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SECONDARY VOLTAGE CONTROL USING PILOT POINT INFORMATION

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1. INTRODUCTION

In this paper we study the minimal information structure needed for monitoring and control of the voltage profile and the reactive power flow of a given power system.

Historically, the Energy Management Centers (EMC) have been equipped with the similar data structures (like frequency and tie line flows) only for the active power studies. Currently, with the state estimators available most of the utilities monitor voltage magnitude changes throughout the system. However, these data are typically not used for any direct control of voltages.

There may be three possible reasons for this situation:

i) It is much easier to monitor and understand very few data which clearly reflect the systemwide active power imbalance than the large amount of the voltage magnitude data associated with the load buses throughout the system.

ii) The typical active power disturbances have a stronger systemwide effect, whereas many reactive power changes tend to be localized [1].

iii) It is frequently believed that only the active power generation and distribution are associated with the actual cost of the energy.

With the new trends in the operation of electric power systems (presence of cogeneration, power wheeling [2], etc.), reasons ii) and iii) cannot be easily justified even when the system is exposed to relatively small changes. The voltage-reactive power propagation requires a full monitoring under the abnormal operating conditions; recent voltage related blackouts [3] suggest a more systematic approach to the voltage problems.

The main study in this paper is related to i), i.e., the minimal information (data) structure introduced which is required for the reliable decision making in controlling the voltage profile and the reactive power distribution of the entire system. An effort is made to work with fewer voltage data and therefore make the real time monitoring and control more manageable.

A possible solution should have specific characteristics dictated by the nature of the voltage-var system, i.e., it would have to use information from many buses in the system, instead of just a single quantity (such as the system's frequency in the active power monitoring). Also it should be possible to implement in real time to respond to the reactive power imbalances in order to avoid the voltage related disintegration of the system.

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To meet both requirements we have adopted a hierarchical information and control structure, using a pilot point concept [4], [5], as it will be described in detail in this paper. Other authors have developed a variety of schemes [6] - [10], all of which depend upon the centralized information processing of all the voltage data. To take any control action, every voltage control device would need the data about the entire system. These fully centralized schemes require large communications support among all compontents, if they are to respond quickly to a disturbance.

At present, decentralized schemes are the only alternative to the centralized approach, and they are primarily used in the existing power systems. Under a decentralized control scheme the various voltage control devices (like the capacitor banks, load tap changing transformers, automatic voltage regulators) have access only to information at their own location and thus act independently. The decentralized control can act fast and it is not reliant upon the operation of a central processor; however, it cannot respond to the systemwide conditions. Therefore, both centralized and decentralized control have their advantages and disadvantages. A detailed study of the economic comparison of these two approaches to electric power systems was recently reported [11].

In an attempt to compromise, Thorp et al. [12] have studied the hierarchical information and control structure. Here, the various voltage control devices (automatic voltage regulators for generators, load tap changing transformers, capacitor banks, etc.) attempt to maintain their voltages within a threshold of the desired reference voltages. Only local information is used at this (primary) control level. Next, a secondary control scheme using systemwide information from the pilot points (to be described later) acts to update the reference voltages of the primary control devices. The secondary control scheme activates only if the primary decentralized control is insufficient. This concept is illustrated in Figure 1.

In this paper we only study the secondary, pilot point, based control. The problems related to the primary voltage control are studied elsewhere [13], [14], [15]. We believe that the idea of the pilot point information and control structure was theoretically introduced for the first time in France and it has been implemented since [5]. A pilot point is a load bus at which the voltage is to be measured in real-time and used for control actions. The number of load buses is much larger than the number of the pilot points. The selection of load buses as pilot point candidates is made so that, although there are few of them, the information from them is sufficient to control the voltage profile of the system. In [4], the pilot points for the French system are selected in the following way: First the system is divided into regions typically associated with the particular power pools. One pilot point is selected for each region to be the load bus with the largest short circuit current. Once the pilot points are found, a control scheme for resetting reference (set) points for voltage controlling devices (on the French system only automatic voltage regulators of generators) is implemented such that all of the generators in a certain region are dedicated to controlling the load voltage at the pilot point, and the information available to all generators is only the voltage at the pilot point in the specific area. Furthermore, all generators in a given region are operated at the same rate of relative reactive power ("aligned" operation). Thus control of the pilot point voltage in a given region involves only one measurement and one control decision making. Once the control is obtained for one generator, the others in the same region operate with the same portion of the maximum reactive power that they can produce. Note that this concept assumes that the voltage control is regional (not systemwide) and that it is therefore necessary to have a systemwide coordination of the reactive power flow between different regions. This control level is referred to in the French literature as the tertiary control, and it has not been automated yet.

