Global Hybrid Control for Large Power Systems

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Abstract

This paper presents an overview of an approach to total control of complex power systems. It provides a framework for coordinated development of control to address all major dynamical problems. The ideas will be illustrated by consideration of coordinated control for transient stability, voltage regulation and emergency voltage control.

1 Introduction

Power systems are amongst the most complex systems ever designed. In particular, they have large scale, are strongly not linear and have substantial uncertainty in their modeling. This paper is aimed to give an overview of programs towards a general methodology for control of large power systems which allows for high levels of complexity. The ideas connect to most prior work on the development of power system stability controls. In arriving at progressively more general and flexible approaches, various techniques from advanced modern control have been absorbed such as dynamic programming, model predictive control, nonlinear control, so-called fuzzy control (just as a non-linear control formula), switching and hybrid control. The overall framework to devise controllers which deal with complexity is called global control.

Models are assumed to be of a heterogeneous hybrid kind, ie a mixture of differential, algebraic and switching equations with different versions in different spatial and state domains. The various control elements correspond to existing physical controls, typically designed independently and assumed to be tunable, and other modules to be designed. Control is implemented in several layers of continuous and discrete actions. Global hybrid control is presented as natural way to harness all the control elements optimally to coordinate a control response to dynamical problems as they arise. The controlled response can be designed to achieve feasible secondary specifications such as for transient behavior, quality of supply, economy.

The structure of the paper is as follows. Section 2 will discuss global control in general terms. Section 3 presents the specific illustration of transient stabilisation with voltage regulation. Section 4 gives some conclusions.

2 Global Control Ideas

2.1 Introduction

Global control is a further development of modern control towards the capability to handle complex systems. Like power systems, many practical systems have the following four major characteristics: 1) substantial nonlinearity; 2) large-scale; 3) variable uncertainty in the model; and 4) hybrid or heterogeneous form. The last aspect refers to a mixture of control actions, ie discrete and continuous, and control requirements, possibly in different regions of operation. Adaptive, robust, intelligent and stochastic control are well-known methodologies which overcome parametric variation, unstructured uncertainty, unknown models and random disturbances respectively. Here it is of interest to note more recent developments in so-called multi-model, switching and hybrid control [28][3][34][6][14] as at least partially able to address the problems of complexity in a holistic way. It remains to develop these methods to address systems of serious large-scale and mixed uncertainty types such as appear in power systems. In practice, a framework is needed for designing controls of a truly global kind which act in a coordinated way across the whole system geographically and for all operating situations, ie for all states and in-the-large (in the sense of stability theory) as parameters and conditions vary. This appears possible by combining ideas already developed for power systems with some of the newer techniques in control.

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There are several specific features of complex systems which apply in the case of power systems: 1) the system has a large-scale network structure; 2) many of the controls are embedded in the system with some having scope for tuning; further control design must allow for and enlist where possible these existing controls; 3) the overall control scheme will have a hierarchical structure; 4) the control actions available physically are already largely determined and have diverse timing, cost and priority for action; 5) the control goals are multi-objective with local and global requirements which vary with system operating state, eg normal and insecure states in power systems. Of course, many systems in industry, such as chemical processes, shares these features. A related issue which is often mentioned in more practical discussions of general control science needs is "reconfigurability". It is recognised that the control designers have a huge toolbox of techniques for developing the models and local controllers throughout a system. There needs to be more effort on the higher levels of control to deal with failures and external events. Power systems engineers certainly need no reminding of this issue.

In general, we need a high-level version of distributed adaptive optimal control which "swarms" around the complex system attacking problems as they arise, but keeping a meta-view so that other problems are not ignored while attending to a particular one. Needless to say the implementation requires accounting for physical features like physical sparseness and time-scales as always to reduce computation demands.

2.2 Hybrid Models

The use of hybrid models in power systems is already well-accepted to capture the use of mixed continuous and discrete control actions [35]. The equations often take a differential-algebraic-difference (DAD) form as follows

$$\begin{aligned} \dot{x} &= f(x, w, z(k); \lambda) && (1) \\ 0 &= g(x, w, z(k); \lambda) && (2) \\ z(k+1) &= h(x, w, z(k); \lambda) && (3) \end{aligned}$$

The dynamic state variables x are variables that appear as derivatives in the differential equations and cannot change instantaneously. On the other hand, the algebraic state variables w do not appear as derivatives, and can thus change instantaneously due to changes in x or $z(k)$. The discrete state variables $z(k)$ have discrete-time dynamics and can change only at fixed time instants given by a selected sample time. The dynamic state variables relate to generator flux, continuous control and load dynamics; algebraic state variables relate to network voltages and currents, and the discrete states $z(k)$ typically arise from discrete control logic such as relay controls. The parameters are denoted λ and may include control parameters, independent parameters and action variables. We can write $\lambda = (\theta, \vartheta, u)$ where θ represents tunable parameters, ϑ represents the (structured) uncertainty and u the control variables which are yet to be designed. The basic DAD model will include control algorithms (discrete and continuous) for which no further tuning is planned.

