

INVESTIGATION ON THE EXPECTED DYNAMIC BEHAVIOUR OF VERY LARGE SYNCHRONOUSLY INTERCONNECTED SYSTEMS

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Summary – *The paper addresses the dynamic phenomena that can arise in very large synchronously interconnected systems at the occurrence of perturbations. Firstly, an overview of the present trend in extending interconnections in Europe and the neighbouring regions is provided. Then, after a classification of the dynamic phenomena, the interactions between the different kinds of transients are presented. As a matter of fact, in large systems the cross-coupling between the dynamic evolution of the system and the action of the control loops makes it difficult to discriminate between angle and voltage instabilities. To this purpose, examples derived from the study of the Mediterranean Electric Ring are shown. Finally, the most appropriate actions to be undertaken to enhance the dynamic security are presented. Beyond an adequate primary frequency control and well-tuned PSS, possible measures to enhance dynamic security can be classified in soft (e.g.: defence plans) and structural (e.g.: installation of SVCs) measures.*

Keywords: *Synchronous interconnection, Steady-state stability, Transient stability, Long Term dynamics, Voltage stability, Power transfer dynamic limits, Modal analysis, Time domain simulations, Defence plans.*

1. INTRODUCTION

Since the beginning of last decade we are witnessing a remarkable boost to interconnect power systems previously isolated or to strengthen the interconnections within synchronous pools. This trend is presently ongoing almost all over the world with outstanding examples in China [1], where inter-tie projects between major regional systems are planned by the year 2010, in India [2], where several projects, mainly based on HVDC technology are in progress to ensure greater reliability and security levels and in the Indochina region [3] where

the interconnections among Laos, Thailand, Cambodia and Vietnam will bring substantial benefits in terms of reduction of fuel costs and increased reliability.

In South America the tendency towards the creation of regional economical blocs (e.g.: ALADE, MERCOSUR) is accelerating electricity trade to better exploit the primary energy resources and this is favouring several interconnection projects [4] among which we may recall:

- Bolivia-Brazil, where the natural gas of Bolivia can fruitfully be exploited to modulate the hydro power of Brazil;
- Argentina-Uruguay-Brazil, seeing Argentina basically as the exporting country towards Brazil, while Uruguay has a substantial wheeling role;
- North-South interconnections in Brazil enabling to better integrate hydro inflows in the Brazilian states[5].

As for Europe, the expected evolution and reasons for the enlargement of the interconnected systems in the Continent and the neighbouring regions will be presented in sect. 2. More information about interconnection projects around the world can be found in [6].

As it can be easily understood, the main driving forces prompting to the extension of interconnected systems derive from a mix of technical (enhanced reliability and security levels) and economical factors (international trading of electricity as a consequence of power market implementation).

However, the potentially enormous benefits from interconnections can be strongly reduced or even cancelled if the behaviour of the overall system isn't carefully examined in advance with special concern to its dynamic evolution facing the occurrence of perturbations. This paper will namely address the analyses to be carried on for the investigation of the dynamics of large interconnected systems and for the definition of the most appropriate remedial actions to be

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undertaken. Applications to the future tri-continental interconnected system around the Mediterranean basin will be shown in order to highlight the complex dynamic phenomena that can arise. As a matter of fact, the dynamic evolution of very large systems is affected by the mutual influence of different control loops making it difficult discriminating the original cause of possible instabilities. Beyond the necessary expertise of the planner, the use of a power system simulator with enhanced Graphic User Interface (GUI) and diagnosis functions is of great help. To this purpose, the power system simulator SICRE [7], developed by CESI, proved to be very effective for applications to large networks, even ill-conditioned such as the South-Eastern Mediterranean grid.

