21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

2016 CIGRE-IEC Colloquium
May 9-11, 2016
Montréal, QC, Canada

Wide-area control of New York State Power Grid with Multi-Functional Multi-Band Power System Stabilizers

D. RIMOROV[1], A. HENICHE[1], I. KAMWA[1],
G. STEFOPOULOS[2], S. BABAEI[2], B. FARDANESH[2]
[1]Hydro- Québec Research Institute
Canada
[2]New York Power Authority
USA

SUMMARY

This paper describes the results of the work done for the project undertaken by the Hydro-Québec Research Institute (IREQ) jointly with the New York Power Authority (NYPA). The aim of the study is to investigate the potential for dynamic behavior improvement of the New York state grid by means of Multi-Functional Multi-Band Power System Stabilizer (MF-MBPSS) technology. This type of advanced control, developed by Hydro-Québec, is an evolution of an existing PSS4B type stabilizer that is capable of utilizing wide-measurements available from PMU units or other devices.
The prescribed action of MF-MBPSS is to modulate the reference value of a voltage/reactive power control device following a disturbance to damp subsequent system oscillations. This type of control can be applied to various devices in the system, including power electronics interfaced equipment. Such voltage modulation can be extended to improve frequency response following an active power imbalance event in the system (loss of load or generation, sudden load increase, and so on). This type of control often necessitates real-time information on system state, including stability metrics and signals that bear important information about dynamic behavior. Such information can be made available via wide-area measurements.
The paper describes the methodologies behind siting, input/output signal selection and tuning of several MF-MBPSS units installed in a large interconnected grid. Special attention is given to FACTS devices capable of controlling bus voltages. Instead of developing analytical models for different aspects of system dynamic behavior, a more practical approach suitable for large systems is adopted. Where applicable, controller settings are established using sensitivity analysis conducted on an actual simulation model. In several cases the obtained data can be used to build equivalent linear models using system identification (SI) methods. Such transfer functions allow for numerous analysis and controller design tools to be used to tune the MF-MBPSS units.
The results of the paper demonstrate oscillation damping enhancement of the dominant inter-area modes; observable reduction of initial frequency drop following a loss of generation in the system and faster frequency recovery; larger values of frequency response metrics that define active power reserve requirements in the system. Aforementioned stability enhancements are achieved by utilizing limited reactive power reserves without undue voltage excursions in the system.

KEYWORDS
Eastern Interconnection, Frequency Control, Multi-Functional Multi-Band Power System Stabilizer, Oscillation Damping, Transmission grid, Wide-area Control

Rimorov.Dmitry@ireq.ca

I. INTRODUCTION AND PROJECT DESCRIPTION

The aim of the project commenced jointly by IREQ and NYPA is to investigate and establish possible benefits of Multi-Functional Multiband Power System Stabilizers for dynamic stability improvement of the New York State power grid. MF-MBPSS is a further development of the PSS4B technology [1] that is capable of processing remote signals.

The focus of the project is improvement of the following aspects of system dynamics: frequency response, frequency stability and oscillation damping. Primary frequency control achieved with MF-MBPSS is determined by load voltage sensitivity. Temporary change of voltage at certain buses of the system can thus arrest initial frequency change following a disturbance and accelerate frequency recovery [2]. Similar mechanism is behind damping inter-area modes in interconnected systems [3]. Tackling both frequency response and oscillatory stability can benefit from exploiting remote signals – multiple measurements from PMU units throughout the system can provide accurate information about the frequency trend and utilize signals with high observability of dominant modes.

The paper addresses the issues of citing, tuning and input/output [4] signal selection of MF-MBPSS controllers in the context of very large interconnected systems. Practical techniques and measures are described and applied to the model of the bulk transmission system of the Eastern Interconnection (EI) grid. One of the features of the paper is application of simple metrics that can be easily obtained from simulation results to the problems of siting, tuning and signal selection for MF-MBPSS control.

The results of the paper demonstrate how coordinated action of just a few of MF-MBPSS units can contribute to frequency response and oscillation damping improvement, even on a scale of large interconnection. The benefits are achieved without undue excursions of voltage profile in the system.

The rest of the paper is organized as follows: Section II describes the methodology, techniques and metrics for establishing appropriate input/output signals and location for the devices participating in frequency control and damping; Section III shows the results of the proposed control on an EI grid; Section IV concludes the paper.

