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An integrated lookahead control-based adaptive supervisory framework for autonomic power system applications

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ABSTRACT

Management of the power system infrastructure is a challenge due to its complex dynamics, size, deregulated operation, quality of service demands, and stability concerns. Autonomic computing has recently gained interest on power systems arena for self-healing, self-configuration, self-optimization, and self-protection schemes. Robustness and reliability of the power system can be enhanced with appropriate autonomic control action following the disturbances. Predictive optimal tuning of real time control parameters from the finite set of control actions is considered in this paper to prevent from impending system deterioration. We present the formulation of a generic, higher layer model-based Limited Lookahead Control (LLC) approach that can be applied to a variety of power system applications. The system model, including the lower level controller, load dynamics, and a network assists the controller action. Discrete time control decisions are made based on the optimization of the predicted response to a limited horizon from the developed model. Heuristics based A$*$ algorithm is integrated into the framework to reduce the control overhead for real-time operation. Finally, we present a case studies on Matlab, and *RTDS*® to demonstrate the applicability of the proposed framework. A nine bus multi-machine power system benchmark is considered for voltage control application with the finite set of capacitor tuning.

Introduction

Specification for electric power system services are increasing proportional to the involvement of a system component's complexity. Rising user demand and the deregulation of the market has driven the system operation point closer to its limits. Such conditions require stringent controls with more constraints including environmental, economic and safety considerations. Human intelligence to tackle such issues at all levels of the controls becomes tedious and error prone. The control actions on future power systems should be autonomous and be able to manage themselves with high level guidance from humans. The control objective should coordinate multiple types of controls with various levels of control hierarchy and simplicity in design procedure to maintain the specified Quality of Service (QoS). Current research trends have been directed towards exploiting the existing control actions and exploring novel strategies for developing adaptive and autonomous system level control framework.

Many varieties of power system controls approaches including classical feedback control, expert system, artificial intelligence, and rule based systems have been implemented. Model-based control [1] has formed a strong theoretical foundation in process control ranging from modeling and identification to optimal and robust control. This approach is more robust in principle and is better prepared for unforeseen consequences which adapt to the environment accordingly. Models from first principles [2], probabilistic models [3], and data-driven models [4] have been used for power system prediction, regulation, disturbance rejection and optimization. Designs incorporating the system model assist on proactive control [5] with the near future predicted trajectories of particular objectives. Such a control policy closely works with the developed plant models for optimal steady state operation. Generation dispatch control and short term operations including reference voltage settings, load control, tap settings and shunt capacitor switching have been considered under such policy.

Model Predictive Control (MPC) has been used as a representative model based approach in multiple power system applications. Research works have proposed supervisory MPC controller for voltage control [6], stability [7], and corrective actions in emergency conditions [8]. As the power system requires the solution of the differential algebraic equation (DAE) along with the discrete switching actions, broad set of solutions have been reported within such model-based framework. A heuristics tree search algorithm is implemented to find the optimum control variables for voltage

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control in [9]. Ref. [10] provides a multi-start pattern search, a direct-optimization method which does not require gradient or Hessians to solve non-linear MPC. However, such a solution requires proper coordination between the complex optimization procedures and the system formulation. In addition, this method is more suitable for continuous domain system.

The trade-off between accuracy, complexity and computational burden is considered on selecting the prediction model of the future trajectories. Simulation of the DAE for each evaluation of cost function is computationally complex; however, it provides non-linear insight. The Euler state prediction approach is reliable in the presence of monotonic dynamics. The trajectory sensitivity calculation [11] is another approach which provides more insight into the system behavior as compared to the simulation. Higher level abstraction for modeling [12] considers only variables of interest, thereby reducing the complexity and increasing suitability for model-based framework.

Power system management functions, including adaptive protection scheme, optimal generation dispatch, stability, energy efficiency, and security constrained long-term planning, should be explored from the system level with a corresponding time frame [13]. Such functionality needs to be coordinated in the central framework with proper situational awareness. In addition, short-term protection has to be addressed in regard to load variation and contingencies to supply the proactive control solution. Dynamic security assessment for credible contingencies consider the constrained operation, thereby assisting the control algorithm. Such continuous assessment of the system status is followed by appropriate control actions. The supervisory controller works in coordination with such control functions, working to strengthen the grid. Appropriate modeling abstractions for load characteristics and other power system components are necessary to be embedded in model-based, multi-agent or other possible frameworks to support supervisory control policy.