2. EVOLUTION OF THE SYNCHRONOUSLY INTERCONNECTED POOLS IN THE EURO-MEDITERRANEAN REGION

The continental European power system underwent deep changes since the beginning of '90s. On the one hand, the events that affected the Eastern European interconnected power system (IPS) led to the separation of former-East Germany, Poland, Czech and Slovak republics and Hungary from IPS. These countries in 1996 started the synchronous operation with the western European pool UCTE [8]. On the other hand, the war events occurred since summer 1991 led to the separation of Serbia-Montenegro, FYROM, Greece, Albania and part of Bosnia-Herzegovina from the main continental grid, creating the so-called "second UCTE synchronous zone", synchronously interconnected with Romania and Bulgaria, which in turn disconnected from IPS.

As a consequence, the present situation of the Euro-Mediterranean pools is that shown in Fig. 1.

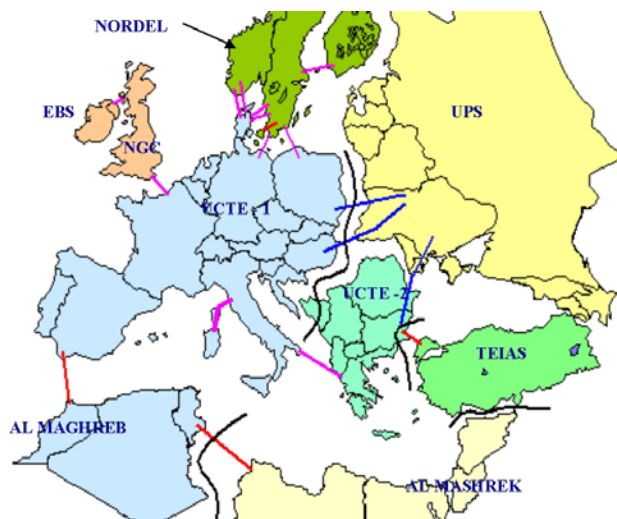


Fig. 1 – Synchronous blocs in the Euro-Mediterranean region.

The issue in 1996 of the European Directive for the creation of a single Internal Electricity Market (IEM) in EU [9] is putting more and more pressure to eliminate

physical barriers in cross-border transactions. To this purpose, in December 2001 the European Commission unveiled a 3-part package designed to boost EU energy infrastructures, establishing a "minimum level" of interconnection capacity to be reached by each country in a reasonable time delay [10]. The "minimum level" of interconnection capacity has been fixed at 10% of the installed generation in each country with higher values for transit countries.

In parallel to the above process, the enlargement of the IEM is already envisaged. Three areas are going to be involved with different time horizons (Fig. 1):

- accession countries, including Turkey, and the South-East Europe countries not yet candidate to join EU;
- the CIS countries [11];
- the South-East Med countries [12].

All that requires a huge effort in building new network infrastructures to smooth the physical barriers (e.g.: the interface between Central and Western European countries represents a bottleneck against a further increase in the East-West power transactions [13]). Moreover, the enlargement of synchronously interconnected pools must be preceded by accurate checks on the expected performances of the new system, mainly as regards its dynamic behaviour

3. DYNAMIC BEHAVIOUR AND CRITICAL PHENOMENA

When increasing the system size through an extension of the interconnections, the most important dynamic phenomena to be considered are as follows:

- Possible electromechanical oscillation modes at low damping and, more in general, possible steady-state stability problems, mainly due to power transfers along very long distances (due to extended longitudinal or ring structures)
- Transient instability of large network areas, sometimes involving an entire country or more than one country, subsequent to loss of important connections and evolving on a relatively long time scale
- Critical transients due to long term dynamics, with voltage instability, or with unacceptable final operating points due to voltage collapses
- Possible final operating conditions critical in terms of operability because of low voltage profiles or high current values.

All such phenomena should be carefully examined in order to characterise the system dynamic behaviour in terms of:

- steady state stability
- transient stability
- long term stability
- post fault equilibrium point existence

The aim of the analysis is to grant the system security for a great number of operating conditions and to verify

the feasibility of the most convenient power exchanges derived from economic studies.