II. METHODOLOGY

1. MF-MBPSS for primary frequency control

An important issue that needs to be addressed is the device location to install MF-MBPSSs for primary frequency control. A simple way of establishing relative contribution of a device to frequency support is identifying average frequency sensitivity to voltage change at a particular bus. This sensitivity is primarily determined by the relative proximity of a device to large load centers, device's size and reactive power capacity. Such analysis can aid in identifying equipment that can contribute to frequency control the most without undue voltage deviations. Typically the size of the device (i.e. rated power) should be significant. Thus initial screening for the MF-MBPSS application candidate should be restricted to large plants and voltage control devices close to system loads. The aforementioned frequency sensitivity can be directly obtained from the simulation model by applying small step change (e.g. 1-5%) to a device voltage reference signal.

For the purpose of frequency control MF-MBPSSs can be utilized by enabling just the low frequency band. By properly setting the band central frequency desired phase compensation can be achieved to produce roughly in-phase voltage modulation following a frequency change. Often trial-and-error is required to find satisfactory central frequency values; however, a simple visual inspection of the frequency progression following a voltage reference step change can aid in identifying the overall response and thus necessary phase compensation offset. The main criterion for the choice of central gains is avoiding excessive bus voltage deviations caused by the action of MF-MBPSS. Given the structure of feedback control, the controller effort is proportional to the magnitude of the input signal (average frequency deviation in this case), which in turn depends on the size of the disturbance. Therefore, the choice of appropriate gains should in principle consider probability distribution of the amount of active power loss in power systems. To give an example, the impact of the action of the MF-MBPSS on the voltage may be considered excessive if the loss of 1000 MW (relatively probable) results in voltage excursions at certain buses that exceed 5%, whereas it may be considered appropriate if the loss of 4 GW (relatively improbable) results in voltage excursions about 10% of nominal values.

2. Wide-area damping with MF-MBPSS

Design of MF-MBPSS for damping control can be done more rigorously than simple trial-and-error if linearized system models are available. System identification methods are particularly convenient for that purpose, especially in the context of large systems [5]. The inputs of certain controls are probed by pulse signals and the resulting response is recorded from simulations and later used in the identification procedure [6].

A two-stage siting and input signal selection approach is proposed.

1) Stage I concerns with identifying the devices on which MF-MBPSS is to be installed. For this purpose:

- Conduct preliminary screening, restricting the attention to large plants and/or FACTS devices with sufficient control capabilities
- After choosing several candidates, apply SI to reconstruct a linear $n \times m$ MIMO (multiple-input-multiple-output) system where n – number of inputs (reference signals associated with control of the selected devices), m – number of outputs (typically associated with local signals of the devices, such as speed, bus frequency, and so on).
- Once the linear model is obtained, measures of controllability and observability can be calculated to assess best devices and associated signals for damping control [4].

2) Stage II deals with selecting appropriate MF-MBPSS input signals that bear high observability of the concerned modes.

- The reference signal associated with the control of a selected device is again probed with an excitation pulse signal. However, this time the recorded signals are the parameters that are selected as the candidates for the MF-MBPSS input signals. Many criteria can be employed to choose those: for instance, attention can be given to large plants, since the participation factors of their associated states in electromechanical oscillations are high; additionally, signals readily available from PMU measurements can be considered as well.
- While a similar procedure outlined in 1) can be used to build another linear system (SIMO in this case), in case of many candidate signals such approach can be time consuming. A simpler and more direct method that hinges on the ideas of linear system analysis can be employed.

Consider a SIMO (single-input-multiple-output) system, where impulse response of the k-th output signal can be represented as follows:

$$y_k = \sum_{i=1}^{n} R_{ik} e^{-\lambda_i t} \quad (1)$$

Where R_{ik} is the residue associated with i-th mode between the input and j-th output. The residues can be directly related to the joint observability/controllability measures [3]. Given that controllability measure is associated with the input probed by the excitation signal, the excitation strength of the output signal can give accurate information about the observability measures of the dominant modes. Furthermore, the excitation strength can be inferred from the following calculated index:

$$r = \sqrt{\sum_{j=1}^{m} \left(y_j - y_{ss}\right)^2} \quad (2)$$

Where y_j corresponds to the value of the discrete output signal at time t_j and y_{ss} is its steady-state value. Index (2) is proportional to the RMS value of the output signal. More excited signals with higher mode observability thus have larger values of r. It is important to mention that (2) does not distinguish between individual modes but rather considers their overall mix in the output signal. However, given the simplicity of its application and calculation in the simulation environment, it proves useful for large systems.

