A never-finished report: Power system loads and stability

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Chapter 1

Power Systems and Control

Electrical power systems are connected collections of many and various instances of components from several basic groups — e.g. generators and transformers — and are justifiably claimed as the largest and most complex systems that ever have been made. Advances in computers, telecommunications and control techniques keep extending the possible amount and precision of measurement, control, and off-line and real-time planning. Changes in system components, especially in the type and location of generating plant, provide new potentials for control action but also for problematic interaction.

Use of these advanced methods and new resources to allow higher utilisation of transmission and distribution systems has been encouraged by recent competitive cost-cutting drives consequent to the deregulation that has happened to the power industry in many countries over the past decade, also by increasing pressures against the building of new lines and power stations.

The transfer capacity of power systems is increasingly limited by constraints of stability rather than thermal limits, within which the critical constraint is increasingly that of voltage stability. The shift in critical security limit is due partly to improvements in other constraints such as angle-stability and thermal limits, partly to operational changes such as greater long-distance transfers, and potentially also to changes in load and generation types.

The common 'Independent System Operator' (ISO) model in deregulated systems is one where the generation and load are connected through an independently managed network, often with decisions on power transfers being made directly between the generator and user according to charges and limits set by the system operator. An ISO has the responsibility of maintaining system frequency and voltages and ensuring that stability and thermal limits are not exceeded, yet must ensure that system capacity is not wasted. Separated from the traditional control over generating plants, many basic services such as response of generators' active and reactive powers to system frequency and voltage are ones that must be specifically bought by the ISO, perhaps on a market similar to the one for active power.

Control of power systems, apart from the slowest, highest levels of control, is still decentralised: the control loops for voltage and speed control of generators and for network voltage control by reactive power devices and controllable transformers are local, with at most perhaps a reference signal being set from a central controller. The dynamic behaviour of the interconnected system composed of these local loops is therefore dependent on the local controllers as well as on the controlled plant. The problem of designing the controllers for good performance of the local system and of the interconnected system is complicated by the variability of system parameters and operating point. Use of modern communications for control of distributed resources, such as small generators and compensation equipment, may in some cases be beneficial: coordination may allow use of resources to be closer to optimal, over a range of steady and emergency conditions.

1.1 Power System Dynamics

1.1.1 Overview

The components of a power system are able together to participate in a huge number of dynamic modes. It can be helpful to reduce the problem by taking advantage of a limited time-scale of response, weakly connected locations or weakly connected types of variable or component, to limit the number of modes considered for a study.

The type of dominant unstable control value may be used to classify system instabilities into those concerning mainly frequency, angle or voltage. Modes in the interconnected system often involve certain types of components and variables much more than others, allowing physical classification of the mode to be made. Large disturbances of realistic power systems tend, however, to excite significantly modes of more than one of these classes: the distinctions between, particularly, short-term angle and voltage, and long-term voltage and frequency dynamics, are therefore often not clear in practice.

Another system of classification of dynamics is by time-scale; time constants in stability analyses range from tens of milliseconds to many minutes, and analyses are commonly concerned with a limited range. Traditional angle-stability studies deal with control frequencies of tenths of Hertz to a few Hertz, assuming changes in turbine power and other slower dynamics to be negligible or modelled only by that plant's shortest time-constant. Frequency control studies often deal with time-constants from seconds up to hours for thermal turbines and boiler and reactor plant, assuming all faster dynamics to be static. Load-flow is a static analysis, assuming *all* of the states of all time-scales to have reached equilibrium.

1.1.2 Classification of Dynamics

Frequency

Frequency control is the matter of balancing mechanical input powers to generators with the system electrical load, to maintain system frequency. Dynamic characteristics of all prime-mover plant and of the governors (frequency controllers) of turbines are important, along with the responses of loads to changes in frequency. The components involved in frequency control have time-constants ranging from the practically instantaneous responses of devices such as discharge lamps with near-saturated ballasts, through the order of seconds for motors and turbine governors, to many minutes for thermal turbines and boilers. Unless angle instability occurs, changes in frequency exist over the entire interconnected system, so pure frequency stability problems are the most widespread of all.

A lot of work has been done on frequency control, particularly on load-distribution between generators, and on the effects of the automatic coordinated control of active power generation (known as Automatic Generation Control, AGC) popular particularly in the U.S. However, a lot more research has been done on transient and small-signal angle stability, whose respective possibilities of occurring very quickly or during otherwise normal operation make them particularly important to operators.

Angle

Angle stability requires that the phases of interconnected synchronous machines neither monotonically diverge, through a lack of sycnhronising torque, nor periodically vary, except immediately after a disturbane,through a lack of damping torque. The subject of angle stability has been researched ever since power systems began to have multiple alternators operating in synchronism, and it is by far the most heavily researched of the three categories mentioned above. There are now many design methods available for stability analysis, controller design and device placement, etc., and many practical methods employed to slacken stability boundaries, e.g. high-speed excitation systems, supplementary control signals, single-pole switching, and load-dumping resistors.

Components involved in oscillatory angle modes have time-constants of hundredes of milliseconds to tens of seconds; the natural frequencies of generator inertias and the interconnecting reactances give this constraint to the oscillation period. Monotonic angle modes may be affected within any time-scale, from line-loss to gradual decline of voltage; monotonic angle modes are often linked with voltage modes.

Voltage

Voltage instabilities share with angle instabilities the possibility of existence as localised or system-wide phenomena. They can occupy the whole range of time constants of angle and frequency instabilities, from milliseconds to minutes or hours. All components in a power system are of importance, as all contribute to the dynamic relation of system voltages and system power injections. Many components are non-linear, often by limits (SVC, generator) or by discrete steps (LTC).

The direct involvement of network and load components in voltage instability makes invalid many simplifying assumptions used in conventional angle stability studies. For thorough studies, usually undertaken to verify simplified methods, it is necessary to use non-linear simulation over a wide range of timescales and with greater depth of system modelling than is often used in frequency and angle stability studies; the distribution system and loads are more important when multi-timescale effects of voltage changes are important.

Voltage instabilities in typical transmission systems usually stem from large transfers of reactive power; the predominantly series-inductive and shunt-capacitive nature of transmission lines causes high sensitivity of voltage drop and reactive line-loss to reactive power transfer. An alteration of system flows due to generator or line loss is a typical situation in which increased reactive power consumption may cause reduced voltages and exceeding of line and generator limits.

It was quite late in the history of power systems that voltage instabilities were recognised as being of practical importance. An early reference to these phenomena is a 1968 paper entitled "Voltage Stability of Radial Power Links", [17]; it earliest citation is a Russian work on 'load stability' published in 1961. Reference [17] treats voltage instability as the pure case of load instability when fed from an infinite source. It uses static analysis of viable load-flow solutions, and mentions many important aspects such as the modelling of voltage-dependent loads, the problem of induction motors consuming constant or even increased active power when at reduced voltage, the importance of motor mechanical load ccharacteristic, the effects of on-load tap-changing transformers on maximum power transfer and critical voltage, and the importance of reactive power provision at voltage-weak points. As an indication of the lower significance then of voltage-instability problems, the conclusion states that

> In a power network under normal operating conditions it is extremely unlikely that operation near the voltage stability limit would take place.

This is tempered by the next statement that emergency conditions such as a lost line *could* need investigation. Modern systems and conditions can, however, be close to voltage stability limits even without line-loss.

A bibliography published in 1998 [2] follows the development of voltage-stability understanding and assessment from 1968 to 1998; the interest grows strongly in the later part of this period.

Chapter 2

System Components

2.1 Physical Loads

Loads have a huge range of characteristics, spread from negative to highly positive dependence of active and reactive power on voltage and frequency, and with timescales from milliseconds to hours. Here, an overview of physical loads is given, grouped by the output energy form. Voltage characteristics and other stability-related properties are described, in their relevance to the freuancy, angle and voltage classifications of instability already explained.

2.1.1 Motor Loads

Motors constitute over half of the consumption in developed power systems, and much greater proportions in some industrial areas. Within the few broad categories for stability purposes there are important variations due to motor size and mechanical load characteristic. Motors and mechanical loads will be treated separately here, and types that are neither large themselves nor connected in large numbers are ignored as unimportant to stability studies — an example of such a type is the small series-wound universal motor common in hand-operated appliances.

Induction Motors

Induction motors are very widely used, often directly connected to the line. Starting requires large currents with a large reactive component, so situations of supply restoration to large groups of motors at zero or low speed may fail to start the motors even when the feeding bus is close to nominal voltage. Undervoltage drop-out relays disconnect large and small motors at around 70 and 60% voltage respectively, but some popular induction-motor applications such as small-scale refrigeration rely only on thermal cut-outs with a delay of several seconds.

