Toward PMU-Based Robust Automatic Voltage Control (AVC) and Automatic Flow Control (AFC)

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***Abstract*—This paper is motivated by the need to automate adjustments of deviations in key output variables from their scheduled values. In particular, it is important to maintain load voltages within their pre-specified limits in response to many disturbances, for example load power factor deviations. Similarly, it is important to regulate real power line flows to within their pre-specified limits as disturbances around scheduled real power generation dispatch take place. Such automation is a feasible goal since the PMUs could provide accurate and fast sensing of key output variables of interest. Given the number of PMUs, the selection of best locations of PMUs and the control design based on these measurements becomes an engineering design problem. In this paper we provide a problem formulation for a robust Automated Voltage Control (AVC) and Automated Flow Control (AFC) design based on selecting the best locations for placing the PMUs. The AVC and AFC designs are illustrated using a small 5-bus example first. This is followed by illustrating potential performance of such design on an equivalent NPCC 36-bus system. The results indicate that the $(N-1)$ reliability criteria can be met by combining the economic dispatch for scheduling resources given demand forecast, and by relying on an automated feedback to ensure that voltage and line flow deviations remain within the pre-specified limits in between scheduling intervals. This is done without having to know the exact location and magnitude of disturbances.**

I. Introduction

As the electric power systems are beginning to be used in qualitatively different ways than in the past the need for more efficient utilization without experiencing reliability problems is becoming more obvious. This is particularly governed by the likely large penetration of highly variable resources, including price-responsive demand. It is no longer possible to schedule for accurate forecast and not adjust settings of key controllers in near-real time. Without an automated feedback scheme for adjusting set points of primary controllers there is a possibility that frequency, voltage and line flow deviations from schedules would be unacceptable.[1] Given new measurement and communications technologies and the fact that these technologies are already being deployed, it is definitely necessary to design new automated control schemes for managing voltage and line flow deviations by adjusting set points of the controllable equipment throughout the system. In particular, we suggest that the use of PMUs and communications between the measurement locations and the participating controllers would be beneficial to maintaining both load voltage and line flow deviations around their schedules. In this paper we introduce a formulation of PMUs-based AVC first in Section II. This scheme is motivated by the existing AVC in several European countries which is based on traditional SCADA-measurements of so-called pilot points [1]. This AVC is an automated secondary control scheme for adjusting the ΔQ_G and/or ΔV_G settings of scheduled controllers in response to small reactive power load disturbances ΔQ_L. The measurements are pilot point load voltage V_p in each voltage zone which are used to adjust Automatic Voltage Regulator (AVR) settings of generators participating in AVC according to pre-computed control gains. The objective is to maintain the pilot point load voltage deviations ΔV_p close to zero, and assuming that other load voltage deviations will remain close to the pilot point voltage so that all voltages would be regulated. One of the main open problems has been how to select the best location of zonal pilot points and, unless the zones are administrative, how to cluster the system into the best zones. In [2] a systematic worst-case design problem formulation was introduced to select the best pilot point locations. These are selected through an extensive search over all possible combinations of reactive power load disturbances within ΔQ_L so that the worst-case load voltage deviation is minimized. Based on this initial work, we introduce a robust AVC design which is capable of guaranteeing that the worst-case load voltage deviations remain within the pre-specified limits (for example, $\pm 5\%$) as long as the reactive power load flow deviations remain within the disturbance bound $|\Delta Q_L| \leq \gamma$. Furthermore, we illustrate that if the measurements are either too slow or noisy, the AVC scheme will not have robust performance. As we look forward to the integration of many highly variable resources, it is going to become critical to rely on automated set point adjustments on AVRs and/or T&D controllable equipment. It is with this in mind that we stress the role of fast and accurate PMU measurements. In Section III we illustrate the AVC concepts and the results of applying this control scheme. In Section IV we introduce an adaptive clustering algorithm which builds on the algorithm in [3]. We describe its further enhancements particularly its ability to create zones of nearly equal size and not excessively large. The results of this clustering algorithm for the equivalenced NPCC 36-bus system are illustrated and the robustness is verified by simulating system response with both slow and fast measurements and the same control scheme in Section V. The clustering method results in decomposing the NPCC system in 3 zones. In Section VI a multi-

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[1] We do not consider frequency regulation in this paper.