In our study the regional solution as practiced on the French system is just a particular case of the more general secondary control approach in which systemwide pilot points are found: not necessarily just one pilot point is associated with one region and all the generators work together to maintain the systemwide voltage profile. In this sense, no additional coordination is necessary. This is the same as in [12], in which it was shown that the French control concept is only one version of a possibly more general concept of the reduced voltage information structure for monitoring and control.

2. SECONDARY CONTROL

As previously mentioned, secondary voltage control is used to reset the reference values of various voltage control devices (automatic voltage regulators, load tap changing transformers, capacitor banks, etc.). For the sake of clarity we consider only generators, whereas the general formulations for other control devices can be found in [16].

This control concept is based on the linearized model of the reactive power-voltage load flow equations

$$\begin{bmatrix} \Delta \underline{Q}_1 \\ \Delta \underline{Q}_2 \end{bmatrix} = \begin{bmatrix} \underline{B}_{11} & \underline{B}_{12} \\ B_{21} & B_{22} \end{bmatrix} \begin{bmatrix} \Delta \underline{V}_1 \\ \Delta \underline{V}_2 \end{bmatrix} \qquad (2.1)$$

where the subscript 1 indicates generators whose reference voltages are controlled, and the subscript 2 correponds to all load buses. Further notation in (2.1) stands for

- $\Delta \underline{Q}_i$ - vectors of the injected reactive power changes from the base case at buses of type i, i = 1,2
- $\Delta \underline{V}_i$ - vector of the voltage changes from the base case at buses of type i, i = 1,2

The matrix B has submatrices $B_{ij} = \frac{\partial \underline{Q}_i}{\partial \underline{V}_j}$ evaluated for the base case operating conditions.

Next, solving equation (2.1) for $\Delta \underline{V}_2$ in terms of the other variables obtains

$$\underline{x} = M\underline{q} + N\underline{u} \qquad (2.2)$$

where

$$\underline{x} = \Delta \underline{V}_2 \ , \ \underline{q} = \Delta \underline{Q}_2 \ , \ \underline{u} = \Delta \underline{V}_1 \ , \ M = B_{22}^{-1} \ ,$$

$$N = B_{22}^{-1} B_{21}$$

The notation $\underline{x}$ stands for the (unknown) voltage at load buses, $\underline{u}$ is the control if the generators are modeled as PV buses, and vector $\underline{q}$ corresponds to the changes in reactive power injections, which is considered to be a cause of change on the system. We assume here that the primary control is fully successful in keeping $\Delta \underline{V}_1$ at its reference value once a reference value is assigned through the secondary control action $\underline{u}$. The time intervals between two successive actions of the secondary control are typically long enough so that the system reaches a new steady state, i.e., all transients caused by the previous control action $\underline{u}$ have died out before the next control action is taken. Therefore, the information needed at the control location about the disturbance is reflected through the term $M\underline{q}$.

It follows from (2.2) that vector $M\underline{q}$ corresponds to load voltage deviations prior to applying the secondary control, i.e., with $u \equiv 0$.

