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Monitoring and Control of Process and Power Systems : Adapting to Environmental Challenges, Increasing Competitivity and Changing Customer and Consumer Demands

Status report prepared by the IFAC Coordinating committee on Process and Power Systems

Denis Dochain * **Wolfgang Marquardt** ** **Sang Chul Won** ***
Om Malik **** **Michel Kinnaert** † **Jan Lunze** ‡

* *Cesame, UCL, 4 av. G. Lemaître, 1348 Louvain-la-Neuve, Belgium*
e-mail : denis.dochain@uclouvain.be, fax : 32-10-472180
** *RWTH Aachen, Lehrstuhl für Prozesstechnik*
Templergraben 55, 52056 Aachen, Germany
*** *Dept Electr. Eng.,Pohang Univ. of Science of Technol.*
San 31 Hyojadong Namku, Pohang 790-784, Korea
**** *ECE Dept. Univ. of Calgary, Calgary, T2N 1N4 Canada*
† *Control Engineering Department, ULB*
CP 165/55, 50 av. F.D. Roosevelt, 1050 Brussels, Belgium
‡ *Lehrstuhl für Automatisierungstechnik, Rhur-Universitat Bochum, Germany*

Abstract: Process and power plant control, along with fault detection/isolation are being addressed by significant on-going research with many theoretical developments focused on improvements for all of these major industrial applications. This report provides an overview of the current key problems, recent accomplishments, trends, and forecast of anticipated developments in this application field.

Keywords: Process systems, power systems, fault detection and isolation

1. INTRODUCTION

Most major industrial systems in todays economy use automation and control systems technology. These industrial systems focus on many diverse and very important fields including many process control industries, of which Chemical Processing is a major example. Likewise, Power Plants and Power Systems as well as Mining, Mineral, and Metal processing are similarly important throughout the entire industrial world. A critically important support technology which impacts virtually all control-related industry is Fault Detection and Isolation.

The world has undertaken major changes over the last decade, if not to say over the last few years. The environment and the climate are more and more a major issue for tomorrow. This, but not exclusively, has a major impact on the demands from the customers of the industrial companies and from the consumers. For instance, in the field of energy production, there is an increasing demand from the consumers for renewable energy. Nanotechnology and biotechnology are also two major fields that are pushing to the development of new control concepts and to the enlargment of the applications spectrum.

Process and power plant control, along with fault detection/isolation are being addressed by significant on-going research with many theoretical developments focused on improvements for all of these major industrial applications. This report provides an overview of the current key problems, recent accomplishments and trends, as well as a forecast of anticipated developments within this very important field of industrial applications.

2. CURRENT KEY PROBLEMS

Most of the key problems in chemical, mining, mineral, metal, power generation/distribution, and other processing industries stem from the paradigm shift that can be observed throughout the power and process industries. Two areas have to be roughly distinguished in the context of the process industries : (1) manufacturing of well-established bulk chemical products and (2) development and production of specialties as well as particulate and functional products. Specific key problems can also be identified for power plants and power systems related to restructuring due to de-regulation and development of distributed generation from renewable energies, and in the field of Fault Detection and Isolation (FDI).

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2.1 Bulk Chemical Manufacturing

The production of well-established bulk chemical products faces increasing economical pressure due to saturating markets, maturing technologies, and a steadily growing number of potential suppliers in the developing countries who are offering high quality products at competitive prices. Production can only be successful economically if the processes are driven to their true potential in order to reduce the production cost and at the same time achieve a maximum of flexibility. High performance multivariable control is a key to drive the processes closer to their constraints in order to achieve the desired high profits. Any reduction of the variance in the control loop will ultimately allow operators to move the process closer to quality, equipment or safety constraints. Variance reduction directly translates into improved economics because in most cases, economically operating points are typically located on one or more of the process constraints. The technology for the design and realization of high performance model-based constrained control systems, e.g. typically linear model-predictive controllers, for large-scale continuous plants with a large number of manipulated and controlled variables at reasonable engineering effort is one of the key challenges faced by industrial practice. The embedding of such controllers in the automation hierarchy as well as the monitoring and continuous improvement of such controllers remains a major challenge. In this context, model-based supervisory control systems that bridge the gap between the human operator and the automation system to guarantee economical and safe operation even in abnormal situations are of significant interest.

Model-based control of large-scale continuous plants has to evolve from set-point following and disturbance rejection to any-time economically optimal despite the highly dynamic environment determined by the supply chain. Obviously, the duration of close to stationary steady-state plant operation is going to be reduced. Numerous transient phases, for example due to grade or load changes, are more and more required to achieve the required agility of the plant to meet demands of flexible just-in-time production. Typical examples are refineries, bulk petrochemical and bulk polymer plants. Linear control technology often is not sufficient to achieve the objectives of agile plant operation. Hence, model-based control and operation support systems based on rigorous nonlinear and large-scale physicochemical process models are more appropriate in these situations. This shift in control technology results in a number of well-known challenges including development and maintenance of rigorous process models of sufficient closed-loop predictive capabilities, nonlinear model reduction technologies, nonlinear estimation and reconciliation techniques, nonlinear optimal control algorithms, and highly efficient numerical methods for the solution of large-scale nonlinear dynamic optimization problems to name only the most important. Ultimately, discrete decisions have to be taken by the control system together with the determination of the control profiles which are continuous in time. These discrete degrees of freedom stem on the one hand from the control logic, for example superimposed by the supervisory control system, and on the other hand from the purely discrete decisions which characterize plant operation. The scheduling of campaigns for the production of various process grades is a typical example of this kind. Consequently, more systematic methods for hybrid (discrete-continuous) nonlinear control as well as improved numerical algorithms for the solution of mixed-integer dynamic optimization problems are required.

2.2 Specialty chemicals manufacturing

The manufacturing of specialty chemicals, particulate or even functional materials requires related but different technologies. Time to market as well as the low volume often suggests batch rather than continuous production processes. The effort and time which can be spent for modelling is limited, uncertainty in first principles models is inevitable and has to be accounted for in a systematic way during the development of model-based solutions. Ideally, the control technology should be refined from very simple control schemes to more sophisticated model-based solutions in parallel to the process development from bench to production scale. An appropriate integration of process and control systems development should account for the accumulation of process knowledge and systematically transfer this knowledge not only into the improvement of the product and the manufacturing plant but also into the improvement of the control and operations support systems. Ideally, the process and its control and operations support system should mature simultaneously, driven by the continuously evolving process understanding.