Reactive power is always consumed in an induction motor, as the airgap is magnetised from the supply. As motors are designed for operation near the saturated region of the iron at rated voltage and frequency, there is a strong sensitivity of reactive power demand to changes in voltage and frequency around the rated values. Reactive losses in the leakage reactance increase with the much increased currents that are drawn when operating at reduced voltage with insensitive mechanical loads.

Active power consumed is the sum of the mechanical power produced and the electrical losses; the proportion of electrical losses decreases with increasing motor size, and is small (less than 10%) in all but the lowest power and quality motors. Common parameters of an induction machine lead to a torque/speed curve such as fig.2.1, where the very steep gradient in the normal operating region shows little change in mechanical speed over a wide range of loadings. Reduced voltage shrinks the curve, but mechanical speed still varies very little with loading until the peak of the curve is reached, after which point the motor's speed falls (a stall) until an equilibrium is found at a lower or even zero speed, depending on load characteristic.

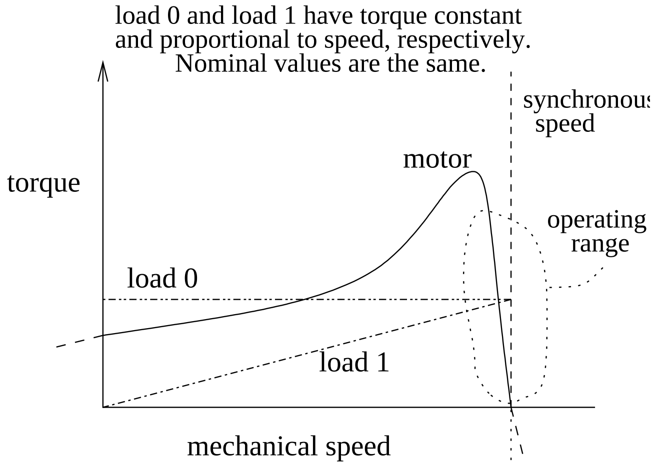

Figure 2.1: Example of an induction motor torque/speed curve at rated voltage

Therefore, until stalling occurs, mechanical load speed varies only a small amount with changes in voltage; mechanical loads with constant torque behaviour will require nearly constant mechanical power while not stalled, and mechanical loads with a quadratic dependence of torque on speed will require reduced mechanical power but possibly still not to such an extent as the voltage reduction. As maintaining mechanical output torque in conditions of reduced voltage requires higher currents in a motor sensibly designed for operation at nominal conditions, the electrical losses are increased, and the total active power input may decrease only little, or even increase. The time-constant for this load recovery depends on the motor's and mechanical load's inertia relative to the motor's power, and ranges from fractions of seconds to many seconds; this time is important for the dynamic response both of active and reactive power to voltage changes.

Stalling results in low speed and consequntly high current draw, mainly reactive. Restoration to the norml running condition requires a considerable increase in voltage, and with many stalled motors it may be impossible for all to restart simultaneously even with nominal voltage applied at the transmission bus; it is important that stalled motors are are rapidly disconnected from the supply. Motor protection ranges from small motors' fuses, thermal cut-outs and basic undervoltage drop-outs, to sensitive relay protection of large motors. The effect of a large proportion of small motors with aggressive (constant torque) loads and slow stall-protection has been important in several experiences of voltage instability. The slow protection of small air-conditioning units, and the resulting delay in transmission voltage recovery, are discussed in [18].

Electromagnetic time-constants, an important one being that of the rotor flux, increase with motor size: small induction motors may have rotor time-constants so short that their relevant dynamics are simply mechanical load acceleration, but large induction motors require electromagnetic dynamics to be modelled also.

Synchronous Motors

Synchronous machines are sometimes used as motors in high power ratings (several MW), at which the added complexity over an induction machine is outweighed by the virtues of higher efficiency, controllable reactive power, and the sychronous nature itself that guarantees a speed fixed to within 1% of nominal under normal system conditions.

Synchronism makes the relation between voltage and mechanical loads less strong than with an induction motor: except during transient changes in speed, or when synchronism is lost, the load torque and consqeuently the mechanical power are determined entirely by the system frequency. Active power input in these conditions therefore varies with voltage only because of changes in losses.

Steady-state loss of synchronism will occur when the voltage becomes too low to maintain the (frequency dependent) load torque. Transient loss of synchronism occurs if a disturbance such as a cleared short-circuit momentarily decelerates the rotor beyond the angle that would allow the restored supply voltage to support the load torque. The load's torque/speed characteristic is important during the angular swings of a transient disturbance; it also determines how quickly and to what speed a loss of synchronism will tend, but this condition should result in disconnection from the supply anyway.

When out of synchronism the only resultant torque generated is by asynchronous effects such as induction in rotor damper windings and iron, so a stall will often be to very low speed and if prolonged may easily damage damper windings that were not designed to cope with such high energies as induction motors' rotor windings. Synchronous machines are therefore given protection that will isolate them when synchronism is lost, making them less of a problem than typical aggregations of induction machines when the supply reaches very low voltages.

Reactive power is controlled as with a synchronous generator; variation of the excitation can be used to adjust reactive power, constrained by field and armature heating limits and minimum synchronising torque. The objective of synchronous motor reactive power control is usually to control the power factor of the machine and perhaps of parallel induction machines. The initial period after a voltage reduction will have the familiar 'fixed voltage behind impedance' characteristic of increased reactive power generation, but the action of the control will then determine a possibly very different steady state response. Small machines may have fixed field current or permanent magnets, giving a transient and steady response of fixed voltage behind impedance unless thermal protection operates.

Inverter-driven motors

Induction and synchronous motors, and other broad type such as reluctance motors, are increasingly commonly driven by inverters. Apart from the thyristor converters sometimes used for large synchronous machines, modern inverter drives use Voltage Source Converters (VSC) for the inverter stage. How the supply voltage affects active and reactive power consumption depends on the type of input rectifier used, the control strategy, and the design limits of supply voltage that still allow full output voltage on the d.c. link — typically 90%. As with synchronous motor field control, electronic drives are currently designed for low initial cost, losses and reactive power consumption, rather than for the provision of reactive power to help the network at times of low voltage.

Mechanical Loads

A mechanical load's inertia and torque/speed characteristic dictate strongly the dynamic and steady electrical behaviour of the motor.

The range of torque/speed characteristic runs from the pliant T , $\alpha\,\omega^2$ of a centrifugal fan or pump, through the direct proportionality and speed-independence of, for example, a positive pump supplying a pipe resistance or constant-pressure reservoir, down to loads that have increased torque at lower speed. The latter group has often a non-smooth torque, e.g. a rock-crusher at very low speed has torque varied by the individual lumps passing into it, which it must be able to crush with motor torque rather than by the sharp force imparted by the inertia of motor and mechanism at higher speed. Stiction, an increased friction at and around standstill, can also add a component with increased torque at lower speed to a load.

Since induction and synchronous machines have a speed that is largely or entirely set by supply frequency, the torque/speed characteristic is essential for frequency-response studies. Voltage stability in time-scales greater than those of the inertia and rotor-flux,

The frequency dependence is also important for small-signal angle stability of synchronous motors and of induction motors that have electromagnetic time-constants of as much as the oscillation time. Voltage dependence is important if the inertia is low enough that the speed can change significantly in the oscillation time. For transient angle stability, inertias and

Inertia and in large machines rotor-flux decay are important in transient angle and voltage stability; the combination of these determines damping and stalling. The torque/speed characteristic is important mainly for voltage stability of

2.1.2 Lighting

With domestic lighting using primarily very inefficient incandescent lamps that have a higher duty than most other domestic equipment, and with the great use of discharge lighting in commerce, industry and street-lighting, lighting loads can be a significant part of system load. The obvious point that most lighting is on during the evening and night, when most other other load device types are less used, enhances importance of lighting load at certain times. There are two main classes of lighting, with very different characteristics; these are treated separately here.

Incandescent Lamps

An incandescent lamp is a resistor with a high opeating temperature and a positive termperature coefficient of resistance. It therefore consumes negligible reactive power, and has no frequency dependence. Active power consumption is between constant current and constant impedance, a voltage exponent of about 1.55 [11]. Thermal dynamics are relevant to stability studies only in uncommonly large sizes of hundreds of Watts.

Discharge Lamps

High and low pressure sodium vapour discharge lamps are common for street-lighting. High pressure mercury lamps are used in similarly large applications requiring a whiter light than sodium's characteristic orange-yellow, and low pressure mercury discharge lamps with fluorescent coating are used for almost all high volume interior lighting in non-domestic buildings.