directional multi-layered Dynamic Monitoring and Decision System (DYMONDS) for implementing AVC is presented. We next formulate the problem of PMUs-based AFC in Section VII. This is a new concept. The formulation is similar to the PMUs-based AVC formulation except that the state variables and output variables of interest are different. The role of phase angle measurements is key to such scheme since it is not possible to implement AFC without measuring phase angle differences in a fast and accurate manner. Conceptually, this is also an automated secondary control scheme which is used for adjusting the settings by ΔP_G around scheduled governor settings in response to the real power load disturbances ΔP_L. The measurements are phase angles δ_p at key buses in each real power zone and this information is used to adjust governor settings of generators participating in AFC according to the pre-computed control gains. The problem posing is similar to the designing problem for AVC. Namely, we formulate the worst-case design for selecting the best PMU locations for measuring phase angles first. The control gains are computed so that the worst-case line flow deviation remains within the pre-specified limits given the bounds on real power load disturbances $|\Delta P_L|$ for which the control is being designed. In Section VIII we first illustrate the AFC concept on a small 5-bus power systems example. This is followed by the design of AFC measurement-control architecture for the equivalenced NPCC 36-bus system in Section IX. It is important to bear in mind that the selection of best measurements and the computation of the corresponding control gains are done off-line at the design stage. The actual implementation is very straightforward and it resembles the implementation of current Automatic Generation Control (AGC). In Section X we illustrate potential use of AVC for regulating voltage deviations in response to wind power variations. We show the effects of closed loop AVC and AFC on the quality of voltage and line flows by comparing voltages with and without such secondary automated control schemes on the equivalenced NPCC test system. In the closing Section XI preliminary conclusions and simulations findings are described and future open questions are stated.

II. PMU-based Automatic Voltage Control (AVC) Design

In this paper, a PMUs-based AVC is introduced. The PMU measurements are used to automatically adjust the set-points ΔQ_G of AVRs on generators participating in this closed-loop control. The small reactive power load disturbances ΔQ_L are causing deviations in load voltages and the PMUs are used to measure the zonal pilot points load voltage deviations ΔV_p. Control gains are computed so that the closed-loop load voltage deviations are minimized for any disturbance. If, in addition, the disturbance bounds are given, the gains and measurement locations are computed so the load deviations remain robust with respect to disturbances. Namely, an off-line design is carried out to ensure that load voltage deviations remain within the pre-specified limits. The basic problem is formulated as in [2]. The secondary voltage control is intended to regulate voltage deviations in response to relatively small disturbances in reactive power, and consequently, the deviation of closed-loop load voltages are expected not to to vary significantly around the scheduled (nominal) voltages. This makes it possible to use a linearized model. The minimization of L_∞ (the largest) norm control design can ensure that the system worst voltage deviation remains within the given limits. To summarize this worst case robust optimization problem as introduced some time ago in [2], we start by stating the decoupled linearized reactive power-voltage constraints subject to which the optimization is done.[2]

$$\begin{bmatrix} \Delta Q_G \\ \Delta Q_L \end{bmatrix} = \begin{bmatrix} B_{GG} & B_{GL} \\ B_{LG} & B_{LL} \end{bmatrix} \begin{bmatrix} \Delta V_G \\ \Delta V_L \end{bmatrix} \tag{1}$$

In Equation (1), ΔQ_G and ΔV_G stand for the reactive power and voltage increment of generator buses; ΔQ_L and ΔV_L are the reactive power and voltage increment of load buses. We next rewrite Equation (1) by inverting the B matrix.

$$\begin{bmatrix} \Delta V_G \\ \Delta V_L \end{bmatrix} = \begin{bmatrix} Z_{GG} & Z_{GL} \\ Z_{LG} & Z_{LL} \end{bmatrix} \begin{bmatrix} \Delta Q_G \\ \Delta Q_L \end{bmatrix} \tag{2}$$

where $Z = B^{-1}$. Due to the local excitation system control, the voltage deviation of generator buses always stays at zero, which means $V_G \equiv 0$.[3] Assuming voltages are kept unchanged at the generator buses, the load voltage deviations are determined by deviations in the reactive power load and generation power voltage deviation as follows.

$$\Delta V_L = Z_{LL}\Delta Q_L + Z_{LG}\Delta Q_G \tag{3}$$

where ΔQ_L is considered as the reactive power disturbance and ΔQ_G as the control by the generators participating in AVC. Let $x = V_L$, $M = Z_{LL}$, $\Delta y = \Delta Q_L$, $N = Z_{LG}$ $u = \Delta Q_G$ and $w = Z_{LL}\Delta Q_L$, so 3 comes to be

$$x = w + Nu \tag{4}$$

In this paper, a linear feedback control law is used for control design, the same as in [2].

$$u = \sum_{j=1}^{p} w_j v_j \tag{5}$$

where w_j is the jth entry of the reduced information load voltage deviation measurement w^1 at the p pilot points (PMUs).

$$w^1 = M_1 \Delta y \tag{6}$$

where M_1 is the rows of Z_{LL} corresponding to the monitored buses.

Another important and practical claim here is that during two short-time measuring intervals, in real-world electric power systems the disturbance will always stay within some upper bound, which means most of the time the system will occur disturbance not larger than some value. It can be presented as

$$\|\Delta y\|_\infty \leq \gamma \tag{7}$$

To ensure that the system worst voltage deviation remains

[2] These are obtained by simply using decoupled reactive power-voltage Jacobian computed at the given nominal operating point. Assuming that at the nominal point losses are neglected, voltages are very close to 1 p.u. and angle differences are relatively small, the decoupled $Q-V$ Jacobian becomes system susceptance matrix B. For notational simplicity B is used throughout the paper. The simulations presented use the linearized $Q-V$ Jacobian. Moreover, it is conceptually possible to compute the best PMU locations and control gains for several representative loading schedules.