The control technologies required for batch processes have a lot in common with those for continuous processes operated in a large envelope of operating conditions. Nonlinearities and transient operations are key characteristics which have to drive the development of control technology and operation support system.

Because of the high added value and complexity of these products, quality control is often more important and also more difficult to achieve for speciality, particulate or functional products. This is due to the fact that the direct measurement of quality relevant process quantities is even more difficult than in the manufacturing of bulk chemicals. Sophisticated measurement techniques stemming from analytical chemistry have to continue to move into the process environment. Obviously, appropriate algorithms calibration and estimation algorithms have to be added to get valid information of the state of the process materials.

2.3 Mining, Mineral and Metal (MMM) processing

The Mining,Mineral and Metal processing (MMM) industry has been faced with drastic environmental changes. In response to the constantly increasing demands and massive orders from customers, it has become inevitable for the companies to maximize the productivity of existing facilities. High-end products have become gradually more important; consequently, realignment in the global MMM industry has to be further accelerated.

Similar to other industries, the MMM industry is currently confronted with three major problems associated with industrial control: design of accurate process modeling, development of advanced control strategies, and realistic approaches to system analysis and synthesis for complex systems. Moreover, one of the general problems which will soon affect the industry within the next few years is loss of skilled operators due to retirement. If these problems cannot be solved, the future of MMM industry will be greatly jeopardized. Some of the specific key problems existing in each MMM fields are the following. In the mining industry, grinding consumes about 50% of the electric energy; therefore, the development of new, effective grinding control and mining integration technologies are vitally in need. The extractive metallurgy of gold has problems in process dynamics and kinetic modeling. The relationship between gold distribution in particles (particles size, gold grains size, associated minerals and exposure of gold to reagents) and cyanidation kinetics is still poorly quantified. The role of gold surface passivation on dissolution kinetics is also poorly modeled to this date. This is also true for the behavior of cyanidation within grinding mills. The automatic control of gold leaching processes is largely limited by the problems related to gold content measurement in solids and liquids. In mineral separation processes, the interaction between grinding and floatation is still poorly modeled, although it is a key to the optimization of the overall comminution/separation process.

The engineers also are experiencing difficulties in fine control of the metallurgical processes. In general, the main obstacle to automatic control of processes is related to the noise measurement and the number of immeasurable critical process variables, for instance furnace hold-ups and process load properties (temperature, composition, mechanical properties) in pyrometallurgical processes and grindability and floatability in mineral processing plants. Moreover, observers are difficult to design because of the lack of good phenomenological models as discussed above.

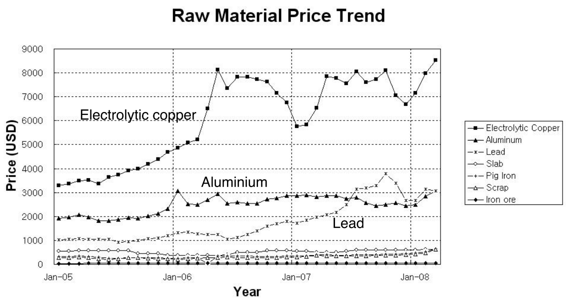

Fig. 1. *Raw material price trend*

Recycling and waste management are also key issues to be addressed not only to improve the productivity but also to protect the environment. Because raw material prices are going up, recycling is getting more important. Figure 1 shows the price trend of raw material in this triennium based on the report from the Korea Importers Association. The worlds most recycled material is steel; additionally, steels can be recycled indefinitely without alterations to their properties. Steel recycling is very beneficial because it saves energy (up to 75% when compared to iron ore steel making), conserves natural resources (1 ton scrap saves 1.5 tons of iron ore and 0.5 tons of coal), and reduces landfill waste. Thus, the steel recycling rate is rapidly increasing every year around the world. The recycling rate of steel can be defined by the ratio of recycled steel to the total crude steel produced. In 2004, the average recycling rate in EU was 58%, and in 2005, USA recycled an average of 75% of steel (steel can=63%, automobile= 102%) while Japan recycled about 89%. In 2006, the worldwide average of steel recycling rate was 42.3% (steel can=63%, automobile= 90%). There is definitely more room for improving the recycling rate, and solving these problems is key to sustainable growth of the MMM industry, where control technologies can play an important role.

2.4 Power Plants and Power Systems

With a history of development of over one hundred years, power systems are considered a mature technology. They have also been called the largest machine humans have ever built. However, they are continuously in a state of flux.

In more recent years, the unprecedented technological developments and economic evolution over the past couple of decades have had a tremendous impact on the electric utility industry. It has led to extended operation near congested mode with demand outstripping supply, less tolerance for extended maintenance, heavy reliance on information technology and a strong link between the technical and the financial tools as the tides of deregulation are changing the competitive landscape.

Other factors offering a challenge to this industry include the aging infrastructure, and production of CO_2 as a byproduct and its effect on the environment. A number of major blackouts in rapid succession in diverse parts of the world heightened awareness of security of the physical plant.

The experience of the electric power industry, subsequent to the restructuring and emergence of market environment in many countries of the world over the past 20 years or so, has highlighted a number of problems that have been encountered:

- the subject of relation between tariff for energy consumption and ancillary services;
- market mechanisms of management versus state regulation;
- adverse impact on reliability of electric power systems and power supply to consumers.

As a result, the transition to a competitive model of power industry organization calls for thorough and comprehensive studies.

2.5 Fault detection and isolation (FDI) systems

Fault detection, supervision and safety of technical processes cover a very broad research area which includes

- monitoring systems and systems for fault detection, isolation and identification
- ault tolerant control
- reliability estimation (including failure-mode and effects analysis (FMEA), dynamic reliability)
- risk and hazard analysis
- maintenance modeling and optimization

The emphasis of this review of the SAFEPROCESS activities will be on the first two points, although the connection with the other points will be stressed in the forecast section.

