

Optimizing strategies of Transient Stability and Voltage Regulation in Multimachine Power Systems

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Abstract: The main contributions of this paper are threefold: 1) use of a STATCOM and battery energy storage procedure to enhance transient balance and furnish voltage regulation with SG and DFIG; 2) demonstrating the applying of nonlinear manipulate conception (particularly the IDA-methodology) for the design of a stabilizing suggestions controller in gigantic-scale power techniques to give a boost to transient approach efficiency; and three) establishing a methodology that can use the further levels of freedom in large-scale energy techniques with the intention to further reinforce procedure performance, in targeted the transient balance margin measured through critical clearing time (CCT)] and the dynamic transient performance of the process. In order to achieve power angle stability along with the simultaneous regulation of frequency and voltage, the performance of the proposed control scheme after the occurrence of large disturbances is evaluated and compared with a conventional power system stabilizer and a feedback linearizing controller.

Index Terms—Battery energy storage systems (BESS), interconnection and damping assignment passivity-based control (IDA-PBC), multimachine power systems.

I. INTRODUCTION

SYSTEM stability is the most important issue for power systems; if stability is lost, network collapse may occur with devastating economical losses and power grid damages, see [1], [2]. Traditionally, transient (angle) instability has been the dominant stability problem. With the continuing growth of power system interconnections and the increased operation in highly stressed conditions, different

forms of system instability have emerged. For example frequency stability, inter-area modes of oscillations and voltage stability have become great concerns [3]. A clear understanding of different types of instability and how they are interrelated is most important for the satisfactory control design and operation of power systems. The work presented in this paper is motivated by the occurrence of system instability and blackouts which may be preventable by use of advanced control techniques. Lack of properly automated and coordinated power system controllers to take immediate performance enhancing actions against system events has been recognized as one of the contributing factors for recent power system blackouts [1], [2], [4].

Power systems are modeled as complex, nonlinear and highly structured systems. It is well known that the generator excitation control system can provide one of the most cost effective ways to stabilize power systems. Conventional power system controls primarily deal with small disturbances about an operating point. This type of control can suffer performance degeneracy and in fact linear controllers may even destabilize the system if the operating point of the power system is changed away from the equilibrium point at which the approximate linearization is realized [5]. Control methods for handling system-wide large disturbance problems need to be developed, particularly ones which concern power system nonlinearity and unforeseen circumstances leading to large sudden operating point deviations. To address this issue, this paper applies DFL as a flexible and structure preserving nonlinear control technique, see [6]–[8]. This technique simply uses the Implicit Function Theorem to selectively eliminate system

nonlinearities and the well known nonlinear control approach based on the geometric coordinate transformation is not needed. Considering the effect of plant parametric uncertainties and power system interconnections, the robust control technique is further developed in this paper and applied to ensure the stability of the DFL compensated system. Only the bounds of uncertain parameters need to be specified and the exact time varying network parameters need not to be known. Much effort has gone over the years into the mathematical modeling and market restructuring of large power systems and, to a lesser extent, systematic stability control design. Development of stability control from both control theory and practical point of view continues to be an interesting subject. The major areas of concern are transient stability, oscillations and voltage stability/regulation. Particular features which motivate the work in this paper are:

- power system nonlinearity, uncertainty and dimensionality in the design of stability controllers;
- the interplay between angle and voltage behavior;
- problems of control coordination;

The main concern is the operation of the generator in var control mode while the power system stabilizer (PSS) is in operation. In [6], [9] we have discussed detrimental stabilizing effects through classical root locus analysis of the linearized power system model. A concern for coordination is a practical problem, which has become a theoretical problem in control theory. How to achieve satisfactory stability performance is an important issue and this motivates the topic of global control [10]. Transient stability and voltage regulation are both important properties of power system stability control, but they relate to different stages of system operation, i.e. the transient period and the post fault period. Different behavior of nonlinear power systems in different operating regions requires different control objectives and therefore different controllers need to be activated or switched to under varying operating conditions. One method to implement such control utilizes membership functions pioneered in the well known Takagi-Sugeno design which effectively provides smooth switching, see [11]. Global control is

the weighted average of the local controllers, where the weights are provided by the operating region membership functions [12].

