load category. The common feature shared by these loads is their great sensitivity to voltage variations. For example a variable speed drive may be stopped completely for a voltage variation of

around $\pm 15\%$. Added to this is a certain potential sensitivity to frequency variations, making these devices part of those loads affected by the stability problems of electrical quantities.

The same applies to computer equipment.

2.3 Transformers and connections

Transformers, lines and cables used to convey electrical energy between sources and loads, are characterised by their impedances which create voltage drops and active energy losses according to the current flowing through them. Their importance is decisive in the transient state:

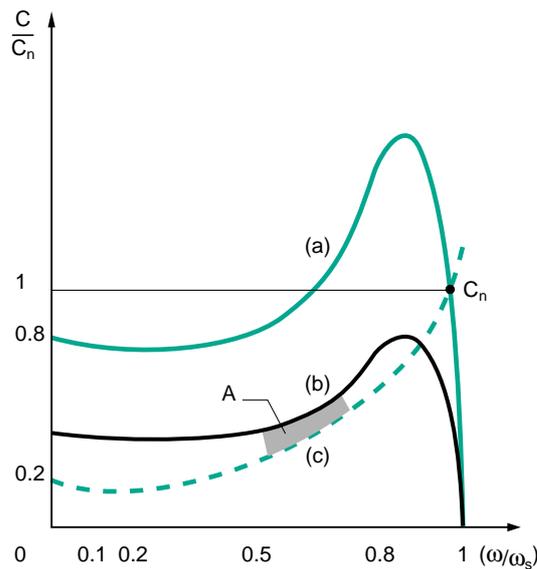
- strong inrush currents cause voltage drops which can be critical,
- the impedance that they induce between synchronous sources (known as « electrical distance ») may be the cause of long-lasting oscillations.

2.4 Asynchronous machines

Their dominating presence in industrial networks (up to 80% of power consumption in some installations) gives asynchronous motors a preponderant role in stability phenomena.

■ Effect of voltage sags

The torque/speed chart for an asynchronous motor in **figure 2** is represented for a double cage motor supplying a pump.



- (a): curve $C(\omega)$ at full voltage
- (b): curve $C(\omega)$ at reduced voltage ($0.7 U_n$)
- (c): curve $C_r(\omega)$

fig. 2: torque/speed charts for an asynchronous motor.

The operating point is located at the intersection of the motor torque and load moment curves. Motor torque is proportional to the voltage square.

Motor stability depends on the relative positions of the driving torque and load moment curves. If the motor undergoes a power cut or a marked voltage sag for a few moments, it will slow down and adopt a reduced speed, for example 70% of synchronism speed. Whether it can then reaccelerate and resume its original stable state depends on the value of the voltage when it is restored. Say that, due to current inrushes in the network, the voltage is $0.7 U_n$ at this moment

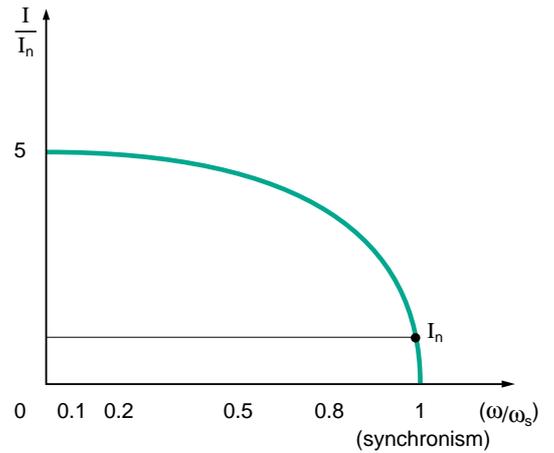


fig. 3: asynchronous motor - Current as a function of speed.

(see **fig. 2**). Driving torque is only very slightly greater than load moment (zone A, **figure 2**): the motor will « crawl » (accelerate very gradually) and will be disconnected by the tripping of overlong startup protection devices, thermal or undervoltage relays.

Figure 3 shows that when a motor slows down slightly, it absorbs a strong current. This current causes voltage drops which make reacceleration even more difficult. If all the motors in an industrial installation slow down (for example as a result of a serious voltage sag in the electricity board's network), the current absorbed by all motors on reacceleration would create voltage drops which could make reacceleration impossible. A common solution is to use a progressive load shedding and restoration PLC. Stability can then be managed by minimising current inrush and consequently voltage drop.

In short, asynchronous motors have a vital role to play in dynamic stability and may encounter operating problems as a result of a sudden drop in voltage.

■ Effect of undervoltage

In undervoltage conditions the motor generates a self-induced residual voltage at its terminals which is damped in a few dozen seconds. In the case of a large motor and if reactive power compensation capacities are present, this voltage may persist for nearly one second. On undervoltage, the remanent voltage phase drops behind the network phase due to

deceleration of the motor (see **fig. 4**). The motor, as it slows down, can restart without risk when voltage is restored provided that the voltage $U_{reaccel}$ remains within acceptable limits. When $\theta = 180^\circ$, $U_{reaccel}$ is at its greatest value, i.e. nearly twice network voltage. The consequences are destructive torques, and currents (15 to 20 I_n) far greater than starting currents.

Points to note:

- The importance of rotating mass inertia - motor plus driven machine- characterised by its inertia constant, H, which expresses the sensitivity of the speed of the machine to variations in voltage or load:

$$H = \frac{\text{rated rotating kinetic energy}}{\text{rated apparent electrical power}}$$

- The effect of the mechanical load torque characteristic as a function of the speed of the various rotating loads.

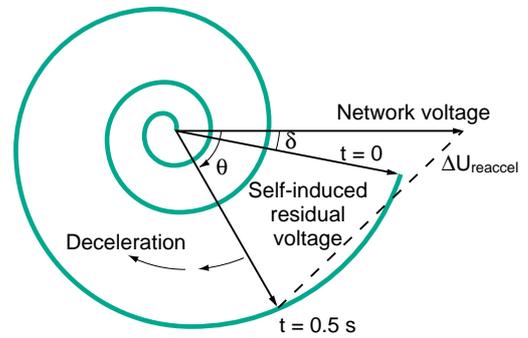


fig. 4: residual voltage and « reacceleration » of an asynchronous motor network voltage.

- In motor transient behaviour, its operating conditions depend on the various characteristic time constants of the motor.

2.5 Synchronous machines

Synchronous machines are a common feature in industrial networks. They may be installed for a number of reasons:

- recovering energy from an exothermal or cogeneration process,
- need for a complementary source of electricity for:
 - an « EJP » contract: specific EDF contract encouraging consumers to limit their energy consumption at peak times.
 - standby source,
 - peaks,
- reactive energy compensation.

These machines play a vital role in network stability phenomena. A brief reminder is provided below.

Static stability

A synchronous machine can be represented by the diagram in **figure 5a** where:

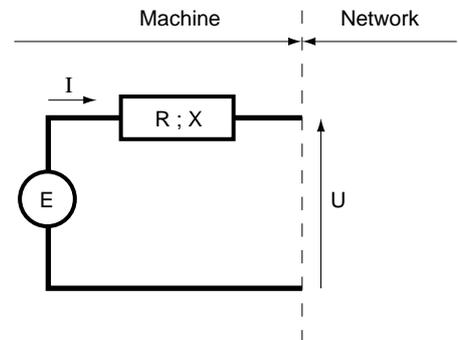
- R: stator resistance,
- X: synchronous stator reactance,
- E: stator e.m.f. created by the rotor exciting winding,
- U: voltage at the terminals of the on-load stator.

