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Optimal Energy Management in Multi-Machine Grid Connected Systems using Static Compensators and BESS

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Abstract:

This project proposes a new strategy to achieve voltage regulation in distributed power systems in the presence of Static Compensators and battery storage systems. The goal is to find the minimum size of battery storage and its corresponding location in the network based on the size and place of the integrated solar generation. The proposed method formulates the problem by employing the network impedance matrix to obtain an analytical solution instead of using a recursive algorithm such as power flow. The required modifications for modeling the slack and generator buses are utilized to increase the accuracy of the approach. The use of reactive power control to regulate the voltage regulation is not always an optimal solution as in distribution systems R/X is large. In this paper the minimum size and the best place of battery storage is achieved by optimizing the amount of both active and reactive power exchanged by battery storage and its grid Tie inverter (GTI) based on the network topology and R/X ratios in the distribution system.

I. INTRODUCTION:

WITH the rapid increase of the size and complexity of power systems, power system stability and performance are of increasing importance in the operation of power systems. Recently, power system operation is faced with the difficult task of maintaining stability when a diversity of disturbances unavoidably occur in the system, including the variability introduced by distributed renewable energy resources (DRERs), including the integration of wind power into conventional power grids.

As the diversity of the generation mix increases and larger and larger amounts of power are being obtained from renewable generating sources, differences in the dynamic behavior between conventional and alternative generators can play an increasingly important role in the stability and security of the power system when faced with both small- or large-signal disturbances. This paper investigates the application of energy storage for improving the transient stability and voltage regulation in a large-scale power system with conventional and nonconventional generators through the design of a high-performance stabilizing control system that is capable of keeping the closed-loop system transiently stable under a diversity of multi machine power system operating conditions. Transient stability as studied in this paper addresses the impact of large disturbances such as faults, loss of generating units, large sudden changes in loads, etc., on the ability of the system to converge to a stable post-fault equilibrium after the fault is cleared from the system.

STATCOM:

In 1999 the first SVC with Voltage Source Converter called STATCOM (STATICOMpensator) went into operation. The STATCOM has a characteristic similar to the synchronous condenser, but as an electronic device it has no inertia and is superior to the synchronous condenser in several ways, such as better dynamics, a lower investment cost and lower operating and maintenance costs. A STATCOM is build with Thyristors with turn-off capability like GTO or today IGCT or with more and more IGBTs. The static line between the current limitations has a certain steepness determining the control characteristic for the voltage.

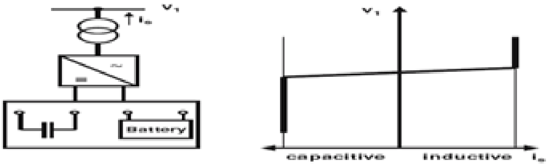

Fig 1: STATCOM structure and voltage / current characteristics

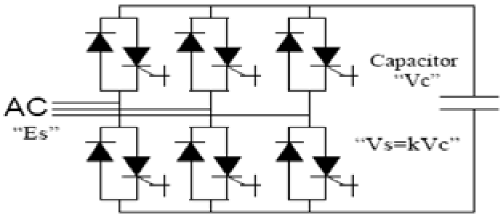

Fig 2: 6 Pulses STATCOM

A practical STATCOM requires some amount of energy storage to accommodate harmonic power and ac system unbalances, when the instantaneous real power is non-zero. The maximum energy storage required for the STATCOM is much less than for a TCR/TSC type of SVC compensator of comparable rating.

II.STATIC SYNCHRONOUS COMPENSATOR (STATCOM):

Introduction:

The STATCOM is a solid-state-based power converter version of the SVC. Operating as a shunt-connected SVC, its capacitive or inductive output currents can be controlled independently from its terminal AC bus voltage. Because of the fast-switching characteristic of power converters, STATCOM provides much faster response as compared to the SVC. Moreover, much research confirms several advantages of STATCOM. These advantages compared to other shunt compensators include:

- Size, weight, and cost reduction
- Equality of lagging and leading output.
- Precise and continuous reactive power control with fast response.
- Possible active harmonic filter capability.