[3] This assumes sufficient excitation for the AVR control.

within the given limits, we use the minimization of L_∞ norm in control design, as follows

$$\min_{v_1,v_2,\ldots,v_p} \max_{\|\Delta y\|_\infty \le \gamma} \|M\Delta y + N[v_1, v_2, ..., v_p]M_1\Delta y\|_\infty \tag{8}$$

which equals to

$$\min_{v_1,v_2,\ldots,v_p} \gamma\|M + N[v_1, v_2, ..., v_p]M_1\|_\infty \tag{9}$$

Solving this optimization subject to the above equality constraints is in the essence of the robust PMUs-based AVC proposed. In what follows we illustrate the performance of the AVC first on a very small 5-bus system, and then on a 36-bus equivalenced NPCC model. We have performed tests on very large systems, and the performance is consistently robust.

III. Illustration of the AVC Design on a Small 5-bus Electric Power System

In this section, the general idea of robust AVC is illustrated on a small 5-bus power system shown on Figure 1. In this

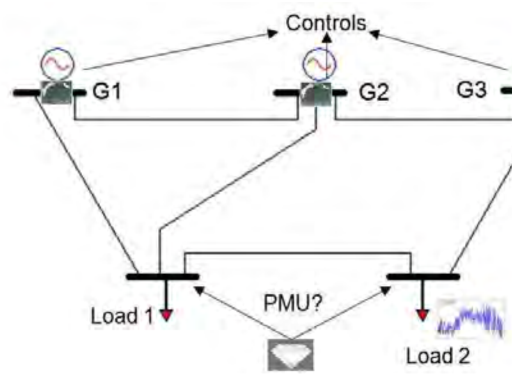

Fig. 1. Simple 5-Bus Power System with AVC

figure the jade diamonds stand for generators participating in AVC and the silver diamond is the PMU measurement. The robust AVC design for this small system amounts to deciding whether to place the PMU at Load 1 or Load 2. This measurement is to be used as the pilot point measurement for the linear feedback control. The second part of the design is computing the control gains for the selected PMU location. To find the best location, we compare control-designs by placing the PMU at different places, perform and exhaustive off-line search of all possible placements and choose the one corresponding to the optimal control performance. For this system the off-line simulation study showed that when the PMU measurement is placed at Load 2, the 3-generator control gains for generators 1, 2 and 3, respectively, are set as $[-0.4870 - 0.42900.0157]$, and the disturbance bound $\gamma = 0.1p.u.$ the system-wide worst voltage deviation can be decreased to $0.0004p.u.$

IV. A Multi-Layered Clustering Algorithm for Defining Reactive Power Zones

A possible implementation of robust AVC for large-scale systems raises several questions concerning basic communication and control architecture. The choice of architecture determines the underlying computational complexity. There are two basic approaches. The first approach is to consider a large power system as one single control area and perform off-line optimization to determine the best locations for a given number of PMUs; control gains are computed assuming all controllers communicate with the PMUs. The second approach is to consider a large electric power system as an interconnection of several weakly connected subsystems. The best locations and control gains are computed for each subsystem separately as a stand alone system. Since power system voltage control typically has localized effects (each controller can only influence the voltage of buses in a relatively smaller local area), the second approach is recommended in this paper. This is again similar to the AGC in which each control area responds to its own imbalances by controlling its own resources. The AVC problem for large-scale system is generally more complicated because it requires decomposing the system into reactive power zones according to the electrical characteristics of the transmission system. Moreover, voltage deviations within a zone are generally more locally characterized than the frequency deviations within a control area. Because of this there is a definitive challenge of selecting the most effective locations for the voltage measurements for each reactive power zone.

A. Numerical Problems With A Single-Layer Clustering Algorithm

In this section we introduce a new algorithm for clustering a large-scale system into reactive power zones. Once these are computed, the method for selecting best PMU measurements in each control area is used based on the algorithm described above. The proposed algorithm draws on the early work in [4] and [3]. The algorithm in [3] is applied to the reactive power Jacobian matrix B in Equation (12). The original algorithm starts by identifying buses in each zone by finding the weakest transmission elements connected to each bus. These transmission lines weaker than certain pre-determined susceptance are eliminated and groups of buses which are isolated from each other are clustered into separable zones. We refer to the original method in [3] as α clustering. In short, it comprises the following steps:

1) Choose the cutoff value α.
2) Search for the largest diagonal element of matrix B which is called d.
3) Normalize B by dividing every element by d.
4) For each row i of the normalized matrix B, rank the absolute values of the off diagonal elements from smallest to largest. Then the elements with the smallest absolute values are eliminated from each row i until the sum of eliminated elements is close to but still smaller than cutoff value α.
5) Groups of buses which are still interconnected after the weakest branches connected to each bus are eliminated form weakly connected separable reactive power zones.

This algorithm is repeated by pre-setting a table of different values for α, by trying each α from the table and selecting the decomposition which best meets the clustering specifications, such as the desired number of groups and/or number of buses,ie. size, of each group.

