Response-based Control through Dynamic Optimization in Large-scale Power Systems

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Abstract: Modern real-time measurement equipments and associated communication/computing networks allow developing advanced power system control architectures able to identify dangerous states of power systems, and, when necessary, evaluate and apply remedial control actions. An approach, derived by a dynamic optimization methodology, for evaluating response-based control actions and enhance power system security, is presented. In this paper, studies performed for wide-area control of transient phenomena are reviewed. Despite severe computational efforts and time requirements, the authors' position is that the nowadays technology can make the approach feasible.

1 INTRODUCTION

New smart technologies are the current drive for achieving profound modifications in the way power transmission system are built and operated. The pervasive diffusion of power converters and flexible systems, large storage facilities, adaptive relays, smart meters and sensors allows the achievement of improved levels of automation, intelligence, monitoring and control in power systems (Momoh 2009); (Bose 2010).

A key enabling technology for such change is to be found in Phasor Measurement Units (PMUs) (Phadke and Thorp, 2006) whose deployment in power systems has been possible thanks to the on-going process of substitution of old electromechanical relays with new digital relays, started in the early 90s and under completion in most advanced countries. PMUs are devices that allow to measure synchronously electric variables (currents and voltages, in module and phase) in several nodes of the network, giving a real-time realistic snapshot of system conditions and state.

According to the vision presented in (Bose et al., 2004a; 2004b), data coming from PMUs can be collected and elaborated in order to achieve real-time control of power systems. The diffusion of IEC-61850 protocol-based equipments, will facilitate the integration of such devices into SCADA/EMS data base and simulation tools, and will achieve, at the same time, interoperability of all active elements of the network (for example digital protection relays, power converters and flexible AC transmission systems - FACTS, remote controlled switches, etc.).

Such real-time control architecture can be based on a revolution of classical dynamic security assessment (DSA) functions that are traditionally based on off-line models and simulations and on "event-based" predetermined control rules.

The idea is to develop powerful real-time tools for on-line updating of power system parameters database (usually stored in SCADA and updated only occasionally), power system behaviour prevision and real-time control assessment, leading to the definition of a "response-based" real-time control approach to power system security (Taylor et al., 2005).

This approach is based on the integration of dynamic optimization methodologies with modern real-time measurement equipments (PMUs and wide area measurement systems - WAMS) and is aimed at evaluating real-time corrective control actions, as soon as degraded dynamic trajectories are detected.

Since unstable transients must be controlled within hundreds of milliseconds from the insurgence of the fault, in order to implement "response based" remedial actions, fast actuators are needed. Load/generation shedding can be fast enough to

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correct the undesirable transient behaviour (Bose et al., 2004b) but more advanced fast control actions can be implemented through FACTS devices (Bruno et al., 2012a), line switching techniques (Bruno et al., 2012b) or fast tuning of adaptive relays (Bruno et al., 2012c). In addition, real-time tuning of distance relays settings performed considering actual, or forecasted, configurations of the power system will allow to overcome the classical conflict between dependability and security (Bruno et al., 2011) and to avoid improper operation of such devices in vulnerable conditions and during major blackout events.

In this paper, the authors' experience, devoted to assess the feasibility of advanced power system control architectures, is reviewed. The paper presents the authors position about the possible implementation of response-based control architectures for controlling transient phenomena on a wide geographical scale. Despite the severe computational effort required by the response-based simulations and the tight time requirements, the authors' position is that the nowadays technology can make the approach feasible.

2 EVOLUTION OF CONTROL ARCHITECTURES

In this section, an advanced control architecture oriented at evaluating and implementing control actions as soon as power system dynamic behaviour worsens is proposed. This architecture, basing on real-time measurements and fast simulation tools, guarantees a substantial evolution with respect to event-based control approaches.

2.1 Event-based Control Strategy

The control of power system stability is mainly operated by means of automated control systems that feedback local signals to generation unit control systems (automatic voltage regulators, power systems stabilizers, governor, etc.) (Kundur, 1994). This kind of control enhance power system stability behaviour (especially small-signal stability) but it is not fit to ensure stability when large and severe transients are experienced. Moreover, local control schemes cannot provide enough information on phenomena arising on wide geographic areas and detectable only on wide-area spatial scale (for example inter-area oscillations, voltage instability, etc.).

Large oscillations and transients are usually controlled by means of another class of controls that includes both preventive and corrective control approaches. These controls are operated via SCADA/EMS by local relays or by means of Special Protection Systems (SPS) (Taylor, 2000).