The corresponding vector chart is given in **figure 5b**: the internal angle, δ , of the machine is defined as the angle between the vectors \vec{U} and \vec{E} . This angle is equal to the angle by which the rotor is offset with respect to its no-load operating position (if $I = 0$, $\delta = 0$).

By ignoring R, a quick calculation shows that the active electrical power transmitted to the network

is calculated by:
$$P = \frac{E U \sin \delta}{X}$$

a - Diagram of a synchronous machine



b - Vector chart for the above machine

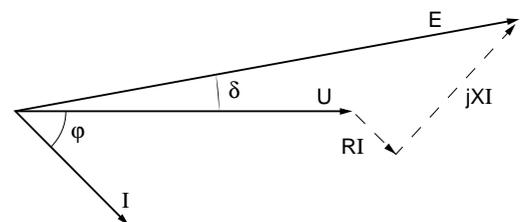


fig. 5: representation of a synchronous machine.

It is obvious that the electrical power transmitted

to the network is limited to the value of $\frac{E U}{X}$ a value which is reached for $\delta = 90^\circ$.

P can be represented as a function of δ (see **fig. 6**). In this diagram the mechanical power P_m

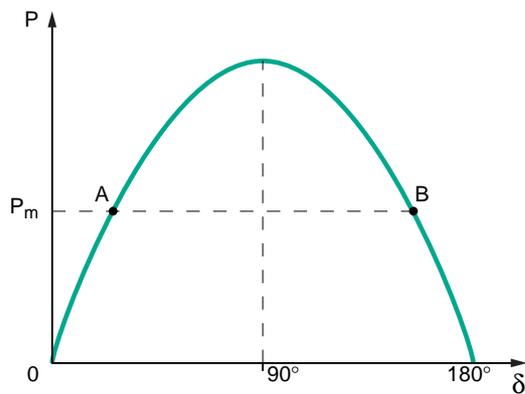


fig. 6: power generated by a generator as a function of the internal angle.

supplied by the driving machine (turbine or diesel for example) is represented by a horizontal straight line. The operating point is given by the intersection of this horizontal line with the sine wave. In point of fact, two operating points, A and B, are possible. Starting from A if, for any reason, the angle δ increases, the power transmitted to the network will increase and the machine will slow down. This causes δ to decrease, the starting point is resumed and operation is stable. An identical reasoning shows that point B is unstable, just like all points on the rectilinear part of the curve.

If we no longer assume that $R = 0$, the limit

$$\text{for } \delta \text{ is an angle } \psi \text{ such that } \operatorname{tg} \psi = -\frac{X}{R}$$

The static stability of a generator (i.e. its ability to cope with a slow variation in load) can be defined according to two complementary practical considerations:

- operation is stable only if the internal angle δ remains less than a limit angle close to 90° ,
- the active power transmitted to the network is limited. It is at its greatest when the stability limit is reached.

Dynamic stability

Dynamic stability problems result from the machine moving from one stable state to another. Let us consider the example of a sudden power variation on the turbine which moves abruptly from a supplied power P_1 to a supplied power P_2 (see fig. 7).

The slow increase in power from P_1 to P_2 would cause a gradual shift from point A to point C while remaining on the curve. However the sudden application of this power increment is not possible, as mechanical inertia makes it impossible to suddenly move from an angle δ_1 to an angle δ_2 . This explains the instantaneous move from point A to point B.

The angle δ then increases from δ_1 to δ_2 . However on reaching point C, stabilisation is not

immediate, and inertia continues the move to point D. From this point, deceleration to point E finally stabilises the phenomenon, after a few oscillations.

Energy calculations show that the position of point E is defined by the criterion area: areas ABC and CDE are equal. Consequently, the maximum internal angle, δ_{\max} , can be greater than 90° in transient manner. The dynamic stability limit is thus higher than the static stability limit.

However the difference between P_1 and P_2 may at times be so great that the criterion areas ceases to apply (see fig. 8).

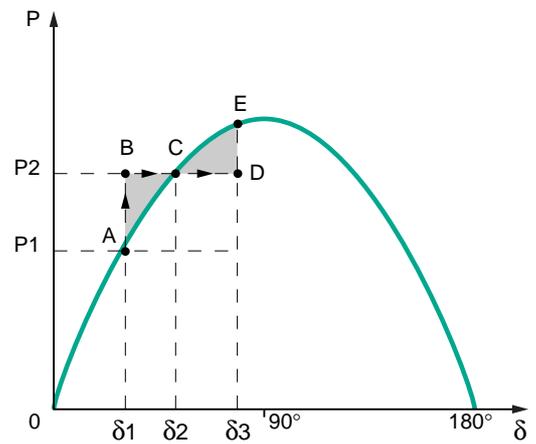


fig. 7: displacement of the generator operating point further to an increase in mechanical power.

There is no point D corresponding to the law of areas. The generator accelerates from point B to point C, then up to point X: at this point it continues to accelerate while remaining on the curve, and the power transmitted to the network decreases. If the network is supplied by other sources, loss of synchronism occurs due to overspeed.

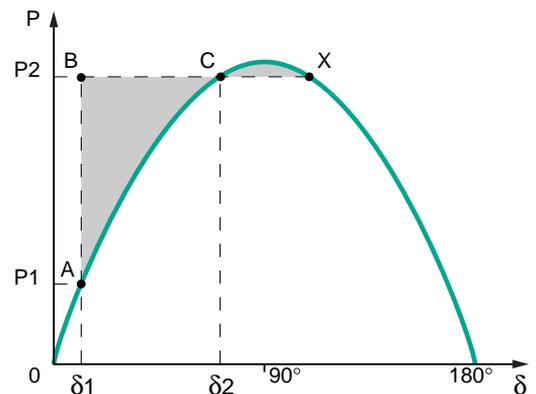


fig. 8: instability (overspeed) further to a mechanical power step.

Two important observations must be made at this point:

- the risks of dynamic stability losses are linked to sudden major changes in network or turbine state,
- the risks of dynamic stability losses increase as the power supplied by the synchronous machine reaches the static stability limit.

These facts are expressed by the notion of

$$\text{synchronising power } P_s = \frac{dP}{d\delta} = \frac{EU}{X} \cos \delta$$

which shows that for a given variation in drawn power, modification of the electrical angle decreases with the angle.

Note that in reality, in transient state, the transient and subtransient reactances of the machines, taking account of time variations in flux, must be considered in addition to X.

However speed and voltage controls play a crucial role in enhancing the reactions of the set to the network.

2.6 The regulations

The purpose of the regulations is to ensure correct operation:

- stability of voltage amplitude,
- stability of network frequency during variations in load or driving power,
- sharing of active and reactive electrical powers.

■ Frequency/active power regulation.

□ Take the simple case of a generator, the only load source, equipped with a speed regulator. Network frequency, proportional to generator rotation speed, is set by the primary speed adjustment of the mechanical drive device adapting the power to be supplied. The resulting automatic regulation is defined by its droop characteristic which expresses the total frequency deviation for the complete power range (see [fig. 9](#)).