Structure of STATCOM:

Basically, STATCOM is comprised of three main parts (as seen from Figure below): a voltage source converter (VSC), a step-up coupling transformer, and a controller. In a very-high-voltage system, the leakage inductances of the step-up power transformers can function as coupling reactors. The main purpose of the coupling inductors is to filter out the current harmonic components that are generated mainly by the pulsating output voltage of the power converters.

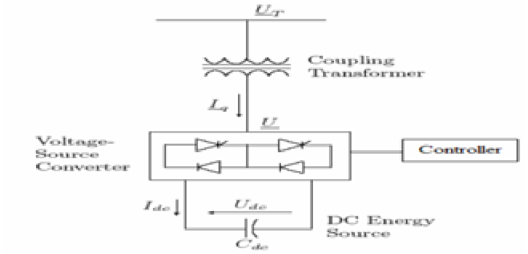

Fig 3: Reactive power generation by a STATCOM SYSTEM MODEL

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 modelled as constant impedances. Dynamic models of this multi machine 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

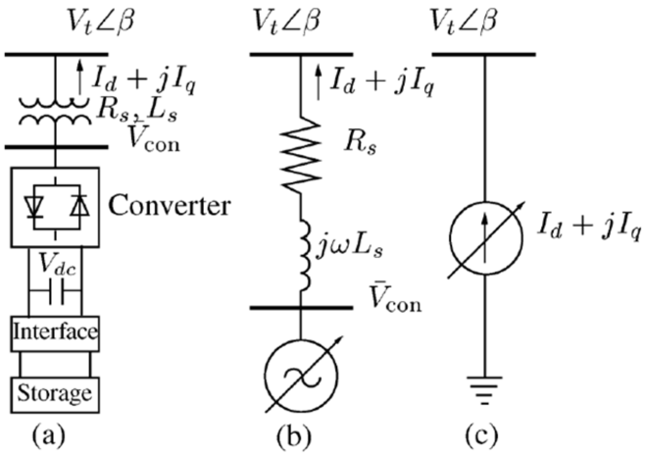

Fig 4: STATCOM/battery models (a) Schematic diagram. (b) Equivalent circuit (Controllable voltage source) (c) Equivalent circuit (controllable current source)

III. IDA-PBC METHODOLOGY:

Interconnection and damping assignment-a formulation of passivity-based control (PBC), introduced by Ortega et al. 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 rending 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 interested reader is referred to the survey and tutorial paper for more details, and, in particular, and for applications to transient stability of power systems with synchronous generators alone. Consider a nonlinear system that is affine in the control input with dynamics given by the following set of differential equations.

$$\dot{x} = f(x) + g(x)u \qquad (7)$$

With the state variables and the control input. And are smooth vector functions in the appropriate dimensions. The idea of IDA-PBC is to make the closed-loop system with a stabilizing (static) feedback control an explicit port-Hamiltonian system of the form

$$\dot{x} = (J_d(x) - R_d(x))\nabla\mathcal{H}_d(x) \qquad (8)$$

where the matrices) and , which denote the desired closed-loop interconnection structure and dissipation, respectively, are determined by the designer, a Hamiltonian function is the desired total storage function for the closed-loop system that satisfies . is the gradient of . In order to make, a solution of the so-called matching equation needs to be determined from

$$f(x) + g(x)\beta(x) = (J_d(x) - R_d(x))\nabla\mathcal{H}_d(x) \qquad (9)$$

with the matrices and as design variables. The equilibrium point (can be transferred to the origin) of the closed-loop system is stable if the desired Hamiltonian is positive definite. Consequently, the time derivative of along closed-loop trajectories becomes

$$\frac{d}{dt}\mathcal{H}_d(x) = -\nabla^T\mathcal{H}_d(x)R_d(x)\nabla\mathcal{H}_d(x) \leq 0. \qquad (10)$$