Steady-state stability analysis

Steady-state stability, mainly related to damping of electromechanical oscillations, is the first aspect to be analysed as regards the dynamic behaviour of the system in the planning phase or when interconnecting power systems which were previously isolated [14]. Therefore, a complete linear analysis should be carried out, on the basis both of eigenvalues and eigenvectors computation with reference to a complete detailed model. This analysis is devoted to identify the main oscillation modes, determine their damping, evaluate the influence of a good primary frequency control and the effect of well designed power system stabilisers.

Transient stability

Once designed suitable control functions to obtain stable equilibrium points, a complete transient stability analysis should be performed, in order to verify the dynamic security against any credible large disturbance (contingencies), such as the loss of a single important connection or a single important unit. Additionally, more severe contingencies, composed of more than one event, can be applied to the system to detect possible, although less probable, transient stability problems.

The aim of these checks is double: to evaluate the transient stability limits of the system, mainly in terms of maximum power transfers among countries or extended areas; to introduce suitable stability margins by designing adequate control actions and/or defence plans.

Long term stability

Together with the transient stability analysis, stability on more extended time scale relevant to all the slower control loops acting on the power system has to be verified. Such are the frequency and load-frequency control loops, the over and under-excitation control loops of the alternators, the dynamic associated to TCUL, the dynamic associated to the various controls present on the supply systems of the different types of units.

In case of large interconnected systems, this analysis is very important as the electromechanical transients and the slower transients (due to the aforementioned controls) often interact with mutual effects on each other.

For the before said reasons it turns out difficult to discriminate between voltage stability and angle stability, and, in addition, the remedial actions used for increasing voltage stability, may significantly influence the transient stability.

Post-fault equilibrium point existence

Another important question for extended systems is to verify not only the stability of the trajectory, but also the existence of the post-disturbance equilibrium point. The lack of final equilibrium points is practically revealed by possible voltage collapses.

The voltage collapse, detected by a non convergence of the load flow, is due to the lack of a feasible operating condition. The dynamic simulation, in case of voltage collapse, presents a more or less slow decline of the voltages followed by an angle instability, due to static power transfer limits reaching.

3.1 Critical perturbations

The list of disturbances to be analysed includes credible contingencies and extreme contingencies: the first ones refer to a N-1 analysis and consist of tripping of a single connection or a single group; the second ones include tripping of more than one group or more than one line or a combination of tripping of lines and groups.

It seems reasonable to include in the list of credible contingencies also the double circuit lines on the same tower and the cases in which the tripping of the first line causes a cascade tripping of the other in parallel connections causing some area separations.

It shall be noted that in very few cases a contingency that is credible in one situation can become extreme in different operating conditions, depending upon the transits and the load flow solutions.

3.2 Electromechanical modes and frequency control

The analysis of the steady-state stability of synchronously interconnected systems, starts from the examination of the electromechanical natural oscillation modes of the network.

To obtain information on the oscillation modes and, above all, the relevant damping, a two-stage approach based on a mix of modal analysis and time domain simulations has been applied by the authors to a large scale system: the future Mediterranean Electrical Ring (MEDRING). A preliminary phase, based on modal analysis performing the computation of eigenvalues and eigenvectors with a simplified model (machines represented with a second dynamic order), allows to identify periods and oscillation modes starting from a network topological structure. Then, resorting to time domain simulations with more complete models of generators and regulators, the assessment of the oscillation damping is carried on.

Electrical systems of very large geographic extension can be characterised by electromechanical oscillations of very low frequency. This behaviour is particular evident for networks with a longitudinal structure, where oscillations with extremely slow periods can be observed. For instance, the planned Mediterranean ring is characterised by a slow electromechanical oscillation with a period in the range of 8-16 s depending upon the operating conditions and the system structure. In case of the whole ring closed, the relative oscillation amplitudes referred to the slowest period (8 s) are shown in *Fig. 2* where it is possible to note that the South-East countries oscillate against the European ones with an electrical

centre in Morocco; for shorter periods, oscillations became more local.