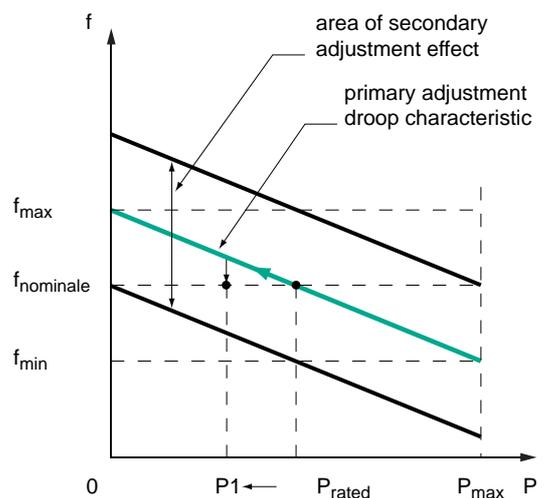


fig. 9: generator droop characteristic and effect of secondary adjustment area of secondary adjustment effect.

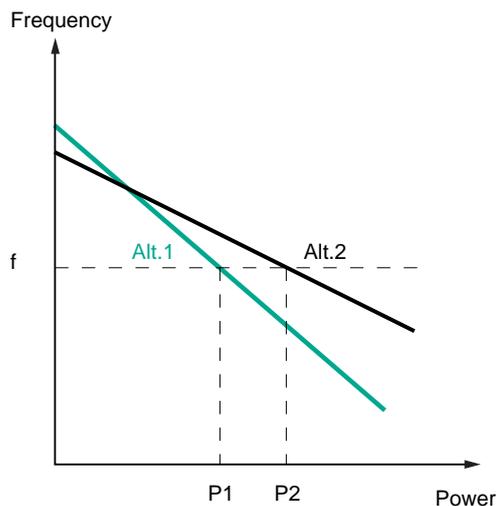


fig. 10: coupled generators - power distribution as a function of droop.

As we move away from the operating point (P_n, f_n), any increase in active power supply causes a drop in frequency and vice versa. Thus, for example, a 4% droop guarantees a frequency of 49 to 51 Hz ($50 \text{ Hz} \times 4\% = 2 \text{ Hz}$). To remove this error, a compensation can be introduced which moves the droop characteristic parallel to itself as a function of speed thanks to a secondary adjustment.

In dynamic state, the system time constants vary from a few hundred ms to a few seconds. A corrector (Integral, Derivative, lead/lag modules) are used to partially relieve the inevitable consequences of this relative slowness.

□ When two generators are coupled, their operating point depends on their droop and their power (see [fig. 10](#)).

Any power variation is accompanied by a frequency variation, and the sharing of power between the generators is in proportion to their respective droop. It is thus possible to imagine a whole host of different operating configurations.

- The case of coupling a generator to a network is an extension of the above case where the network has a virtually almost zero droop. In other words, frequency is imposed on the generator, and its regulation is then a power regulation.
- In short, the action of the electromechanical regulator of the generator's driving machine is

used to adjust network frequency and/or the active power transmitted.

■ Voltage/reactive power regulation.

If the above logic is transposed to the use of a generator excitation regulator, we observe that network voltage amplitude and/or reactive power transmission can be adjusted in order to solve the problem of the natural characteristic ($U = f(I)$ at constant excitation) of the generator and the problem of load fluctuations.

2.7 The electricity board's network

The electricity board normally delivers a specific voltage, guaranteed by contract in a certain amplitude and frequency range.

For example the EN 50160 standard which characterises the quality of the voltage supplied by public networks, stipulates the variations accepted for frequency and voltage (see **fig. 11**). The electricity board gives the short-circuit power

of the source at the point of common coupling (normally three values: high, low and medium, allowing for the configuration of its network). Faults present on the electricity board's network are passed on to the customer: their characteristics and frequency are random, and the protection plan installed may result in standard supply breaking times.

LV/MV network	One week 95% period	One week 100% period
Synchronous connected to interconnected system	50 Hz \pm 1% 95% of rms U_n (10 minutes) \pm 10%	50 Hz \pm 4% ; - 6% 95% of rms U_n (10 minutes) \pm 10%
Not connected to interconnected system	50 Hz \pm 2% 95% of rms U_n (10 minutes) \pm 10%	50 Hz \pm 15% 95% of rms U_n (10 minutes) \pm 10%

fig. 11: accepted variations for frequency and voltage in public networks (as in EN 50160 standard).

2.8 The protection devices

The purpose of these devices is to protect persons and equipment. They are mainly used when an abnormal transient phenomenon occurs. The following disturbances are at the origin of transient phenomena:

- electrical faults occurring on the electricity board's network,
- internal electrical faults,
- supply and consumption transfer operations (manual or automatic),
- startup and reacceleration of large motors or production units,
- loss of part of production (tripping of a generator set, transformer or line).

The protection devices are designed to remove faulty parts selectively and rapidly and to ensure, insofar as possible, supply of priority and vital process loads.

The main protection devices are:

- overcurrent protections, which can be:
 - constant/reverse time, instantaneous/time delayed,
 - directional.
- Undervoltage protections,
- more specific protection devices such as frequency drop, overspeed, reverse power, residual current, under impedance...

These protection devices are backed up by automatic devices such as source changeover switches, load shedders/restorers which have the effect of attenuating or of generating power transients on the network.

The action of both the protection devices and the automatic devices is decisive in treating dynamic instability.

2.9 The network as a whole

Overall network behaviour is the result of the individual behaviour of each of its components, including protection and monitoring/control equipment, and of their interactions.

■ Static stability defines the power flows in the network for all normal operating modes of the industrial site (configuration of the network and productions in progress). In each case the « voltage operating schedule » specifies the actions to be performed to keep voltage within acceptable limits (e.g. better than 3%) and to minimise losses for:

- power delivered by the sources,
- adjustment of transformer taps,
- compensation capacitors.

■ Dynamic stability constraints condition network evolution according to operating modes and incidents, as well as the actions to be taken to minimise risks and disturbances to the process.

Note that monitoring and control plays an important role in both normal and abnormal operation of the network in that it provides knowledge at all times of generator power flows, voltage and load.

At this level the complexity of the global problem is far greater than that of a « static » state. Dynamic stability studies are then used to recommend the most appropriate measures to be taken and solutions to be implemented for each individual case.

3 Dynamic stability study of industrial networks

The purpose of this chapter is to provide general information on the objectives assigned to the studies and on the study content, with particular emphasis on the causes, effects and solutions of

dynamic instabilities. Finally a study conducted by the « Electrical System Analysis » Department will be presented as an example.

3.1 General

Study objectives

Dynamic stability studies consist of analysing and acquiring prior knowledge of the variations in time of electrical quantities at various points of a network, and of the changes in the mechanical parameters of rotating machines as a result of sudden disturbances.

The purpose of these studies is to find:

- the network operating conditions able to ensure proper continuity of load supply,
- the maximum available power when a disturbance occurs,
- the optimum adjustment values of the protection system components,
- the load shedding plan to ensure supply of vital loads,
- the best machine regulation adjustments.

Each study is based on a specific case depending on:

- types of sources,
- types of loads,
- network architecture,
- network operating mode,
- the instability causes taken into account.