Therefore, serves as a Lyapunov function for the closed loop system and the equilibrium point (the origin) is stable. Asymptotic stability can be guaranteed provided that is strictly positive definite. In order to solve the matching equation, we split into two parts: a fully actuated part and an unsaturated part. Let be, where denotes a full-rank left annihilator of, i.e., , while denotes a left inverse of , i.e., , respectively. After multiplying the left by, we obtain a partial differential equation (PDE) and an algebraic equation, respectively, as follows:

$$g^{\perp}(x)f(x) = g^{\perp}(J_d(x) - R_d(x))\nabla\mathcal{H}_d(x) \qquad (11)$$

$$\beta(x) = g^{\dagger}(x)[(J_d(x) - R_d(x))\nabla\mathcal{H}_d(x) - f(x)]. \qquad (12)$$

From the PDE above, and are free to be chosen by the designer given that is skew-symmetric and is positive semi definite; may be totally or partially fixed if we can ensure that the Lyapunovstability conditions are satisfied: namely: 1) and 2) . The functions and need to be determined to satisfy with the Hamiltonian having an isolated minimum at the desired equilibrium point so that the equilibrium is stable, with the Lyapunov stability conditions also satisfied. In addition, is in the largest invariant set under the closed-loop dynamics contained in. An estimate of the domain of attraction of the closed-loop system is then given by the largest bounded level set. As a result, the control law can be directly computed as follows

IV. SIMULATION RESULTS:

Here, the proposed control methodology is implemented on a multi machine power system with a STATCOM/battery system, and the closed-loop performance of the system is evaluated using computer simulation studies under various transient conditions.

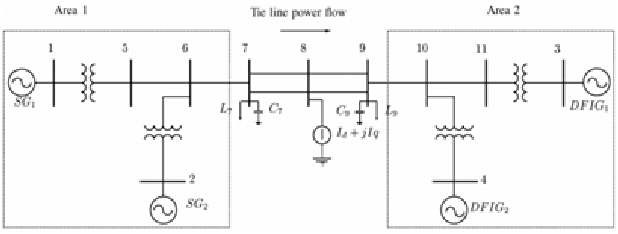

Fig. 2. Simple two-area system with STATCOM/battery.

Fig 5: two-area system with STATCOM/battery

The complete system dynamics is obtained solving the differential equation in the MATLAB environment. The time domain simulations are carried out to investigate the damping performance of the designed controllers, in the system under study. The performance of the proposed controller (IDA-PBC with STATCOM/battery) under a variety of test scenarios is compared with the following existing controllers.

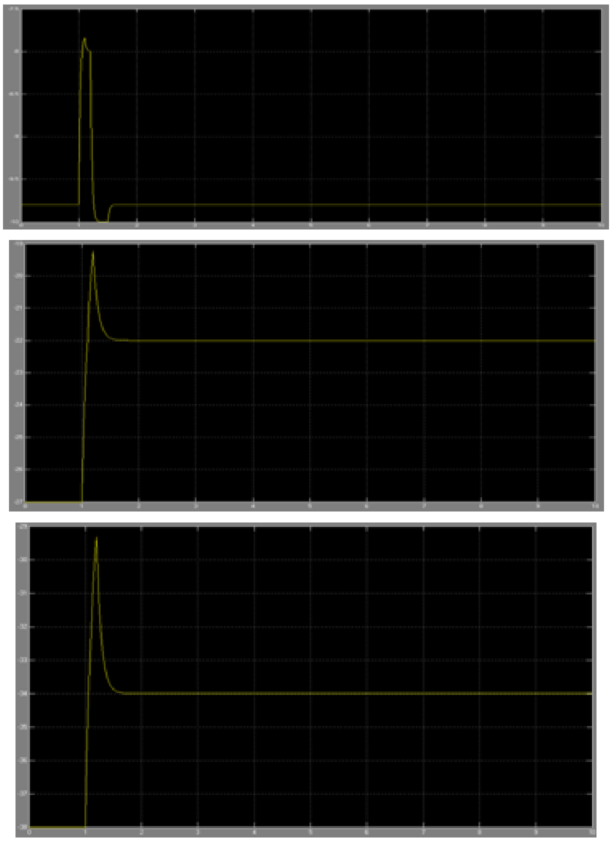

Fig 6: Controller performance in case of three-phase fault-relative rotor angles (δ_2-δ_1, δ_3-δ_1, δ_4-δ_1)

