C02 - Real time management and monitoring of power systems – an introduction (II)

2.1. Overview

In the last decade of the 20th century, the electricity sector has undergone through major changes, because of the need of realigning it with the economical realities of the time.

The constant decrease of the fossil fuels reserves, on which the production of electricity was still mainly based, coupled with continuingly increased demand, transformed electricity into essential merchandise. This trend made obsolete the old vertical integration system which was used by the electrical utilities. Instead, the deregulated electricity market model was proposed, which promoted competition between producers and suppliers, free trade of electricity and lower prices and possibility of choice for the consumers.

However, on the technical side, this evolution meant profound changes in the way the electric power systems were operated. The free market concept meant that electricity was sold and brought based on the basis of its price, rather than taking into account the optimal conditions which ensure the best security and efficiency in operation.

This meant that power flows pattern changed, large quantities of power being directed from where the electricity was produced to where it was acquired, over very long distances, if required.

For this, systems previously not interconnected or low connected systems now were part of a whole larger system. The interconnection of these smaller systems meant that either a single system operator should have watched over a more complex system, or a system was managed by more than one system operators, some of them being competitors on the market.

Another radical change, subsequent to electricity markets, was the proliferation of renewable sources, such as wind and photovoltaic, encouraged by environmental concerns and promoted by countries at governmental level by market policies and financial subsidies. The presence of renewable resources producers change the operation of power systems in three main areas:

- predictability: wind and solar radiation are unpredictable by nature, and need to be backed up by classical resources;
- size: wind and solar farms range from very small (a few megawatts) to very large (thousands of megawatts), while classical power plants are mainly large;
- location: wind or photovoltaic farms must be located in areas with maximum availability of wind and solar radiation, often being connected in the system at the distribution level.

From the technical standpoint, when operating a meshed electrical system, the term of **control** implies satisfying at all times certain technical requirements:

- the generated power must match the consumed power plus the power losses in the system;
- the bus voltages must be as close as possible to the rated values of the bus voltages;
- the generated active and reactive powers at generator buses must not exceed defined limits;
- the line and transformer loads must not exceed the limit values over an extended period of time;

To assess these conditions, it is required that, for a known physical structure and load pattern, all the characteristic state variables of the system must be determined and checked against the range of acceptability. This problem is known as load flow analysis. And when an incident occurs in the system, its type, strength and location must be identified, so that appropriate measures could be taken. These are possible through **monitoring**.

The development of electricity markets and renewable resources changed the way systems are monitored and controlled. The differences can be studied by comparing some key aspects in the way systems were operated *before* (in the old vertical integrated model) and *after* (the deregulated market model) these changes occurred.

Before:
Economical aspects

- The economical aspects were managed at centralized level, by the vertically integrated national utility, which was, as a general rule, controlled by the state.
- The principle was that all consumers must be supplied (Fig. 2.1).

Technical aspects

- The systems were smaller and supplied mostly local consumers
- Systems were considered at local, regional, at most national level (Fig. 2.3)
- The system was managed in all its aspects (generation, transmission, distribution, consumption) by a single entity, which had a clear picture of everything that was going on in the system
- The operating conditions were more predictable and the required analysis tools were less complex
- The technical and security restrictions were the main concern in operation.

After:
Economical aspects

- The key principles in operating an energy market are profit and competition, which would ensure lower prices and liberty of choice for consumers.
- The production, transmission, distribution and supply utilities are unbundled activities carried out between players in direct competition on the market (Fig. 2.3).
- The technical aspects of system operations are in direct conflict with the economical and environmental concerns, which are the core of the energy market.