A common feature of these discharge lamps with traditional, non-electronic control gear, is a series inductor to limit the current in the arc. These ballast inductors are usually operated near saturation, and are compensated by a capacitor. Moderate changes in voltage therefore produce large changes in reactive power consumption, with a voltage exponent as high as 4. Active power consumption varies much less with voltage, being close to a constant current characteristic. Electronic control gear gives discharge lighting more of a constant power characteristic with low reactive power consumption, as long as the converter can accommodate the input voltage.

When the supply voltage falls below about 0.7 to 0.8 p.u. for a conventional ballast, the arc extinguishes. The time delay before current is drawn again, the time taken before restrike succeeds, and the restrike currents, can all vary with the type of lamp and control gear, but a few seconds without load is usual. The effect is generally desirable for voltage stability, and location-dependent for angle stability.

2.1.3 Heating

Resistive In countries with low temperatures and good hydro resources, electricity is widely used for space and water heating and for cooking. Many other countries use electricity for cooking and supplementary heating, or have schemes for night-time use of electricity to heat a storage medium for later use. In all such cases, the load is purely resistive. Cooking and non-storage heating applications also have the feature of thermostatic control, whose effect is to restore power demand to the original value after a disturbance, limited by the maximum power available when all thermostats are on.

Other Heating in industrial processes, such as induction furnaces and arc furnaces, is mainly by means other than simple resistance, and the response to voltage and frequency depends then on the process and its control and supply equipment. Arc furnaces are large loads, and have a characteristic that

2.1.4 Electronics

Power-electronic converters are use in many modern appliances, especially computers. A good quality converter capable of accepting a wide range of input voltage has the unhelpful effect to the system of consuming quite constant power even at, for example, 40% for an international supply on a 230V system. The trend to reduced cost and size by high switching frequencies and small energy storage components means that the response time of such devices is practically instantaneous for purposes of voltage stability. Older converters using simple fundamental frequency input rectifiers with a fixed d.c. voltage (e.g. battery chargers) may on the other hand be very sensitive to voltage changes, passing no current at all after a moderate voltage reduction.

2.1.5 Other Load Devices

parts of the distribution system, such as ltc transformers, lines, cables, and reactive compensation equipment have not been covered in this specifically load-device oriented discussion; they are, however, included in bus-load models.

2.2 Load Models

Modelling loads on a system requires large amounts of approximation, as the total load is composed of millions of individual loads of unknown useage-periods and dynamic and static responses. The word 'load' is used in various senses: there follows a list of some, using where they exist the suggested explicit names from the 1993 IEEE Taskforce on Load Representation for Dynamic Performance.

- **load device** an individual device
- **bus load** the aggregate effect of the system below a bus
- **system load** the total load on a system
- **generator load** electrical demand on a generator
- **mechanical load** the mechanical load connected to a motor

For a stability study of a power system, at transmission or distribution level, it is necessary to model loads as bus loads, although very large load devices such as arc-furnaces and electrolysis plants may warrant individual inclusion. The response of bus load depends upon the very important effects of LTC transformers, MSCs, SVCs and network branches as well as generators and the load devices themselves; simple addition of the responses of load devices may not yield a sufficiently accurate model.

A thorough model of a bus load on a transmission system needs to relate consumed active and reactive power to frequency and voltage, over a wide magnitude and time-scale of variation. The model will be dynamic, and parameters of time-varying demand and composition may be needed for accurate representation. When, however, the model is required to approximate only a small range of amplitudes or frequencies of variation of bus voltage and frequency, great simplifications can be made. Load-flow calculations assume steady state conditions to be reached and conditions to be close to normal, so on the assumption that network voltage-control devices have manintained voltage, and recovery loads have attained their demand values, bus load is considered to be constant power. Small signal angle stability studies have traditionally assumed that the short time-periods of oscillations and the small changes in value make constant-impedance models sufficient, although this has changed recently with operation closer to limits and with a higher proportion of rapidly controlled loads.

2.2.1 Static Load Models

Assumptions of small and quite rapid changes in voltage and frequency, and absence of electronic loads in the early days of small-signal angle stability analysis, justified the use of simple static, voltage-dependent load models of the exponential form

$$P = P_0 \left(\frac{V}{V_0} \right)^{K_{pv}} \tag{2.1}$$

where V is the present voltage, V_0 the nominal voltage, P_0 the nominal power, and K_{pv} the exponent chosen for best match with the load characteristic. The same structure is used for reactive power. The exponential relation allows constant power, current or impedance to be represented exactly, and combinations to be approximated. Some loads such as heating in timescales shorter than thermostat operation will match one of these characteristics well over a large range of voltages, while others such as discharge lamps and motors may only match over a very small range of voltages.

Inclusion of frequency effects in such models is even more limited; a purely linear relation is commonly used

$$P = P_0 \left(\frac{V}{V_0} \right)^{K_{pv}} [1 + K_{pf}(f - f_0)] \tag{2.2}$$

where the additional parts are a frequency coefficient K_{pf} and the actual and nominal frequencies, f and f_0. Table 2.2.1 gives parameters from [11], for the North American system; the differences between the industrial and residential areas are very marked.

Bus-load type	*Power Factor*	K_{pv}	K_{pf}	K_{qv}	K_{qf}
residential	0.9 – 0.99	1.0 – 1.7	2.5 – 3.1	0.7 – 1.0	−2.3 – −1.3
connercial	0.85 – 0.9	0.5 – 0.8	2.4 – 2.5	1.4 – 1.7	−1.6 – −0.9
industrial	0.85	0.1	0.6	2.6	1.6

Table 2.1: Example parameters for exponential load model

A slightly more complex model uses a quadratic function of voltage to allow a wider range of validity; the parts of the function correspond to constant Impedance, Current and Power, hence the name 'ZIP' model. Enhancements sometimes add further components with arbitrary exponents.

$$P = P_0 \left[A \left(\frac{V}{V_0} \right)^2 + B \left(\frac{V}{V_0} \right) + C \right] \tag{2.3}$$

2.3 Network Branches

The electrical network consists of overhead lines, underground cables and transformers linking connection points together. Series reactors may also be used for deliberate reduction in fault levels, and these will clearly have the stability effect of connecting machines more weakly and increasing voltage drops and reactive losses under load. Stability-related properties of the other types of branches are described below.

Transformers may be considered for purposes other than electromagnetic transients as a shunt magnetising reactance and a series impedance composed of the resistance of the winding-pair under consideration and of the leakage reactance. These values will change with saturation of the iron; the effect of saturation on magnetising reactance is strong in operation at nominal voltage, with sensitivities of 3 to 7 [12].

Autotransformers are sometimes used in the transmission system, for their saving in size as losses; they have a smaller series reactance than multi-winding transformers, due to the passage of some current directly from primary to secondary.

Overhead Lines are used for all voltages in rural environments. Exposure to atmospheric pollutants, ice, water, wildlife and particularly lightning, causes overhead lines to have frequent faults that require temporary isolation while ionised air disperses. These faults and the open-circuit time before circuit-breaker reclosure are a common type of disturbance in angle and voltage instabilities. The necessarily large spacing of air-insulated conductors at transmission voltages gives these lines a low characteristic impedance. Thermal loading is not such a constraint as with a cable, as the conductors have a consistent, predictable means of cooling and are allowed to reach quite high temperatures, e.g. 70 degrees Celsius or a line-sag related limit. Surge impedance loading is therefore typically less than maximum thermal loading for an overhead line, meaning a consumption of reactive power at high loads.

Cables are often clustered, in densely loaded urban areas. They differ from overhead lines in several ways of importance to the initiation and contribution to instabilities. Faults are far less common, but when they do occur the cable may be out of service for a long time. Characteristic impedance is far lower than that of an overhead line, necessitating shunt reactors to absorb excess reactive power at times of light load in a large cable network, and causing reduced voltage drop at rated load. Temperature must be considered more carefully than with an overhead line, as insulating materials deteriorate rapidly at elevated temperature.

2.3.1 Branch Parameters

The series reactance of all branches affects stiffness of coupling for angle stability and voltage drop and reactive power consumption under load for voltage stability. The presence of shunt capacitance increases the sensitivity of reactive power to changes in current flow, as the voltage and thus the reactive generation are reduced by higher current flows and losses. Tables 2.3.1 and 2.3.1 show examples of transmission system branch parameters. [1]

Type	*Rating (kV)*	Z_0 *(Ω)*	*SIL (MVA)*	*Capacity (MVA)*
OHL (2 cond.)	275	290	260	870
OHL (4 cond.)	275	270	280	1200
Cable	275	34	2220	786
OHL (2 cond.)	400	280	570	1895
OHL (4 cond.)	400	250	640	2533
Cable	400	34	4700	1294

Table 2.2: Example parameters of supergrid lines and cables (U.K.)