Corrective schemes operate following an event-based control approach (Figure 1) that requires no intervention of system operators: defence schemes react automatically when an event is detected (event-driven actions). SPS working principle is based on the pre-arming of actuators that react automatically following pre-defined control strategies at the detection of a certain disturbance. The arming of SPS is based on off-line (preventive) simulations, performed on the basis of a predefined set of postulated contingencies (event-based approach).

Since this approach is based on off-line simulations, off-line models and on a set of postulated contingencies, it might fail anytime unexpected events or anomalous conditions are experienced. The failure of the automatic load shedding scheme called EDA (Elaboratore Distacchi Automatici) in avoiding disaster during the major Italian 2003 blackout is a clear example of such problematic (Berizzi 2004); (Berizzi and Sforna 2006).

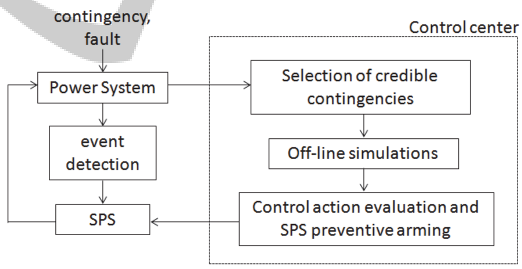

Figure 1: Event-based control strategy.

2.2 Response-based Control Approach

Given the actual availability of advanced measurement and communication systems, it is possible to imagine a new control architecture for response-based control of power systems. Real-time measurement equipments and associated communication systems (i.e. PMU and WAMS) can be exploited for developing such advanced control approach.

In the proposed control scheme, power system trajectories, acquired in real-time, allow the identification of threats to system security and of degraded dynamic states. If necessary, through simulation or sensitivity analysis, suitable corrective control actions can be evaluated and implemented sending in real-time corrective signals to any fast actuator device (e.g. load/generation shedding schemes, FACTS devices, line switching, adaptive relaying).

A schematic representation of a response-based control system is given in Figure 2. Such scheme reacts to static and dynamic constraints violations by means of control actions calculated and implemented on transient time-scale.

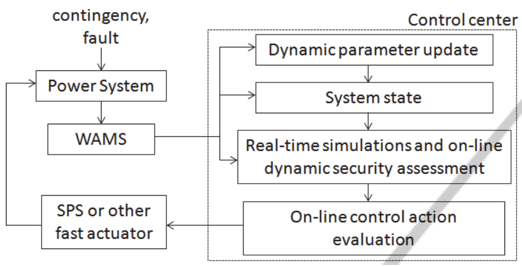

Figure 2: Response-based control approach.

A response-based control strategy, integrated with WAMS, has the potential to grasp the whole picture of dynamic system behaviour and perform calculations on-the-fly on the basis of actual dynamical state, taking also into account possible sudden changes in grid topology of operating conditions as usually experienced during severe cascading events leading to major blackouts.

The proposed approach when integrated into a WAMS architecture gives rise to what is defined Wide Area Measurement and Control system or WAMC.

2.3 Wide-area Measurement and Control Architecture

The proposed WAMC architecture requires the existence of a measurement and communication network that collects and distributes real-time information about system state. PMUs can be easily located in strategic points of the system (substations, generation points or important interconnection points), giving real-time measurements of voltage and current phasors, suitably synchronized through GPS time signals.

A Phasor Data Concentrator (PDC) collects data sent continuously by PMUs and exports measurements as soon as they have been correlated and normalized. Real-time data sent from all PDCs to the Control Centre provide a coherent picture of the system state. Data are elaborated through real-time power system simulators reproducing power system trajectories and detecting possible threats to system security.

The proposed approach is based on creating a dynamic replica of power system dynamics, permitting the assessment of system dynamic performances and a rapid calculation of real-time control actions through sensitivity approaches or through the solution of dynamic optimization problems.

In smart transmission grids, both innovative IT infrastructure and the standardization process have been implemented. This scenario enables the achievement of important objectives, such as seamless interoperability and fast communication and information exchange. The International Electrotechnical Commission IEC has produced the IEC TC57 standards reference framework that defines two important standard families: IEC 61970, also known as Common Information Model (CIM), and IEC 61850 for substation communication.

Control centres, thanks to IEC TC57 standards, can monitor and control any field device. It is foreseeable that control centre operators will be able to gather real-time information about any installed device; in this scenario, a real-time updated database of field devices can be made available for simulation tools. Response based control can take advantage of this possibility by improving system representation and introducing new control functions. At the same time, for example, remote control of field device will made possible to implement fast actions such as changing protection settings or remote line switching.