Therefore Mq is the information available to the controller if the voltage is measured at all points and we write

$$y = Mq$$

However, we intend to measure it at the pilot points only, so the information available to the controllers (i automatic voltage regulators) is written as the vector

$$Py = PMq$$

where

$$\underline{P}_{ij} = \begin{cases} 1 & \text{if bus i is the jth pilot point} \\ 0 & \text{otherwise} \end{cases}$$

The matrix P selects voltages corresponding to pilot points only. We now propose a linear control law of the form

$$\underline{u} = V(PM\underline{q}) \qquad (2.3)$$

where V is the linear feedback matrix. Substituting (2.3) into (2.2), we obtain

$$\underline{x} = M\underline{q} + NVPM\underline{q} \qquad (2.4)$$

Here $\underline{x}$ corresponds to the new load voltage deviations due to the control actions of generators (2.3) after the transients have disappeared.

To determine the best control for generators V, given the choice of pilot points P the following criteria is used

$$I(V,P) = \int_{\underline{q} \in D} p(q) \ \underline{x}^T Q \underline{x} \ dq \qquad (2.5)$$

where D denotes the set of all possible load disturbances (not necessarily single bus), p(q) is the probability distribution for the fault to occur over the given bounded range D, and the matrix Q which could take into account that maintaining the load voltages at given values is more important at some buses in the system than at the others. (This could be based on the economic dispatch for the normal operation of the system.)

If the load outage is not treated as a random variable, criteria (2.5) reduces to the deterministic criteria of the form

$$I(V, P) = \underline{x}^T Q \underline{x} = \left((I + NVP)M\underline{q}\right)^T Q \left((I + NVP)M\underline{q}\right) \qquad (2.6)$$

The nature of the performance index (2.6) is to reflect the average voltage magnitude changes throughout a given power system. The control index (2.5) is just an expected value of (2.6).

The choice of control matrix V which minimizes I(V,P) in (2.5) for a given P is found to be [17]

$$V(P) = (-N^TQN)^{-1}N^TQGP(GP^T)^{-1} \quad (2.7)$$

where $G = MCM^T$ and

$$C = \int_{\underline{q}\epsilon D} p(q)\underline{q}\underline{q}^T \, dq \quad (2.8)$$

Note that the correlation matrix C, is the only information required for the probabilistic approach. Having found V(P), the performance index in (2.5) becomes

$$I(V(P),P) = H - \text{trace } ((PGP^T)^{-1}PFP^T \quad (2.9)$$

with

$$H = \text{trace } (GQ) \quad (2.10)$$

and

$$F = GQN(N^TQN)^{-1}N^TQG \quad (2.11)$$

Unfortunately, the selection of the optimal pilot points, i.e., minimizing (2.9) with respect to the choice of P is a difficult combinatorial problem. The cost function is still easily evaluated for a new choice of P, since matrices F, G and H can be computed beforehand and only once. The exact search for the optimal P involves the evaluation of the cost for all possible combinations of pilot points. For small systems searching all pilot points combinations exhaustively is feasible, since it has to be done once off line. This process was reported in [12] for a small 30-bus system.

For larger systems it becomes feasible to search for a large number of possible combinations, but not all of them. Other methods of attempting to find the lowest cost pilot point combination are employed here. In particular, recently introduced annealing algorithm for optimization [18], [19], is exploited here for the first time on an electric power system.

3. THE ANNEALING ALGORITHM FOR THE PILOT POINT SELECTION

As mentioned before, the only guaranteed way to obtain the optimal pilot point combination is to use an exhaustive search, in which the cost (2.5) is evaluated for every pilot point combination. For realistic size systems a more heuristic (but still reliable) algorithm must be found. Recently in optimization theory much attention has been paid to the annealing algorithm [18] - [19], because it appears to have most of the advantages of a descent algorithm, but has the possibility of finding a global (rather than local) optimum of the performance index. The annealing algorithm used here will be that described in [18] and it proceeds as follows.