Also note that for correct direct comparison of (2) signals must be either properly scaled or be of similar nature (machine speeds, bus frequencies, etc.). Once the device and associated input signal are identified, MF-MBPSS tuning must be performed to achieve desired improvement of the dynamic behavior. Given the availability of low-order transfer functions from the SI methods, nonlinear constrained optimization approach described in [8] can be readily applied for this purpose.

III. RESULTS

1. Frequency response improvement of Eastern Interconnection

The scenario considered in this section is frequency response improvement by means of coordinated action of several MF-MBPSS controllers following a generator rejection. If the objective is to improve the average frequency response of the whole EI, the average frequency should be utilized as an input signal for MF-MBPSS. This in turn requires accurate measurements of the frequency behavior throughout the system. However, in the context of the project only the measurements available from the PMU units located in the NYS grid are considered. Thus, available measurements are confined to a certain part of the grid. This poses two potential challenges for utilization of such signal:

1) Behavior of the PMU-based frequency depends on the electrical distance to the outage and thus may be rather different from the average frequency trend (Figs. 1A, 1B).

2) Relative proximity of the measurements has a downside of nonzero observability with respect to inter-area modes. Thus care must be taken when tuning MF-MBPSS for frequency support, so that the damping is not deteriorated.

In order to assess MF-MBPSS performance two contingency scenarios have been considered (denoted #1 and #2). Both involve generation outage of approximately 1000 MW, but differ in the location: contingency #1 is electrically close to the PMU buses, while #2 is sufficiently far. Fig. 1 shows how the frequency measured by PMU depends on the proximity of the disturbance.

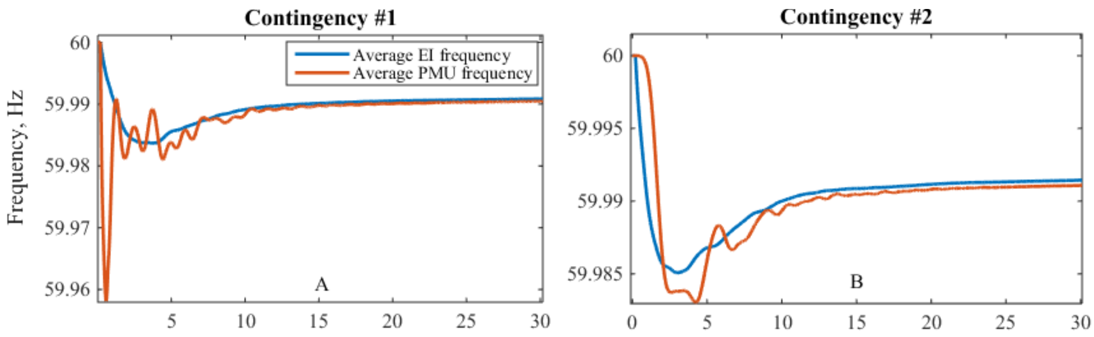

Fig. 1. EI frequency response: dependence of PMU measurements on outage location

Next, two types of MF-MBPSS signals are considered for both contingencies: average EI frequency (ideal) and average PMU buses frequency. The settings of MF-MBPSS units are shown in Table I. The devices were chosen based on the sensitivity analysis described in Section II. The MF-MBPSSs are tuned using the average frequency signal for simplicity. Parameter R in Table I determines the bandwidth of the low frequency band and is chosen to increase voltage recovery time. It allows frequency to approach the steady-state value faster.

Table I. MF-MBPSS settings for primary frequency control

Device	S_{base}, MVA	R	Low band frequency	Low band gain
Plant #1	690	0.01	0.08	92
SVC #1	570	0.01	0.061	65
Plant #2	690	0.01	0.085	95
Plant #3	4x320	0.01	0.075	90

Simulation results for both contingency scenarios are shown in Figs. 2A and 2B. Fig. 3 shows the impact of MF-MBSS control on system parameters for contingency #1.