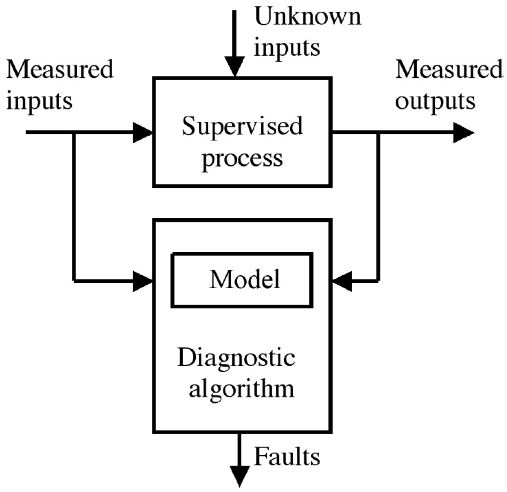

Fig. 2. *Structure of model-based diagnosis*

The main idea of model-based diagnosis is shown in Figure 2. A diagnostic system evaluates the sequences of measured inputs and outputs together with a model of the supervised process in order to detect, isolate or identify faults. If the measurement sequences are inconsistent with the model of the fault free process, the process is known to be faulty. If consistency occurs with the model of the process subject to fault f, the fault f is called a fault candidate. The main problem of fault diagnosis is to develop methods for finding the set of fault candidates for a given system.

For continuous-valued and discrete-event systems the diagnostic methods differ due to the different nature of the dynamical systems under consideration. For continuous systems, a typical structure for fault detection, isolation and identification is made of two parts: a residual generation module and a decision system (Figure 3). The residuals are signals that, in the absence of faults, deviate from zero only due to modeling uncertainties or disturbances, with nominal value being zero or close to zero under actual working conditions. If a fault occurs, at least one residual deviates from zero with a magnitude such that the new condition can be distinguished from the fault free working mode. This deviation indicates the inconsistency of the process behaviour with the model used by the diagnostic system. The role of the decision system is to determine whether the residuals differ significantly from zero and, from the pattern of zero and non-zero residuals, to decide which is (are) the most likely fault(s), and in turn, which component(s) could be the origin of the fault(s) [1].

Such systems can be used for health monitoring of a technical process with a view to maintenance planning. They are also a building block of an active fault tolerant control system. In this case, the decision module can trigger a reconfiguration action upon occurrence of a fault. This action should assure that the technical process keeps fulfilling its main mission(s) despite the presence of the fault, possibly with a degraded performance.

Currents problems in fault detection and isolation (FDI). Passive and active systems for fault detection and isolation should be distinguished. In the first one, no external solicitation is introduced in order to help exhibiting the fault(s). On the contrary, in active FDI an external solicitation is designed in such a way that, when applied to the supervised process, it excites the modes in which the faults show up most significantly.

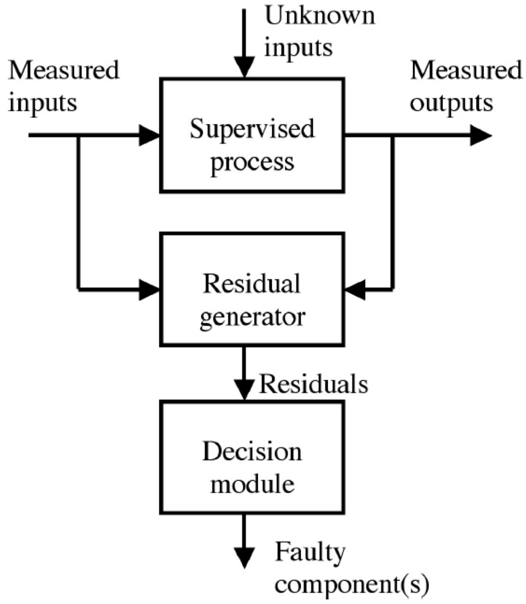

Fig. 3. *Model-based diagnosis of continuous systems*

For both passive and active approaches, performance robustness of the fault detection and isolation systems is still the object of significant research work. The problem is to be able to detect and isolate faults as soon as possible despite the presence of structured or unstructured modeling uncertainties, as well as non measured external disturbances acting on the process.

Extension of the existing FDI approaches to a wider class of systems, like multi-dimensional systems, systems described by algebro-differential equations and hybrid systems is the object of continued research effort.

For discrete-event systems, the complexity of the model and, hence, the complexity of the diagnostic problem is a main concern of current research. Modular, hierarchical and decentralized diagnostic method are currently being developed [13][15].

Whereas the diagnosability analysis of continuous systems is well established, analysis methods for discrete-event systems are still in their infancy. Particularly for nondeterministic systems, there is a debate about reasonable definitions of diagnosability, where some notions claim the possibility to uniquely determine the present fault whereas others accept ambiguous results [11].The latter is appropriate for stochastic systems.

Currents problems in fault tolerant control. Fault tolerant control is the object of significant research activities, particularly with a view to chemical process applications, but also in application areas outside of the scope of this paper like aerospace and vehicle.

Both passive approaches and active ones are considered. In the first ones, faults are accounted for by modeling uncertainties, and a single controller is designed to achieve the required performance both in normal operating modes and upon occurrence of the considered faults. In the second case a system for fault detection, isolation, and possibly identification is used to determine the faulty component and the severity of the fault. This information is then exploited within a reconfiguration mechanism that modifies the control law, and possibly the actuators and sensors that are used, in order to fulfill the main missions despite the presence of faults. In most recent publications either sensor or actuator faults are considered. In the first case, the authors aim at detecting and identifying sensor faults like bias and compensating for them. In the second case, stuck actuators are often considered and an appropriate redistribution of the control action over alternative actuators is determined.

A distinct research line is dealing with the evaluation of the reliability of fault tolerant control systems. In this case a priori knowledge on the probability of occurrence of each fault is assumed to be available, as well as a characterization of the imperfections of the FDI system. The later are expressed in terms of transition rates of the FDI system from one mode to another, each mode corresponding to specific healthy or faulty operating conditions. The aim is then to determine the probability that the FTC system will keep the required performance level during a specified time period.