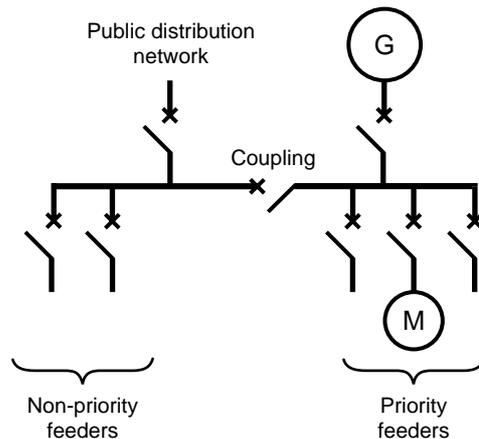
There are various reasons for studying dynamic stability:

- preventive study when designing a network,
- addition of high power generators and/or loads on an existing network,
- curative study when an incident occurs.

If the study is conducted before the installation is produced, these factors can be modified for the most part. Operators can thus be certain that in transient modes, the behaviour of the network

and machines will match expectations and requirements.

Studies can either be global or limited to a precise problem, for example in the case of coupled operation between an EDF network and a generator: determining the exchanged energy limit ensuring in the event of decoupling that an unstable operating point of the priority network is not reached (see [fig. 12](#)).



[fig. 12](#): double source network with priority feeders.

Causes of instability

■ Electrical phenomena.

The disturbing phenomena affecting network stability are those which cause variations in active/reactive power:

- variation in source characteristics:
 - short-circuit power,
 - voltage sags and drops,
 - short or long power cuts,
 - frequency variation (isolated network).
- Variation in network load, for example:
 - at rated load, generators have a low synchronising power,
 - off-load a network can become capacitive.
- Electrical faults, the most noteworthy of which is the full three-phase short-circuit.

■ Network composition and operating mode.

The many parameters involved in network operation offer a whole host of configurations, some of which favour risky situations:

- the machine interconnection mode and coupling to the electricity board's network, as well as the priority and non-priority busbars,

- the rated operating point of generators, on which the available power margin and the synchronising power depend,
- the regulation mode of synchronous machines: speed or active power regulation, voltage or reactive power regulation,
- coupled impedances (e.g. parallel-connected transformers),
- the protection plan: types of protections and adjustments, coupling/decoupling logic, load shedding/restoration,
- the characteristics of motor torques and driven machine load torques (see appendix 1).

■ Process operation.

In the case of backpressure turbo-generators, process fluctuations cause variations in steam consumption and thus variations in the mechanical power supplied by the turbine. These fluctuations can generate unstable operating states of the electrical network due to the resulting power fluctuations and oscillations. Fluctuating loads, such as resistance furnaces regulated by a.c. voltage controllers, by their very nature cause power variations.

Piston compressors have a load torque comparable in absolute value to the one supplied by diesel motors. The resulting speed oscillations have a high probability of entering into resonance with a natural frequency of the regulation system and of causing stability losses. This phenomenon is likely whenever the load supplied by the network varies rapidly, for example in tack welding workshops.

Effects of instability

■ On rotating machines.

During transients, the power exchanged between machines and between machines and the network generate sudden variations in torque. The resulting mechanical stresses may give rise to mechanical failures (shaft breaking).

The frequency and voltage of generators stressed beyond their capacity drop, and their voltage and speed regulations may enter into resonance with a disturbance and amplify the instability effects.

Motors subjected to frequency oscillations and voltage drops slow down. When the disturbances have been eliminated, the high current absorbed and marked voltage drops can make reacceleration a problem: some motors crawl or even stall accompanied by abnormal temperature rises, and the network finds it harder to return to stable operation except in the case of rapid load shedding of some large units.

- On the network.

The power oscillations responsible for very high currents in the connections and transformers cause temperature rises which seriously affect equipment withstand.

Voltage drops resulting from the high currents, cause malfunctioning of certain sensitive devices (e.g. contactors, electronic equipment...). Disconnection of one or more generators destroys the consumption/production balance and may cause total collapse of the network.

Mastering instability

A number of measures can be taken to prevent the instability limit from being crossed: when these measures are taken at generator, network or load level, they either prevent instability or help fight against it effectively right from the start.

- At generator level:

The use of generator sets with very high mechanical inertia reduces the effect of load variations.

The adjustment parameters of the various regulations give response speed choices well suited to the disturbances considered.

Choice of generator operating point is important: power margin available on request, synchronising power potential.

- At network level.

- All measures tending to decrease impedances of tie lines increase the chances of returning to a stable state after an incident,

- redundancy of sources and the possibility of shedding non-priority loads, minimises the duration and depth of voltage sags. Load shedding/restoration by power step prevents major disturbances.

- Rapid, selective elimination of the short-circuited part of the network limits harmful consequences for the network (rapid-action, limiting circuit-breakers).

- The protection plan must take account of the various instability scenarios (choice and adjustment of protection devices, use of logic discrimination instead of time discrimination).

- Tripping by separate phase in order to eliminate single-phase faults in transmission networks, and use of shunt circuit-breakers for MV distribution networks, have beneficial effects on factory network stability.

- At load level.

- Use of « starters » to attenuate the motor energising current,

- implementation of undervoltage and directional protection devices and transit monitoring of powers for large motors,

- monitoring loads with cyclic or intermittent operation.

3.2 Stability studies

Positioning the problem

We remind you that the dynamic stability of a network is the capacity of this network to resume normal operation after a sudden disturbance. A stability study thus consists of analysing the electrical and mechanical behaviour of machines from the time when the disturbance appears to the time when, the disturbance having been eliminated, the network returns or fails to return to normal operating conditions. The problem is a three-fold one:

- Electrical: involving the standard network equations (Kirchoff's laws) where the machines are represented by Park's equations enabling their transient states to be studied.

- Dynamic of the variations around a state of equilibrium involving the speed and excitation regulation transfer functions.

- Mechanical as we need to know whether or not machine speed is maintained; the mechanical equations of each machine

$J \frac{d\omega}{dt} = C_m - C_r$ take account of the moment of inertia J and the characteristics of load and motor torque.

Calculation methods used

- Analytical method.

In simple network cases, i.e. networks containing only one machine (possibly two) and passive loads, the analytical description of machine parameter evolution if a fault occurs is feasible. This analysis is possible in cases where speed can be considered constant. The machine equations describe their behaviour in sufficient detail even if some parameters are overlooked.

The various methods of analysis (Behn-Eschengurg, Potier's diagram, Blondel's diagram) enable knowledge of the efficiency, excitation current and voltage drops of generators and motors. Park's transformation applied to machines enables both steady and transient states to be analysed.

■ Digital simulation.

This method is the one universally used today. A computer digitally solves the equation systems describing network behaviour. The increasing power of microcomputers now enables large networks to be simulated in reasonable times and fine analyses of the behaviour of machines and network components to be considered. As all loads and generators contribute to operation of the whole and interact with one another, the problem is a large-scale one and if we are to remain within a range compatible with microcomputer capacity, data must be simplified so as to represent only a few dozen machines:

- by grouping passive loads,
- by grouping motors as « equivalent motors » with identical behaviour,
- by grouping generators in the same way,
- by comparing a very powerful source with respect to the powers studied, with a perfect source in series with an impedance.

These calculation preliminaries are obviously vital as they define the assumptions which must be reasonably complex and representative of reality.