Type	*R (%)*	*X (%)*	*B (%)*
OHL (2 cond.)	0.0017	0.0185	0.6080
OHL (4 cond.)	0.0011	0.0168	0.6850
Cable	0.0009	0.0080	17.6991
Transformer	–	1.3	–

Table 2.3: Example percent (on 400kV, 100MVA) per kilometre impedances of branches (U.K.)

2.4 Protection

Disconnection of faulted or overloaded parts of a system is necessary to protect equipment and to mitigate the effects of faults on supplied power. The circuit breakers that perform the disconnection are triggered by controllers (relays) that exist in great variety, distinguished by the input variables used and any time delay element. The increased impedance due to disconnections in a network may cause instabilities of voltage or angle, but may prevent instabilities by quick removal of faults that hold voltage low. Situations such as large voltage drops and phase angles across lines, that arise in stressed conditions often close to stability margins, can provoke false operation of a protection system that has not been designed for such unusual operating conditions, or may cause intended tripping of branches after a time delay when current flows exceed thermal ratings.

Many types of protective relays are used for automation of circuit interruption: generators and transformers may have restricted earth-fault protection for their windings, transformers have additional gas-pressure operated relays, and all branches and buses have some form of overcurrent and earth-fault protection. Branch and bus protection are significant in the behaviour of a disturbed system, as they can cause disconnection of network branches in response to abnormal conditions caused by large angular swings and depressed voltages.

Impedance, Admittance, (distance – same), current, differential.

2.4.1 HVDC — direct current links

High Voltage Direct Current (HVDC) transmission is used for such reasons as:

- linking asynchronous systems (inc. different nominal frequencies)
- lower total cost for long distances
- small contribution to fault-level
- allowing long cables to be used without charging problems, e.g. undersea links
- very rapid control of active power flow, over the full range in either direction

[1]Calculated from U.K. National Grid Company's 2001 Annual Report. Per-unit bases are rated voltage and 100MVA.

[2]Using bases of 400kV, 100MVA. Only 400kV lines and cables, and 400/275 or 400/66 kV transformers are included in this table.

Conventional current source converters (CSC) using thyristor valves are still the only type economic for high ratings. CSCs consume reactive power of around a third to a half of their active power flow [16], and produce large amounts of characteristic harmonics starting at only the 11th and 13th. CSCs therefore use large filters on the a.c. side (capacitive at power frequency), and reactive compensation is often done by capacitor banks, leading to a very 'voltage-brittle' system with large responses of reactive power production to voltage. Commutation of a non-forced CSC requires a strong voltage source on the a.c. side, and in some cases where the a.c. system is weak a synchronous compensator (unloaded synchronous machine) may be used intead of shunt capacitors, to provide both the reactive power and the low impedance voltage sourc. This will be advantageous in providing a more voltage-strong system, particularly if the overload capacity and field and armature thermal limiters allow short-term boosting of reactive generation.

In cases where a link is in parallel with a.c. lines its control may still be used for damping of system oscillations and giving some control over the total transmitted power, although limits of the parallel lines may affect the extent of d.c. power variation allowed. A HVDC link between asynchronous systems allows arbitrary transfer of active power, with very rapid reversal possible.

The transient effects of HVDC connections depend on the control system and the electrical parameters of the d.c. line and capacitors and reactors. Only the short-term overload capability of the valves is of any longer time-constant than a few seconds. Other power electronic devices and generators may therefore participate in fast dynamics with HVDC links.

Voltage stability is affected by the HVDC active power transfer's effect on loading of generators and of parallel a.c. lines, and by the large reactive proportion of converter current at the a.c. buses, particularly the receiving end whose converter is constrained by a larger minimum phase-angle. The injection of large currents into a voltage-weak network to supply active power can cause problems by drawing more reactive power into the inverter from the a.c. side, depressing the a.c. voltage and so reducing the reactive contribution of the harmonic filters and shunt capacitor banks. Voltage Dependent Current Order Limits (VDCOL) are a standard way to reduce this problem by reducing the current when voltages are low. The desirability of increases in HVDC infeed depends then on the balance of the effects of increased reactive power consumption at the inverter and possibly decreased reactive power consumption in a.c. lines if the HVDC infeed reduces line flows in the a.c. system.

Recent rapid development in devices with controllable turn-off has led to voltage source converters becoming available, first for motor drives and small inverters, and now in product ranges from several companies aimed at the smaller scale power system market. The advantages of VSCs are that they usually are designed to switch considerably faster than fundamental frequency to give reduced low-order harmonics, and they can sink or source reactive power to an extent limited by the converter rating and the active power transfer – the converter can hold its terminals at a specified voltage until overloaded.

Having such converters on a system is therefore rather like having STATCOMs: there are added constraints that extra active and reactive powers are limited by the apparent power rating of the converter, and active power injections from the HVDC system must balance.

2.5 Tap-changing Transformers

2.5.1 A single unit

Variable Ratios

Power Systems world-wide have quite similar sets of voltage levels, with usually three or four voltage transformations between the highest level and small consumers. Transmission-connected generators work at around 12 to 25 kV, with generator transformers to connect them to the transmission network. Voltage control is therefore available at many points in the system by changing transformer ratios; most transformers do have different 'taps' available, to allow their ratio to be varied.

Small distribution transformers' tap settings are set manually on installation or when the system changes considerably, so that the the supplied voltage at each load is within its required limits for the expected voltage range at that point on the feeder.

In all large systems there is the scope for automated on-load changing of transformer ratios between certain levels of the system; transformers so equipped are known as on-load tap-changing transformers (abbr. LTC, ULTC, OLTC).

Tap-changing is used primarily to compensate changes in system voltage caused by changing load, but it may also have a profound effect on the higher parts of the system, in a way that depends upon the characteristics of the network and load. Maintaining load area voltages can reduce feeding system load by reducing line currents and increasing shunt-capacitor VAr generation when the loads are effectively constant power, or can increase total load if the loads are effectively constant impedance. In some extreme cases, 'tap-blocking' may be ordered, to prevent automatic changes — usually to a higher secondary voltage — from occuring.

The cheapest transformer tap-changer design usually places the tap-changers on the neutral end of a star-connected higher-voltage winding, allowing minimum potential and currents. As the variable ratio is thus on what is usually the 'input' side to the transformer, in a conventional distribution system sense, an increase of tap leads to a decrease of secondary voltage for a fixed primary voltage; the term 'tap up' is, however, normally used in the sense of increasing the secondary to primary voltage ratio rather than necessarily increasing the tap position. Taps are taken at intervals such as 1.43% (a typical value in the U.K.), and changing of taps involves an interim period in which the present and future taps are both connected to the terminal, via a reactor in the tap-changer; there is thus no interruption, less difficulty in switching the current, and the voltage changes in smaller steps.

Automatic LTC control

In its simplest form the voltage control for the tap-changer compares terminal voltage to a reference, and calls tap-changes when a band around the set-point is exceeded. Figure

2.2 shows the steady-state relation of loading and feedback voltage for a typical case where the tap-step is about 70% of the dead-band width of the control. Figure 2.3 shows the significance of the feedback voltage V_f; with pure terminal voltage regulation, V_f can be taken as the terminal voltage, but with remote voltage being controlled the terminal voltage will be offset from the feedback voltage by a current-dependent amount.

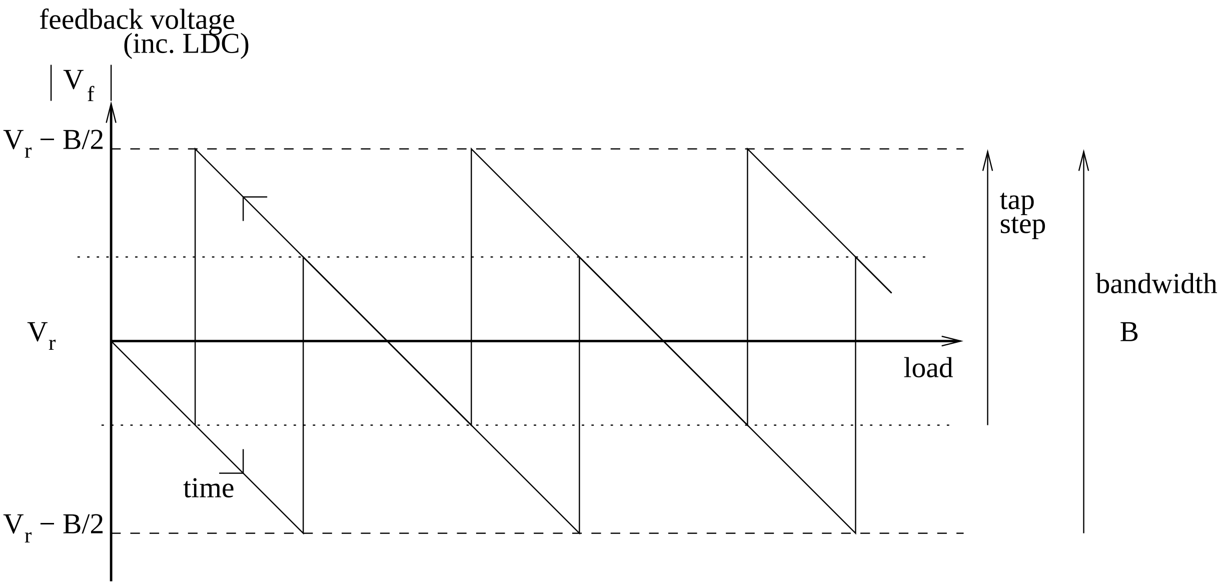

Figure 2.2: LTC load-cycle behaviour; load rising then falling

It is usual to assume balanced three-phase conditions, and so to use one phase current and one voltage as input to the control relay. Phase-shifted voltages, taken across phases rather than to neutral, may be used depending on the relay type, to achieve compensation in parallel-connected transformer groups (sec. 2.5.2).