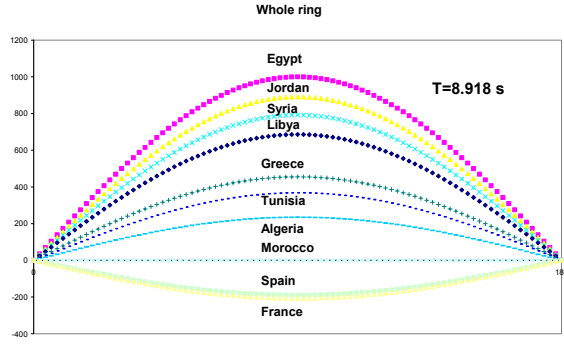


Fig. 2 – Relative oscillation amplitudes with the Mediterranean electrical ring closed

The opening of the ring in the East part (Syria-Turkey) leads to a longer period that interests basically the long antenna created (Fig. 3)

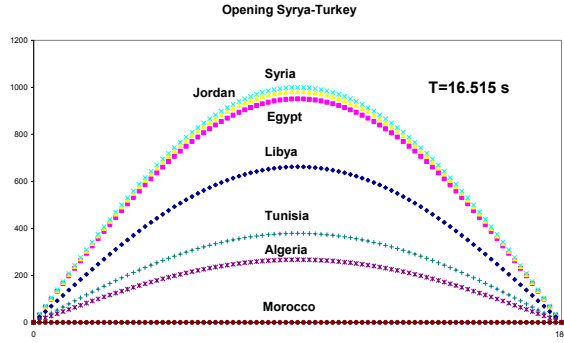


Fig. 3 - Relative oscillation amplitudes with ring opened between Syria and Turkey

It has to be remarked that the slowest oscillations are normally well-damped thanks to the highly positive contribution to damping by the primary frequency control loops of the power plants. This behaviour, which can be explained in analytical terms, is evident because an oscillation frequency around $0.07 \div 0.13$ Hz belongs to the "frequency range" of primary frequency control. Therefore, for a good damping of the slow electromechanical oscillation modes an effective primary frequency regulation is recommended. Fig. 4 shows a suggested block scheme for a frequency control of "canonical" type, valid both for thermal and hydro units, with a transfer function:

$$P_m(s) = F[f(s)/f_n, P_{rif}(s)] = 20 (1+3s)/(1+10s).$$

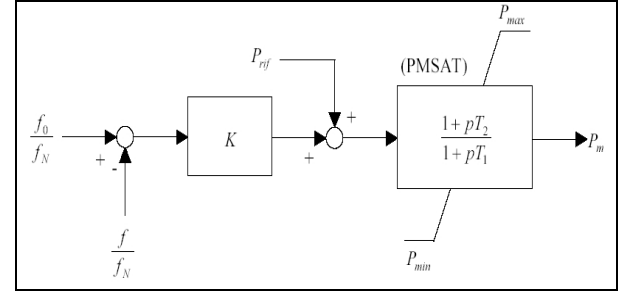


Fig. 4 – Primary frequency control

In order to obtain a good frequency control in large interconnected power systems, it is necessary to take into consideration also all the remaining (inter-area and local) electromechanical oscillations (periods in the range from 7 to 0.4 s). These oscillations proved to be well-damped by using Power System Stabilisers, with usual values of gains of the stabilising signals derived from the generator speeds and delivered active powers. The corresponding control schemes are presented in Fig. 5.