Technical aspects:

- Through interconnection, the systems became much larger and complex (Fig. 2.4)
- One of the essential conditions of the electricity market is the separation of production, transport and distribution activities. These activities are managed by separate entities, sometimes private companies, which means that the communication and data availability at system level is often difficult or even impossible (Fig. 2.2).
- Given the complexity of the system, the risk of failure and any other unpredictable events increases, and these could potentially affect a larger area, with heavier costs than before. This means that more complex and fast analysis algorithms are required to assess the state of the system and take any necessary measures
- Energy flows through the system change radically and can vary significantly from hour to hour, in parts of the system. Electricity is acquired based on the lower price principle and can travel a long way from where it's produced to where it's consumed. This means increased stress on the system. Often, the technical limits must be stretched to the maximum possible who would allow a safe operation of the system.
- A new component, the distributed generation (small generation sources found on the consumer's side), must be managed.
- another layer of complexity is added by the presence of renewable electricity sources such as wind and solar, which are intermittent by their nature (sun doesn't shine and wind doesn't blow all the time and cannot be controlled), which must be served all the time and backed up by conventional sources.

In the centralized planning model, with smaller independent subsystems and slow changing load patterns, the need for monitoring and control was limited to keeping the system at optimal security and operation parameters in normal operation conditions and dealing with unexpected events due to malfunctions.

In the electricity market + renewable resources framework, the control and monitoring of the system must be:

- preventive, by planning the transactions on the market taking also into account the restrictions imposed by the need of having a secure operation of the system and available transport capacity
- corrective, when contingency conditions can lead do congestions on heavy loaded branches in the system, or even stability loss.

This task can be further complicated by the size of the system. If, for instance, the monitoring is done on a system, at global scale, and the system is partially managed by several competing entities, compatibility and rapid and full cooperation between the involved parties is mandatory.

2.2. Real-time monitoring and control of power systems

In any power system, there are many variables of interest for assessing its state, such as: bus voltages, transmission line loadings, transformer taps, power flows between areas, alarm locations. The new operation conditions generated by interconnection on the electricity market substantially increase the amount of needed data. The advent of the new players, the attendant increase in the total number of players, the increasing role of markets in the new environment and the proliferation in the number of transactions are resulting in major changes in power systems operations. To this adds the unique feature of the power system that electricity cannot be stored in large amounts and changes in the system affects almost instantaneously large areas and numbers of players. These result in a severe data overwhelm problem, even in normal operating state, and its management requirements. Extensive changes are needed in terms of development of effective analytical and software tools.

The real time monitoring and control system (RTMCS) can be seen, from the perspective of the deregulated market system, as consisting of three interconnected layers:

- the generation and physical delivery layer (generation, loads, transmission and distribution facilities and their associated embedded control and protective equipment, the system operator)
- the market layer (trading markets, physical participants, energy exchanges)
- the communication, monitoring and control layer (the sensor and measurement equipment installed in the system, the data communication network and the RTMCS commands and signals)

2.3. The need of security and market constraints

Power systems are continuously subject to a wide range of disturbance types, such as sudden changes in load demand, customer load changes, loss of one or more generation units or transmission lines due to outages, resulting in modifications in the system configuration, equipment outages and generator failures, renewable sources' uncertainty. System reliability or security is an instantaneous condition. It is a function of time and of the robustness of the system with respect to imminent disturbances. The notion of security is the basis of all real-time monitoring and control in today's power systems.

The working definition of security is in terms of the system state. The system state is a compact description used to summarize key information about the system; once the system state is known, it can be used to express any variables of interest.

A state is classified as being one of three possible types:

- normal state, when all constraints and loads are satisfied thorough the system
- emergency state, when one or more of the physical operating limits are violated (a collapse is imminent)
- restorative state, where one or more of the loads are not met, partial or total blackout, but the partial system is operating in a normal state

The notion of security is defined with respect to a set of credible contingencies or unwanted events that may happen in the system. A normal state is secure if all postulated contingencies result in secure normal operation.

The main role of power system control is to maintain its secure system state, to prevent the system state from transitioning from secure to emergency over the widest range of operating conditions. The RTMC system is a collection of processes, computing equipment, measurement devices and communications used for accomplishing this role. The RTMC system uses real-time measurements to identify whether or not the power system state is normal (monitoring). If the state is normal, it then determines whether or not it is secure (security assessment).

