Developing Scalable Smart Grid Infrastructure to Enable Secure Transmission System Control

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Abstract	Modern power systems are being pushed to operate ever closer to their security limits due to the rapid growth of electricity demand and the unmatched infrastructure constructions. When exposed to a severe contingency, the system is more prone to losing its dynamic security, which can result in catastrophic consequences such as cascading outages and/or widespread blackouts. To protect the power system against dynamic insecurities, preventive actions based on dynamic security assessment and different control strategies are carried out. Here in this report we reflect on the key references on the application of modern power system components (FACTS devices and wind farms) to increase the dynamic security as well as new assessment and control schemes to improve the stability and security of the system and mitigate risks.			
Keywords	Corrective and preventive actions, dynamic security analysis, oscillation damping			

Contents

Abbreviations

ANN	Artificial Neural Network
DG	Decentralised Generation
DT	Decision Tree
GPS	Global Positioning System
MLQG	Modal Linear Quadratic Gaussian
MPC	Model Predictive Control
MPPT	Maximum Power Point Tracker
OPF	Optimal Power Flow
PD	Pattern Discovery
PMU	Phasor Measurement Unit
POD	Power Oscillation Damping
SVM	Support Vector Machine
VSC	Voltage Source Converter
WECS	Wind Energy Conversion System

1. Introduction

Modern power systems are being pushed to operate ever closer to their security limits due to the rapid growth of electricity demand and the unmatched infrastructure constructions. When exposed to a severe contingency, the system is more prone to losing its dynamic security, which can result in catastrophic consequences such as cascading outages and/or widespread blackouts. To protect the power system against dynamic insecurities, preventive actions based on dynamic security assessment and different control strategies are carried out. Here in this report we reflect on the key references on the application of modern power system components (FACTS devices and wind farms) to increase the dynamic security as well as new assessment and control schemes to improve the stability and security of the system and mitigate risks.

2. Dynamic Security Improvement by HVDC Supplementary Control

Due to recent changes in generation patterns and demand increases, system operators are under pressure to operate transmission systems closer to their stability limits. Supplementary and wide area control of FACTS devices can be employed to enable the stable operation of power systems closer to their designed thermal limits. Additionally, the trend of renewable energy connection to the grid has brought about large variations in the traditional energy flow. The high penetration of renewable energy into the power grid, as well as load variations and contingencies can introduce numerous uncertainties in the system and consequently a wider range of operating points that a power system might operate at. Such diversity in the state of the system necessitates the robust analysis of a power system damping controller during the design stage.

Among various types of FACTS devices, HVDC links are more effective at improving transient stability due to their flexible operation in transferring active power in bulk between distant areas [1]. Modulation of the active power set-point of a HVDC linkhas been effectively used for Power Oscillation Damping (POD) controller design based on a linearised system model at the steady state condition. Various control schemes, including optimal techniques such as mixed H2/H∞ [2], LQG [3], MPC [4] and optimization [5], fuzzy and neural network based [6] designs as well as non-linear methods [7]–[9] have been reported within this area.

The controllers mentioned above are able to achieve an acceptable damping level for the tested networks around the nominal operating point of the systems for which they have been designed. Little study has been carried out on the extent to which a controller is capable of damping oscillations over a wide range of operating points. A robust analysis of the controllers has been evaluated based on a limited number of steady state conditions [10]–[12]. This clearly does not truly reflect the variable nature of power systems. The application of statistical methods has been reported [13]–[15] to assess the overall stability of the system without the presence of any wide area POD controllers. Further research is required to statistically evaluate the robustness of the designed POD controllers. A Modal

Linear Quadratic Gaussian (MLQG) controller has been implemented and tuned in [16]–[18] to address the robust requirement of the POD controller design.

Recently, the application of the Model Predictive Control (MPC) scheme in power systems has attracted the attention of researchers. Ford et al. [19] introduced a wide area measurement, nonlinear, model predictive control approach to provide first swing stability protection of vulnerable power system transmission lines through installed FACTS devices. A wide area optimal control using MPC approach is suggested by Zweigle et al [20] for higher order contingencies. In another paper, Pirooz Azad [18] compared the MPC with LQG supplementary power controllers for inter area oscillation damping. The advantages and disadvantages of centralised and de-centralised MPC controllers are studied and elaborated in [21]. Their simulations illustrate the performance enhancement obtained with a global MPC-based controller compared to local de-centralised damping controllers.

MPC has gained interests for POD due to its functionality and robustness against noise and disturbances. The authors in reference [22] evaluated the robust characteristics of the MPC scheme on power oscillation damping. To enhance the damping of inter-area oscillations in power systems, they designed and implemented a MPC as a HVDC supplementary controller for improving AC system stability. Additionally, to evaluate the robustness of this method, statistical Monte Carlo simulation has been employed. The application of MPC was also compared with the MLQG scheme to provide a better insight into the robustness of the controller’s functionality. The results prove the supremacy of the MPC controller in damping inter-area modes over a wide range of operating conditions.