3 AN ALGORITHM FOR RESPONSE-BASED CORRECTIVE CONTROL

The power system behaviour on transient time-scale is generally described through a set of nonlinear differential and algebraic equations (DAEs) (Kundur 1994):

$$\begin{aligned} \dot{\boldsymbol{x}}(\mathrm{t}) &= \boldsymbol{f}(\boldsymbol{x}(t),\boldsymbol{V}(t),\boldsymbol{u}(t)) \\ \boldsymbol{g}(\boldsymbol{x}(t),\boldsymbol{V}(t),\boldsymbol{u}(t)) &= \boldsymbol{0} \end{aligned} \tag{1}$$

where $\boldsymbol{x}$ is the state vector, $\boldsymbol{u}$ is the control variable vector, and $\boldsymbol{V}$ is the vector of nodal voltages. The control variable vector $\boldsymbol{u}$ is given by the set-point value (Bose et al., 2004a; 2004b) or set-point time varying trajectory (Taylor et al., 2005) of controllable devices and control action actuators.

The DAEs set (1) can be discretized through a trapezoidal rule and written in implicit form as:

$$\hat{\boldsymbol{H}}(\hat{\boldsymbol{y}}, \boldsymbol{u}) = \boldsymbol{0} \tag{2}$$

where

$$\boldsymbol{H}_i(\boldsymbol{y}_i, \boldsymbol{u}) = \boldsymbol{0} \qquad i = 0, 1, 2, \cdots, n_T \tag{3}$$

$$\boldsymbol{y}_i = \begin{bmatrix} \boldsymbol{x}_i^{\mathrm{T}} & \boldsymbol{V}_i^{\mathrm{T}} \end{bmatrix}^{\mathrm{T}} \tag{4}$$

$$\hat{\boldsymbol{y}} = \begin{bmatrix} \boldsymbol{y}_0^{\mathrm{T}} & \boldsymbol{y}_1^{\mathrm{T}} & \cdots & \boldsymbol{y}_i^{\mathrm{T}} & \cdots & \boldsymbol{y}_{n_T}^{\mathrm{T}} \end{bmatrix}^{\mathrm{T}} \tag{5}$$

$$\hat{\boldsymbol{H}} = \begin{bmatrix} \boldsymbol{H}_0^{\mathrm{T}} & \boldsymbol{H}_1^{\mathrm{T}} & \cdots & \boldsymbol{H}_i^{\mathrm{T}} & \cdots & \boldsymbol{H}_{n_T}^{\mathrm{T}} \end{bmatrix}^{\mathrm{T}} \tag{6}$$

with $\boldsymbol{y_i}$ representing the composition of all state variable and voltage vectors at the generic i^{th} time step and $\hat{\boldsymbol{y}}$ representing the discretization of the whole trajectory of the system; $\boldsymbol{H_i}$ is the discretization of the DAEs set (1) at the generic i^{th} time step; n_T is the total number of time steps relative to the integration interval *[0,T]*.

The methodology proposed in this paper is based on (La Scala et al., 1998); (Bruno et al., 2002). Corrective control actions are evaluated by solving a dynamic optimization problem for non-linear systems, in the presence of static and dynamic inequality constraints. The dynamic problem is formulated in terms of static optimization and solved by applying the Lagrangian multipliers method.

The main difference with regard to (La Scala et al., 1998); (Bruno et al., 2002) is that, instead of formulating and solving a single optimization problem, this method aims at finding the optimal value of the control-vector $\boldsymbol{u}_w$ that solves the optimization problem given for each time window t_w by the equations:

$$\min_{\boldsymbol{u}_w}\left(C_U(\boldsymbol{u}_w) + C_O(\hat{\boldsymbol{y}}_w) + C_P(\hat{\boldsymbol{y}}_w)\right) \tag{7}$$

subject to

$$\hat{\boldsymbol{H}}(\hat{\boldsymbol{y}}_w, \boldsymbol{u}_w) = \boldsymbol{0} \tag{8}$$

and

$$\boldsymbol{u}_{w\,min} \le \boldsymbol{u}_w \le \boldsymbol{u}_{w\,max} \tag{9}$$

In (7), $\hat{\boldsymbol{y}}_{\boldsymbol{w}}$ represents the system trajectory in the time window t_w, C_U represents an objective function aiming at the minimization of the controlling effort; C_O is the objective function whose scope is to improve the dynamic behaviour of the system; C_P is a penalty function that takes into account inequality constraints. Inequality constraints are usually referred to technical and operational constraints and define time-varying domain where system trajectories should be contained.