This paper continues this line of investigation and examines the application of an integrated STATCOM and battery system using an advanced nonlinear controller to enhance the transient stability of a power system that includes both conventional SG and DFIG as found in wind energy conversion systems. The IDA-PBC control design methodology is used to achieve power angle stability and to provide both frequency and voltage regulation. To evaluate the effectiveness of the proposed approach for improving transient stability, simulation studies are carried out on a classical four-machine benchmark system, and performance results of the proposed system are compared to conventional control system implementations.

II. SYSTEM MODEL

Consider the power network that includes – conventional machines (SG) and – wind power systems [doubly-fed induction generators (DFIGs)] with – STATCOM/battery units and load that is modeled as constant impedances. Dynamic models of this multimachine power system can be divided into three main groups: namely, synchronous generators (SGs), DFIGs, and STATCOM/battery systems as follows.

A. STATCOM/Battery Models

Here, the model of an integrated STATCOM and battery energy storage system is developed. This system relies on a power electronic voltage-source converter and will be used as a regulating device in the ac transmission network by delivering and absorbing both active and reactive power simultaneously.

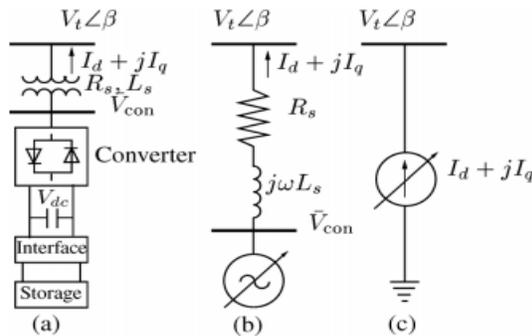


Fig. 1. STATCOM/battery model. (a) Schematic diagram. (b) Equivalent circuit (controllable voltage source) (c) Equivalent circuit (controllable current source)

This system can support electricity networks by improving power factor and voltage regulation and helping to damp electromechanical oscillations and enhance transient stability of the first swing dynamics that result from severe fault conditions.

A basic schematic diagram of a STATCOM and energy storage system is shown in Fig. 1(a). The STATCOM/battery includes a voltage-source converter, a transformer or reactor, and a dc-link with the energy storage device, for example, with battery energy storage systems that are considered in this paper. The STATCOM/battery can be modeled as either a controllable voltage source () as shown in Fig. 1(b) or a shunt-controllable current source, as shown in Fig. 1(c), where the STATCOM is used to regulate the terminal voltage by controlling the reactive power injected or absorbed from the power system while energy stored in the battery is used to maintain active power output, regulate system frequency, and damp power oscillations, hence increasing the operational reliability and security of the power system. For instance, as a controllable current source, the converter is able to inject or absorb a current into the power network via the transformer. Both active and reactive power are able to instantaneously be exchanged with the network by controlling the amplitude and angle of the injected current based on the capacity of the battery energy storage device.

B. SG and DFIG Modeling

For the machine conventional power system the nonlinear dynamic model of the n th synchronous generator.

Remark 1: Although this DFIG model is analogous to a one-axis model of a synchronous machine, there are substantial differences, namely:

- 1) is analogous to a voltage behind transient reactance in a synchronous generator despite the fact that it is not generated from an external excitation current;
- 2) the angle is similar to the angle of the rotor flux magnitude with respect to the synchronously rotating reference frame not a stroboscopic angle of rotation of the shaft; and
- 3) the angle dynamics contains two extra terms as compared with the angle equation of a synchronous machine because of the variable speed operation of the DFIG.

The representation of the DFIG model has a distinct advantage because the form of the model is similar to the SG and we can directly apply existing nonlinear control design techniques like feedback linearization, backstepping, etc. For both conventional (SG) and wind power systems (DFIG) including STATCOM/battery, the output electrical power of the n th synchronous generator and the n th DFIG can be computed, and, after some lengthy but straightforward calculations.