3. Dynamic Security Assessment and the Corresponding Preventive Control Techniques

The continuously growing demand for electricity, driven by deregulated electricity markets, has forced modern power systems to operate closer to their secure operating energy and this may impact transmission systems by bringing more uncertainties to the grid operation. It becomes more challenging to protect a modern power system from insecurity by relying only on localised protection schemes. Hence, a power system should be secured proactively at the system level by advanced system protection schemes for online situational awareness and proactive wide-area coordinating control [23]. For instance, an elaborate proactive system protection scheme may integrate both online DSA for the identification of potentially insecure conditions and system-level optimization and execution of control strategies for prevention of the identified insecure conditions. Phasor Measurement Units (PMUs) can provide high-resolution real-time power system measurements synchronised by a Global Positioning System (GPS).

Pattern recognition techniques, such as Artificial Neural Networks (ANNs) [24], Support Vector Machines (SVMs) [25], and Decision Trees (DTs) [26] can be applied in DSA of power systems. Among DT algorithms, those with the “white box” nature have gained increasing interests because they not only provide the results of security assessment but also reveal the principles learned by DTs for security assessment. Those principles provide useful information required for the remedial actions against recognised insecure conditions. With the aid of WAMS and advanced computing resources, DTs may be integrated into online DSA tools for large interconnected complex power systems. For instance, the work in [27] applies DTs in an online DSA method by adaptively updating the database to train DTs on a daily basis for foreseen system conditions. In [28], a method for efficient database generation for DT training is introduced to enhance DT accuracy in DSA and decrease the computation burden in DT training. In [29], multiple optimal DTs are proposed to increase the accuracy for the assessment of static voltage security. In [30], DTs are used for preventive control (i.e., generation rescheduling) and for corrective control (i.e., load shedding) by determining the dynamic security regions. The preventive and corrective controls are then optimised in terms of the fuel cost and the amount of load to be shed, respectively.

With the increasing penetration of renewable energy resources and other Decentralised Generation (DG), more uncertainties will be brought to the operation of transmission systems. This is because these resources are not as accessible for direct monitoring and control from control centres as in the case of conventional central power plants. Thus, a significantly increased number of scenarios need to be covered to address these uncertainties. However, it also becomes more important to minimise the computation burden for real-time DSA and the associated sensitivity analysis. Most of the existing works apply DTs mainly for security assessment and the predictors to be measured in real-time are those system variables that are most effective in detecting security problems, e.g. line flows and angle differences. However, the DTs focusing on decision support for preventive control may employ a different set of predictors that are directly controllable, e.g. generation outputs, so it is advisable to build two DTs, respectively, for DSA and preventive control based on two sets of predictors selected separately. The DT-based approach proposed in [23] aims to address the aforementioned problems.

Under a similar knowledge extraction and utilization framework, [31] applies an alternative, yet more robust, statistical learning technique called Pattern Discovery (PD) in developing a preventive control method for transient instability prevention. PD belongs to unsupervised learning in an unbiased and comprehensive manner and statistically discovers the hidden structure in a database and provides objective, transparent, and interpretable knowledge called patterns for specific use. The patterns are geometrically non-overlapped hyper-rectangles in a Euclidean space, easy to present and interpret; when discovered in a power system critical feature space, they can represent the dynamic secure/insecure regions, providing decision support for real-time security monitoring and situational awareness. By explicitly formulating the patterns into a standard Optimal Power Flow (OPF) model, the preventive control can be achieved transparently and efficiently.

4. Real-Time Transient Stability Analysis

The evolution of modern power systems is leading to changes in grid architecture that promote system stability analysis as an ever growing topic of importance. Growing penetration of non-synchronous renewable generation resources is likely to lead to a decline in system inertia, thus reducing transient stability margins; However, in parallel with these developments, measurement equipment such as PMUs are being deployed within the grid leading to more timely and accurate observations of system states. Consequently, while stability may grow as a concern for operational planning due to reduced margins, new technologies will likely enable improvements in stability analysis techniques.

When analysing system transient stability, a number of alternative techniques are available, each with their own limitations. Time-domain simulation methods rely on the construction of an accurate state-space system model prior to analysis. These methods offer the most accurate stability estimation results, but the computational requirements of the ordinary differential equation solvers, which permit time-domain simulation, prohibit the method from being used effectively in real-time. In addition, a time-domain simulation provides little insight into the margin of stability for a given fault, for example estimating the critical clearing time for a given fault. In contrast to time-domain simulations, direct methods [32] seek to more rapidly assess the stability of a system using a post-fault state measurement. While these methods compute rapidly, they often lead to overly conservative stability estimates.