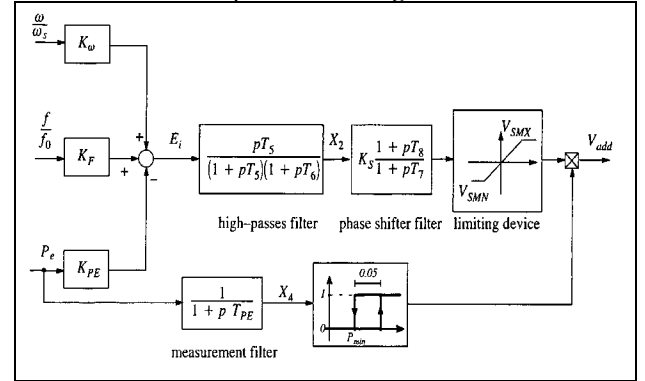


Fig. 5 - Block diagram of the model of a PSS device

The importance of adequate PSS for all the most important generation units of a system is highlighted in the cases illustrated in Fig. 6, where different transients obtained from simulations applied to the MEDRING are presented, with and without PSS on the largest units.

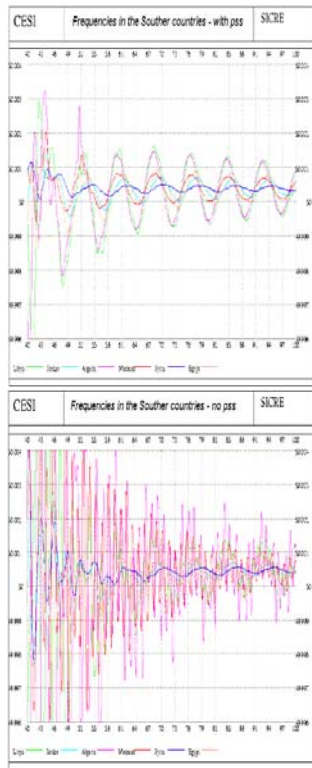


Fig. 6 - Comparison of frequency oscillation with and without PSS devices

3.3 Interaction between primary and secondary frequency control

In large and stretched synchronous interconnected systems, very slow transients may arise at the occurrence of perturbations. This condition is evident in the MEDRING system, particularly when opening the ring in its Southern part in the presence of heavy power transfer. As a consequence, while the primary frequency control is still working, because of the interaction with the slowest electromechanical modes of the network, the LFC action (or secondary frequency control) starts to be no more negligible. The latter control loop acts normally with slower time constants, in the order of some tenth of seconds. The combination of the effects of electromechanical oscillations, primary frequency control loop and LFC causes still slower transients for the system.

For such a reason, in order to detect possible instabilities, the time domain simulations have to be prolonged at least up to about 100 s. or more.

Moreover, for such extended networks, it is not possible to assume the hypothesis of the same frequency for the entire system, even in case of long term dynamics. The consequence is a response function of the frequency error that depends upon the proximity to the disturbance, and a different speed transient for each country for a long time. As an example, in the MEDRING case presented in Fig. 7, relevant to the opening Turkey-Syria section (exchange 210 MW), the

action of the primary control is still evident after 30-40 s (see evolution in the phase angles). The regime is reached after about 2 minutes.

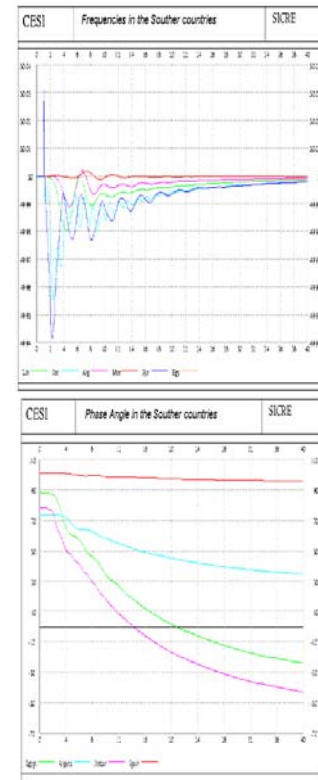


Fig. 7 - Frequencies in Libya-Egypt-Jordan-Syria-Algeria-Morocco - Phases Egypt, Algeria, Jordan, Spain

3.3.1 Reclosure problems

A manoeuvre that may reveal critical is the closing (or re-closing after opening) of an interconnection link when the system is still synchronously connected through a second path of very high impedance, as seen from the closing points. In this case, the phase difference of voltages (still synchronous) at the end of the re-closing breaker, can't be easily controlled

The reclosing manoeuvre might present high risk of distance protections intervention immediately after the reclosure. Particular attention, therefore, shall be paid in defining the maximum admissible phase difference and in obtaining such a difference in normal operating conditions.