Let the cost c(x) be defined on some finite space X, and the optimal x* is searched for at which c(x) reaches its minimum value. The annealing algorithm is based on the notion of a neighborhood of N(x) for each x in X. The neighborhood N(x) should be a subset of X, typically small. In addition, it is supposed that a transition probability matrix R is defined so that $R(x, x') > 0$ if and only if x' is in N(x). Furthermore, let a sequence of numbers $T = \{T_1, T_2, \dots\}$, (called a "cooling schedule"*) be given such that

$$\lim_{k\to\infty} T_k = 0 \qquad \text{and} \qquad T_k \geq T_{k+1} \quad (3.1)$$

Then the annealing algorithm can be described as follows:

1. Choose an initial guess for x^0, set $k = 1$, $y = x^0$.
2. Choose a potential next x_{k+1} from the neighborhood $N(x_k)$, using the transition matrix R.
3. If the cost at the x_{k+1} satisfies

   $$c(x_{k+1}) > c(x_k) \quad (3.2)$$

   then x_{k+1} should be set to x_k with the probability

   $$p_k = \exp([c(x_k) - c(x_{k+1})]/T_k) \quad (3.3)$$

   Otherwise x_{k+1} remains the same.
4. Set $k = k + 1$
5. If $c(y) > c(x_k)$ then set $y = x_{k+1}$.
6. If the stopping criteria

   $$\|c(y) - c(x_k)\| < \varepsilon \quad (3.4)$$

   is satisfied (with ε a small predefined number), then print y and stop. Otherwise go to step 2.

This algorithm differs from that described in [18] only in that the algorithm here remembers the lowest cost state y ever visited, whereas the other does not.

There are two ambiguous problems in setting up the annealing algorithm: i) the definition of neighborhoods with transitions probabilities and ii) the definition of the sequence T.

The definition of neighborhoods is particularly ambiguous since there are no rules for any particular problem. There are, however, some general guidelines. One is that they should be relatively small subsets of X, and the other is that the neighbors of a state x should be similar to the state x, and have similar costs. For our application, the neighbors of a pilot point at x are obtained by taking one particular pilot point, P_i, which is a member of X and moving it along a connecting transmission line to another point P_i', such that P_i and P_i' are both connected by a transmission line. In other words, the neighborhood of

$$x \stackrel{\Delta}{=} \{P_1, P_2, \dots, P_{n_p}\}$$

and the R matrix are given implicitly by the procedure for choosing a random neighbor, which is

1. Choose a $P_i \epsilon X$, with all P_i's being equally probable.
2. Choose a new P_i' which is connected to P_i in the system by a transmission line, with all possible P_i's being equally likely to be chosen.
3. If $j \neq i$: $P_i' = P_j$, then go to step 1, otherwise, set $x' = \{P_1, P_2, \dots, P_i', \dots, P_{n_p}\}$

This choice of neighborhoods and transition matrix R is easy to implement, the neighborhoods are small, and one state is closely related to its neighboring states on the graph which represents the system. An example of this process is given for the studied power system in the next section.

The other ambiguous problem which must be dealt with is that of the choice of T. There are requirements on this sequence in order to make the algorithm convergent, which can be stated as

*The same terminology is kept here for the algorithm as in [18] - [19]. If this algorithm is accepted for power systems applications, the terminology should be adapted correspondingly.

$$\sum_{i=1}^{\infty} e^{-d/T_i} = +\infty \qquad (3.5)$$

where d is a problem-dependent constant, but this requirement can be satisfied for any arbitrarily specified subsequence T_i, $i = 1, \ldots, n_{an}$, $T_{n_{an}}$, so the requirement is not useful in choosing the first n_{an} values (as long as they remain greater than zero). Furthermore, the constant d is probably more difficult to obtain than the actual answer to the problem. More theoretical work is needed on this issue as related to the optimization of electric power systems. In the initial simulations decreasing exponential was chosen for this sequence.