The problem is solved by applying the optimization method of Lagrangian multipliers:

$$L = C_U(\boldsymbol{u}_w) + C_O(\hat{\boldsymbol{y}}_w) + C_P(\hat{\boldsymbol{y}}_w) + \boldsymbol{\gamma}^T \hat{\boldsymbol{H}}(\hat{\boldsymbol{y}}_w, \boldsymbol{u}_w) \tag{10}$$

$$\frac{\partial L}{\partial \hat{\boldsymbol{y}}_w} = \frac{\partial (C_O + C_P)}{\partial \hat{\boldsymbol{y}}_w} + \boldsymbol{\gamma}^T \frac{\partial \hat{\boldsymbol{H}}}{\partial \hat{\boldsymbol{y}}_w} = 0 \tag{11}$$

$$\frac{\partial L}{\partial \boldsymbol{u}_w} = \frac{\partial C_U}{\partial \boldsymbol{u}_w} + \boldsymbol{\gamma}^T \frac{\partial \hat{\boldsymbol{H}}}{\partial \boldsymbol{u}_w} = 0 \tag{12}$$

$$\frac{\partial L}{\partial \boldsymbol{\gamma}} = \hat{\boldsymbol{H}}(\hat{\boldsymbol{y}}_w, \boldsymbol{u}_w) = 0 \tag{13}$$

From (11) and (12) derives:

$$\frac{\partial L}{\partial \boldsymbol{u}_w} = \frac{\partial C_U}{\partial \boldsymbol{u}_w} - \frac{\partial (C_O + C_P)}{\partial \hat{\boldsymbol{y}}_w}\left[\frac{\partial \hat{\boldsymbol{H}}}{\partial \hat{\boldsymbol{y}}_w}\right]^{-1} \frac{\partial \hat{\boldsymbol{H}}}{\partial \boldsymbol{u}_w} \tag{14}$$

Usually, in off-line applications, the optimization problem is solved through an iterative algorithm, updating at each iteration the control-vector

$$\boldsymbol{u}_{wnew} = \boldsymbol{u}_w + \alpha \frac{\partial L}{\partial \boldsymbol{u}_w} \tag{15}$$

simulating a new dynamic trajectory, calculating a new control vector update in a recursive approach that stops when the sensitivity term $\partial L / \partial \boldsymbol{u}_w$ is lower than a specific tolerance limit.

In the response-based approach presented in [4-5], the trajectory $\hat{\boldsymbol{y}}_{\boldsymbol{w}}$ is acquired through WAMS and cannot be modified. The control-vector $\boldsymbol{u}_{w+1}$, evaluated optimizing $\hat{\boldsymbol{y}}_{\boldsymbol{w}}$ trajectory, can be applied only after that the trajectory itself was acquired. The control variable is therefore updated after each time step with a simple sensitivity analysis as shown in Figure 3. After the implementation of control actions, new corrective actions are evaluated after that a new piece of trajectory is acquired, and so on.

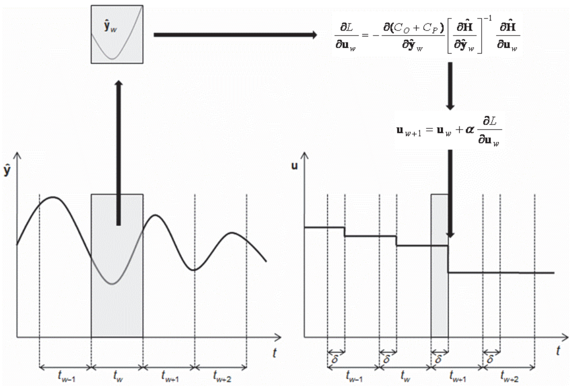

Figure 3: Schematization of the proposed response-based approach.

The approach in [4-5] is feasible having considered that suboptimal solutions are still suitable if stability is ensured in response to large disturbances and severe threats to system integrity.

A further evolution of this approach, can be achieved if trajectories $\hat{\boldsymbol{y}}_w$ were forecasted through powerful simulating tools before they are actually experienced and acquired. In such case, a real-time optimal control of power system trajectories would be achieved. This paper embraces the opinion that through real-time dynamic simulators, or simulators even faster than real-time, such approach might be possible.

An important observation on this regard is that the approach is feasible as long as control actions can be applied with a reasonable time delay δ. The overall time delay δ takes into account the time necessary for data acquisition from WAMS, data transmission to the Control Centre, data synchronization, CPU simulation time, data transmission to actuators, triggering of the corrective control actions.

4 TIME REQUIREMENTS

Some experiences have been carried out considering a representation of the Italian power system and part of the interconnected UCTE network. The model is characterized by about 1333 nodes, 1762 lines, 273 generators and 769 transformers, implying that state variables are 1638 and voltages are 2666. At each time step 4304 variables are involved in a typical index-1 problem. Due to the discrete time approach, the trajectory of the system have to be evaluated for about 10s i.e. for about 500 time steps: Consequently the trajectory vector consists of about 1.3 millions of variables and the overall problem (eqns. 11-13) can have the size of more than 2.6 millions of equations depending also on the number of control variables and time discretization.