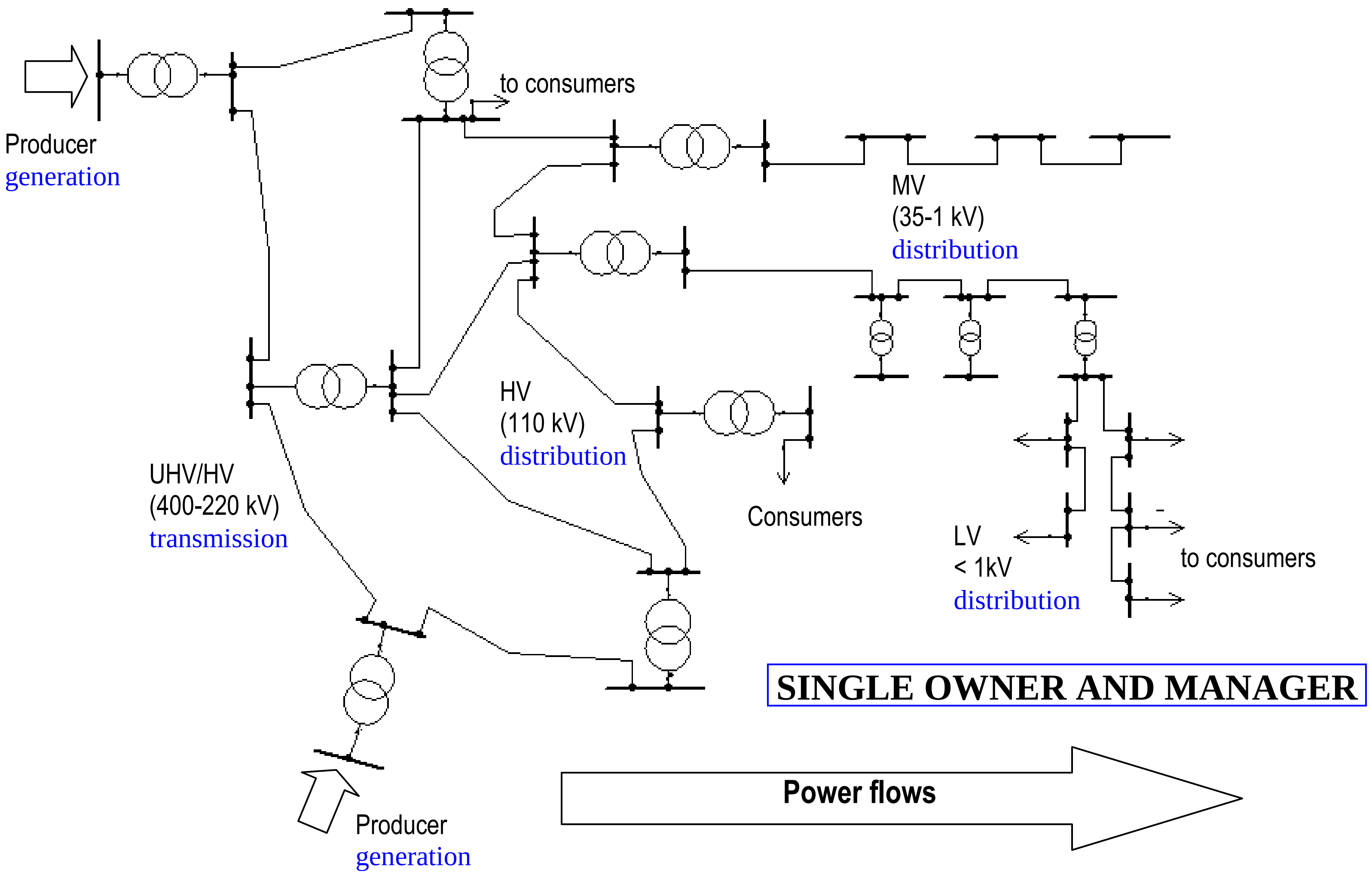

Fig. 2.1 – System management and ownership – the old model

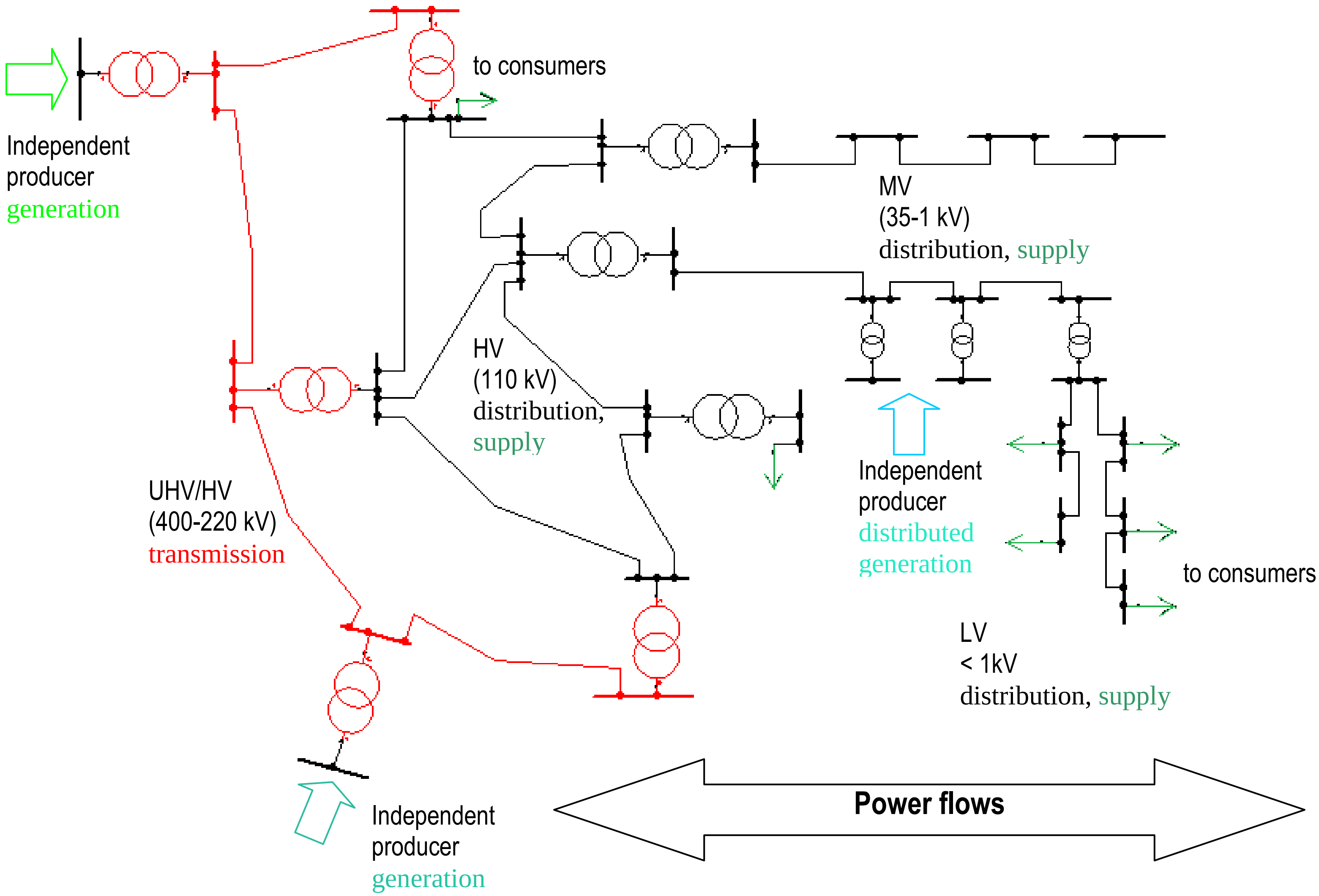