However the original clustering algorithm generally experiences implementation problems. In particular, the method is quite sensitive to the choice of α. If α is too large every bus becomes a subgroup; and if α is too small, the entire system becomes a single subgroup. To overcome this problem, we propose next a multi-layered algorithm which continues to divide the largest subgroup of the system once the first level decomposition is done.

B. A Novel Numerically Stable Multi-Layered Clustering Algorithm

Typically the single-layer algorithm results, at best, in several rather large subgroups and many relatively small subgroups for any chosen α. For several implementation reasons it is much more desired to have zones of relatively similar size no larger than 100 buses or so, even for very large systems. Given this design objective, we propose the following multi-layered clustering algorithm. Each single layer subgroup is further decomposed multiple times until the desired specifications are reached. The implementation is as follows:

1) Find the largest subgroup k of the system. (At first step the largest group is the system itself).
2) Implementing the single layer method for the largest subgroup corresponding to a given cutoff accuracy α. This requires to select the cutoff value α and implement the single-layer clustering algorithm to group k.
3) Managing ”missing buses”– The resulting sub-matrix after Step 2) may have some rows which have no off-diagonal elements because the α was chosen too large. These rows represent the “missing buses”. This requires identifying the missing buses and determining whether they have any connections with the existing subgroups. If a specific missing bus has a connection with the existing subgroups, it gets integrated into the subgroup with which it has the strongest connection according to system matrix B. This generally leads to a size increase of the existing subgroups. If the missing bus has no connections to the existing subgroups, continue to find the next missing bus which has interconnection with an existing group. The disconnected missing bus gets reconsidered and it ultimately gets integrated to a subgroup.
4) Specify value m which defines the minimal number of buses one group should have, and compare the size of each subgroups obtained at Step 3). For the groups whose size are larger than m, no further action is required. For the groups whose size is smaller than m, compare the strongness of their connection to all existing subgroups and integrate them into with the subgroups with which they are interconnected in the strongest way.
5) Check if the subgroups obtained in Step 4) meet the requirement of being of a similar size, and if the smallest group has number of buses larger than the pre-specified minimal subgroup size. If yes, stop; if no, go back to Step 1) and repeat from 1) to 5).

Once the clustering is done, a re-numeration is done to define Jacobian matrices corresponding to each subgroup (zone).This is simply done by selecting from the original matrix B rows and columns for each bus in the zone. A separate design for finding the best PMU location is done and the control gains for each subgroup based on the algorithm of Section II are computed. Typically, given relatively small zone size the single best PMU measurement is found.

V. Illustration of Zones, PMU Locations and Control Gains for the NPCC 36-bus Test System

In this section an equivalenced Northeastern Power Coordinating Council (NPCC) power system [5] (shown as Figure 2)is taken as an example to illustrate the clustering and control algorithm proposed above.

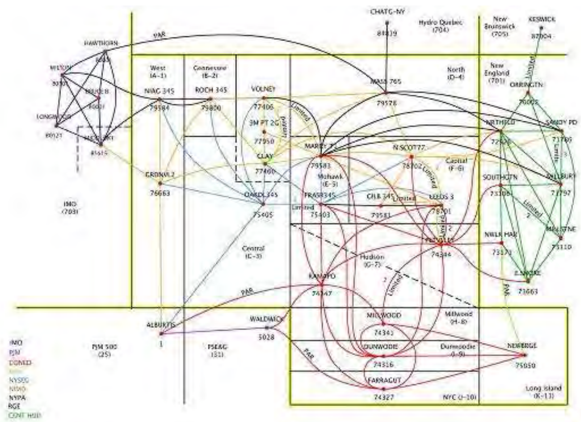

Fig. 2. NPCC Power System [5]

First, the clustering algorithm is applied to decompose the entire system into 3 subgroups (reactive power zones). The clustering process is shown as Figure 3. It can be seen how the algorithm starts from one subgroup by treating the entire system as one. The single layer clustering algorithm results in one larger subgroup and two smaller subgroups. Finally, after the multi-layered algorithm is used the system is decomposed into three weakly connected subgroups whose sizes are close to each other. These form the reactive power zones, and the AVC design is applied to each zone. Once the zones are computed, the best locations for PMU measurements and control gains for each zone are designed. For the three zones, the PMUs should be placed at buses 79584, 75050 and 71797, respectively. The generators participating in AVC selected are located at buses [77950,1, 75405, 79800, 74347, 74327, 79581,70002, 72926,73106, 73110,87004,80001, 80031], respectively. The generators in Area I are [75405,77950,79800,80001,80031]. The generators participating in AVC in Area II are [74327,74347,79581]. The generators participating in AVC in Area III are [72926,73106,73110,87004]. And the corresponding control gains for area I, II and III, respectively, are [-10.2138 -7.0818 -2.6749 -17.7724 0.1303], [41.8319 -58.6805 -38.6160 -9.1087] and [-8.4944 -10.1475 7.2821 -33.7978 14.4205].

Figure 4 shows the control and communication systems architecture based on the proposed design for the NPCC system. In this figure, the jade diamonds stand for generators participating in AVC, and silver diamonds represent the PMUs. The dashed bi-directional lines represent the communications between controllers and PMUs.