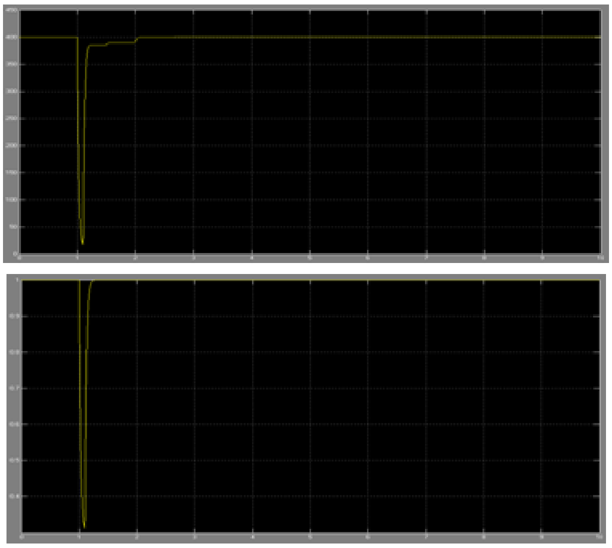

Fig 7: Controller performance in case of three-phase fault-transmission power from area 1 to area 2 and voltage at bus 8

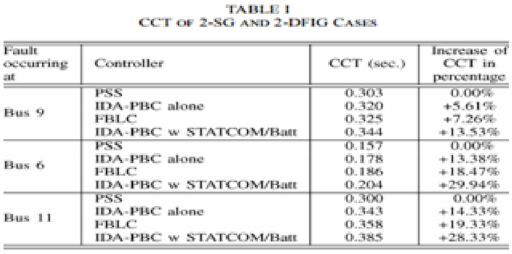

TABLE I
CCT OF 2-SG AND 2-DFIG CASES

Fault occurring at	Controller	CCT (sec.)	Increase of CCT in percentage
Bus 9	PSS	0.303	0.00%
	IDA-PBC alone	0.320	+5.61%
	FBLC	0.325	+7.26%
	IDA-PBC w STATCOM/Batt	0.344	+13.53%
Bus 6	PSS	0.157	0.00%
	IDA-PBC alone	0.178	+13.38%
	FBLC	0.186	+18.47%
	IDA-PBC w STATCOM/Batt	0.204	+29.94%
Bus 11	PSS	0.300	0.00%
	IDA-PBC alone	0.343	+14.33%
	FBLC	0.358	+19.33%
	IDA-PBC w STATCOM/Batt	0.385	+28.33%

B. Load Change:

Test Load changes are considered as a type of transient disturbance in this study. For example, a sudden increase (or decrease) in load demand at particular buses can induce transients in the system, that if inadequately damped can lead to system instability. The performance of the two area power system is investigated for a transient 50% decrease of the load at Bus 7 during the time period 1.0–1.5 s. Consequently, such a decrease in load results in changes to the values of and in the system's bus admittance matrix, and this effects the network configuration and the power transfer characteristics of the power system. Temporary differences in the power balance between the mechanical power (assumed constant) and the electrical power of each machine can lead to acceleration (deceleration) of rotor angles for the entire power system.