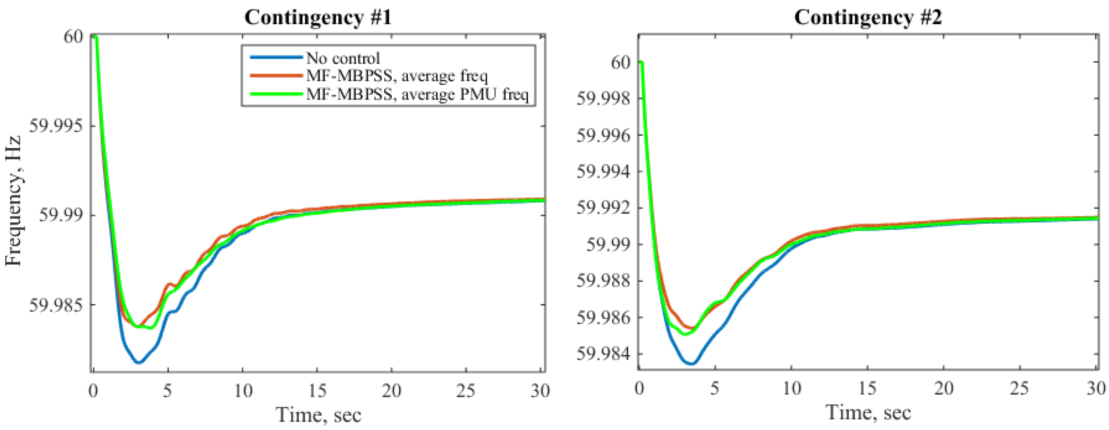

Fig. 2. Impact of MF-MBPSS control on frequency response

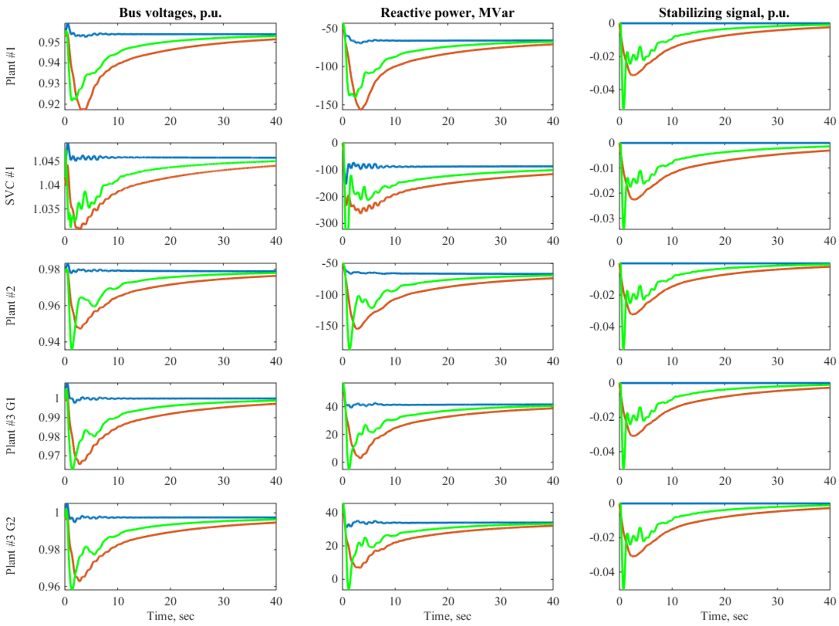

Fig. 3. System parameters for contingency #1

As can be seen, utilization of both ideal average frequency and PMU measurements-based frequency achieves similar results, despite the aforementioned limitations of the latter signal and the fact that the MF-MBPSS parameters have been chosen considering the average EI frequency. Calculation of frequency metric called Nadir-Based Frequency Response (NBFR) described in [8] further corroborates the claim (Table II). MW gain is determined as an increase of NBFR compared to the case without MF-MBPSS control.