In order to assess the feasibility of the proposed response-based control architecture, three different tests have been carried out considering different actuators: FACTS devices (Bose et al., 2004b) and load shedding schemes (Bose et al., 2004a), line switching (Bruno et al., 2012b) and adaptive relaying (Bruno et al., 2012c); (Bruno et al., 2011). In tests, corrective control is applied with a variable time delay δ after the onset of the fault, in order to understand how far it is possible to delay the application of control actions, and still ensure system stability. The evaluation of maximum time delays is a key issue, permitting to assess communication channels technical requirements, computational time and actuators' response speed. In such tests, it has been assessed that time delays around 300-500 ms are still compatible with stability requirements for most simulated contingency cases.

4.1 Actuators

Actuation for load shedding needs about 100ms and can be considered negligible for FACTS devices and adaptive relaying. Our position is that delays of few hundred milliseconds (let us say 300 ms) are enough for response-based control to be able to correct most of unstable behaviours. The next step is to assess if computational and communication timings fit this challenging requirement.

4.2 Computational Time Delay Assessment

Since in the proposed approach, trajectories are assumed to be known by WAMS, corrective actions can be derived through the mere solution of the linear system (11-12) and the consequent application of eqn. (14). It should be considered that, in the evaluation of the lagrangian multipliers γ, it is not necessary to adopt the same time step discretization as for the evaluation of the trajectory. It was observed that time steps equal to 0.1s are sufficient to provide a good approximation of the trajectory of Lagrange multipliers γ.

The solution of such equations, having considered the abovementioned system model (1333 buses) and a time windows of 0.1s, requires about 0.32s on a standard PC equipped with a Intel Core2 Quad CPU Q9650 processor, 3 GHz, 4 GB RAM.

It can be concluded that CPU timings should be more or less compatible with response based control if reduced by a factor 4. This possibility is at hand considering that more powerful computational resources (supercomputers, parallel computing environments) can be adopted. As an example, a speed-up around 9 can be obtained through vectorization (Granelli et al., 1993) or speed up around 6 with message passing machines or distributed machines equipped with 32 CPUs as proved in (Aloisio et al., 1997).

4.3 Communication Time Delay Assessment

Potentials of WAMS architectures and advanced stability control architectures were investigated during a full-scale experiment (La Scala et al. 2006).

The experiment was carried out benefiting from the collaboration of PMU manufacturing companies and dealt with the installation and testing of PMU devices, and with the assessment of SPS performances, including telemetry, monitoring and wide-area detection.

On the basis of data acquired during the above mentioned experiment, time performances of the communication infrastructures have been monitored. The overall time delay for acquiring, transmitting (to the Control Centre) and re-transmitting (to actuators) data has been estimated in the range 70-100ms (25ms for each one-way data transmission) (La Scala et al., 2006); (Naduvathuparambil et al., 2002). This result is also consistent with results of an Italian WAMS project (Cirio et al., 2011).

4.4 Final Observations

Performances of a centralized wide-area monitoring architecture are not yet compatible with a response-based control approach, since the delay associated to data acquisition and control action implementation may exceed the maximum delay assessed in the previous section.

On the basis of the results obtained so far, it can be estimated that the overall architecture would need around 400ms for computations, 100ms for communications and 100ms for actuating remedial actions as an example. Thus we are close to the goal but we did not score yet.

Our position is that computation is not the bottleneck. Since the elapsing time related to the dynamic sensitivity calculation can be drastically reduced through high performance computing, we believe that the bottleneck in the time response of the control chain is still associated to the communication system and to the actuators.

The position is that, fast actuators such as FACTS devices, but also less expensive ones such as adaptive relays, can meet the time challenge with regards to actuation delay. More investments in the high-speed communication infrastructure can provide the right answer to meet the strict requirements imposed by a centralized response-based control architecture.

5 CONCLUSIONS

In this paper, a centralized wide-area control architecture for evaluating and implementing response-based corrective control actions has been illustrated. Feasibility studies of the integration of dynamic optimization methodologies with advanced monitoring and control technologies have been carried out. Moreover, the maximum acceptable overall delay, ranging from 300 to 500 ms, has been assessed to stabilize the Italian power grid with a response-based control strategy.

The position is that the presence of WAMS, fast actuators, high performance computing and high-speed communication infrastructure can meet the challenge of a response-based control for large scale power systems.

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