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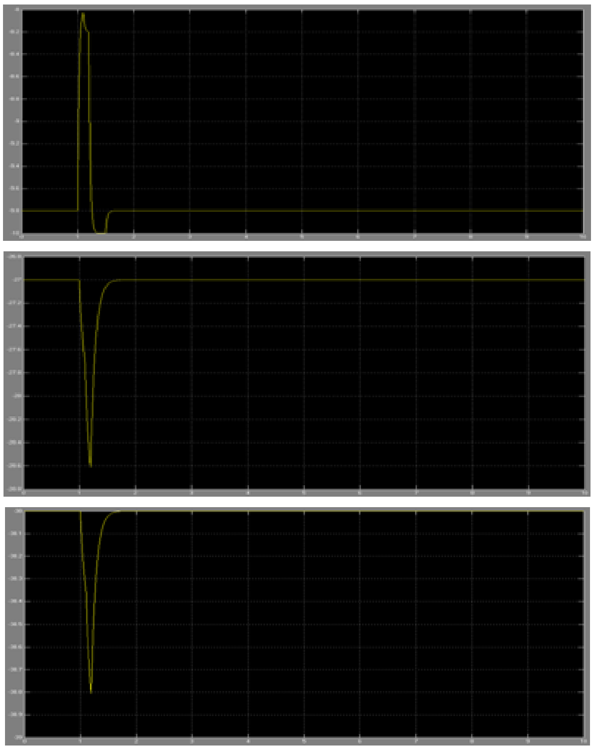

Fig 8: Controller performance in case of load changes-Relative rotor angles(δ_2-δ_1, δ_3-δ_1, δ_4-δ_1)

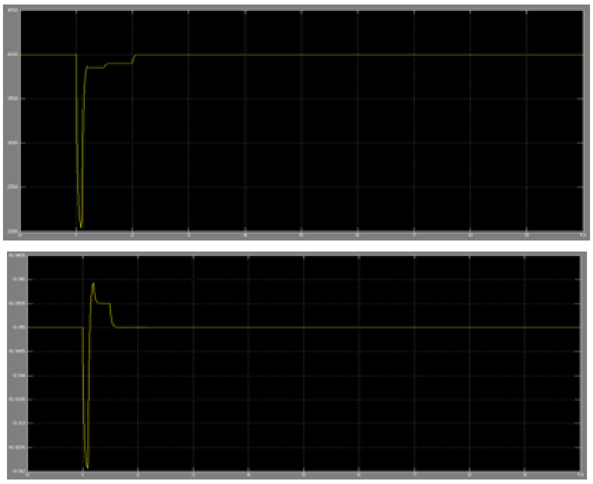

Fig 9: Controller performance in case of load changes-Transmission power from area 1 to area 2 and voltage at bus 8

Transient stability analysis of a multi machine Power system:

The stability of power systems has been and continues to be of major concern in system operation.

Modern electrical power systems have grown to a large complexity due to increasing interconnections, installation of large generating units and extra-high voltage tie-lines etc. Transient stability is the ability of the power system to maintain synchronism when subjected to a severe transient disturbance, such as a fault on transmission facilities, sudden loss of generation, or loss of a large load. The system response to such disturbances involves large excursions of generator rotor angles, power flows, bus voltages, and other system variables. It is important that, while steady-state stability is a function only of operating conditions, transient stability is a function of both the operating conditions and the disturbance(s).

Modelling Of Power System Components:

The classical system model represented above can be supplemented with other power system components for a detailed study or for implementation of the stability improvement measures. The block diagram models can be simulated within the Simulink environment almost in the same form. However, the representation of the transfer functions in the form of an integrator and gain with unity feedback is more convenient.

Simulation Results:

System responses are given for different values of fault clearing time (FCT).Figs 3 shows the individual generator angles and the difference angles.