Table II. Frequency metrics for two contingency scenarios

Contingency scenario		**Min frequency**	**NBFR**		
		Hz	MW/0.1Hz	MW gain	Gain, %
C1	MB control, PMU freq	59.984	6254.1	667.78	11.95
	MB control, average freq	59.984	6286.2	699.88	12.53
C2	MB control, PMU freq	59.985	6599.6	648.4	10.9
	MB control, average freq	59.985	6749.7	798.5	13.42

2. Oscillation damping improvement of NYS power grid

For the purpose of the oscillation damping improvement two FACTS devices are considered – SVC (different from SVC#1 used for frequency control) and STATCOM. According to the methodology in Section II, 2x2 linear system with voltage reference signals as inputs and local bus frequencies as outputs is found using the SI algorithm. The modal characteristics for two load conditions are shown in Table III (“open-loop” columns). Results of the modal analysis shown in Fig. 4 suggest that STATCOM is a better candidate for the MF-MBPSS application for damping both inter-area modes.

Table III. Dominant modes of identified system

Case	Mode #	Frequency, Hz		Damping ratio	
		Open-loop	Closed-loop	Open-loop	Closed-loop
spring	1	0.979	0.951	0.0572	0.089
	2	0.804	0.823	0.0788	0.198
summer	1	0.9506	0.913	0.0863	0.143
	2	0.754	0.812	0.1145	0.314