Fig. 2.2 – System management and ownership – the new model

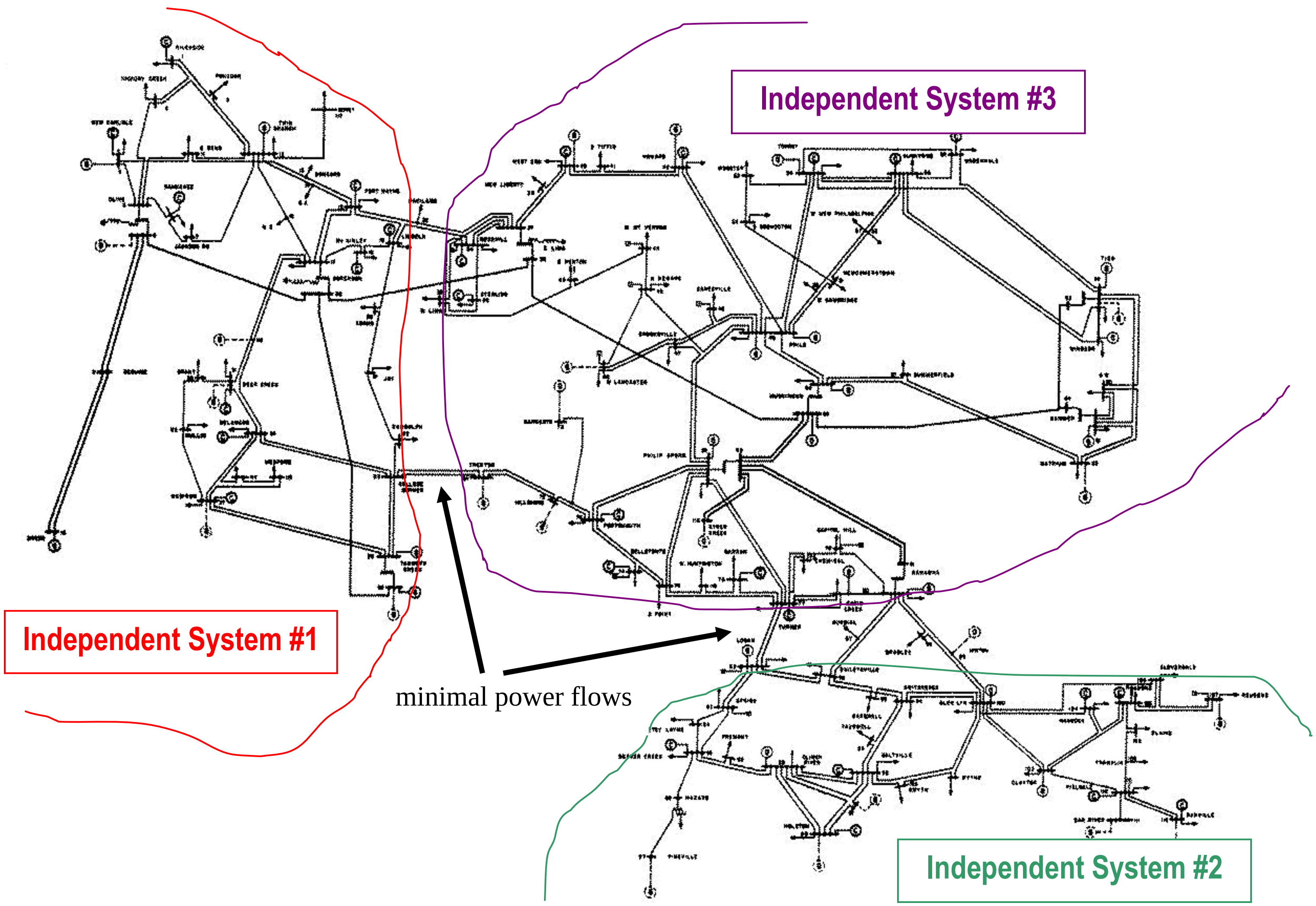

Fig. 2.3 – System operation – the old model

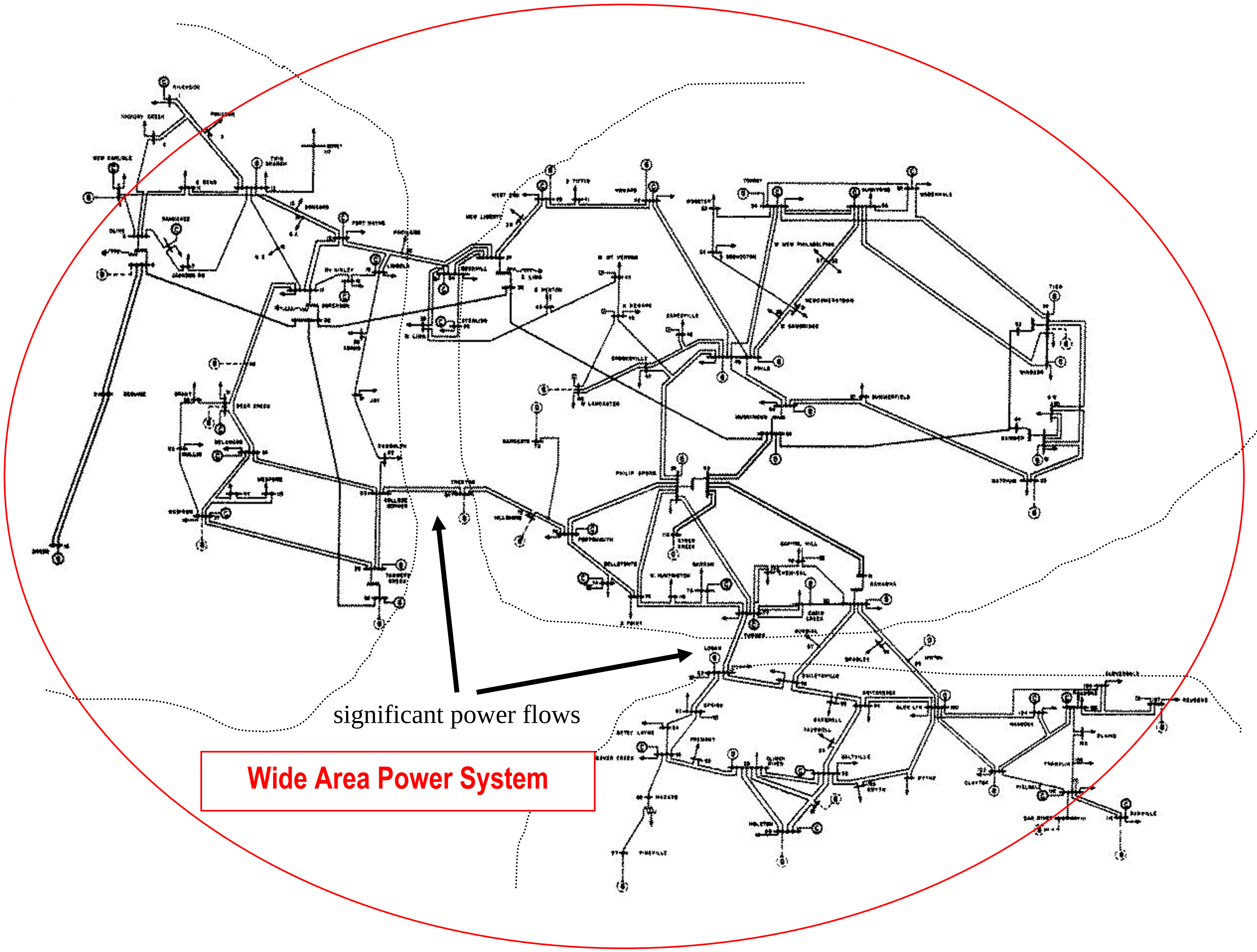

Fig. 2.4 – System operation – the new model

Currently, the EMS/SCADA system is the central nervous system of the power network of the traditional utility and is the principal tool to aid the operators in the real-time operations and control of the power system. The deregulation of the power industry had a major impact in the RTMCS area.