A wider issue is the development of a systematic methodology to define the structure, the FDI algorithms and the control algorithms within a FTC control scheme, in such a way that a prescribed reliability is achieved.

Fault tolerant control of systems over networks is also a topic on which significant focus is seen in the last few years. Data networks bring about a new flexibility of the information structure of the diagnostic system, but issues like data loss, uncertain transmission delays and decentralized supervision and control are key problems in this context. Important applications include power systems, railway networks, communication networks and the combined on-board/off-board diagnosis in the automotive field.

3. RECENT ACCOMPLISHMENTS AND TRENDS

3.1 Chemical process control

There have been numerous interesting developments in recent years which have advanced the field of chemical process control. Some important developments are merely listed in the following without trying to be comprehensive.

1) Numerical methods for dynamic optimization and control (large-scale linear and nonlinear MPC algorithms, parametric programming, dynamic optimization of hybrid continuous-discrete systems, adaptive parameterization methods in dynamic optimization).

2) Linear and nonlinear MPC algorithms (design for nominal stability of nonlinear MPC, robustness of linear and nonlinear MPC, decentralization of MPC, offset-free tracking of MPC, output feedback MPC, feedback MPC schemes, integration of predictive control, dynamic real-time optimization and scheduling (INCOOP project)).

3) Nonlinear estimation (design of nonlinear constrained estimators for stability (in the sense of convergence), techniques based on system inversion, robust estimators).

4) Control system performance assessment (single and multi-loop techniques, multivariable control, stationary as well as transient operation).

5) Tuning procedures for linear controllers (single loop PID, tuning rules and self-tuning algorithms, multi-loop PID schemes, tuning rules for specific configurations, multivariable (predictive) controllers).

6) Monitoring and fault detection (further development and application of statistical techniques (PLS, PCA etc.) to batch and continuous processes, multi-scale monitoring methods, data mining and process visualization techniques).

7) Batch process control (batch-to-batch control, NOC tracking to facilitate optimal control implementation, statistical process control methods, iterative learning control, particulate process control (e.g. crystallization), polymerisation reactor control, fed-batch fermentation control).

8) New sensor technologies (image processing for feedback quality control in combustion, food processing and multiphase processes, spectroscopic techniques for in-line concentration measurement in closed-loop applications, particle size distribution measurement in closed-loop quality control).

9) New areas of applications (biotechnology, biomedical, electronics processing, advanced materials, pharmaceuticals).

3.2 Mining, Mineral and Metal (MMM) processing

Various industrial control methodologies have been applied to improve the performance of each control loop of processes. Furthermore, more improvements have been made in plant-wide optimization, which maintains and controls set-points for those control loops, and applied in various MMM fields. In order to save the energy, alternative solutions are presented to minimize specific power consumption by extending the equipment availability and producing the right amount of anticipated power consumption in the comminution processes. One of the challenges is the Real Time Optimization of gold extraction plants in an environment where gold mineralogy is changing as well as cyanide costs, gold market value and rules regarding rejects contaminated with cyanide.

Throughout the MMM fields, the plant-wide automation and optimization are being applied with the gradual development of instrumentation to directly measure necessary system variables and parameters. Especially, the visual image analysis is a trend in instrumentation for measuring particle size, ore composition and flotation froth properties; however, their use for the process control is still quite limited. In order to design state variable observers, the trend is to use techniques based on data reconciliation with mass and energy conservation constraints, models which require less effort compared to full kinetic models. However, the use of these techniques in a real time environment is still in its infancy because of the problem of having to take account of the process dynamics, i.e. of the mass and energy accumulation rates.

There have been large developments in the field of recycling. To renew old steels, there are two contemporary technologies available: BOF (Basic Oxygen furnace) and EAF (Electric Arc Furnace). BOF process uses 25 to 35 percent of old steel, and the final products include: automotive fenders, encasement of refrigerators and steel can packing whose major required characteristic is drawability. EAF process uses virtually 100 percent old steel, and its main products are structural beams, steel plate and reinforced bars whose major required characteristic is strength. So It can be said that steel recycling is closely related to EAF process; nonetheless, it has its own inherent drawbacks for using 100% old steel. Old steels may contain organic, non-organic impurities or non-ferrous alloying element such as Cu and Sn, which can not be removed metallurgically making the yield strength high and the drawability to be decreased. This is the reason why the steel from EAF process is not applicable to products whose required characteristic is drawability. The best way to prevent such drawbacks is to apply pre-processing called the shredding process, which crush the old steel products into pieces and generate three streams: iron and steel, nonferrous metal, and fluff (fabric, rubber, glass, etc.). The iron and steel are magnetically separated from other materials and recycled.

Applications of methodologies for fault detection and isolation are also important to prevent problems during operation. On-line measurement and monitoring system aid most on-line applications and improve flexibility, controllability, reliability, safety, efficiency, and performance. The internet use for remote monitoring and control applications is attractive because of its ubiquity, cost, and standardization of equipment and communication protocols. Recycling and waste management are new fields in the MMM industry, and these are viewed today as a way to minimize negative impacts on public health, environment and economy. In addition, much more care must be placed on the control and automation.

3.3 Power Plants and Power Systems

A majority of todays power system infrastructure was put into place in the second half of the twentieth century. During this period there has been a tremendous growth in load demand. The climate change being faced globally makes attention to the energy sector an imperative. This makes taking seriously the potential for radical changes to the current system. In addition, considering the number of incidents of major system blackouts around the world over the past few years, questions have arisen about the capability of these systems to meet the requirements of tomorrow. Various proposals and approaches are being considered to make power systems more suitable to meet the new conditions. Some of them are discussed below.

Renewable energy. Programs directed to increasing the share of renewable energy sources and efficiency of power generation by cogeneration of heat and power (CHP) are being considered and planned in many countries. As an example, the European Commission has set targets for renewable energy sources for each country in the European Union to increase the share of the renewable energy sources from 16% to 22% and the share of CHP to be doubled from 9% to 18% by 2010.