III. IDA-PBC METHODOLOGY

Interconnection and damping assignment—a formulation of passivity-based control (PBC), is a general design method for high-performance nonlinear control systems that can be described by a port-Hamiltonian model. This method not only assigns suitable dynamics to the closed-loop system, but, as it is a Hamiltonian formulation, it is also capable of providing a control design that achieves stabilization by rendering the system passive with respect to a desired storage function and the injection of a suitable level of damping. Here, we

present a brief recapitulation of the the IDA-PBC method applied to the control of a power system with STATCOM/battery.

The key step in this design method is the solution of the PDE that guarantees the stability of the closed-loop system. This technique relies on the concept of exact model matching of the closed-loop system with desired behavior determined by the pre-specified interconnection structure and dissipation matrices. In order to solve the matching equation above, there are different approaches to solve the PDE (11) as follows.

- Nonparameterized IDA: and are selected to accomplish the desired structure of the closed-loop system subsequently, all assignable energy functions compatible with that structure are characterized. This characterization is provided in terms of a solution of the PDE. In addition, from the family of solutions, we choose the one with equilibrium.
- Algebraic IDA: when the desired energy function to be assigned is selected a priori, then PDE (9) becomes an algebraic equation in and . Eventually, the controller is designed.

In this multimachine power system application, the Algebraic IDA approach is used to convert the PDE to an algebraic equation and this equation is used to find the controller that is capable of achieving the desired closed-loop system performance requirements, namely:

- 1) the equilibrium point is asymptotically stable and
- 2) power angle stability along with voltage and frequency regulation are simultaneously achieved. Implementation of the IDA-PBC design methodology to a practical power system requires modeling a multimachine system that consists of -SG and -DFIG and includes the STATCOM/battery system.

Remark 1: In general, SGs, DFIGs, or both exhibit poor mechanical damping, and, when there is no coupling between the electrical damping and the mechanical damping, this results in significant power oscillations in the system under fault conditions. In

order to avoid and mitigate any damage to the systems, these oscillations have to be damped effectively. Thus, additional damping should be included through a coupling between the mechanical subsystem (SGs and DFIGs) and the electrical subsystem (STATCOM/battery) which can be assigned by selecting suitable interconnection and damping structures.

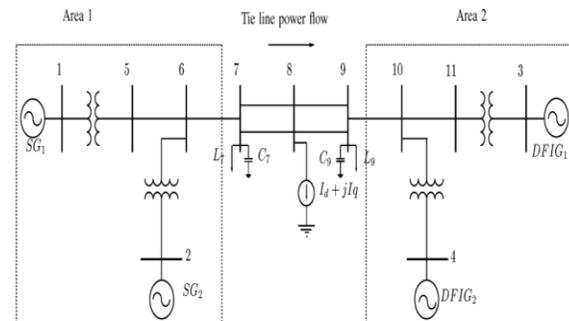


Fig. 2. Simple two-area system with STATCOM/battery.

In order to gain insight into the performance improvements that can be achieved in multi-machine power systems using the proposed control design approach, we study a classical four-machine power system as shown in Fig. 2. We recognize that even though these results are preliminary, they do suggest the improvements that can be achieved using the proposed approach. In particular, we evaluate the effectiveness of the proposed IDA-PBC control design methodology on transient stability enhancement when a STATCOM/battery is installed at the midpoint of the transmission line between area 1 and area 2. This system is modified by replacing two conventional generator and with two wind farms, in particular and in area 2 for the test system used in this paper. For controller design, synchronous generators and of area 1 are conventional plants or aggregates of plants along with aggregated wind generators (DFIGs) in area 2. The parameters and the normal operating condition along with the data used for the synchronous generators, transformers, and lines of the four-machine system can be found.

IV. CONCLUSION

In this paper, the IDA-PBC nonlinear control design method has been proposed to enhance the transient

stability and frequency and voltage regulation of multi-machine power systems that include both SG and DFIG and a STATCOM/battery energy storage device. Integrating the STATCOM/battery into the power systems using the IDA-PBC control design methodology provides additional damping to the system and dynamic simulations on a two-area multi-machine power system have shown that the nonlinear IDA-PBC control design approach is capable of providing improved system damping and better transient stability performance.

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