The use of hybrid or DAD models has been discussed in more general terms for power systems in [18][10]. In particular, the discrete time actions can be generalised to allow for switching and reset events which depend on system behaviour. Recent advances in modelling software make use of such models more straightforward. For instance, we can use the modelling and simulation tool Dymola, which has a power systems library[23].

As exists for differential equation models and DA models, eg. see [17], a basic set of analysis tools for DAD systems is needed. This is currently the subject of active research. Some results have been summarised in [26][11].

2.3 Control Elements

One of the problems with applying modern control methods like adaptive, fuzzy or robust control to power systems is that they are established in a generic framework which is not sensitive to the structure of particular practical systems. A challenge is to blend these new ideas into the overall scheme of control which exists, ie excitation control, PSS, network regulators, eg tap-changers, security control. Typically, much of this is already trusted and we only need some new control modules and some overall co-ordination.

Co-ordination has not been a strong point of power system control in the past. Generally a sequential design approach has been taken rather than a holistic (or global) approach. It has often been the case that the solution to the last problem has caused the next problem, eg fast excitation systems for transient stability led to self-excited oscillations. It might be though that this has about met its limit with recent changes in the industry - see later. However, modern information technology for control, communication and computing (CCC) gives us possibilities to use intelligent distributed algorithms to complement more traditional approaches. It is worth noting that many of these issues have been dealt with in a simpler form in development of coordinated PSS schemes in the 1980's[1] [12][25]. The PSS modules were designed largely according to local stability criteria. They could be designed sequentially or simultaneously to accommodate the effect of interactions, but this could be a large computational task either way. The simultaneous approach amounts to an optimisation of any tunable parameters within certain operating constraints to position the closed loop modes of the system with adequate damping.

In looking to generalise these ideas to the whole control problem of maintaing stability while providing specified performance, we start by identifying the basic *control elements,* ie those existing controllers and their tunable parameters which are free to adjust for system-wide purposes.These will be based on physical devices or at least the designs for them. The controller could have the form

$$u_i = U_i(x_i, w_i, z_i(k); \theta_i, \vartheta_i) \tag{4}$$

where subscript i refers to a geographical part of the system and/or some special control task, eg. transient stabilisation in power systems. The controller is typically expressed as a function of state variables or as a dynamical system driven by certain system outputs. This controller could be anything from a simple classical PID controller to the most sophisticated nonlinear controller (including rule-based, fuzzy or model-based designs such as feedback linearisation). The controller is required to perform well inspite of the uncertainty ϑ_i. The parameters θ_i are available to implement coordination with other controllers.

2.4 Bifurcations and Global Control

The development of nonlinear control theory has generally evolved along several lines of thought. There are many books on this topic - see for instance the recent ones [19][31][30][2]. Emerging from mathematics of dynamical systems and the study of some specific systems, there has been an extensive study of nonlinear systems dynamics in terms of underlying bifurcations in the models [30]. This line has been extensively pursued for power systems analysis [16]. While bifurcation control has been developed for special systems of scientific interest [9], it has not been developed for power systems in any practical way. Most work on generic nonlinear control, eg[19][31][2], does not deal with the bifurcation structure. In fact, many assumptions used in the development of nonlinear control algorithms effectively rule out bifurcations of dynamical behaviour.

Our global control objective is to achieve good control performance over a wide range for the anticipated operating region with robustness to different faults whose sequences are not known apriori. The bifurcation boundaries define domains of operation where the dynamical behaviour is qualitatively different, see [16] for review papers. A possible control strategy, accepting the boundaries, is to design controllers for each structurally stable region and switch between them in some way. A scheme which has the abovementioned two-level structure has been presented and used for a standard example in [32]. The switching controller has a weighted Sugeno type form used in fuzzy control, but is motivated by the need to allocate control effort according to dynamical behaviour. Assuming the state-parameter space is partitioned into two domains, the control u takes the form:

$$u = u_e + \mu_1 u_1 + \mu_2 u_2 \tag{5}$$

where u_e provides the new equilibrium manifold; μ_1 and μ_2 are functions of an indicator variable expressing the closeness to a particular region or control concern; and $v_1$and v_2 are the local controllers. The overall control for a specific design is just a special form of nonlinear controller which can have the general form (4), ie it may have tunable parameters. There maybe many such controllers acting on the complex system.