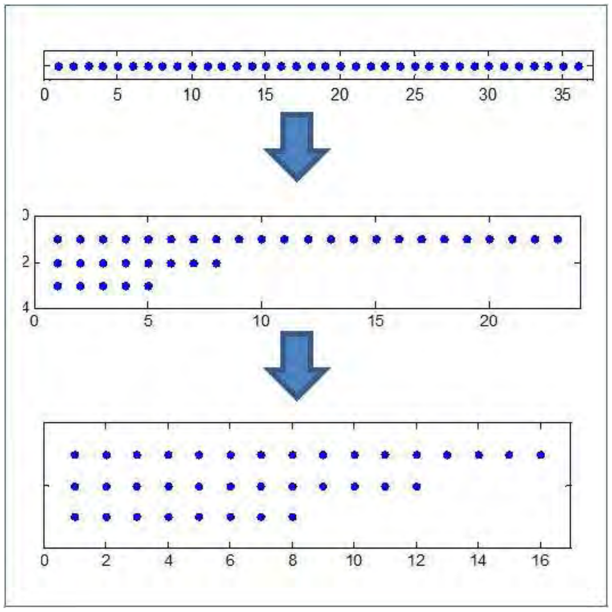

Fig. 3. Multi-layered Clustering Process for the NPCC Power System

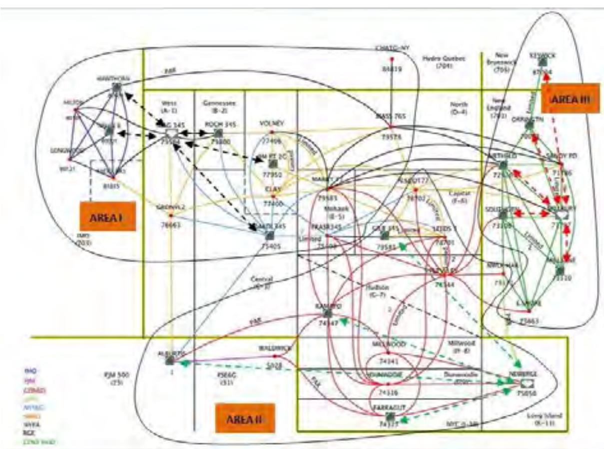

Fig. 4. NPCC Power System with 3 AVC Areas

VI. Simulations of the NPCC System Equipped with PMUs-based AVC

Simulation studies have been done to demonstrate potential effectiveness and robustness of the combined clustering and AVC control approach for the NPCC power system. Shown in Figures 5 and 6 are sample time varying forecast and actual reactive power loads, respectively. In Figure 5, reactive power system load is assumed to be constant. Hard-to-predict reactive power fluctuations corresponding to the actual reactive power load are shown as the fluctuating curve in Figure 6. The reactive power load fluctuations around the forecasted value cause load voltage deviations. This is why the AVC becomes necessary to ensure that despite these load fluctuations the voltage deviations would be maintained within the acceptable operating limits. This is achieved by the generators participating in AVC and adjusting their ΔQ_G set points in response to the measurements obtained by the PMUs.

This proposed robust AVC is applied to the NPCC power

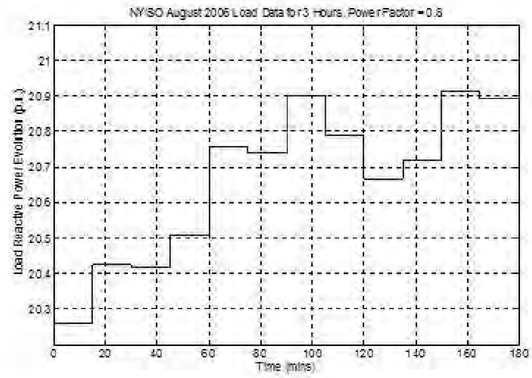

Fig. 5. 3 Hour Ahead Reactive Power System Load Forecast

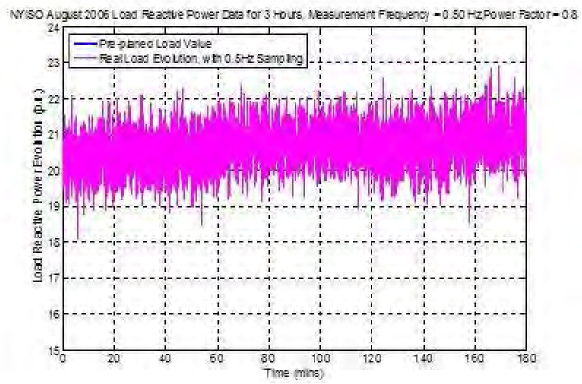

Fig. 6. Actual Reactive Power System Load

system to maintain the worst voltage deviation in response to random reactive power load fluctuations which take place as shown in 6. The effect of AVC is shown in Figures 7 and 8. It can be seen that for both low and high power factor load, the effects of load disturbance around the forecast power factor fixed value on load voltage deviations are compensated. The worst voltage deviation is maintained under $\pm 5\%$.