The resolution method chosen is a stepwise one taking account of:

- slowly varying quantities: motor torque, relative rotor speed, inductor winding flux, excitation voltage,
- rapidly varying quantities: currents and voltages in the various network branches and the various machine circuits, voltage at the machine terminals and power delivered.

This method is implemented by a software designed to treat all types of industrial networks, such as for example the MG-STAB calculation code developed by Schneider.

Developing a study

A stability study follows a certain logic and is broken down into a number of steps described briefly below:

■ The calculation preliminaries.

As result accuracy is directly linked to the exactitude of network data, the study begins by collecting these data and thus looks for the exact numerical values of the network component characteristics.

Modelling then consists of quantitatively describing the physical laws governing operation and interconnection of network components in the form of a data file.

Calculation of the initial state of load flows is determined by the computer whose specific stability programme processes the data file: voltages at nodes, currents and powers in branches, sources and loads, machine operating points.

■ The simulations.

Network topology and components vary from one study to another. Types of disturbances are numerous and the point of application variable.

In the light of the diagram studied, the specialist will select the disturbances and their application point according to how critical the problem is.

The points considered are normally undervoltage on the electricity board's network, short-circuits (medium voltage, sources), partial supply losses (lines, transformers, generators), starting of large motors and effects on electrical energy of important process phenomena.

Calculations of dynamic state in time, allowing for the disturbances considered, reproduce the expected real reactions of the network and the actions to be taken. The various scenarios are played through in order to treat all the chosen cases and sensitivity to parameters.

■ The results.

Results are given mainly by curves changing in time: voltages on the various busbars, currents in feeders, power flows, machine data (speed, electrical and mechanical torque, excitation), regulation of excitations and mechanical drive devices.

In short the results concern operation of the electrical system in disturbed operating conditions and enable:

- verification of stability,
- knowledge of potential backup capacity on a fault,
- confirmation of the protection plan,
- adjustment of the regulations.

3.3 Study example

The case described below is taken from a real study of a standard heavy industry industrial network. The aim is to study the impact of a short-circuit at the secondary of a 63/20 kV transformer (see **fig. 13**).

Description of the network

The network contains (see **fig. 14**):

- A 63 kV EDF source delivering on the 20 kV busbar of the factory through 63/20 kV transformers.
- An autonomous source made up of two couplable generators delivering on the 20 kV through 3.2/20 kV transformers.
- Asynchronous motors supplied in 5.5 kV through 20/5.5 kV transformers connected on the 20 kV network, on priority or non-priority busbars: some of these motors are equivalent machines.
- An equivalent passive load representing all the other factory loads on the priority busbar.

The protection devices considered in this example are overcurrent, directional ones, applied to the network transformers.

Objective of the study

- Study assumption:

A full three-phase short-circuit occurs on the secondary of one of the two EDF 63/20 kV supply transformers (see **fig. 13**).

- Undesirable event:

The fault must not cause the loss of the 5.5 MW motors.

- Question to be solved:

What is the maximum acceptable fault elimination time if dynamic instability is to be avoided?

The qualitative description of phenomena, for the scenario considered, is as follows:

- When the fault occurs, voltage at the short-circuit point and on the entire 20 kV common busbar is zero (negligible coupled impedances). The power supplied by the generator sets moves from the initial value to a very low value due to losses in the step-up transformers: load shedding decrease of active power results in acceleration of the generators which continue to be driven by the turbines whose mechanical regulations do not immediately react. At the same time the voltage regulation will raise excitation current to its maximum value to try to compensate the undervoltage. The motors deliver in the short-circuit in the first phase of the transient state until the flux dies out. Then absence of motor torque, due to very low voltage, causes a deceleration.

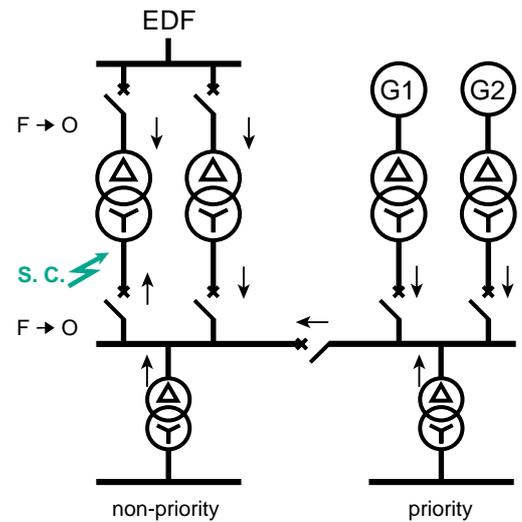


fig. 13: studied configuration.

The electricity board's network supplies a current corresponding to its short-circuit power in series with the parallel-connected transformers.

- The overcurrent directional protection devices will eliminate the only faulty transformer.
- On elimination of the fault, voltage is restored at the 20 kV busbar. Its value depends on the combined action of the EDF network, the maximum overexcitation generators and the load current inrush. The generators are no longer either in phase with one another or with the network (in fact each source has evolved separately from the others as voltage was virtually zero) and their speeds are different. The power they supply is low as turbine energy supply has been reduced by the regulators and they will slow down. The motors have slowed down, the rotor field is shifted with respect to the stator field produced by the network, and their speeds are different. The inrush current is of the order of magnitude of the starting current, a fact which causes serious voltage drops in the connections as all motors try to reaccelerate at the same time.
- Oscillating energy exchanges then take place between the various machines via the network connections and transformers. If the generator speed deviations, which are at the origin of these transient phenomena, decrease, normal operating conditions are resumed. Otherwise the synchronous machines fail to recover their synchronism and fall out of step. The asynchronous motors stall or crawl.

The behaviour study for this network thus requires complex calculations to ensure return to a stable operating state and knowledge of variations in electrical and mechanical quantities.

Quantitative study

The simulation takes place as follows: once the steady state has been calculated for 0.1 second (thus ensuring good model behaviour), the short-circuit is simulated at the secondary of the 60/20 kV transformer, then eliminated by simultaneously opening the upstream and downstream circuit-breakers. The calculation is

then continued for 5 seconds, which is sufficient to analyse network lifetime. Two assumptions are made concerning protection device tripping time: 300 and 350 ms, values close to the acceptable target limit.

NB: to simplify the example, only the upstream and downstream protection devices of the two EDF incoming transformers are considered.

We shall now look at the simulation results for one of the 12.5 MVA generators (the generators are identical), followed by the behaviour of one of the 5.5 MVA motors.