Another problem to be addressed is the problem of restarting the annealing algorithm. Restarting is the process of starting an algorithm repeatedly. This is done for algorithms which can only find local minima, so that in case the function has several local minima, there will be a good chance that the local minima found is also the global minimum. The literature does not address this issue. The resultant pilot point combinations are different in almost every case here. This is because the annealing algorithm is a stochastic algorithm and it finds the solution with certain probability. It is interesting to note, however, that the resultant costs are all close (Table 1). The annealing algorithm is thought to avoid local minima already, restarting is considered superfluous. However, when the annealing algorithm is terminated after a certain number of steps, there is no guarantee that a global minimum has finally been reached. It is therefore a question for experimental research, whether given a certain amount of time in which to solve a given problem it is best to perform one long annealing algorithm or a number of shorter ones with restarting. When the problem of finding the optimal number of restarts is combined with the problem of finding the best sequence T, the resulting problem, if solved, would offer much insight into the behavior of the annealing algorithm under practical constraints.

In the next section the results of applying the annealing algorithm with various values of n_{an} (the number of steps in a single run) and n_{re} (the number of restarts) are given for the actual power system.

4. SIMULATION RESULTS

The annealing algorithm for finding pilot points was applied to the Central Illinois Light Company (CILCO) system. The system consists of 160 loads, 3 generators, 9 transformers with the possibility of under load tap changing operation and 3 fixed capacitors. The pilot points for the system are found and tested for the disturbances of the system which were suggested as the most severe ones. The Q-matrix for (2.5) was determined by the following formula

$$Q_{ij} = \begin{cases} \max(1, |q_{BASE}|_i) & \text{if } i = j \\ 0 & \text{if } i \neq j \end{cases} \qquad (4.1)$$

where $q_{BASE,i}$ is the per-unit base case reactive power demand at bus i. The reasoning behind such a choice is based on the assumption that changes in larger loads will affect the systemwide voltage profile more. As stated earlier, if any other weighting is given it could be used, for example based on the economic dispatch under the normal conditions.

The correlation matrix C is chosen to be

$$C_{ij} = \begin{cases} |q_{BASE,i}|^2 & \text{if } i = j \\ \alpha|q_{BASE,i} \cdot q_{BASE,j}| & \text{if } i \neq j \end{cases} \qquad (4.2)$$

where $\alpha = 0.5$. Again, if more data were available for the probability distribution of load outages, different C may be used.

In the presented simulations, the cooling schedule was chosen to be

$$T_k = B \frac{n_{an} - k + 1}{n_{an}} \qquad (4.3)$$

where k is the iterative step of the algorithm and the other parameters were defined in the previous section.

The parameter B was chosen to estimate the average change in cost associated with a change from one pilot point combination to a new combination, where one load bus is replaced by the neighboring bus. The buses in the system are referred to by bus number as used in the load flow studies of the system. Since this is a large system, the names and locations of all buses are not included in this paper, but may be obtained by contacting the authors. The oneline diagram is given in Figure 2.

The annealing algorithm is simulated with an a priori knowledge of the number of the pilot points. Results in Table 1 are displayed for different combinations of 2 and 3 pilot points. In the table n_p is the number of pilot points, n_{an} is the number of iterative steps in a single run of the annealing algorithm, n_{re} is the number of restarts of the annealing algorithm in a single run. The results show that the minimum cost is not strongly dependent on the number of restarts of the annealing algorithm, but the choice of pilot points might be. Also the sensitivity of the pilot point choice to the parameter B is shown.

TABLE 1

n_p	n_{an}	n_{re}	B	I(V,P)	Pilot Points Obtained
2	1	100	0.002	0.3946	95, 81
2	10	10	0.002	0.3924	1, 81
2	100	1	0.002	0.3933	30, 79
2	1	100	0.02	0.3946	95, 81
2		10	0.02	0.3946	122, 81
2	100	1	0.02	0.394	21, 48
3	1	100	0.002	0.3902	70, 67, 81
3	10	10	0.002	0.3914	81, 70, 94
3	100	1	0.002	0.3943	48, 35, 80
3	1	100	0.02	0.3916	81, 84, 7
3	10	10	0.02	0.3914	77, 2, 78
3	100	1	0.02	0.3928	79, 137, 18

The process of finding the neighboring combinations of pilot points is illustrated in Figure 3. If in the illustration, buses 1 and 2 were the present pilot point combinations, which will be denoted (1, 2), the possible neighboring combinations would be (1, 9), (3, 2), (5, 2), (6, 2), (7, 2), (8, 2), and (9, 2). Combinations (1, 1) and (2, 2) are excluded since they contain repetitions, even though they could be obtained by moving a single pilot point along a transmission line. Note that (4, 2) cannot be a pilot point combination because 4 is a generator and not a load bus.