A. The Key Role of Fast and Accurate PMU Measurements

Shown in Figures 7 and 8 is a comparison of the effects of the same control law with slow and fast measurements. Using the slow measurement information the system worst voltage deviation exceeds, after 6s, the pre-specified $\pm 5\%$ voltage constraints. In contrast, with the fast measurement information, the worst voltage deviation remains within the operating limits. This comparison verifies the robustness of the AVC based on a fast measurements such as the ones available from the PMUs. This is because generally the load reactive power disturbance increase/decrease between two fast measurements is smaller than the disturbance detected by the slow measurements. Consequently, the same control which relies on fast and accurate PMU measurements at each step has to respond to relatively smaller reactive power disturbances. As a result, the control using fast measurements can compensate for the wider range of reactive power disturbances, everything else being equal. This, in turn, points out to qualitatively new ways of ensuring voltage security in response to fast load disturbances.

We have also tested the PMU-based AVC against partial short-term failures of controllers. It is illustrated in Figure 11, for example, that if the system randomly lost one controller during the sample time 60 to 61 minute, the worst voltage deviation still remains within $\pm 5\%$. The same is not possible using slow measurements in this scenario.

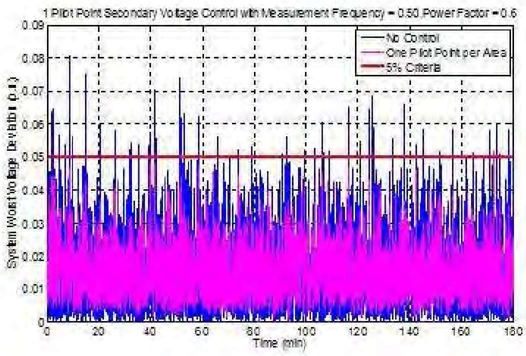

Fig. 7. Effects of AVC Control on NPCC voltages; Low Power Factor Case

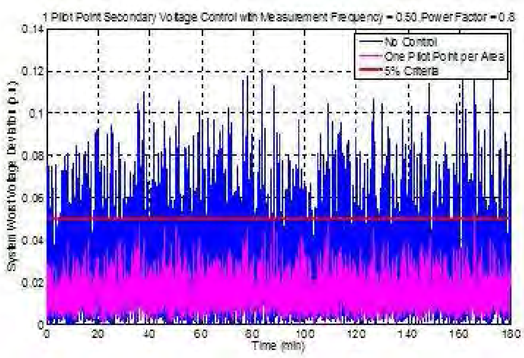

Fig. 8. Effects of AVC Control on NPCC voltages; High Power Factor Case

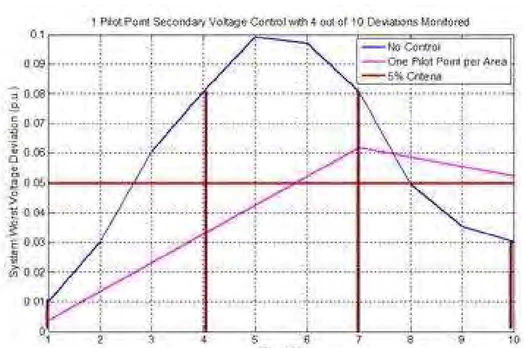

Fig. 9. Effect of Control with Slow Measurements

VII. PMU-based Automatic Flow Control (AFC) Design

In this section, a novel method for automatic control of line flow deviations in response to hard-to-predict real power load deviations is proposed. The problem formulation is similar to

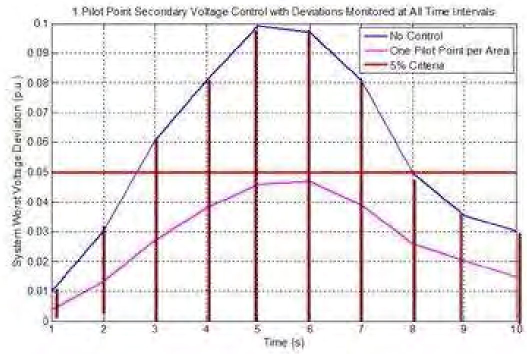

Fig. 10. Effect of Control with Fast Measurements

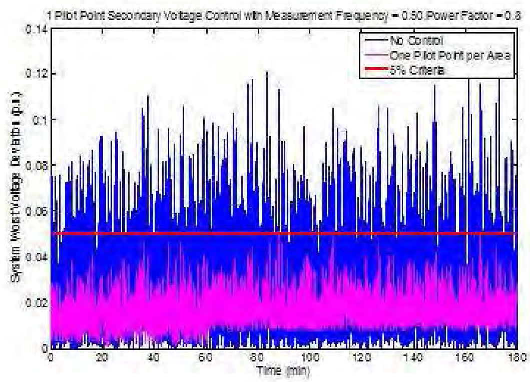

Fig. 11. 3 Hours Control with Randomly Losing 1 Controller for 1 Minute

the problem formulation of PMU-based robust AVC above. The linearized relation between deviations in real power injections and the resulting line flow changes is defined using well-known distribution factors matrix D_f.

$$\Delta F_{Lines} \quad = \quad D_f \Delta P_{Inj} \tag{10}$$

where F_{Lines} denotes the flow vector for all lines; and P_{Inj} is the real power injection vector into all buses except the system slack bus.