In recent years, the complexities on smart grid operation and control are being considered through the autonomic computing innovations [14]. It considers the addition of intelligent approaches to develop adaptive system using the modern information technology (IT) for fully operation of the grid. At the same time, various software architectures [15] are being introduced along with the different algorithms [16]. Additionally, solving the computationally complex system for processing coordination data is also a challenge [17].

As discussed above, the MPC has been mostly used for continuous state space as well as continuous input domain. In this paper, we propose the LLC based integrated framework rooted on the linearized discrete predictive model for power system applications. LLC is a form of MPC which is well suited for discrete (finite) input sets [18] such as switches, capacitor switching, transformer tap settings, and step load control. The underlying control policy in this framework facilitates the use of tree search techniques rather than integer linear programming (ILP) to solve the problem. We extend our previous work [19] with the A$*$ algorithm which reduces the complexity for larger input sets and longer prediction horizon.

Also, the LLC has a way to prove stability [20] even for complex non-linear systems with multi-mode dynamics. Modern control including MPC and LLC becomes the natural choice as classical control does not usually apply to non-linear systems, let alone those with discrete (finite) inputs [21]. However, the choice between them depends mostly on the nature of inputs and the problem domain. We present a case study for bus voltage control to clarify our approach, where a finite set of capacitor steps are considered as a control parameter. The linearized, discrete model-based optimal design is presented here to keep the system robust to withstand disturbances such as line, generator trip or equipment failure. The proposed approach is not only applicable for voltage control problem but also for tuning for many other control processes in power systems.

The paper is based on the LLC framework to acknowledge power system problems and makes the following contributions:

- The adaptive model-based supervisory LLC based framework is proposed for generic power system controls applications. The generic framework is flexible and can be extended to autonomic computing applications on building the next generation grid.
- The complexity reduction algorithm is integrated utilizing the same model to help generate the heuristics. This method not only reduces the control overhead time but also reduces the design complexity by utilizing the same model, a combination not stated in power system controls literature.
- The proposed control framework is validated for the voltage control application through the *RTDS*® testbed considering the time delay.

Controls framework

The functional decomposition of the integrated lookahead control based framework for general power system applications is shown in Fig. 1. Different module works in coordination with each other towards the common system goal. *Power Grid* measurements are obtained from Supervisory Control and Data Acquisition (SCADA) or even in advanced form from phasor measurements unit (PMU). Breaker statuses are also monitored for reconfiguration and protection scheme; thus, obtained measurements and statuses are used by the state estimator and then by the power flow equations. Specific assessment of the system condition is performed to detect any abnormalities. This assessment block represents the functions such as online dynamic security assessment (DSA). In case of occurrence of any disturbance and prediction of the potential violation of pre-defined system constraints, the model-based control action is invoked by the *Analysis Block*.

The *Environment Module* contains the predictive filter which takes the input of current environmental measurement data gathered by distributed environment monitors. This module generates the predicted workload and operation condition forecast estimations for system module. Predictions are made based on the prediction and estimation library and the environment model to provide real-time decision support for optimized operations.

The *System module* consists of the system abstraction, which is formed and updated periodically from the power flow data and the direct measurements depending upon the application. Dynamic models are the key components of model-based framework and require in-depth knowledge about the particular domain. Strong assumptions on the system dynamics are avoided. Expected system states are computed with the knowledge of the forecasted environment variables along with the current system states, and existing information stored in the system database.

The *Management Module* works to satisfy the performance specification provided from *Service Level Agreement (SLA)* block by solving optimal control problem. All the QoS parameters are associated with utility function while satisfying the constraints. The discussed framework is flexible for optimization methods. we explore the search tree with the A$*$ algorithm as explained in Section 'Complexity reduction algorithm'. The *SLA block* specifies the performance specifications including stability, fault management, power management, or any other optimal reconfiguration strategies, in correspondence with the *Additional Module*. The decision support modules including system assessment, generator dispatch control, and unit commitment could be included in *Additional Module*. The framework's open architecture, that includes multiple functional modules to address several control issues, is exploited through this module.

The *Human Machine Interface (HMI)* reads the system states and other necessary information from various modules. Operators can override the optimizer action all the time.