3.4 Discrimination of voltage collapse and transient instabilities

An important task, in the case of a very extended interconnected system, consists in detecting, monitoring and understanding the nature of possible very slow transients arising in the systems. Severe transients may arise as consequence of contingencies determining some weaknesses in the system structure. As shown above, in such cases, electromechanical oscillations at very long period can interact with the primary and sometimes also the secondary frequency controls, causing slow frequency variations and consequently slow voltage

phase variations. The slow voltage drops observable during the transients can be identified either as voltage collapse or evolution of angle instabilities.

An exact understanding of the nature of this critical phenomenon is very important in order to adopt the most suitable countermeasures both in planning stage and in operation. Appropriate operation rules in conjunction with possible automatic control actions should be adopted to guarantee the system security and alleviate emergency situations.

The difficult task of discriminating between angle instability, voltage instability and voltage collapse may be accomplished by resorting to time simulation functions able to switch from a description of the system through a complete model taking into account simultaneously all the dynamics, fast and slow, and a simulation function utilising a reduced model neglecting the electromechanical transients (see sect. 4). The model reduction is achieved, by considering only one speed for all the machines of connected areas. Through this technique it is possible to separate, in case of slow dynamics, the transient angle instabilities from the voltage instabilities and the voltage collapse.

More precisely, the criterion adopted is to pass from the STD (short term dynamics) simulation to the LTD (long term dynamic simulation), as the last one takes into account only mean frequency transients, neglecting loss of synchronism among machines. If a post-contingency equilibrium point is found, taking into account only the slow dynamics, possible other instabilities are to re-conduct to transient angle instabilities.

An interesting system for studying this type of questions is the MEDRING, because of its filiform structure in the Southern part. In fact, following system splitting (ring opening in the Southern part), it is possible to observe in the simulated transients very slow variations of electrical quantities both in cases leading to stable steady-state conditions and in case of instability. This phenomenon can be explained by remembering that the slowest electromechanical modes last for so long to interact with the primary frequency control loop, causing even slower transients and the consequent need to prolong the simulations to detect possible instabilities.

In the MEDRING system, nearly all the instabilities, caused by the opening of the ring in its Southern part, are characterised by slow transients leading to voltage collapses for reached static power transfer limits. Such phenomenon is illustrated in Fig.8, where, after the opening of Turkey-Syria interconnection, the voltage collapse, particularly evident in Egypt area, is seen to precede the frequencies deviations (Fig. 9) with consequent angle instability.

The voltage collapse evolves on a time frame of tenths of seconds, allowing us to design automatic control actions to avoid the phenomenon. On the contrary, the loss of synchronism of areas of network is in general

faster and requires control actions more rapid and more difficult to implement.

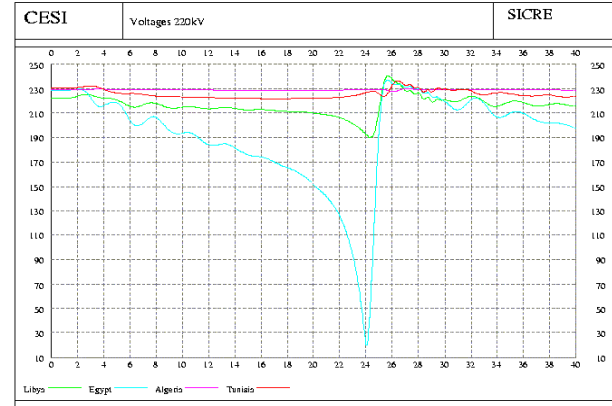


Fig.8-Voltages 220 kV Egypt-Algeria-Libya-Turkey (Active power exchange before fault from Syria to Turkey 474 MW)