Extensive study is required to determine the impact of such large increase in dispersed generation on power system structure and power system operation. New control techniques will have to be developed to ensure secure operation of the power system with such a large share of mostly non-dispatched power sources and to determine the reserve power required to compensate so that power fluctuations can be limited to ensure safe network operation.

With substantial increase in renewable generation already installed and planned in the future, it is becoming a real alternative. With the generation connecting into remote, and generally weak, parts of the grid because of the remote location of many of the renewable generation, it will present specific challenges for the transmission network. Take for example wind power. If adequate supplies of reactive power are not provided while connecting wind farms, the grid could become unstable leading to outages.

This requires improvements in the power transfer capabilities of transmission lines. One recently developed technology that can help in increasing the transfer capabilities of transmission lines is the Flexible AC Transmission Systems (FACTS). FACTS devices form a group of technologies that are designed to improve the capability of long transmission lines and thus help improve AC transmission system stability. FACTS devices, integrated into a transmission system, can provide power flow control, reactive power compensation, loop flows and improved damping of power oscillations.

Communications. Communication infrastructure supports power grid operations. Better communications are key to providing improvements in security, efficiency and reliability.

The extreme complexity of present day power systems is being coordinated with rudimentary communication technology and an infrastructure that is many decades old. With these systems, stability problems in the grid can develop faster than they can be reported. There is a need to fundamentally transform the capabilities of the communication infrastructure that supports power grid operations [5].

The control model based on the communication structure is almost exclusively one of slow automatic control by the control centers- to balance load and generation- and of manual control by system operators- to open and close circuit breakers. The only fast controls, mainly for protection, voltage control and some special controls, make decisions based on local measurements. This structure has a limited ability to cope with gridwide phenomena, which becomes more important as the grid becomes more vulnerable to fast cascading phenomena.

Special protection schemes are required to meet some of the wide-area control needs that cannot be addressed within the current communication architecture.

Technology for monitoring and measurement has evolved with the increasing deployment of intelligent electronic devices, e.g. synchronous phasor measurement units (PMUs), being used to help develop a much more detailed picture of the grids dynamics for system planning, control and post incident analysis. However, this data cannot be used beyond the substation in which they were generated due to the grids limited communication infrastructure.

One use of this rich data source is the PMUbased Wide Area Monitoring Systems (WAMS) used to dynamically monitor the transmission system [6].WAMS can play a key role in increasing access to the available maximum capability of transmission network by providing precise, realtime monitoring and control of its operation. Knowing the current state of operation of the entire grid allows the grid operators to maximize power transfer while still maintaining sensible stability margins.

Through many basic and advanced functions offered by WAMS, they offer great potential for upgrading the supervision, operation, protection and control of modern power systems.

Restructuring and re/de-regulation. Reorganization of the power industry into a competitive model requires the application of better measures to guarantee the reliability of operation in the restructured power systems. One possibility of taking care of reliability issue is with self-healing mechanism. Grid security, restoration, black start are pertinent aspects to be considered from the reliability angle. Reliability coordination in every aspect plays an important role right from load forecasting to system operation under this changing scenario with the development of power markets. Another specific feature is economic interrelation between power supply organization and consumers in terms of reliability assurance. They necessitate the development of economic mechanisms of coordinating the interests of power supply organizations and consumers to provide supply reliability.

A growing challenge in the restructuring of the electrical sector, where competition is introduced in the generation area, is to achieve equivalent efficiencies in the electrical distribution service. In this environment, the state has evolved into an even stronger regulator of activities that are natural monopolies, such as electric power distribution. Approaches introduced to regulate the distribution stage intend to introduce a virtual competition, trying to make companies more efficient by minimizing the present value of all their costs. This has meant distribution tariff reductions, but there is a risk involved where the institutional and industrial structure is still weak.

3.4 Fault detection and isolation (FDI) systems

Fault detection and isolation. The following contributions can be pointed out in the area of robust fault detection and isolation. New model invalidation methods for linear uncertain systems, for which faults induce a change in the dynamics have been developed notably by resorting to a combination of sampling and linear matrix inequality optimization (LMI) tools [8].Residual generation methods for some classes of uncertain nonlinear systems or nonlinear systems with unknown inputs have been developed by using sliding mode observers and particle filters. An optimal statistical fault detection method for linear dynamic systems subject to nuisance parameters has been derived [3].Methods for handling the effect of bounded disturbances on the residual in the decision stage have been proposed such as new algorithms for the computation of a time varying threshold and set membership approaches.

Further developments have taken place in the area of active fault detection and isolation. Moving horizon approaches have been proposed to determine the control sequence that achieves the best discrimination among a finite set of linear models corresponding to the healthy and faulty operating modes of the supervised process. Besides, optimal input design has also been considered for model discrimination among a family of uncertain sampled-data linear models describing the different operating modes of the supervised process [10].

Software toolboxes are being developed to help in the design of FDI systems. They merge structural analysis tools and analytical design methods (parity space and observer-based approaches for instance). The first ones allow for a preliminary study exhibiting analytical redundancy relations between measured inputs and outputs of the supervised system. The parameters within these relations are then determined to obtain appropriate filters for detection and isolation of the considered faults. Plant-wide control loop performance assessment is also the object of software developments that combine data driven analysis and representation of process connectivity.

Design methods for a decision system that best exploits a given set of residuals together with an associate set of change detection tests have been investigated. Indeed, quite often the residual generators and their associated evaluation tests are provided by domain experts. It then remains to design a decision system that outputs the list of possible faults and their associated probability or belief by processing the results of the different tests. Bayesian network techniques have notably been investigated to this end.

Numerous applications of fault detection and isolation have been reported, including some industrial prototypes. The application area is very broad and goes beyond the processes within the scope of this paper. It includes tire pressure monitoring systems, tire-road friction monitoring, fault diagnosis in rolling mill processes, in fuel cells, compressor fouling monitoring and others.