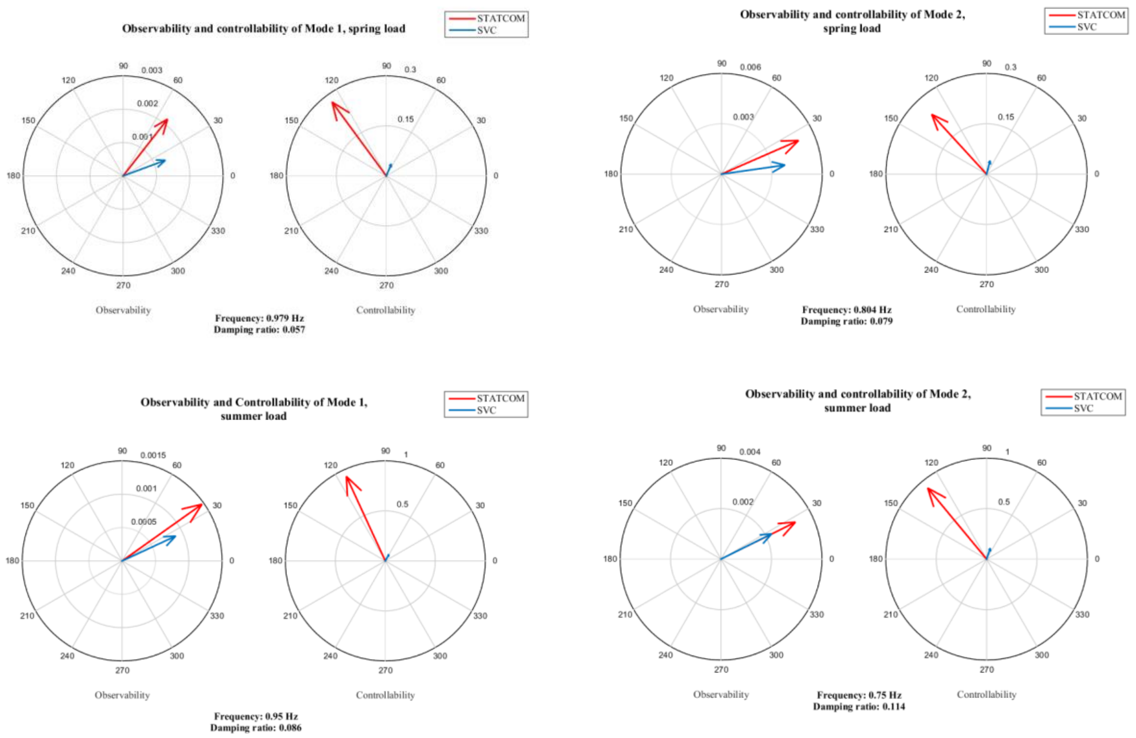

Fig.4. Modal analysis for various load conditions

Next, PMU buses are considered as potential candidates for the remote signals. Application of (2) revealed that out of 22 PMU buses only 7 have a higher value of the index calculated using (2) compared to the STATCOM bus (local signal). All 7 of them exhibit perfectly coherent behaviour and have been plotted in Fig. 5B. Thus the one with the highest value r is chosen. The implicit assumption here is that coherent response observed in Fig. 5B corresponds to coherency of the observability vectors for both inter-area modes, i.e. observability vectors for all 7 remote signals are collinear, albeit with different amplitudes. For the sake of clarity, only the signal with the highest r is shown in Fig. 6A. Results of Fig. 6A corroborate the assumptions of (2): remote signal with higher r has higher observability of both modes. However, a negative aspect of the chosen remote signal is clearly visible in the results of Fig. 6A. Particularly, the observability vector of Mode 1 is shifted by almost 180° with respect to Mode 2 vector. Given very close frequencies of both modes, it can be inferred that stabilization of one mode will necessarily destabilize the other one, assuming typical settings of the stabilizer control. This assumption is further corroborated in the root locus of Fig. 6B, where the results of MF-MBPSS action with remote signal as input are shown.

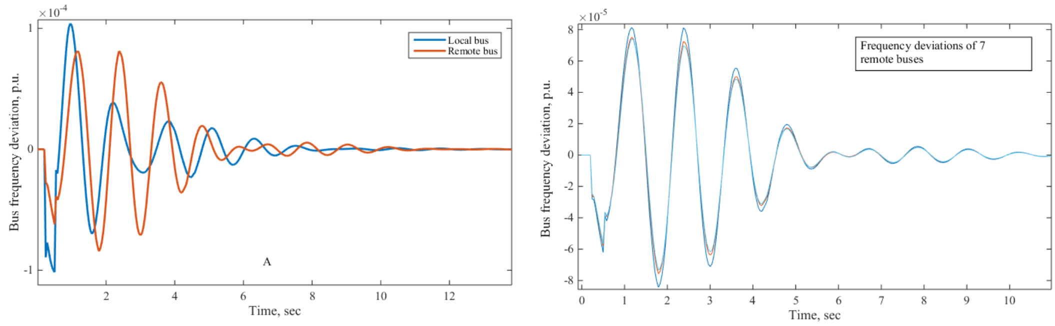

Fig. 5. System response to a pulse signal: A – local vs. remote; B – remote buses coherency

On the contrary, it can be seen in Fig. 6A that modes' observability vectors in the local signal are nearly coherent. Thus, according to the methodology described in Section II and the assumptions made regarding the choice of the controller input signals, utilization of the available NYS PMU infrastructure is not advantageous. Therefore, local signal – STATCOM bus frequency – is chosen as an input signal to the MF-MBPSS installed on the STATCOM.

The parameters of the STATCOM MF-MBPSS found using the approach from [7] are shown in table IV. The closed-loop eigenvalues are shown in Table III. In order to further evaluate the performance of the designed MF-MBPSS, a contingency involving multiple tie-line trips is applied. Post-contingency behaviour is depicted in Fig. 7. Significant damping improvement with a very moderate voltage modulation is apparent.

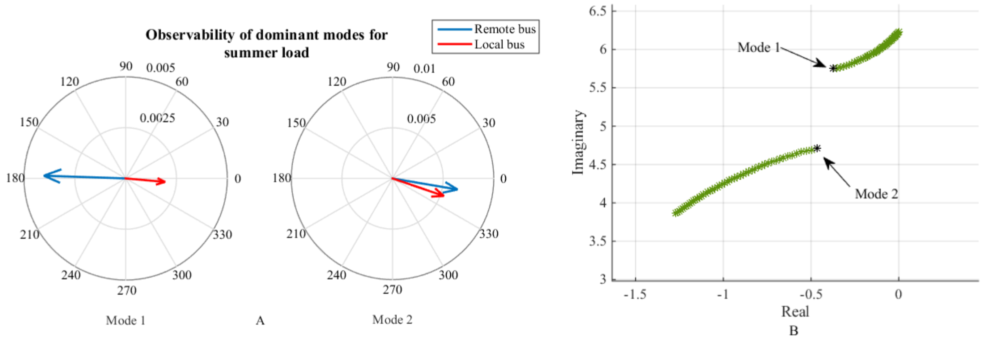

Fig. 6. Signals' properties: A – modes observability; B – root locus with applied feedback for remote signal