To utilise the strengths of both time-domain and direct methods, a set of techniques known as hybrid stability methods have been developed. One of the most prominent hybrid methods is the single machine equivalent (SIME) [33], which is utilised in this study. Hybrid stability methods attempt to form simplified system analysis models based on energy functions, similar to direct methods, but rather than using system state measurements from a single time instance, signals over a narrow time window (including the faulted and immediate post-fault period) serve as the input data. These techniques attempt to find a suitable compromise between accuracy and speed in obtaining a stability estimate. However, identifying the critical generator set in order to determine the generators that are at risk of going out of step during a fault represents a critical stage in SIME techniques [34]. In recent years, the SIME method has been developed into two different modelling approaches. The first approach is referred to as the Preventive SIME (PSIME) method that relies on time domain simulation programs to determine stability scenarios of anticipated contingencies. The second approach is referred to as the Emergency SIME (ESIME) method that uses real-time measurements when considering the actual occurrence of a contingency [35]. In prior research, energy function descriptions of power system properties have been utilised successfully [36].

The authors in [37] proposed a method for real-time stability estimation, specifically by assessing whether a given fault has led to instability. Moreover, it provides an estimate of the margin of stability through assessing the excess kinetic energy accumulated during the fault, and determines which machines are contributing to the instability and are likely to go out of- step. Analytic results such as these may play a crucial role in real-time monitoring and control for modern smart transmission infrastructures [38].

5. Dynamics and Stability Assessment of Power Systems with Wind Farms

The increasing penetration level of wind energy on the existing power networks imposes new challenges to grid designers and operators. The behaviour of these new generation centres is different from the classical ones, composed by large synchronous generators. The current Wind Energy Conversion Systems (WECSs) technologies use variable-speed turbines based on full-converter topologies, or doubly-fed induction generators [39]. The power electronic devices on these turbines, not only allow them to operate optimally for a wide range of wind speeds, but also to independently control their injected active and reactive powers. The latter is useful for improving the overall system performance [40].

A problem associated with high levels of wind energy penetration is the decrease in the frequency regulation capacity of the system. If all the WECSs act as independent active power sources they do not contribute to the total inertia of the system [41], and the network becomes less robust to perturbations, such as load variations and generation tripping. To overcome this problem, and to improve the stability margin of the system, dedicated control strategies for the WECS power converters can be designed.

Several techniques consider the addition of a control action emulating the frequency droop of conventional generators [42], [43]. These controllers exploit a fundamental property of the variable-speed wind farms: due to their power electronic devices, they can resort to the kinetic energy stored in their rotational masses faster than conventional generators. This stored energy is used to transiently support the system frequency. Once the transient event finishes, the wind farm ceases its participation and the power unbalance is compensated by the conventional synchronous generators. Then, to extract the maximum power available in the wind, the Maximum Power Point Tracker (MPPT) algorithm adjusts the turbine speed according to the current wind velocity. The high controllability of the variable-speed wind turbines can improve other features of the power system, such as oscillations damping and voltage regulation [44]. In this regard, [45], investigates the damping of critical eigenvalues for different penetration levels, and the WECS contribution to diminish electromechanical oscillations.

The nonlinear nature of power systems, combined with the special features of WECS, drives the attention to investigate the dynamics from the nonlinear perspective. In this regard, bifurcation analysis provides a powerful tool to study the behaviour of the power system under variations of parameters such as the load consumption level, generation dispatch, controller’s gains, etc. The analysis of power system dynamics using bifurcation theory was explored in many articles over the last two decades [46], and it is currently used to investigate the dynamics of several power system components such as three-phase Voltage Source Converters (VSCs), dc-dc and fly-back converters, photovoltaic systems and permanent magnet synchronous motors. In [39], bifurcation theory is used to investigate the dynamics of a power system including wind farms when they perform ancillary control tasks such as short-term frequency regulation, inter-area oscillations damping, and voltage regulation. The analysis helps in determining new stability/operational regions, revealing organizing centres of the dynamics and assessing the dynamical scenario for non-nominal operating conditions.

6. Conclusion

The present report provides a classified outlook over the recent achievements in risk mitigation in power system transient and dynamic stability using active components such VSC and LCC HVDC links, FACTS devices and wind farms. Key references are selected carefully from numerous publications in this area to both save time for the readers of this report as well as covering the main research categories in risk mitigation techniques in the power system stability field. Sections 2 and 5 explore the key references in stability risk mitigation using supplementary controllers as power oscillation dampers. The supplementary controller employs the active and reactive power injection capability of FACTS and wind turbines to increase the stability of the system, hence reducing the risk of any instability after a contingency. Sections 3 and 4 provided a key reference review on novel techniques in prediction of the system stability margin and consequent optimal measures such as load shedding or generator re-dispatching to avoid any instability problem in the power system.

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