Fault tolerant control. Two major options have been investigated for the design of fault tolerant controllers that handle actuator faults. In the first one, a dedicated controller is designed for each faulty actuator configuration a priori, and the problem is then to decide which fault occurred thanks to an appropriate FDI system and to switch in due time to an adequate controller in order to maintain close-loop stability and performance. Certain solutions combine Lyapunov stability theory and model predictive control in order to reach this goal [9]. The second type of approach consists in computing on line the way to redistribute the control effort upon occurrence of a fault. New methods that do not require a complete controller redesign have been proposed. Among them, the concept of the virtual actuator appears to be attractive [7]. Indeed, in this setting, reconfiguration boils down to the solution of a standard disturbance decoupling problem. Other methods are based on an add-on controller made of an appropriate artificial neural network [12].

Imperfections of the FDI system (false and missed alarms) have been accounted for in the performance evaluation and the design of a fault tolerant control system by using a model with Markovian parameters to describe a fault tolerant control scheme including the different modes of the supervised process and the FDI system. Design of optimal H_2 and H_∞ multi-controller schemes has been considered in that framework.

In multi-controller schemes for fault tolerant control, bumpless switching from one controller to another has to be achieved upon occurrence of a fault. A mathematical framework to deal with this problem has been developed recently. It is based on the notion of ideal or target control signal, namely the signal that would be applied at steady state if the controller imposed after switching had been in the loop for an infinite duration [16].

Many fault tolerant control schemes have been developed for specific applications, with convincing validations in simulation (and sometimes additional experimental results). This includes flight control, control of electromagnetic suspension, of chemical reactors etc.

4. FORECAST

4.1 Chemical process control

In the near future, industry will continue to aim at better utilization of their existing assets. Any systems and control technology supporting this objective will be of continuous and growing interest by industrial practitioners.

Performance improvement for linear multi-loop control systems: Most of the process control systems in industrial practice comprise multi-loop linear control systems. Though there is a significant demand in appropriate systematic methods to design such multi-loop (plant wide) control structures, neither significant progress nor impact on industrial practice is expected. Rather, improved techniques and software tools for periodic control performance assessment of single and multi-variable control loops, improved methods for controller tuning as well as improved self-tuning procedures for single-loop and multi-loop controllers will continue to be of significant interest to industrial practitioners and applications oriented researchers. In addition, diagnosis methods for detecting the malfunctioning of actuators (valves in particular) will see increasing attention. Multivariable constrained control (linear MPC) will be employed more routinely. Proper embedding of such controllers into the automation hierarchy will be of increasing interest.

Modelling for monitoring and control: Data-driven and (combined data-driven and first-princi-ples based) hybrid modelling techniques as well as grey-box closed-loop identification will be further developed to cut down model development effort but still enabling the application of largely linear model-based control techniques. Rigorous first-principles based modelling and model reduction will continue to present a challenge to the control community. These models are essential for the implementation of agile and high performance automation systems for bulk production processes operating in a large envelope of operating conditions. Besides feedback control, such models will see continuous application for soft sensor applications, monitoring and fault detection.

Model-based process operations: There is no doubt regarding the immense economical benefit of model-based techniques for operations and control in particular for non-linear processes which have to be operated in a large region of the operational envelope. However, the cost of modelling will continue to be the major bottleneck of industrial application. Hence, there will be increasing emphasis on systematically dealing with uncertainty in first-principles models and with the adaptation of the model to the process during operation. The traditionally separate areas of set-point tracking and disturbance rejection, real-time optimization to maximize an economical profit function, and even scheduling and planning will continue to merge.

Sophisticated sensor and intelligent actuator technologies: We will see a continuing trend towards the use of process analyzers, image processes, and other high sophisticated sensors in closed loop applications. These new sensing technologies not only will provide us with more information on the process and quality variables. Rather, they will have a significant impact on the whole control system structures since they provide measurements that had to be inferred in the past via estimation. The consequences of this development for process control have still to be experienced in the near future. A similar situation can be observed in the area of actuators. Intelligent actuators comprise of significant sensing and computing technology to perform a number of activities that traditionally had to be handled somewhere else in the automation hierarchy. For example, status information will be available for fault detection and interpretation, performance monitoring of the actuator but also of whole control loop becomes possible. Again these developments will have an impact on the architectural design of the automation and operation support systems.

Application domains: The process control community will continue to broaden its base and to shift its interest from the classical core areas of activity in the petrochemical industries towards specialty chemicals, pharmaceutical, advanced materials, particulate and even functional products as well as to food, water, energy, and waste processing plants. There will be a lot of attention towards biological systems not only in biotechnological production but also in biomedical applications. Systems biology is an emerging field that can greatly benefit from the skills in the analysis of nonlinear complex network-like systems that have been cultivated to a high level of maturity in the process systems engineering and control community. The focus will shift from the plant which is traditionally largely viewed in isolation to the larger systems envelope including the supply chain, the infrastructure systems as well as the environment. Processes in transient mode of operation (such as batch processes or continuous processes in transient phases) will see increasing interest.

Contributions to systems and control theory: The characteristics of process systems (in particular, nonlinearity, large scale, and network-like nature) are drivers for the further development of theoretical methods. Major developments in the process control community aiming at contributions to systems and control theory are to be expected in :

- nonlinear optimal control,
- combined state and parameter estimation for nonlinear systems,
- robustness analysis and robust synthesis methods for nonlinear systems,
- cross-functional integration across the vertical layers of the automation hierarchy,
- spatial decomposition, decentralization and horizontal coordination of large-scale nonlinear network-like processes,
- hybrid discrete-continuous control theory emphasizing systems with equally complex discrete as well as continuous parts.

Drivers for control and operation support systems technologies. Information technology will continue to be one of the key drivers of process control and operation. Increasing computing power and storage capacity will facilitate the implementation of resource demanding nonlinear optimal control techniques. High bandwith communication networks allow for remote monitoring, diagnosis, benchmarking and control of processing plants on a global scale. The entirety of production plants of multi-national industrial conglomerate become more and more a logically uniform virtual production facility which allows for any-time, any-place delivery of high quality product at the desired capacity.

4.2 Mining, Mineral and Metal (MMM) processing

In order to optimize the characteristics of end products in the MMM industry, it is necessary to identify and quantify the influence of the process variables during production, which leads to the concept of plant-wide control. Operator support systems and training simulators are indispensable to cope with the decrease in skilled operators. To continually provide qualified operators, international training centers or engineer exchange programs must be established with the consideration of the demand and supply balance. The expert systems will assist operators to develop and improve decision-making skills, especially, in case of unsteady-state operations. Knowledge management approaches, which can utilize accumulated experience and knowledge, are also promising.