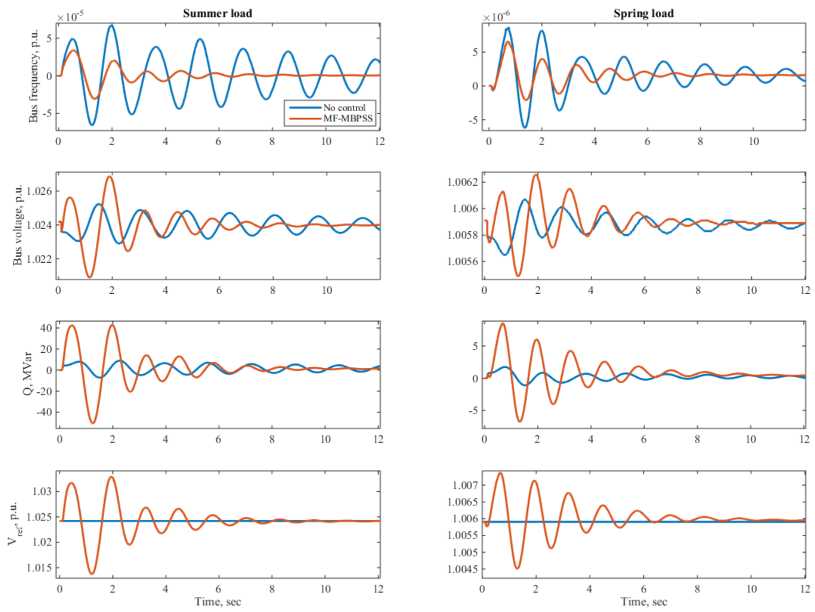

Fig. 7. System response to a contingency

Table IV. STATCOM MF-MBPSS parameters

Band	Low	Intermediate	High
Central frequencies	0.0457	0.8871	1.736
Central gains	120	180	280

IV. CONCLUSIONS

The paper described various efficient methods of wide-area control system design based on MF-MBPSS technology. Application of such system to a model of large interconnected grid resulted in observable improvement of frequency response, including reduced frequency drop and faster recovery, and increased damping of inter-area modes. Aforementioned stability enhancements have been achieved using limited reactive power reserves in the system. As a consequence, voltage conditions in the systems were not jeopardized.

Future work requires further investigation of capabilities for wide-area damping using PMU measurements, along with possibilities for voltage stability improvement using MF-MBPSS control.

V. ACKNOWLEDGEMENT

This work is supported in part by the New York State Energy Research and Development Authority (NYSERDA), under the co-funding agreement 36658. NYSERDA has not reviewed the information contained herein, and the opinions expressed in this report do not necessarily reflect those of NYSERDA or State of New York.

BIBLIOGRAPHY

[1] Grondin, R., et al. "Wide-Band Power System Stabilizer", in CIGRÉ Canada Conference on Power Systems, Montreal, 2006.

[2] Rimorov, D.; Kamwa, I.; Joos, G., "Quasi-Steady-State Approach for Analysis of Frequency Oscillations and Damping Controller Design," in Power Systems, IEEE Transactions on, vol.PP, no.99, pp.1-9

[3] Kundur, P., "Power System Stability and Control", New York: McGraw-Hill, 1994

[4] Heniche, A.; Kamwa, I., "Assessment of Two Methods to Select Wide-Area Signals for Power System Damping Control," in Power Systems, IEEE Transactions on , vol.23, no.2, pp.572-581, May 2008

[5] Kamwa, I.; Trudel, G.; Gerin-Lajoie, L., "Low-order black-box models for control system design in large power systems," in Power Systems, IEEE Transactions on, vol.11, no.1, pp.303-311, Feb 1996

[6] Rimorov, D.; Kamwa, I.; Joos, G., "System Identification Methods for Optimal Tuning of Power System Damping Controllers", in CIGRÉ Canada Conference, Toronto, 2014.

[7] Rimorov, D.; Kamwa, I.; Joós, G., "Model-based tuning approach for multi-band power system stabilisers PSS4B using an improved modal performance index," in Generation, Transmission & Distribution, IET, vol.9, no.15, pp. 2135-2143, 2015

[8] Eto, Joseph H. "Use of frequency response metrics to assess the planning and operating requirements for reliable integration of variable renewable generation." Lawrence Berkeley National Laboratory (2011)