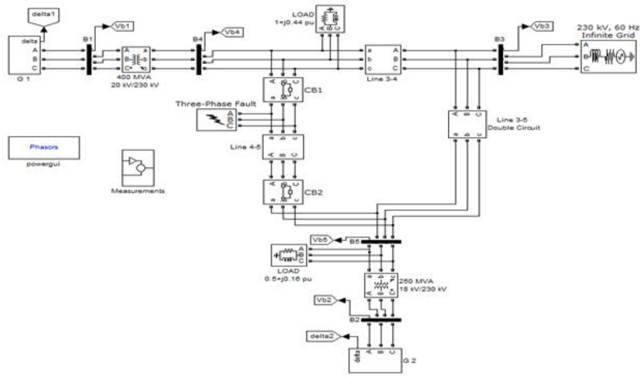

Fig 10: Two-Generator bus System

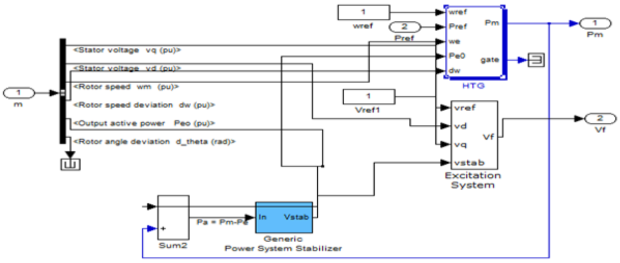

Fig 11: Simulink model of a mechanical hydraulic control (MHC) governing system

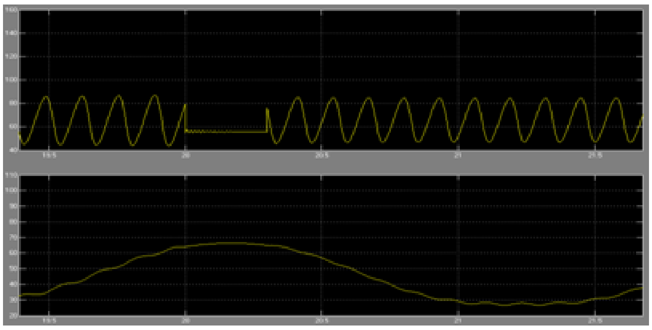

Fig 12: Individual rotor angles during fault conditions (g/r-1 and g/r-2)

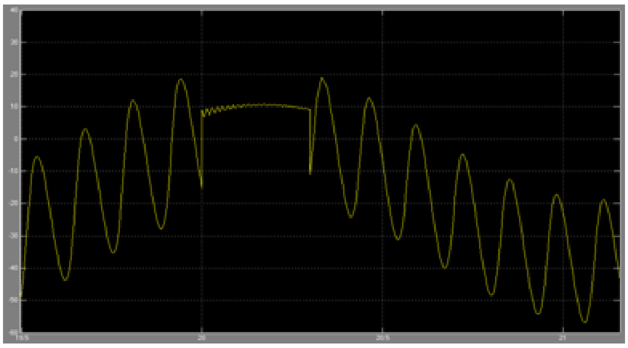

Fig 13: rotor angle difference during fault condition

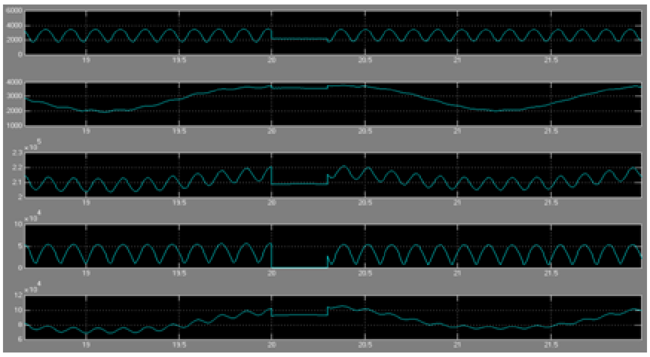

Fig 14: bus voltages during fault (bus-1 to bus-5)

V. CONCLUSION:

The dynamic simulation results have clearly indicated that power angle (transient) stability and voltage and frequency regulation improvements are achievable for large (transient) disturbances. In particular, we observed significant increases in CCT (IDA-PBC with STATCOM/battery) for the two test studies of interest when compared to operation with a feedback linearizing control (FBLC), IDA-PBC-alone and the combined conventional and alternative (wind) power system controllers (PSS), thereby providing a significant improvement in power system stability, robustness and dynamic security. In closing, we recognize that the multi-machine power system results presented in this paper are preliminary and that there is considerable work that needs to be done to extend this approach to large-scale power systems. However, we have clearly shown that integrating a STATCOM/battery into power systems using a nonlinear control (e.g., IDA-PBC) design methodology has the potential to improve power system performance. We are currently working to demonstrate these results on the laboratory scale power system discussed.

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