We start by re-ordering the D_f so that first the buses where the generators participating in AFC are located are listed first, and this is followed by the load buses.

$$D_f \quad = \quad [D_{fc} \;\; D_{fuc}] \tag{11}$$

where D_{fc} corresponds to the sensitivities of line flows to the injections at buses where the control is located; and D_{fuc} corresponds to the sensitivities of line flows with respect to the disturbances.

Using this partitioning, the closed-loop dependence of line flow deviations on disturbances and control is as follows:

$$\Delta F_{Lines} \quad = \quad D_f \Delta P_{Inj} + D_{fc} \Delta P_{Ctrl} \tag{12}$$

Here it is assumed that a real power disturbance could occur at any bus including the buses where the generators participating in AFC are placed. The generators adjust their real power output according to the information obtained from the PMUs in order to regulate the line flow deviations.

The control law for AFC is a constant gain proportional regulator, similar to equation (5) for AVC. The measurement vector here is the phase angle deviation at the key buses where the PMUs are located. From decoupled real power sensitivity matrix, the relationship between real power disturbance and pilot bus phase angle deviation is derived as

$$\Delta\delta_p \quad = \quad J_1 \Delta P_{Inj} \tag{13}$$

Similar to equation (14) for AVC, the control gain design and the selection of best locations for PMUs is posed as the worst-case design problem as follows.

$$\min_{r_1, r_2, ..., r_p} \max_{\|\Delta h\|_\infty \leq \beta} \|S\Delta h + C[r_1, r_2, ..., r_p] J_1 \Delta h\|_\infty \tag{14}$$

which equals to

$$\min_{r_1, r_2, ..., r_p} \beta \|S + C[r_1, r_2, ..., r_p] J_1\|_\infty \tag{15}$$

where $S = D_f$, $C = D_{fc}$, $\Delta h = P_{Inj}$ and $[r_1, r_2, ..., r_p]$ is the vector of control gains corresponding to the number of pilot point measurements p.

VIII. Illustration of AFC on a Small 5-bus Electric Power System

In this section, the general idea of robust AFC is illustrated on a small 5-bus power system which is shown in Figure 12. The design question is whether the PMU should be placed at

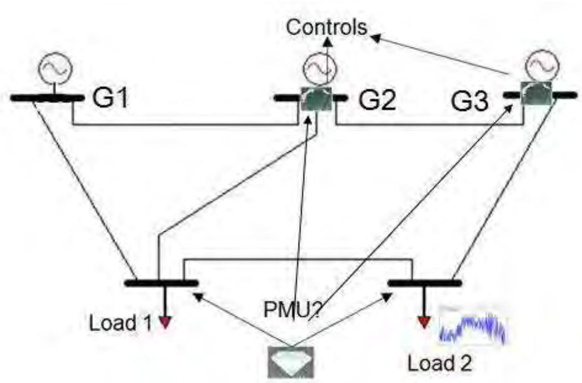

Fig. 12. Simple 5-Bus Power System with AFC

bus 2, 3, 4 or 5 to provide a phase angle measurement to be used by the generators participating in AFC. Moreover, the corresponding most robust control gains must be computed once the best location of PMU is found.

IX. Illustration of AFC Zones, PMU Locations and Control Gains for the NPCC 36-bus System

In this section the proposed AFC is applied to the NPCC system by first clustering the single system into 4 control areas as shown in Figure 13.

Simulation has been carried out and the results are shown in Figures 14 and 15. Robustness of the AFC is tested around a single nominal operating point. A 1 p.u. real power disturbance is simulated and the AFC is used to compensate the line flow deviations caused by this disturbance. The same disturbance is simulated at all buses, one at the time, and the line flow deviations are computed with and without AFC. It can be seen that the closed-loop AFC response is consistently better than the response without AFC, namely the line flow deviations caused by disturbances are smaller.

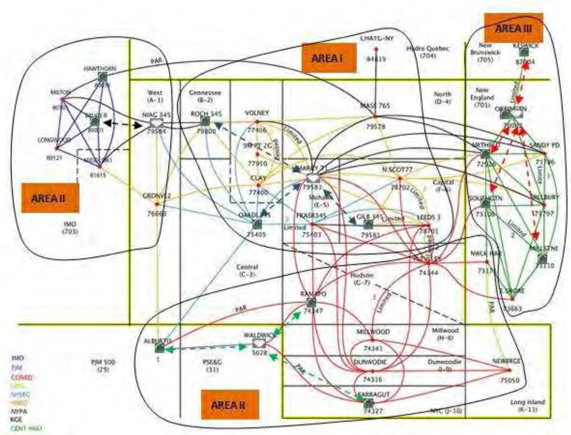

Fig. 13. NPCC power system with 4 control area implementation of AFC

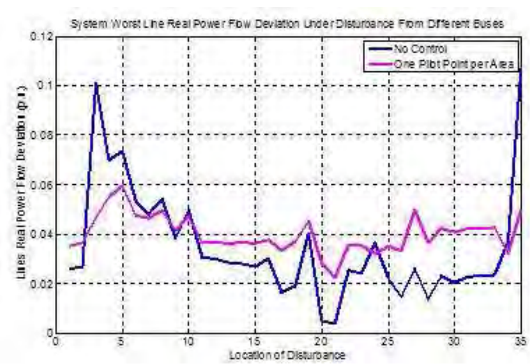

Fig. 14. The Worst System-Wide Real Power Line Flow Deviation Caused by Disturbances at Different Buses