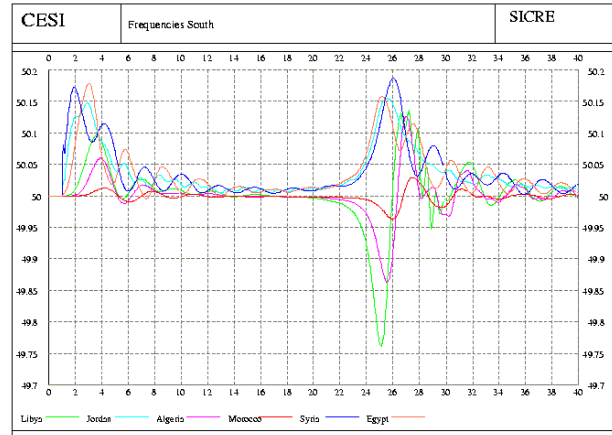


Fig. 9 -Frequencies South Libya-Egypt-Jordan-Syria-Algeria-Morocco (Active power exchange before fault from Syria to Turkey 474 MW)

4. SIMULATION TOOL

From what presented till now, it is clear that accurate and fast time domain simulations are becoming a mandatory task to analyse the electrical power system behaviour either at the operation stage (on-line or extended-real-time analysis) or at the planning and at the operational planning stages. Indeed, in large interconnected systems, static security analysis could give insufficient results whenever the system trajectory between the pre- and post-contingency steady state is strongly affected by the dynamics of the control devices and by the protection interventions.

One of the most suitable tool to investigate in depth dynamic phenomena is represented by the time domain simulation integrated with modal analysis. CESI recognised this need and, by applying a suitable time dichotomy strategy and an object-oriented approach, developed a general purpose power system simulator, named SICRE [7]. The SICRE simulator is able to adequately represent large time scale phenomena

spanning from transient stability (or Short Term Dynamics = STD) to long term dynamics (LTD), with a suitable commutation technique [7] between the two time frames (*Fig. 10*).

The SICRE simulator was conceived in order to comply with a large variety of application domains, mainly related to:

- post-event analysis and reconstruction of major disturbances;
- quasi-on line dynamic security analysis;
- testing and comparing control strategies and defence plans;
- stability assessment in planning and operational-planning stages;
- checking of system protection characteristics and settings;
- planning and testing restoration plans;
- verification and tuning of parameters related to various control loops;
- training engineers and dispatch operators.

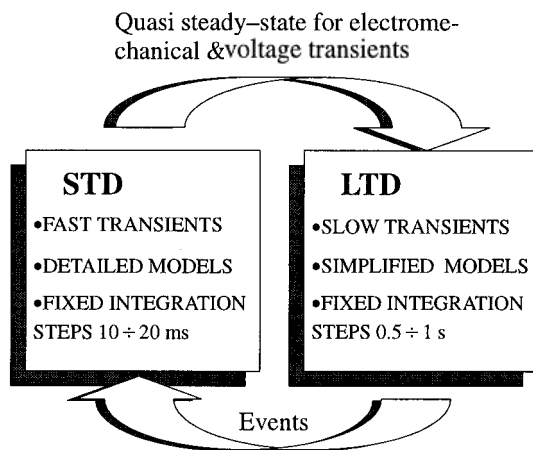


Fig. 10 - From STD to LTD and vice versa

To attain the above mentioned targets, two different simulation modes of SICRE are foreseen:

- mode 1: in such a mode, both STD and LTD are simulated and system components are modelled with different detail depending upon the dynamic conditions of the system (very high detail during STD, simplified modelling during LTD). A criterion for automatically switching from STD to LTD has been implemented;
- mode 2: where LTD only is simulated with simplified modelling of the components. This kind of application allows also meeting the additional requirement of real time simulation.