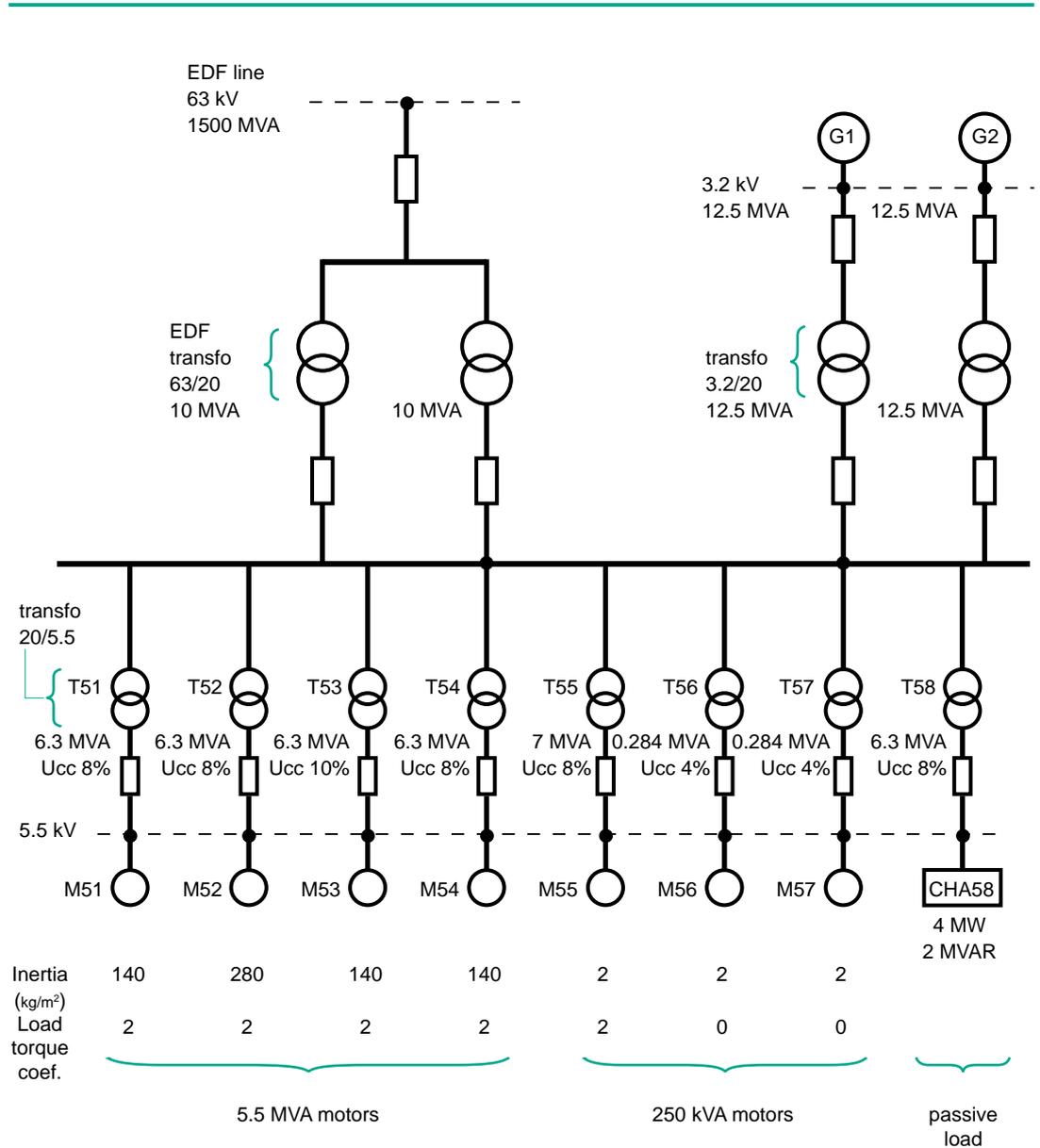


fig. 14: diagram of the studied installation.

■ Generator.

□ Examination of **active power** (see **fig. 15**)

As soon as the fault appears, the active power supplied by the generator decreases markedly and continues to decrease throughout the duration of the fault.

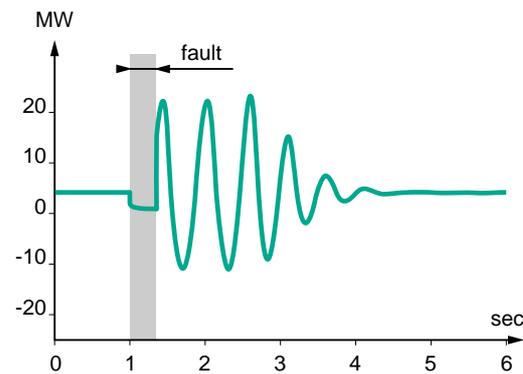
Once the fault has been eliminated, an active power oscillation occurs which is the result of the exchanges between this generator, the other generator and the EDF source. This power exchange corresponds to the power required to

restore synchronism between generator and network voltage. If the protection devices trip within 300 ms (the fault is removed 40 ms later), the power oscillations quickly decrease and settle at the initial value. In the second case, however, the oscillations continue without showing any sign of decreasing, and the generator is unable to resynchronise.

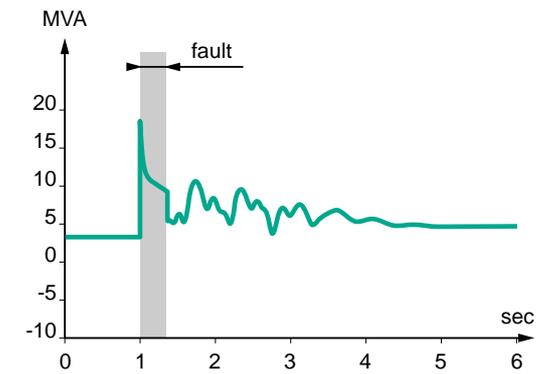
□ Examination of **reactive power** (see **fig. 16**).

When the fault appears, the reactive power increases markedly and is maintained at a high

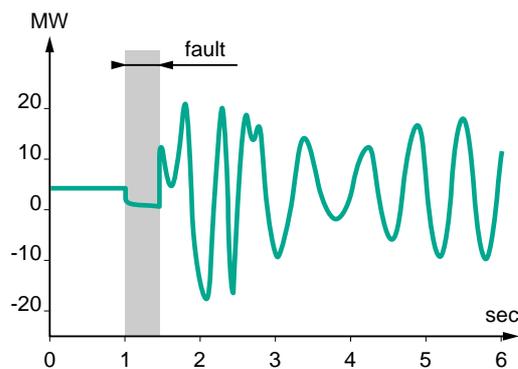
a - Tripping of protection devices in 300 ms



a - Tripping of protection devices in 300 ms



b - Tripping of protection devices in 350 ms



b - Tripping of protection devices in 350 ms

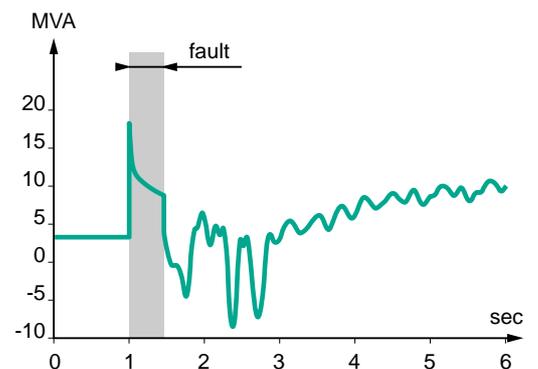


fig. 15: variations in active power of one of the 12.5 MVA generators.

fig. 16: evolution of reactive power of one of the 12.5 MVA generators.