To avoid excessively frequent tap-changing in such circumstances as transient voltage changes from motor-starting, fault clearing, etc., LTC relays have a time-delay of many seconds. This may be a definite-minimum time (DMT), operating immediately the voltage error signal has been exceeded for more than its delay time, or inverse definite-minimum time (IDMT), having a delay in inverse proportion to the voltage error but with a minimum limit. If a single tap-change was insufficient to bring the voltage into the set band, subsequent taps may be set to occur with the same delay or more usually without delay until the voltage feedback is within the band again.

Line Drop Compensation

It is common to provide a voltage feedback signal that relates to a down-stream voltage rather than the transformer terminal voltage. The setting is usually such that increased system loading causes increased transformer terminal voltage and the reduced voltage at the end of the feeder. LDC is usually implemented by subtracting from the terminal voltage the product of measured line current at the transformer and a simulated line impedance – either an actual resistor and reactor, or an electronic relay. As long as R and X (fig. 2.3) are properly modelled by R_c and X_c, this system will maintain the voltage at the remote point in the desired range for any load condition that does not require taps outside the transformer's range.

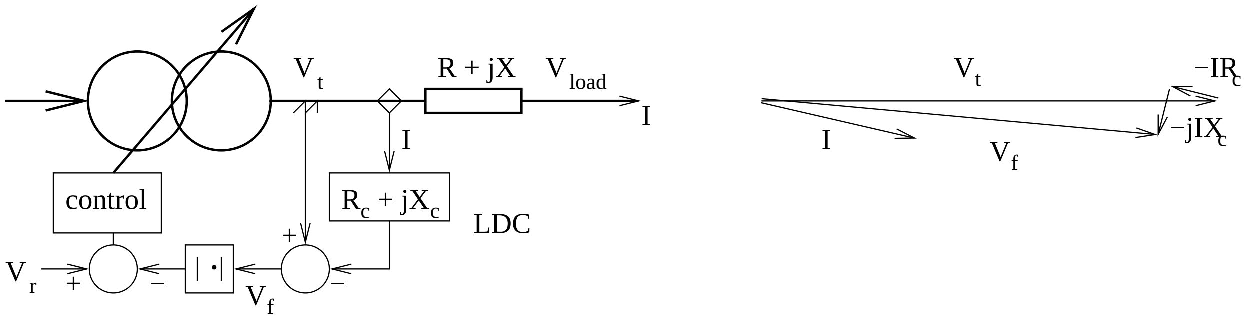

Figure 2.3: Line Drop Compensation on a single transformer

Bad selection of R and X parameters can lead to compensation that seems fine with a particular power factor but is severely wrong when power factor varies. Conventional distribution system loads have a very limited range of power factors, generally from 0.9 lagging to unity, with very industrial areas being perhaps as low as 0.85. The presence of generation in the distribution system has the potential to change the power factor very much: there will b no effect on power factor if the generator's power factor is kept close to that of the average load, but an uncompensated induction generator will draw reactive power and supply active power, thus being in quite another quadrant from normal loads. [15].

Remote Control

Besides the automatic LTC control, it is usual that the set-point of a LTC relay can be altered remotely, to bend the system's voltage profile to meet security needs; typical values are up to 9% decrease or 4.5% increase. Some relays can also automatically do set-point variation to vary load consumption in response to major changes in frequency.

2.5.2 Voltage Control of Parallel Transformers

Instability

When transformers are operated in parallel, automatic tap-changers that are connected to each transformer as described above do not work properly. All transformers' relays will compare the common bus voltage with a fixed reference, and the inevitable presence of small differences in relays and voltage-references will make one transformer tap before the others, thus correcting the voltage and preventing the others from tapping. If the bus voltage continues changing in the same direction, the same transformer will be the first to tap again, and this process will continue until the transformer reaches its tap limit. If the discrepency between relays is a difference in deadband centre rather than deadband width, then the transformer that was first to tap one way will be last to tap the other, leaving a transfomer stuck at a limit unless supply voltage changes so much as to require all transformers to tap the other way.

Even differences of a few tap-steps can drive large circulating currents, with consequent active and reactive power losses in the transformers; it is therefore necessary to ensure that the parallel transformers keep their taps close, ideally with a difference of no more than one step. Figure 2.4 shows how the load is supplied from two parallel transformers on different taps.

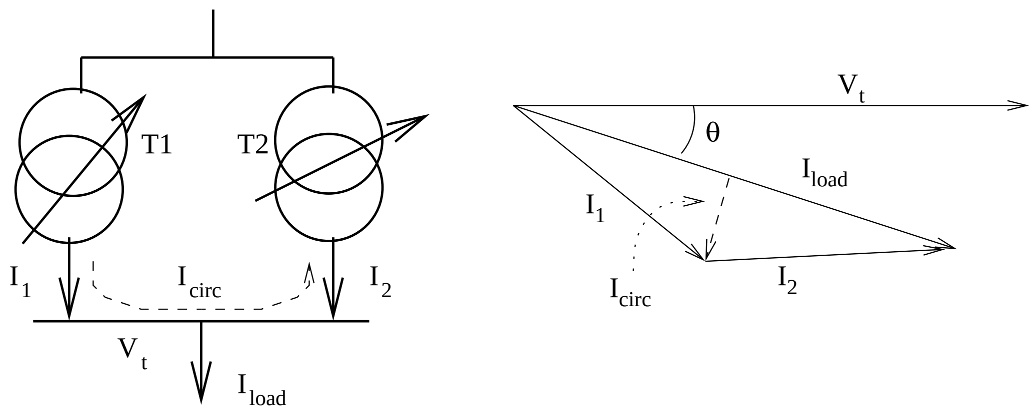

Figure 2.4: Circulating Current, T1 on higher tap than T2

LDC makes this situation worse; the transformer with the highest tap will supply the most circulating reactive current, and its feedback voltage will therefore be reduced by LDC, tending this transformer to tap up again sooner than the others.

Two types of solution are used to allow parallel operation of transformers under automatic voltage control: tap-changing for all transformers can be initiated by one, or else a bias signal is applied to each transformer's voltage feedback so as to tend it to tap towards the average voltage of the parallel group.

Master-follower

This is a general term for the first solution type. One relay is active: it controls a master transformer, and other transformers follows this one's tap setting. Schemes vary in use of tap-change initiation, tap-change completion, time-delays etc. to signal changes along the group of transformers. The control wiring between transformers is complex, transformers need to have similar taps, and although the taps do not change simultaneously, with resultant voltage step, this scheme loses the potential for fine control over voltage by moving just one transformer's tap at a time until voltage is within limits. Master-follower systems are now very unusual.

Circulating Current

If all the transformers are on a common bus rather than spread out on a common network, it is easy for each relay to access current measurements for all transformers. Summation of currents gives the total current to the load, which may be used with a conventional LDC system to alter the voltage feedback to all transformers. The phase-deviation of an individual transformer's current from the total current is determined by the proportion of circulating current flowing in it due to unmatched transformers or taps, and each transformer's circulating current component can be used to bias that transformer's relay to reduce circulating current.

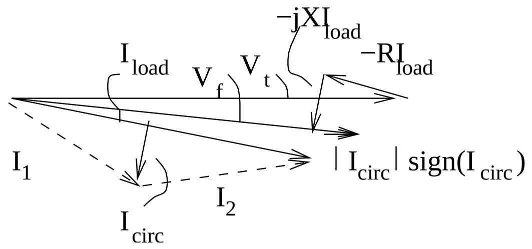

Figure 2.5: Use of circulating current measurement to bias tap-changing

If the load is quite close to unity power factor (e.g. 0.9), phase-shifting a transformer's circulating current component by a 90 degree advance gives a signal that is approximately in phase with the feedback voltage if the transformer is supplying circulating reactive power (tap too high) or in antiphase if it is absorbing circulating reactive power; addition of this signal to the voltage feedback for each transformer therefore gives it a bias to tap towards the mean value for the group.