The efficiency of the SICRE simulator is proven by several studies performed on large electric systems [15].

5. ENHANCING THE DYNAMIC SECURITY

Dynamic constraints in the operation of large interconnected systems can strongly limit power transfers with a consequent reduction in the interconnection

benefits. Measures enhancing the dynamic security allow making less binding the dynamic constraints. These measures can be classified in:

- soft measures;
- structural measures.

Soft measures are essentially based on the adoption of special control schemes or defence plans aimed at preserving the system integrity and avoiding to spread the disturbances from the affected areas to the neighbouring ones. A defence plan is the ultimate response of a power system to incidents, which could lead to a major collapse of the whole system.

At the beginning defence plans were essentially based on local actions triggered by relay installed in critical lines and sensitive to loss of synchronism. Nowadays, more robust defence plans can be achieved through co-ordinated actions based on a set of preventive and curative measures [16]. The tuning of complex defence plans requires:

- efficient data exchange between utilities, in order to be able to simulate correctly the behaviour of the neighbouring system;
- appropriate definition of the scenarios to be analysed;
- mutual collaboration of the expert teams of the concerned utilities.

The mutual co-operation among the partners of the interconnected system can require:

- the on-line exchange of agreed measurements and signals;
- common studies on the system dynamic behaviour, in bilateral or multilateral way, for the off-line detection of potential critical situations during planning or operational planning studies;
- a co-ordination of the main steps for recovering the grid to normal operating conditions after common load shedding occurred.

An example of fruitful collaboration regards, in Europe, the interconnected Italian-French systems. The two grids are strongly interconnected by three 400 kV lines and one 220 kV line with a power transfer from France to Italy exceeding 3000 MW. The two systems adopt different defence plan policy [17].

The French one is based on the organization of the network in "islandable" areas, where the loss of synchronism is detected by the measurement of the voltage phase angle in the different areas. This plan is overlapped to the previously existing one based on local devices (Out-of-Step Relays: OSR) located at both end of predefined EHV lines in order to trip them automatically when voltage beats, characteristic of a loss of synchronism, occur in these lines. On the contrary, the Italian defence plan was tuned by taking into account the typical network structure. Indeed, in the Italian system it is possible to determine some critical "cutsets" (sections) along which, in particular operating conditions, the system could separate.

Structural measures to enhance dynamic security are based to the installation of devices having the capability to control specific electrical quantities, such as SVCs, series or shunt Thyristor Controlled Reactors and Capacitors, Back-to-Back or HVDC links. The installation of the above devices requires a non-negligible investment effort and its profitability shall be based on accurate analyses aimed at defining:

- the optimal location of the device;
- the size;
- the control strategy, especially for the converter stations in case of DC links;
- the enhancement of the power transfer.

With reference to the MEDRING system, examples of possible profitable structural measures are:

- installation of SVC (or similar devices) at the Egyptian-Libyan border to enhance voltage stability;
- installation of a DC link between Egypt and Jordan to increase the power transfer capability fully exploiting the capacity of the submarine cables between the two countries.

6. CONCLUSIONS

After reviewing the complex dynamic phenomena that can arise in large synchronously interconnected systems, the following main conclusions are proposed:

- in large systems the "classical" time dichotomy between transient stability, frequency and voltage dynamics is no more valid;
- as a consequence, in case of instability, it can be difficult to detect its primary cause and, then, to adopt the suitable countermeasures;
- advanced software tools, able to simulate the whole spectrum of dynamic phenomena are of great help for the planner;
- enhancement of dynamic security can be based to soft and/or structural measures. In both cases, detailed studies shall be carried on in advance to define their characteristics.

The presented examples of applications to the future MEDRING system, confirm and highlight the complex transients that may arise in large systems at the occurrence of perturbations. Similar situations might be experienced when synchronously interconnecting UCTE with UPS/IPS and this calls for the execution of accurate dynamic studies before starting the joint operation.

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