Regarding the plant-wide process control, gathering the process and quality data from the entire process chain is absolutely necessary. However, those data must be integrated and synchronized so that it can be used for statistical analysis. This can be done by incorporating a large-scale database systems and fast network systems or data warehouse and software tolls for the cause/effect analysis and visualization of the results. Multivariate analysis, neural nets, nonparametric regression and data-mining are among the promising methodologies for this kind of analysis, and they can be applied to both quality models and process models.

To increase the steel recycling rate, more accurate separation process than shredding process is needed, and this can be possible by using induction heating and infrared sensing technique to detect non ferrous materials that need to be separated. However, in order to produce high drawability steel, more cost-effective technologies must be developed to refine non-ferrous element from old steel in the long run.

The classical control technology, however, has a fundamental limit due to the inaccurate modeling of industrial process and poor measurement systems. Recently, revolutionary advances in computer technology, modern control and machine intelligence have opened a platform for the new generation of industrial control that may provide significant economic benefits through the production of quality products using an integrated computer information and management system. The future trend in the MMM industry is the application of intelligent control technologies in the complex industrial processes. This technology is highly multi-disciplinary and rooted in systems control, operations research, artificial intelligence, information and signal processing, computer software and production background. Therefore, in order to solve various control problems, the intelligent control technology which combines the ideas from fuzzy systems, expert systems, neural networks and learning, fault detection and diagnosis, should be applied in the MMM industry.

Alternatively, new innovative production technology may be the solutions to overcome difficulties instead of improvements of the existing process control technology. Recently, two innovative ironmaking methods have been introduced in the steel industry. One is the FINEX process, an ecofriendly alternative that uses low-cost raw materials, which eliminates the sintering and coking processes resulting in lower production costs and reduced environmental pollutants. In 2004, the first commercial 1.5-million-ton capacity FINEX Plant was constructed and successfully began its operation in 2007.

Another innovative technology is the strip casting, a technological advancement in the steelmaking process, which eliminates most of the existing forging and rolling processes to cast strips of 1- 6mm in thickness directly from the molten steel. Not only does strip casting lower the investment and operational costs, but it also dramatically reduces energy consumption and pollutants. The strip casting technology has been developed since 1989, and a 600,000-ton capacity poStrip demo plant is currently under construction in Korea. These two innovative technologies emerge as a leading iron making technology that will aid sustainable growth of steel industry in the 21st century.

4.3 Power Plants and Power Systems

Power systems have the unique characteristics that they are large-scale, multi-input multi-output, non-linear systems distributed over large geographical areas. Work in many diverse areas is going on simultaneously. Some of the ideas and technologies that may have an impact on the power systems of the future are briefly mentioned bellow.

Wind power. Wind power plants are not dispatchable in the traditional sense and that lessons the ability of system operators to control them [2]. Integration of wind power plants into the electric power systems presents challenges to power system planners and operators. However, there is an indication that wind plants with lowvoltage ride through and variable reactive power compensation capabilities can actually improve power system stability following a major power system disturbance. It appears that the capacity value of offshore wind resources will be better than for onshore wind resources because of better and more consistent wind. Reliability planning and economic planning processes for transmission will be pursued to access these good quality wind resources. Good progress is being made in addressing the modest effects of wind on reserves and regulation, and further research will be done to examine higher wind penetration levels.

Distributed generation. Distributed generation may provide a new framework for the power delivery system that has the potential of increasing its reliability. It makes a significant reversal from the previously prevailing approach to power generation driven by the economies of scale. It offers a number of potential benefits including the ability to exploit geographically dispersed renewable energy sources, the potential to minimize transmission/distribution costs and losses. This will work well in coordination with distribution automation that will allow better control of both the distribution systems and its loads.

Distribution Automation. Automation of distribution feeder circuits, and residential and commercial loads offers many potential advantages including improved power reliability and quality, monitoring of energy use for energy management systems and reduced operational cost to the utility. The challenge in distribution automation lies in its execution so that the entire range of utilities from small to large, with differing technologies, will benefit.

Energy storage. Large capacity electricity storage systems help to stabilize the electricity delivery infrastructure and minimize the cost of meeting peak-load requirements. Fast acting power storage can supplement transmission system stability with a few seconds of active power from a storage device and finding more economical ways to stabilize wind power systems. It can be used as an energy source for primary reserve and also as a rapidly fluctuating power source performing frequency regulation. Electricity storage devices can be used for equipment protection and control functions to improve the performance, utilization, stability, security (e.g. evading blackouts) and reliability of power grid. Superconducting Magnetic Energy Storage is an energy storage technology that stores energy in the form of DC magnetic field. It can provide spinning reserve, and by phase control of converter on the DC link it can also ameliorate the electro-mechanical oscillations resulting from subsynchronous resonance of the turbine shaft and the transmission network by damping the oscillations. This technology thus offers alternatives to enhance the stability of the power system.

FACTS devices. Switching by thyristorconstituted systems can (within limits) control phase angle, impedance, voltage and current in ways that would otherwise not be possible [14]. FACTS can alter the impedance of a line and influence the routing of power within a system and between systems. When a DC line is embedded in an AC grid, by providing damping action through the converter controls the stability of the AC grid can be enhanced. FACTS devices can also supply suitable damping to stabilize AC grid. Harmonics can be significantly reduced by FACTS. A full utilization of the possibilities offered by this technology will greatly improve power system operation.

Vision of future grid. One version of the future grid is a large number of small, distributed power generation units connected to the grid. These small and decentralized electric energy sources will be controlled and operated over the internet as one large generation plant, or the socalled virtual utility. This more complex structure will require extended control of all of the components and the power flow. Internet will be used not only for administrative transactions but also for maintenance and direct control operations of the grid.