Circulating current methods require interconnection to transmit current signals; this is inconvenient in any case, and particularly arkward if the parallel transformers are not at the same site. If the parallel transformers are indeed remote, and are connected by a network of significant impedance, then differences in loads near each transformer group may lead to quite different transformer currents and power factors being natural, a situation that would be misconstrued by the relays as meaning that the group with the lower reactive load should be more inclined to tap up. Wiring to allow curculating current measurement has added complexity from the need to bypass out-of-service transformer CTs.

Negative Reactance

Negative Reactance Compounding, also known as Reverse Reactance Compounding, relies on the assumption 2.5.1 of load power factors being always close to a known value. The system is very similar to plain LDC, but the effect of the reactance is negated.

As unequal tap-positions cause mainly reactive power circulation, and the reactive part of LDC affects the feedback voltage more for reactive current than the resistive part, the reactive part alone is reversed in its effect so that increased supply of reactive power by a transformer increases its feedback voltage, biasing it to tap down. The resistive component of LDC can then be set to a higher value than before, so that under a particular load power factor and LDC line impedance the load voltage is approximately maintained. Voltage regulation will still not be as good over the whole range as with real LDC, and will be easily upset by power factor changes. However, there are large advantages of simplicity; transformers do not need to be similar in rating, tap sizes or tap number, only the voltage and a local current measurement are needed, and the resultant independence of transformers means much less wiring and the possibility of operating in parallel from remote sites. This method of parallel transformer control was analysed at length in 1964 [3], and found by practical and simulated tests to give stable operation and acceptable voltages in a typical system. Nowadays with a very different situation of distribution-connected generators and with perhaps more need for tight voltage control, better methods are desirable.

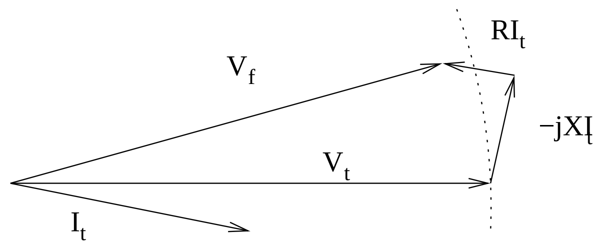

Figure 2.6: Negative Reactance Compounding

Note from fig. 2.6 how an in-phase component of the current will change the reactive feedback voltage very little, but a reactive component will have a strong effect as it is approximately in phase with the terminal voltage when shifted in the reactance. The resistance, meanwhile, has its main effect from the in-phase component, and this must make up for the small change in feedback voltage due to the reactance, as well as the drop in the line.

Phase-shifted Negative Reactance (as in SuperTapp etc.)

This method treats LDC and tap-bias separately, with each relay using a current signal for its own transformer and for the total load current. The relay voltage measurement is 30 degrees lagging the actual bus voltage, so with a moderately lagging power factor the voltage and load current signals to the relay are approximately in phase. LDC is then performed as a direct subtraction of a proportion R of the total load current from the terminal voltage, and bias is applied by phase shifting the transformer current by 90 degrees so that components in phase with the total current add in quadrature with small effect, but reactive components add in phase with strong effect on the terminal voltage.

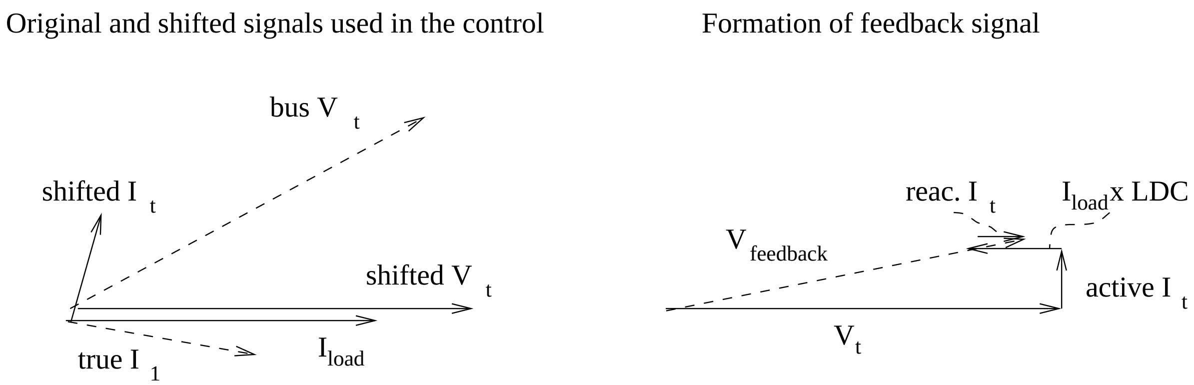

Figure 2.7: Modified Negative Reactance Compounding

2.5.3 Voltage Control of Cascaded Transformers

Instability

Cascading LTC transformers down a system raises the potential for cyclic instability between tap-settings at different levels, excessive operation of tap-changers, and a temporarily reduced voltage profile if tap-changers near loads are the first to compensate voltage fluctuations higher in the system.

Choice of delay time and dead-band width is important in optimising the combined behaviour of tap-changers, and for their coordination with other slow voltage-influencing components such as Mechanically Switched Capacitors (MSC) and Delayed Auto-Reclosers (DAR). Tap-changing should happen only after these other influences have had their effect: tapping in a voltage-low situation will cause excessive immediate demand when voltage rises on reclosure of a DAR, and a reduced primary side voltage due to tap-changing will reduce the effect of MSCs switched on to boost the primary side voltage. The shortest tap-changing delays are therefore rather longer than the delays of these other devices, starting at several tens of seconds.

It is usually true that the aggregate system loads found at LTC transformers have an initial response to voltage of order well over zero (constant power, constant current), and a static component of order no less than zero (constant power). Also, the reactive power part response is likely to be very sensitive to voltage, particularly from transformers and lighting ballasts; only the presence of a lot of motor load with insensitive mechanical torque is likely to change this. So for any but the most industrial of areas, a reduction in voltage will lead to initially much less, and later rather less load.

Local changes in voltage low in the system will clearly not be detected or corrected at higher levels, and should be responded to by local transformers. Changes in voltage higher up will affect all areas below them: correction near the loads will lead to higher current flows and lower voltages in the network, which will depress voltage even more. Consequent tap-changes at the higher level will then occur, and may lead to the lower level tapping back. To ensure that significant voltage changes are first corrected at the highest level at which they occur, cascaded LTC transformers have graded time-delays, increasing lower down the system. The dead-bands are wider higher in the system, so that high-level tap-changes, with their possible effect of causing opposite changes lower down the system, happen as infrequently as possible.

2.6 Synchronous Machines

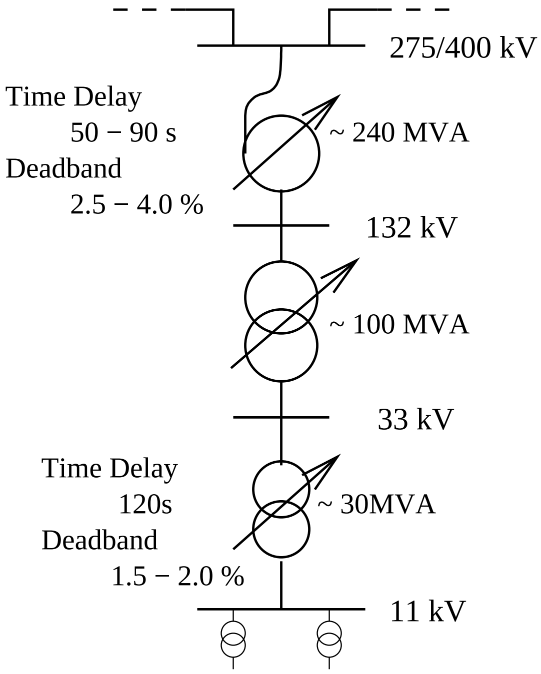

Figure 2.8: Typical U.K. voltage levels and LTC settings

2.6.1 Physical

Large rotating electrical machines (from a few megawatts) are generally of the synchronous type. This is always so at the really high generator ratings of hundreds of megawatts. The synchronous generator goes together with an exciter to supply and control the current to its rotating field coils, and a turbine with a governor to drive the generator and regulate its speed. Figure 2.9 shows a schematic of the connection of these components.