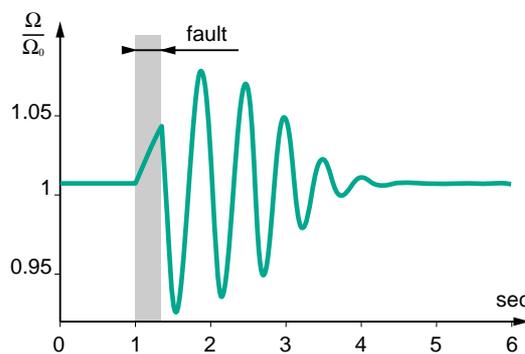
value throughout the duration of the fault. The reactive power which had settled at roughly 2.7 times the value before the fault, continues to increase after elimination of the fault due to the return to a value close to normal voltage value. The reactive power peak corresponds to the magnetisation needs of the network loads.

□ Examination of **speed** (see **fig. 17**). Speed increases when a short-circuit occurs as a consequence of the power load shedding observed (low U!).

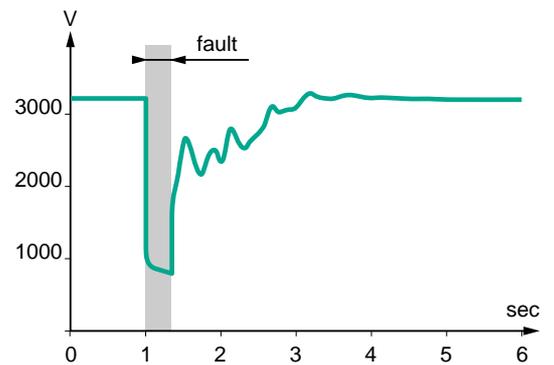
Elimination of the fault causes deceleration of the generator, and its speed begins to oscillate. If the protection devices trip only after 350 ms (see **fig. 17b**), the generator is unable to resume a stable operating state.

□ Examination of **voltage** (see **fig. 18**). If the protection devices trip after 300 ms (see **fig. 18a**), voltage is quickly restored to rated value after elimination of the fault. However, voltage is not restored and even tends to drop if the protection devices trip only after 350 ms (see **fig. 18b**).

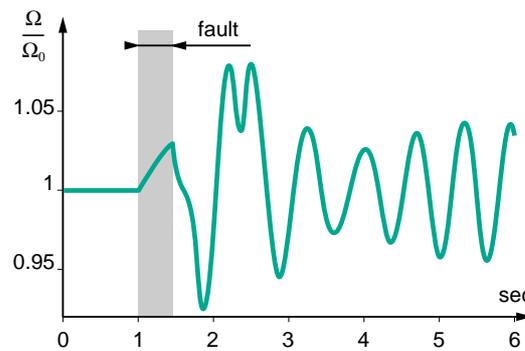
a - Tripping of protection devices in 300 ms



a - Tripping of protection devices in 300 ms



b - Tripping of protection devices in 350 ms



b - Tripping of protection devices in 350 ms

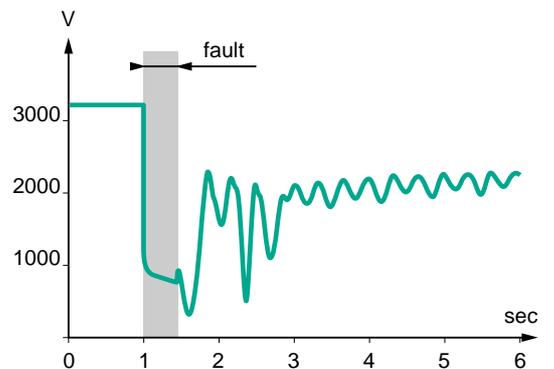


fig. 17: evolution of speed of one of the 12.5 MVA generators.

fig. 18: evolution of voltage at the terminals of one of the generators.

□ Evolution of **current** (see **fig. 19**).

In the same manner as voltage, if the protection devices trip after 300 ms, current returns to the initial value (see **fig. 19a**). However it remains at a high average value if the devices trip only after 350 ms (see **fig. 19b**).

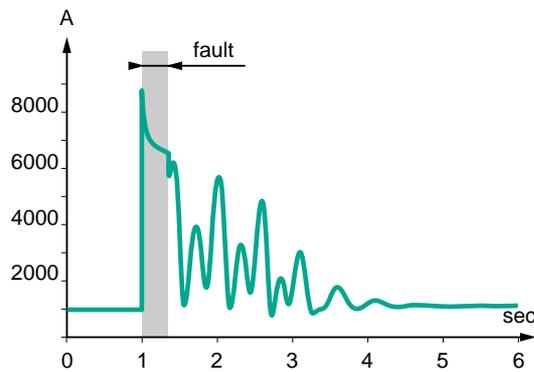
The generator protection devices must disconnect the generator in the event of tripping

after 350 ms, which does not allow correct operation of the installation.

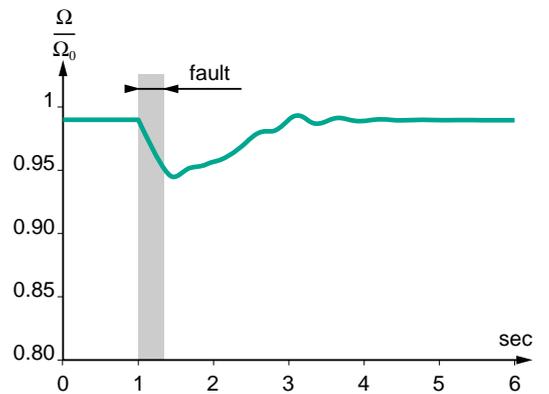
■ Behaviour of a representative motor (see **fig. 20**).

Behaviour of motors during two calculations (tripping of protection devices after 300 ms or 350 ms) is also representative of the instability observed when tripping time is too long. When this time is 350 ms, the speed of the motor

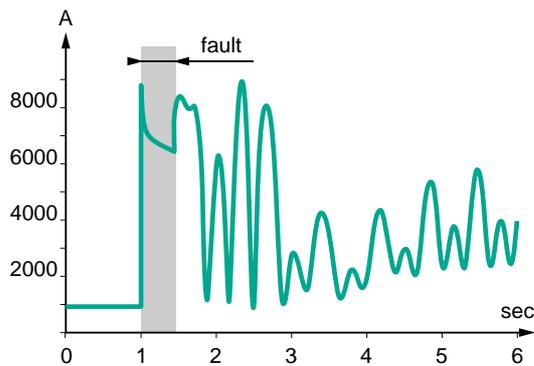
a - Tripping of protection devices in 300 ms



a - Tripping of protection devices in 300 ms



b - Tripping of protection devices in 350 ms



b - Tripping of protection devices in 350 ms

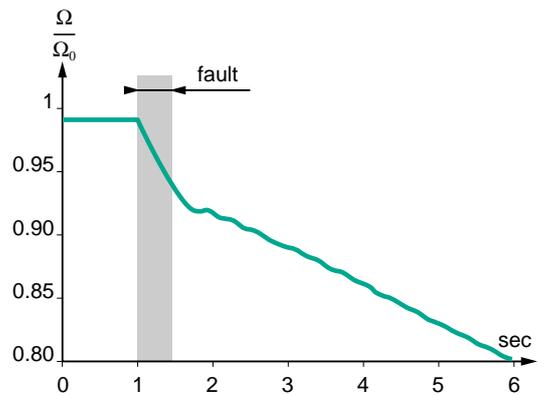


fig. 19: evolution of the current delivered by one of the generators.

fig. 20: evolution of motor speed.