X. Potential Use of AVC and AFC for Compensating Wind Power Disturbances in the NPCC System

Because of the wind variability with time, the fluctuating disturbances caused by wind power integration has become a major concern. The wind power disturbances can be considered to be as any other disturbances in the model used to design AVC and AFC. Therefore these schemes have a real potential to automatically compensate the line flow and voltage deviations caused by wind power fluctuation by adjusting the real and reactive power output set points of conventional power plants on real time. It is shown in Figures (16) and (17) how AVC and AFC could reduce the worst voltage and line flow deviations caused by wind power disturbances at bus 87004 int he NPCC system. Therefore, both AFC and AVC present themselves as potentially applicable to improving system reliability in systems with highly variable hard-to-predict wind power.

XI. Conclusions

This paper presents the first method for using PMUs for secondary AVC and AFC. The potential of these methods to counteract hard-to-predict disturbances is illustrated for both a simple 5 bus power system and a larger NPCC equivalenced power system. The robustness improvement brought by fast

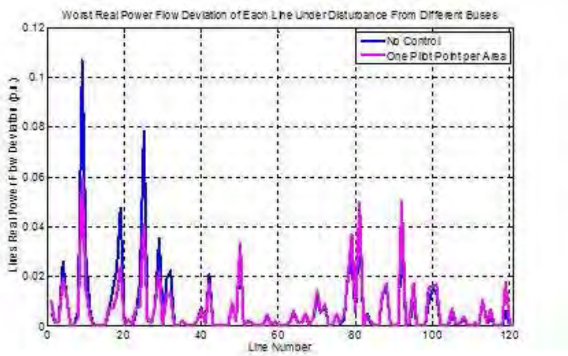

Fig. 15. The Worst Real Power Line Flow Deviation of Each Line under All Tested Disturbances

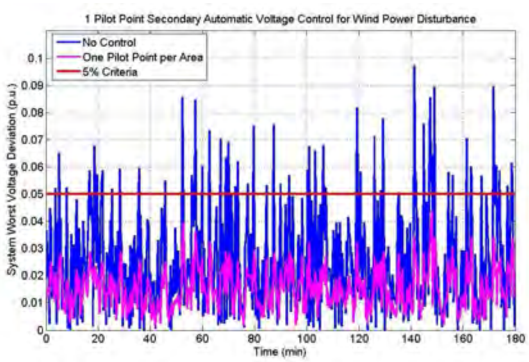

Fig. 16. The effect of AVC on Voltage Deviations in Response to Wind Power Disturbances

PMU measurements is also verified. A novel multi-layer clustering algorithm is proposed to decompose a large system into several small control areas. A combination of the AVC and AFC off-line designs for finding the best locations for PMU measurements for relatively small clusters and a multi-layer clustering algorithm for defining manageable clusters has a potential to become a very effective approach to counteracting voltage and line flow deviations particularly in future systems with wind power plants.

The next step would be to test the AVC and AVC using PMU measurements placed on actual utility systems. Much the same way as with AGC, once the manageable zones and the right output variables and control gains are designed, the size of the system is not critical. We see no critical issues with demonstrating these schemes for large systems. Serious effort will be needed to obtain the data, and set up the measurements in the field ultimately to verify their performance. This task is not out of reach. As a matter of fact, it would be a good use of the PMUs being deployed.

Longer-term, we see that the use of AVC and AFC, could have potential savings in the amount of spinning reserve necessary to meet the $(N-1)$ reliability criteria. The future work also is planned to study the effectiveness of applying multiple PMU measurements per each zone, and to explore whether it would be possible to generalize these schemes for managing line contingencies.

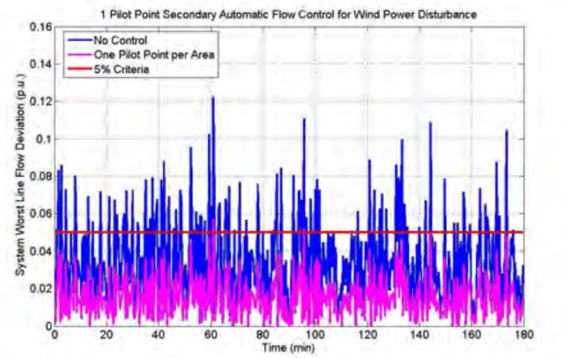

Fig. 17. The Effect of AFC on Line Flow Deviations in response to Wind Power Disturbances

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