The unbundling of activities based on market principles increases the role and responsibility of the system operator(s) who manage(s) the grid and the RTMCS system. There is a general agreement that the power system requires coordination to maintain its integrity and security, however there is considerable controversy on the best ways to implement such coordination under competitive conditions. With the separation of generation and transmission services, their integrated control is a challenge and information availability is a major issue. Maintaining security requires widespread availability of real-time information about physical variables; however this is not compatible with the competitive market rules. A compromise must be made between the required level of security of the system and of the financially sensitive data [PSERC 99].

2.4. Technological advances in measurement, communications, computing and data analysis tools

The estimation of current system operating point and grid configuration from on-line measurements is known as state estimation and is a vital tool of any RTMCS. The state estimator provides the most up-to-date snapshot of the system and is the basis for all security assessment computations. With the increasing complexity of the system, the static estimation is replaced by dynamic estimation or tracking of the state of the system in real-time.

A key problem in assessing the system state in real time is the capability to make phasor measurements effectively. A phasor is a complex number, used to represent a pure sinusoidal function of time (steady state AC voltages and currents). The phasor may be computed from equidistant samples of the wave form under appropriate limitations on filtering and sampling rate [Gavrilaş 09].

Phasors, representing voltages and currents at the buses of the power system, define the state of the power system. If several phasors are to be measured, it is essential that they be measured using a common reference. The reference is determined by the instant at which the samples are taken. In order to achieve a common reference for the phasors, it is essential to achieve synchronization of the sampling pulses. The precision requirements for the time synchronization depend upon the uses of the phasor measurements. The Global Positioning System (GPS) provides a 1 pulse per second (1 pps) at any location in the world with an accuracy of about 1 μsec. In addition to the 1 pps signal, the GPS provides along with other information, the unique time-stamp to the pulse.

The capability of making phasor measurements using GPS is incorporated in the phasor measurement unit (PMU). A multiplexed analog-to-digital converter samples the power system voltages and currents. The time-tagged phasors taken from a number of PMUs installed in the system are communicated to remote locations and used for analysis. PMU's provide a highly useful tool for adding measurements to the set available for state estimation and enable improved system protection and dynamic control [PSERC 99].

2.5. Analysis tools in power systems

Physical models

Before the computer age, the load flow computing methods used physical scale models of the real system. [Georgescu 00]. Overhead and cable lines were represented through equivalent π two-port quadrupoles, transformers were considered by their equivalent impedances, and generators, with an electromotive force and equivalent impedance connected in series. The voltage regulation was modelled using mini-autotransformers.

Reducing the reactance's and susceptance in the system required the use of higher frequency values. These physical models were called DVC and AC analyzers.

Starting with the 1960s, with the advance of computing hardware, numerical methods replaced the physical models.

Load flow analysis in power systems

As a general rule, the mathematical load flow models determine a minimal set of state variables, the bus voltages, in magnitude and angle. Using the voltage values, all the other characteristic values of the load flow analysis can be computed: branch power flows, branch power losses, branch current flows, branch voltage drops.

The state variables are computed using the one-line diagram of the system, the electrical characteristics of the physical elements, topological data and instantaneous bus load values.

The load flow algorithms require as input data a large amount of data: all the active and reactive generated and consumed powers in the consumer buses, the active powers and fixed voltage magnitude in the generator buses, and the voltage, in magnitude and angle, in the reference slack bus.

Gathering all this data when needed in real time analysis required in monitoring studies is not feasible, especially in the multi-owner and large systems. For the first case, a solution is using system equivalents. For the second case, another viable solution is using system estimation algorithms.

System equivalents

Basically, the system equivalents simplify the analyzed system by reducing a large part of it and replacing the reduced part with a simpler, yet precise equivalent model. Then, assuming that the operation conditions didn't change, a load flow performed in the small system should give the same results as the same algorithm applied on the entire system. The advantage of this approach is that a part of the system, unnecessary in calculation, is omitted, while taking into account its influence. Thus, the computing effort is reduced. This approach is also useful in the scenario in fig. XX. Any can use in a global system analysis, instead of complete data about the neighbouring subsystems, their system equivalents. Thus, he can make a complete analysis without needing to have accurate network data about the rest of the system.