More generally the domain boundaries could be defined by regions where modelling is unknown and typically behaviour changes in some major way, so switching control again becomes natural. Between these discrete models the models are incomplete and uncertainty must be allowed for. A complete model becomes an interpolation which can be expressed in various ways, eg see [22][8] for use again of fuzzy-control type membership functions.

2.5 Optimal Coordination and Swarming

Once all the local controllers are designed, the freedom to use them flexibly should be fully exploited. This may involve simply tuning of free parameters, as in the PSS case mentioned above, or a more complicated scheduling exercise which allows for any control redundancy to use scaling and timing according to control costs, dynamic properties and priority. The latter idea is familiar at least for static scheduling in operations research, but is quite complicated for dynamical systems as it requires the solution of the optimal control problem [7] [33]. A technique along these lines has been developed for optimally coordinated voltage security control of power systems [29] using differential dynamic programming (DDP) and trajectory sensitivity methods to set-up the staged use of available controls in an optimal way. However, there is a wealth of techniques which can be explored here. Many ideas in modern control boil down to use of optimal control. In [24], the voltage security problem is addressed using Model Predictive Control (MPC) and search techniques as a way to set up the optimal tuning.

The switching idea expressed above can be interpreted as allowing the controller to adjust the individual contributions of the local controllers according to the particular problem being faced at a given time. For instance when an instability occurs in a certain domain or in a certain variable type, eg voltage instability, the indicators driving the weighting functions will automatically adjust the control to emphasise the appropriate actions. When optimal coordination of many such controllers is considered, we can think of numerous controller elements in a complex system as swarming [5] to deal with problems as they arise.

It is beyond the scope of this paper, but it is easy to

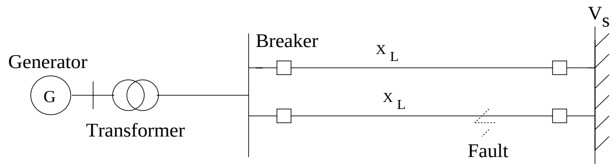

Figure 1: A single machine infinite bus power system

see all special forms of adaptive and learning control as specific examples of a coordinated tuning of control elements framework. The theory of aspects of optimal control for structured nonlinear systems with variable parameters needs further development, but many ideas have already been established in the development of adaptive control- see for instance [27][28][20].

3 Global Transient Stability and Voltage Regulation

The results presented here are a brief summary of those in the paper [15].

We consider the particular SMIB power system arrangement shown in Figure 1. The classical third-order dynamical model of a SMIB power system (Figure 1) can be used [4]. The fault considered in this paper is a symmetrical three phase short circuit fault which occurs on one of the transmission lines.

Feedback linearization [19] is a quite appealing design method for power systems. In the following, we briefly describe the design based on so-called direct feedback linearization (DFL) compensators [37, 38]. This preserves more easily allows actions of physical states than the geometric algorithm version in [19].

For the linearized system, robust control techniques for linear systems [21, 39] can be employed by solving an algebraic Riccati equation (ARE) – see [38, 36] for details. The real excitation control u_f can be obtained – see [15] – as

$$\begin{aligned} u_f &= \frac{x_{ds}}{k_c V_s \sin\delta}\left[v_f - T'\frac{V_s}{x_{ds}}E_q\cos\delta\ \omega + P_{m0}\right] \\ &\quad -T'_{d0}(x_d - x'_d)\frac{V_s}{k_c x_{ds}}\sin\delta\ \omega \end{aligned} \tag{6}$$

where

$$v_f = -k_\delta \delta - k_\omega \omega - k_P \triangle P_e \tag{7}$$

k_δ, k_ω, k_P are the linear gains obtained from the solutions of ARE.

DFL nonlinear control (6) with (7) guarantees the transient stability of power system for admissible uncertain x_L and V_s (proof is given in [38]). However, since V_t is a nonlinear function of δ, P_e and the system structure, any change in the system structure will cause the voltage to reach another post-fault equilibrium point even if δ and P_e are forced to go back to their pre-fault steady values. So the generator terminal voltage V_t could stay at a different post-fault state which is undesirable in practice.

From the above, we can see that although the DFL nonlinear compensator is effective for stability, it cannot guarantee voltage regulation.