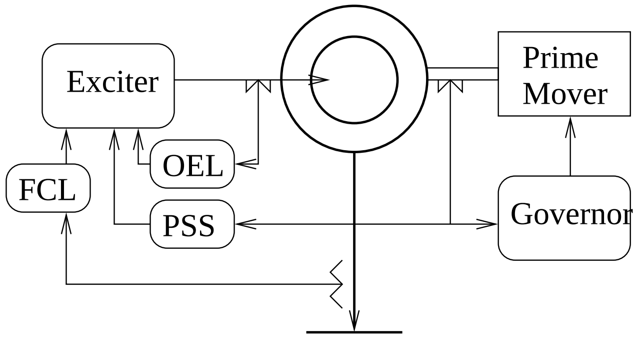

Figure 2.9: Schematic of a synchronous generator with its exciter, prime-mover and governor

2.6.2 Modelling

Modelling of synchronous machines is extremely well documented, and models of a wide range of dynamic orders and applicabilities are available; these need no modification [14]. Machine controls, particularly the Automatic Voltage Regulator (AVR) and associated controllers such as an Over-Excitation Limiter (OEL) and Armature Current Limiter (ACL) are often not included in commercial simulation software that has the traditional angle-stability focus. Quite recent IEEE standards for dynamic modelling of excitation systems were used in conjunction with voltage-stability related papers, to obtain models of these various excitation components.

$$
\begin{aligned}
T'_{do}\dot{E}'_q &= -E'_q + E_{fd} \cdots \\
&\quad - (X_d - X'_d)\left[I_d - \frac{X'_d - X''_d}{(X'_d - X_{ls})^2}(\psi_d + (X'_d - X_{ls})I_d - E'_q)\right] \qquad (2.4) \\
T''_{do}\dot{\psi}_d &= -\psi_d + E'_q - (X'_d - X_{ls})I_d \qquad (2.5) \\
T'_{qo}\dot{E}'_d &= -E'_d \cdots \\
&\quad + (X_q - X'_q)\left[I_q - \frac{X'_q - X''_q}{(X'_q - X_{ls})^2}(\psi_q + (X'_q - X_{ls})I_q + E'_d)\right] \qquad (2.6) \\
T''_{qo}\dot{\psi}_q &= -\psi_q - E'_d - (X'_q - X_{ls})I_q \qquad (2.7) \\
\dot{\delta} &= \omega - \omega_s \qquad (2.8) \\
\frac{2H}{\omega_s}\dot{\omega} &= T_M - (X''_q - X''_d)I_d I_q \cdots \\
&\quad - \frac{I_q}{(X'_d - X_{ls})}\left[(X''_d - X_{ls})E'_q - (X'_d - X''_d)\psi_d\right] \cdots \\
&\quad - \frac{I_d}{(X'_q - X_{ls})}\left[(X''_q - X_{ls})E'_q - (X'_q - X''_q)\psi_q\right] \qquad (2.9)
\end{aligned}
$$

where E_{fd} is the applied field voltage, E and ψ denote internal transient voltages and damper flux-linkages, subscripts d and q refer to direct and quadrature axes, prime and sec superscripts refer respectively to transient and sub-transient quantities, X and I are reactances and currents, ω_s and ω are the reference and machine angular speeds, H is the inertia constant, and T_M is the mechanical input power.

2.6.3 Excitation

A synchronous machine has its field voltage controlled to maintain terminal voltage under load in spite of its leakage reactance and large armature reaction. Old systems used a d.c. generator, usually on the shaft of the main machine, to supply the field current; the d.c. machine's field then required a moderate current that could be controlled by rheostats.

There are several general types of excitation system — D.C., rotating A.C. and static — and the suitable models differ significantly in structure and time-constants. Here, the IEEE DC1a model is used [4, 5]; the only non-linearities are a saturation function and voltage limits, and this type is commonly used in research to give a sufficient representation of exciter dynamics. The dominant equations linking reference and feedback voltages to applied field voltage E_{fd} are:

$$
\begin{aligned}
T_E \dot{E}_{fd} &= -\left(K_E + S_E(E_{fe})\right) E_{fd} + V_R && (2.10)\\
T_F \dot{R}_f &= -R_f + \frac{K_F}{T_F} E_{fd} && (2.11)\\
T_A \dot{V}_R &= -V_R + K_A R_f - \frac{K_A K_F}{T_F} E_{fd} + K_A(V_{ref} - V) && (2.12)\\
& V_R^{min} \leq V_R \leq V_R^{max} && (2.13)
\end{aligned}
$$

where V_{ref} is the setpoint, V is the machine terminal voltage, R_f is an internal state in the stabilising feedback; K denotes a gain, T a time-constant, S a saturation function, and subscripts A, F and E are associated respectively with the regulator, stabilising feedback and excitation machine. A further first order lag on the terminal voltage input, and lead-lag filter on the voltage error are also used in more detailed models.

In order to maintain synchronism under fault conditions, excitation systems are designed to utilise the thermal inertia of a generator's field and armature windings by rapidly applying several times the rated field current to maintain terminal voltage. Overloads may also occur when the generator is operating with depressed terminal voltage due to voltage troubles in the network. There is a need to limit the duration of such overloads, this limitation usually being automatic through supplementary controllers. Armature Current Limiters (ACLs) and Over Excitation Limiters (OELs) act upon the excitation system by supplementing or replacing the error signal. The short overloads for maintaining of synchronism may take advantage of signals to block the limiters. OELs and ACLs are crucial in medium time-scale studies, and suitable models have been published by IEEE Task Forces [9, 10]. The simple model adopted here uses a supplementary signal to reduce the excitation to the rated level at a rate dependent on the magnitude of the overload.

2.6.4 Prime movers

All large generators are driven by turbines; the working fluid is water, steam, combustion gases or heated air.

Hydraulic turbines operate at lower speeds than gas turbines, usually driving salient pole generators with several pairs of poles per phase. The long penstock (water feed pipe) typical of systems with a high head or remote water storage leads to a pronounced non-minimum phase (initial step response in the opposite direction to steady state response) system between power order and power. As the time-constant of this power-change response may be long compared to control actions, governor compensation is required for stability of the mechanical power control. The non-minimum phase is a consequence of the need to accelerate or decelerate the long body water in the penstock when the power coditions are changed. The only way to ensure a suddenly available increase in power output is to use steady-state by-passing of water near the turbine so that up to this much more can be diverted through the turbine suddenly without requiring a change in

The other turbine types with gaseous fluids have quite similar models, usually with several power-producing stages separated by reheat or waste-heat boilers. A simple such model considers the first-order lags of the control valve and the volume of a steam turbine, and the power limits. Long-term dynamics of the steam supply system may be relevant to very detailed voltage stability analysis, and certainly to frequency stability, but are not included here; the dynamic simulations are not envisaged to cover such time-scales with so much detail.

$$T_{CH}\dot{T}_M = -T_M + P_{SV} \tag{2.14}$$

$$T_{SV}\dot{P}_{SV} = -P_{SV} + P_C - \frac{1}{R_D}\left(\frac{\omega}{\omega_s} - 1\right) \tag{2.15}$$

$$0 \leq P_{SV} \leq P_{SV}^{max} \tag{2.16}$$

An extension of this allows for more stages in the turbine, while a reasonably thorough model of an internal-combustion turbine allows for temperature feedback and fuel pressure these being shorter timescale effects than boiler dynamics of steam plant. A model with one reheat stage was adopted.

Chapter 3

Distributed Generation

3.1 Distributed Generation

Distributed Generation (DG), otherwise known as dispersed or embedded generation, is loosely defined as generation that is 'smaller, and closer to the loads' than conventional large power stations. It has become very popular among researchers as well as some government and environmental agencies in the past few years, and its use has recently grown in Europe mainly in the form of wind-turbine plant. Ackermann [1] has made a concise compilation and discussion of the various qualities used by different sources to define D.G., a matter complicated by the great variation in size and siting of conventional power stations.

D.G.'s rationale is that rather than producing all electricity in large plants designed for efficient production of electricity alone, then transmitting vast amounts of power through a hierarchical system spreading out to the many consumer loads, there should be more small generation nearer the loads; an extreme case would be a close balance of installed generation and load in each area, but location of resources may lead to a need for separation of generation and loads even when the generation comes within the definition of DG.

The present 'central generation' model stems from state-controlled companies charged with the duty of providing a large amount of electrical power at low cost, which task was best performed by the increased electrical efficiency and the reduced overheads of bulk generation. Current moves to D.G can be attributed to the recently much improved technology of wind turbines, combined-cycle gas turbines, micro gas turbines *etc.*, combined with demand for more 'environmentally friendly' (*i.e.* less environmentally unfriendly) use of energy. A more integrated approach to energy takes into account the optimum use of primary energy sources, and the use of renewable sources to a large extent: thermal generation of electricity in smaller, dispersed plants often allows almost all waste heat to be used locally; renewable sources such as wind are seldom of such large capacity on a single site as to warrant direct connection to the transmission system; and such sources as solar power can be integrated into buildings to use otherwise wasted catchment area.