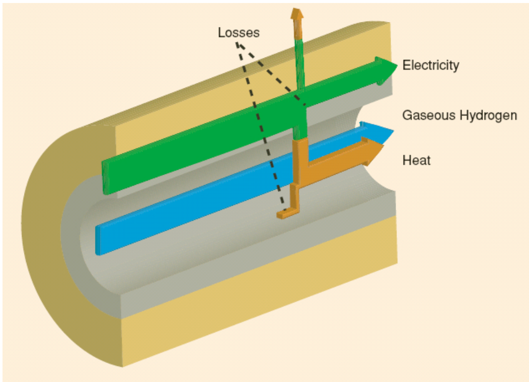

Fig. 4. *Possible layout of a single transmission device [4]*

An alternative vision being considered is that transformation, conversion and storage of various forms of energy be located in centralized units and transportation of different types of energy over long distances be carried out in single transmission devices, see Figure 4 [4].

These long term visions may be termed as evolutionary and revolutionary, respectively, of the development of energy and power systems. In any scenario, control will play an increasingly important role in shaping the power systems of the future.

4.4 Fault detection and isolation (FDI) systems

Interest in on-line monitoring systems is growing in the industries, as more and more companies realize that important savings can be achieved by so-called intelligent or predictive maintenance.

The SAFEPROCESS community has developed a valuable set of tools for the design of such health monitoring or FDI systems, and by intensifying its collaboration with industrial partners it should improve the transfer of this know how to the industrial world. For achieving the full benefit of FDI systems, they should be combined with appropriate prognosis and maintenance planning tools. The first ones aim at predicting the evolution of the fault as time elapses, which requires appropriate prediction models; the second resort to reliability evaluation and optimization methods, issues that are also investigated by the scientific community dealing with safety and reliability outside IFAC, as represented in Europe by ESRA (European Safety and Reliability Association). Cross-fertilization between SAFEPROCESS and ESRA in this area would certainly bring significant progress.

Certain process industries are more and more concerned with reliability issues, since new standards, like IEC61508, IEC61511 and IEC61513 have appeared. Such standards deal with safety instrumented systems (SIS), namely controlled processes equipped with safety systems. The latter are separated from the main control systems and they are used to achieve fault tolerance. Some industries have significant experience in the design and analysis of SIS, and such systems are also studied by some researchers within ESRA. Collaboration of the SAFEPROCESS community in this domain is expected to be fruitful as its know how on control systems and hybrid systems would definitely benefit to the study of SIS. Besides, the connection between SIS and the approaches to fault tolerant developed by the SAFEPROCESS community should be investigated as it could inspire interesting new developments in both academic and industrial approaches to FTC.

The study of networked control systems and their tolerance to fault brings new challenging problems at the border between control, communication and reliability theory, as well as computer science. Diagnosis and fault tolerance may refer to both the data network used for control purposes or dynamical system, which is supervised from remote. Besides, to handle the complexity of distributed systems like power networks multiscale approaches must be developed. They should allow detailed study of fault tolerance and reliability at local level, but also provide evaluation of these properties at the global level. To this end, compact information must be determined in the form of key parameters characterizing performance, fault tolerance, reliability at low level, and ways to combine such information to characterize the global behavior of the distributed system must be sought.

5. CONCLUSIONS

The closer collaborations between TCs are important, especially TCs for safeprocess and chemical engineering, will be very helpful for us.

Process and power plant control, along with fault detection/isolation, are being addressed by significant on-going research with many theoretical developments focused on improvements for all of these major industrial applications. This report has provided an overview of the current key problems, recent accomplishments and trends, as well as a forecast of anticipated developments within this very important field of industrial applications.

Future developments in these fields can be summarized as follows.

In Chemical Process Control (CPC), system and control technologies supporting the objective of a better utilization of the existing industrial assets will be of continuous and growing interest by industrial practitioners. Developments are expected in particular in the following areas : performance improvement for linear multi-loop control systems, modelling for monitoring and control, model-based process operations, sophisticated sensor and intelligent actuator technologies, and contributions to systems and control theory, e.g. nonlinear optimal control, combined state and parameter estimation for nonlinear systems, crossfunctional integration across the vertical layers of the automation hierarchy, or hybrid discretecontinuous control. Applications will continue to be broadened and to be shifted from the classical core areas of activity in the petrochemical industries towards specialty chemicals, pharmaceutical, advanced materials, particulate and even functional products as well as to food, water, energy, and waste processing plants. There will be a lot of attention towards biological systems not only in biotechnological production but also in biomedical applications.

In the Mining, Mineral and Metal processing (MMM) industry, new developments have been made in the plant wide process control. However, the MMM industry has serious problems that need to be solved: development of advanced control strategies and development of realistic approaches to system analysis and synthesis for complex systems. The current control technology, unfortunately, cannot provide satisfactory solutions to the above problems due to inaccurate modeling of industrial process and poor measurement systems. Therefore, a new direction in industrial control technology is explored and intelligent control is recognized as a future trend. The recent research and developments made in artificial intelligence, which include knowledge engineering, pattern recognition, fuzzy logic, neural network and machine learning, etc., have provided great opportunities to solve complex control problems in the MMM industry. An alternative solution is to develop new innovative production technologies along with improving existing process control technologies, such as the Finex technology or strip casting technology in the iron making process. In order to provide qualified operators, international training centers or international engineer exchange programs must be established in the MMM fields.

In Power Plants and Power Systems (PPPS), one version of the future grid is a large number of small, distributed power generation units connected to the grid. These small and decentralized electric energy sources will be controlled and operated over the internet as one large generation plant, or the so-called virtual utility. This more complex structure will require extended control of all of the components and the power flow. Internet will be used not only for administrative transactions but also for maintenance and direct control operations of the grid.

Finally, three issues regarding the perspective for fault detection and isolation (FDI) and fault tolerant control systems are: combined development of FDI systems with appropriate prognosis and maintenance planning tools, systematic design and performance evaluation of safety integrated systems, and multi-scale approaches to design diagnostic systems and fault tolerant controllers for large distributed dynamical systems.

The closer collaborations between Technical Committees (TC's) are important, especially TCs for Safeprocess and Chemical Process Control, will be very helpful for the increase of impact of the scientific activities performed in the fields covered by the present IFAC Coordinating Committee 6 (CC6).

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