The equivalence techniques divide the whole system into 3 areas of interest:

- the internal power system, which is the part of the system which needs to be analyzed in detail. Its structure remains unchanged.

- the external power system – the part of the system which is not of interest, but its influence is important in the result of the analysis
- the far-away system, usually of large dimensions, whose behaviour and changes have no influence on the results of the analysis.

The internal and external systems are connected through a minimal set of branches, connected, at the side of the internal system, into a small number of boundary buses. The external system is replaced by the equivalent, while the far-away system is completely ignored.

The best known system equivalents are the Ward, REI and ETI equivalents.

State estimation

While the load flow algorithms need data from all the buses in the system, the static state estimation algorithms aim to determine the steady state of a power system using a limited set of measurements placed in key points of the system and information regarding the current system topology such as breaker positions.

- The most used state estimation algorithms are
- The weighted least squares (WLS) algorithm
- The Least absolute value (LAV) algorithm
- The Marquardt-Lenvenberg algorithm

The measurements are usually bus power injections, branch power flows and bus voltages.

The traditional WLS algorithm uses for voltages only magnitude measurements. Voltage angles are not used because of significant errors that may occur since these measurements cannot be synchronized.

Depending on the precision and location of the known measurements, the estimated results can vary in precision. Pseudo-measurements, (measurements known a-priori, such as voltages at generator buses) can be used.

Also, the speed of the calculations decreases when the size of the system increases.

For analyzing large systems, extensions of the classic SE algorithms called distribution estimation algorithms. These divide a large grid into several independent subsystems, connected through a small number of branches. Individual estimations are carried out in the independent subsystems. Each subsystem can use the SE algorithm that is most suited to its characteristics and operating conditions. The results of the individual estimations are delivered to a global coordinator, which estimates or re-estimates the state of the interconnection lines and synchronizes the results, obtaining the global estimation of the system.

The main advantages of the distributed estimation vs. the global estimation are that each competitor on the electricity market can benefit from a global estimation while limiting its contribution to its own subsystem, and the precision of the global estimation is improved, each subsystem's state being estimated more accurately at local level.

The Smart Grid concept

The smart grid concept aroused from the necessity to align the outdated existing power systems with the challenges brought on by the new operation conditions imposed by the liberalized market model. Although the concept is discussed in the literature from different points of view, some from a local, even single consumer perspective, up to transnational grids, developing a smart grid means, at core, using available technologies such as smart metering, superconductors, renewable or distributed energy sources and intelligent load response to reduce pollution and costs and improve the system security and efficiency of the entire system.

The key component for having a smart grid is the existence of a real time monitoring and wide area control system (RTMCS). One of the challenges that such a RTMCS should meet is the fast and accurate assessment of the operating state of a wide area power system operated by several TSOs belonging to competing utilities. For this, load flow calculations are often substituted as real time evaluation tools with static state estimation algorithms, coupled with modern intelligent measuring devices such as phasor measurement units, for improving the precision of the analysis.

References:

[CERTS 99] Consortium for Electric Reliability Technology Solutions Grid of the Future - White Paper on Real Time Security Monitoring and Control of Power Systems, December, 1999

[Gavrilaş 09] Gavrilaş M - Recent Advances and Applications of Synchronized Phasor Measurements in Power Systems, Proc. Of the 9th WSEAS/IASME International Conference On Electric Power Systems, High Voltages, Electric machines (POWER '09). Vol. Recent Advances in Electric Power Systems, High Voltages, Electric Machines, ISSN 1790-5117, pp. 82 – 91

[Georgescu 00] Georgescu Gh, Rădășanu D. - Transportul şi distribuția energiei electrice, vol- I, Editura Gh. Asachi, Iaşi, 2000