Many governments have made binding international agreements to cut carbon-dioxide emissions, and there are often domestic pressures too to cut harmful emissions and to consider how countries will meet the growing demand for energy in spite of the decline of the currently dominant hydrocarbon sources. The solution of quickly cutting down consumption to match the available renewable energy production is not remotely practicable, but long term plans suggest much wider use of renewables such as wind and solar power, and intermediate states involve increased use of integrated energy use such as Combined Heat and Power plants. [13]

It is widely acknowledged that the transmission system would still be required even if most generation is in the distribution systems [7]. A House of Lords Select Committee in 1999 stated:

> “We do not accept ... that the grid and centralised generation will ever become superfluous or even the junior partner. The necessary stabilising role of the grid must remain.” [8]

Rather than functioning to take all power from generators to bulk distribution points, the transmission system would provide stabilising services to the distribution systems, and would provide a path for exchanges of large powers between distribution systems or even across countries and continents; there is clearly an advantage to using a resource such as hydro or wind power when it is available, at which point it may be desirable to stop operating thermal generation and even to use electricity to substitute for a CHP plant’s thermal output.

3.1.1 Ancillary services from D.G.

Significant in the separation of generation and consumption from network operation is the reduction of the network operator’s control over the network flows and voltages. Many countries’ governments now believe that there is an advantage to a throughly competitive market in electricity supply: the only natural monopoly is the network, whose operator is regulated by government to limit abuse of this position. Competition between generators is potentially limited by the network’s capacity, so the network operator must ensure that the network’s transmission capacity is kept as high as possible. The network needs such services as reactive power, active power to cover network losses, precise active power balance to maintain system frequency, and emergency black-start capacity. These ‘ancillary services’ may be provided by the network operator or may be bought by the network operator as services from generators. None but the largest D.G. plants currently have facility to sell such services, although there is interest in the extent to which ancillary service provision may spread [6]. Increased use of technology, as is already considered for intelligent loads that are controlled according to electricity price, has the potential to give even small D.G. plants responsiveness to frequency and voltage.

3.1.2 Sizes and types of DG

High level

The generation is electrically close to a transmission system load bus: it is connected to a part of the subtransmission/distribution system (e.g. 132kV in the UK) that is close to the grid substation.

Such DG is typically CCGT plant, operated by a regional electricity company or another private enterprise; many of these medium size CCGT plants have been built in the last decade [1]. Pure steam cycles may be used in cases where a factory generates electricity as part of another process, or as a backup plant. Conventional plant rated at a few hundred megawatts, such as small coal fired or hydroelectric plant, may also be connected to this voltage level. Wind turbines commonly use grid-connected induction generators, which together with recent rapid growth in the sizes of wind turbine ratings and turbines per wind-farm,

Plant worthy of connection at this level may well be centrally dispatched. It will behave, as seen from the transmission system, in much the same way as generation directly on the system: the main difference is the extra impedance and any LTCs on the supergrid transformers linking the transmission and subtransmission systems.

Medium level

The generation is of lower rating than that at the high level, but is still of sufficient rating to require connection at medium voltage, e.g. from 66 down to 11 kV in UK.

This may be the smaller plants of the same type of generation as mentioned above for the high level, but there also be types that are not economically feasible for high ratings: diesel and gas engines, fuel-cells, microturbines that run at high speed through power electronic converters, and possibly other ?renewables? such as photovoltaic cells if it becomes worthwhile to use these in large PV-farms rather than on individual buildings.

Larger plants in this category may be subject to central dispatch, but many are not; it is not yet usual for the potential security and ancillary services of DG to be put to use by increased communication and pricing incentives.

Low level

Generators in this category are connected at very low levels, for example to the 0.4kV or perhaps the 11kV system. This suggests that the generators are owned by domestic customers, businesses and small industries.

Likely renewable DG at this level is small wind generators or roof installations of photovoltaic cells. Domestic or commercial CHP systems promise a larger volumetric power than the renewable sources, and are not limited by a stochastic input source. Microturbines and, with further development, fuel cells, are suitable cores for a combined generator and hot water boiler, while gas engines may also be used in larger installations until usurped by high speed turbines. The low cost of natural gas in many countries, and the rapidly improving technology of small, fast turbines and compact power-electronic converters could make this very controllable type of DG produce a significant proportion of the local system load.

With the current state of the technology it is unusual for small DG to have any sort of designed response to system conditions. DG connecting through a Voltage Source Converter could potentially source or sink reactive power, limited by the inverter?s steady and short-term apparent power capability. There are, however, currently no incentives for domestic customers even to control their own power factors, let alone to provide reactive power services to the network. Certainly, small DG does not yet have the facility to respond to the transmission system?s needs, and usually it is uncontrolled by the

3.1.3 DG as a voltage controller

Many forms and sizes of DG are able to provide reactive power, and many of these can respond quickly enough to be a good substitute for Static Var Compensators. The ability to vary active power also, to change network flows and to make significant effect on voltages in the less inductively dominated distribution networks gives DG an extra dimension of freedom unshared by other reactive compensation equipment, and superior to the limited-time active power capacity of the somewhat exotic energy storage devices such as Superconducing Magnetic Energy Storage.

Voltage control in a transmission system is very much dependent on reactive power injection, or modification of reactive losses by altering real power injections. Voltage control in the distribution system becomes more dependent on real power the further down the system one gets, due to the reduced X/R ratio. Therefore, quick active and reactive power control of DG, if possible by future communication structures, may allow the transmission system to be helped by increased active power generation, reduced system power loss, and possible reactive power control too.

Different DG sources differ in their characteristics of real and reactive power capability. The most promising future sources generate d.c. or high-frequency a.c., so they connect to the network through an inverter. Their real and reactive power outputs are linked only by the apparent power rating of the inverter; this is quite similar to the situation with a synchronous generator. Of the common DG sources it is the direct-connected induction generator that has no separate control over its reactive power output; this machine is used mainly with wind turbines. Suitable price incentives can encourage the purchase of inverters or generators with some margin of reactive power, so that there can be variation even when at maximum active load.

In the case of wind and solar power and some more exotic types such as wave power, the response of real power is limited by the varying supply from the primary source. Improved energy storage methods may help overcome the problems of short fluctuations, or even to smooth out longer fluctuations if technologies improve. The use of storage devices (flywheels, superconducting magnets etc.) may also allow smoothing of system demand as a result of price variation — such generation could then be used to support the system over temporary stability problems. Other DG sources with dependable supplies can more easily be modelled and used as part of the system control, but they too will have dynamics of active power response to demand. Advances control systems and naturally short time constants may let some inverter connected DG respond almost without showing its underlying dynamics, but conventional, larger DG still has maximum loading rates and some long delays, for instance the time constants of a CCGT heat recovery steam generator.

The whole matter of DG, then, has huge potential for modern technologies to come into the power system from the top to the very bottom, and to make for much more participation of small loads and generators in the control of voltages and power flows. The idea sounds ludicrous of relying on, as an extreme example, household boilers to provide security and ancillary services to the transmission system; but when spread over a large number of installations all with quick communication of their potential power variation and price requirements, it becomes apparent that the idea has reason and benefit.

Chapter 4

Stability and Instabilities

4.1 The Desired System State

All current bulk power systems are three-phase alternating-current, constant-voltage, with some extent of meshing in at least the highest level. Direct-current links are sometimes used to interconnect such systems or to provide important transfers within an interconnected a.c. system. Power delivery to the distribution system is, however, all a.c.

There are several properties of the supplied electricity that will matter to consumers:

- Voltage
  - damage from excess power or discharge from overvoltage
  - iron-machines normally near saturation draw high current with overvoltage
  - reduced power, discharge lamp-extinguishing, motor overheating, from undervoltage
- Frequency
  - iron-machines normally near saturation draw much higher currents with reduced frequency
  - motors change load rapidly with frequency changes
- Waveform, Phase-balance,etc.
  -

The approach to voltage stability analysis has come to input increasingly much the dynamics of the system. Of course, use of the term ‘stability’ in the context of a physical system suggests a dynamic system, but practical assessment methods used in the power industry have mainly been based on the quasi-steasy-state situation where fast-dynamics have reached equilibrium, and long-term dynamics may be taken into account by multiple static solutions.

Early assessments concentrated on the idea of voltage instability as being a consequence of insufficient provision of reactive power that lead to power transfers approaching the network’s maximum power transfer capacity. Repeated loadflow solutions were made, with an active- or reactive-power injection, or else a bus voltage, as the independent variable. More powerful computers, and systems stressed closer to limits in electric power market systems, have allowed and required more account of component limits and dynamic interactions in assessing system stability.

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