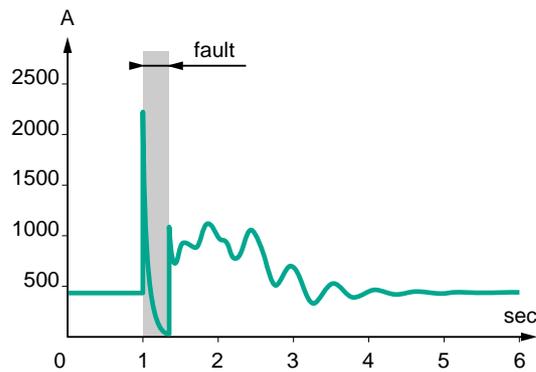
studied continues to decrease despite elimination of the fault (see **fig. 20b**), and the absorbed current remains at an average value roughly equal to $2 I_n$ of the motor (see **fig. 21b**). This operating situation is critical for the motor (temperature rise of windings) and can be dangerous for the driven machine. The protection devices must absolutely cause motor shutdown.

Conclusions of the study

The study of the impact of a short-circuit at the secondary of an EDF transformer in the network considered shows that:

- a 350 ms tripping time to put the transformer out of operation is not acceptable,
- 300 ms is the maximum limit,
- 250 ms allows a safety margin.

a - Tripping of protection devices in 300 ms



b - Tripping of protection devices in 350 ms

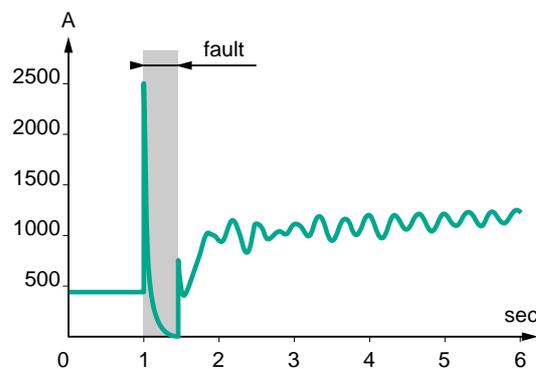


fig. 21: evolution of the current absorbed by one of the motors.

4. Conclusions

A network is a set of interconnected electrical energy production and consumption devices.

The electrical state of a network is the result of all the interactions of its various components. Changes to this state, inherent in network life (process operation, electrical incidents) naturally cause the network to move to a new state which may or may not be stable.

In the latter case (instability in transient state), loss of energy, at least partial and sometimes even total (resulting in network collapse) occurs. For industrial firms this can result in extremely costly production losses, destruction of electrical and process equipment, not to mention risks for operating staff.

This Cahier Technique highlights the advantages of dynamic stability studies whose purpose is to predict the behaviour of electrical networks. Solutions can thus be recommended to avoid instability states, thereby optimising availability of electrical energy.

These studies have their use both in the design of new networks and upgrading existing networks. In many cases they are necessary for the establishment of the protection plan and are interactive with implementation of modern network monitoring and control systems.

Nowadays dynamic stability studies are mainly conducted on high performance microcomputers by means of specialised softwares some of which are available on the market. Use of such software, if it is to be effective, is however reserved for experienced specialists.

These studies take on tremendous proportions in the case of complex, large-sized networks where there are very many possibilities to examine. However they can be used to equal advantage on precise cases or simple installations.

The development of new contracts proposed by electricity boards and cogeneration (private production) points towards many potential network studies.

Appendix 1: starting of asynchronous cage motors

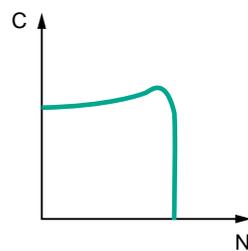
Motor torque must be adapted to the load torque of the load, from shutdown right through to rated speed.

For example, the association of a motor complying with curve 2 and of a load complying with curve B, is correct.

Some configurations must be banned. The association 2-A or 2-D requires considerable motor oversizing, and 1-A or 1-D is to be preferred.

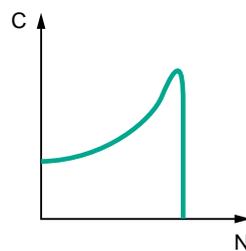
Motor torque shapes

Type 1



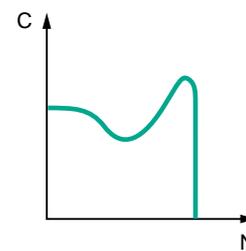
Curve almost flat between C_d and C_{maxi}

Type 2



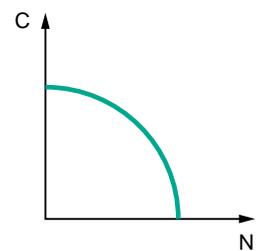
Curve increasing between C_d and C_{maxi}

Type 3



Curve with sag between C_d and C_{maxi}

Type 4



Curve decreasing $C_d = C_{maxi}$

Types of rotor:

simple cage with deep slots and fine bars
simple cage with trapezoidal, L-shaped or T-shaped slot

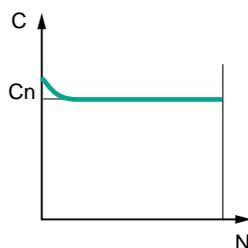
simple cage

simple cage with trapezoidal, L-shaped or T-shaped slots.
double cage

rotor with high slipping

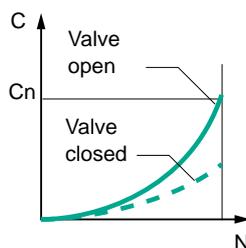
Load moment shapes

Type A constant



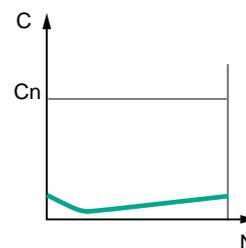
piston compressors, lifting and handling machines, conveyor belts, grinding mills

Type B parabolic



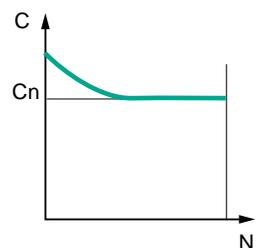
centrifugal compressors
centrifugal pumps
axial-flow pumps
propeller pumps
fans, turbines

Type C negligible



generating machines of converter sets

Type D with high break-away



grinding mills, crushers (after adjustment)

Appendix 2: bibliography

Standards

- CENELEC EN 50160: characteristics of the voltage supplied by public distribution networks.

Cahiers Techniques

- Analyse des réseaux triphasés en régime perturbé à l'aide des composantes symétriques, Cahier Technique no 18, December 1990 - B. DE METZ NOBLAT
- MV public networks throughout the world, Cahier Technique no 155, february 1992 - CH. PURET
- Control, monitoring and protection of HV motors, Cahier Technique no 165, May 1995 - J.Y. BLANC
- Automatic transferring of power supplies in HV and LV networks, Cahier Technique no 161, March 1996 - G. THOMASSET
- HV industrial network design, Cahier Technique no 169, October 1994 - G. THOMASSET
- Protection of industrial and tertiary MV networks, Cahier Technique no 174, June 1996 - A. SASTRÉ

Miscellaneous documents

- Guide de l'ingénierie électrique des réseaux d'usines, G. SOLIGNAC, Electra, Lavoisier Tec et Doc.
- Electrotechnique Industrielle, G. SEGUIER and F. NOTELET, Technique et documentation.