Voltage regulation is an important property particularly in the post-transient period. Its basic objective is to regulate the voltage to reach its nominal value. Voltage controllers have been given in [13] using LQ-optimal techniques and in [40] using a linear robust control technique. Both of them have the problem that they deteriorate transient stability over the whole operating region.

For example, as proposed in [40], differentiating equation gives

$$\triangle\dot{V}_t = f_1(t)\omega + \frac{f_2(t)}{T'_{d0}}\triangle P_e + \frac{f_2(t)}{T'_{d0}}v_f \tag{8}$$

where $f_1(t)$ and $f_2(t)$ are highly nonlinear functions of δ, P_e and V_t – see [40] for details. Since $f_1(t)$ and $f_2(t)$ are dependent on the operating conditions, their bounds can be found within a certain operating region. So a new linearized system which is represented by the vector $[\triangle V_t, \omega, \triangle P_e]$ can be developed. Robust linear control techniques can be applied to obtain

$$v_f = -k_V \triangle V_t - k_\omega \omega - k_P \triangle P_e \tag{9}$$

where k_V, k_ω, k_P are linear gains dependent on the bounds of $f_1(t), f_2(t)$. The real excitation input u_f is chosen as defined in (6).

Since the voltage is introduced as a feedback variable in (9), the post-fault voltage is prevented from excessive variation. It is unnecessary to keep the power angle regulated once transient stability is assured.

However, since the design of the voltage controller involves estimating nonlinearity bounds within a certain operating region, it is only effective locally. In another words, when serious disturbances occur which cause the system to operate in a wider range outside the estimated one, the designed system may not perform well.

By now it can be seen that the DFL nonlinear controller and voltage controller achieve different control objectives in different regions of the states. In [36, 37], a nonlinear coordinated control scheme was proposed where a switching strategy is used between the different control actions to guarantee transient stability enhancement and voltage regulation. However, this scheme is not robust with respect to different faults since the switching time is fixed.

Desired properties of the global controller include robustness with respect to different faults whose sequences are not known apriori.

We use membership functions which are able to indicate different operating stages – see [15] – $\mu_V(z)$ and $\mu_\delta(z) = 1 - \mu_V$, where

$$z = \sqrt{\alpha_1\omega^2 + \alpha_2\left(\triangle V_t\right)^2} \qquad (10)$$

and α_1, α_2 are positive design constants providing appropriate scaling which can be chosen according to different sensitivity requirement of power frequency and voltage. $\mu_\delta(z)$ gets its dominant value when z is far away from the origin, which corresponds to the transient period; on the other hand, $\mu_V(z)$ does so when z is close to the origin, which indicates the post-transient period. Since the membership function values are determined by the directly measurable variables, ω and $\triangle V$, the fault sequence need not to be known beforehand.

It should be pointed out that ω and $\triangle V_t$ are chosen as the index variables in (10) since they sufficiently represent the operating status for the problem of transient stability and voltage regulation.

The global control law is the average of the individual control laws, weighted by the operating region membership functions, i.e., the input v_f takes the form:

$$v_f = \mu_\delta v_{f1} + \mu_V v_{f2} \qquad (11)$$

where v_{f1} is the DFL nonlinear controller (7) and v_{f2} is the voltage controller (9). The real excitation control u_f can be implemented by (6). The global control (11) has the following interpretation: in the transient period system states are far away from the equilibrium, the primary control is to regulate them to enter a neighborhood of the equilibrium without large oscillations; then in the post-transient period around the equilibrium the voltage needs to be tuned to reach the prefault level. The form of control law (11) is such that a smooth transfer between the local controllers is automatically achieved.

Illustration of the performance for this control scheme is given in [15].

4 Conclusions

This paper has given a conceptual framework, called global control, for the control of complex systems. The term global refers to scale (in dimension or geographically) and size of disturbances as is clearly needed for the world's larger power systems. The combination of ideas developed in control science, optimisation and related to the specific structure of power systems provides the possibility of more advanced control in the era of deregulation where more complexity is going to be inevitable. The framework involves hybrid system modelling, bifurcation analysis, switching control and optimal coordination and scheduling of control. For illustration, we showed how global control can improve the coordination of multi-objective control of a single machine on an infinite bus power system. We defined our global control objective as achieving satisfactory control performance over a wide range of anticipated operating conditions; specifically, transiently stabilizing the power system when subjected to a severe disturbance and retaining good voltage level after the disturbance. The controller was of the switching kind using membership functions.

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