The pilot point combination 70, 67 and 98 was chosen as one of a low cost combinations. These load buses lie in the area of the southern part of the system, which is most heavily loaded. The effect of two faults were studied, before and after the secondary control had acted and the results are given in Figures 4-7. These faults were suggested by the CILCO operators as the most severe contingencies.

The first fault corresponds to the total loss of load at bus 138. The resulting voltage profile is given in Figure 4 for all the load buses in the system. Figure 5 shows the voltage profile under the same contingency with the generator set points changed according to the pilot point based control. Figure 5 shows that the secondary voltage control has improved the systemwide voltage profile but it has not removed the problem completely. The largest overvoltage left is at the load bus 161 and an undervoltage occurs at the bus 162. Bus 162 was recognized as the problem area by the CILCO operating personnel and was scheduled to have a 40 MVAR capacitor installed, which can be switched in two 20 MVAR steps.

The second problem fault given to us is indeed a line fault between the two recognized problem buses (161 and 162) from the previous simulation. When the secondary based control acts, the voltage deviations are reduced throughout the system. A relatively large voltage deviation is left at bus 133.

The results with a different pilot point choice (load buses 70, 67, 81) corresponding to a slightly lower cost are as follows: The control matrix V defined in (2.3) for these pilot points takes on values

$$\begin{bmatrix} .145 & .357 & .013 \\ .054 & .104 & .012 \\ -.210 & -.58 & -.008 \end{bmatrix}$$

The load voltage deviations at the pilot points when the first fault occurs are: i) Prior to the control actions -12%, -1.9% and 1.43% and ii) After the control actions .48%, -.62% and .38%.

The required control to achieve the systemwide voltage corrections based on (2.3) results in

$$\underline{u} = [.07\%, -.11\%, -.32\%]^T$$

for all three generators.

The load voltage deviations at the pilot points when the second fault occurs are: i) Prior to the control actions are .012%, .0057% and .1918% and ii) After the control actions .0049%, .01% and .0096%. The required control to improve the systemwide voltage profile is in this case $\underline{u} = [.006\%, .003\%, -.007\%]^T$.

Since the line fault does not cause any net change in reactive power (except for the reactive power losses on the faulted line, the systemwide effect of this type of outage is qualitatively different from the reactive power load outage. This explains significant differences in the values for required control $\underline{u}$ at the generators in the above two cases. However, local voltage problems close to the faulted line may not be possible to avoid by the considered control actions.

To sum, it appears that it is not always sufficient to reset voltage reference values at the generator controls only. All the other controls in the system (like load tap changers and the controlled capacitor banks) could have their reference values reset using the pilot point information. If all this is done, and the voltage problem is still left at the specific locations in the system, possibly new voltage supporting devices need to be installed, as was the case on the CILCO system. Note that this is partly a consequence of the localized voltage propagation [1] since the voltage support available somewhere else in the system is not directly useful for correcting the local voltage problem. The algorithms suggested here could also be used to find the problematic areas, even with the secondary control acting, and in this sense could be useful at the planning level as well.

However, one important observation needs to be made: The secondary control for the CILCO system was studied without any restrictions on the reactive power exchange of this system with the interconnected systems. It was suggested that this constraint be taken into account. This is implementable in our algorithm, but it leaves an open question of operating policies on the var exchange among different power pools. Two solutions are possible: a) a pure regional approach or b) a systemwide approach. This issue is strictly dependent on the existing policies on the interconnected system, while the techniques developed here could cover both. A systemwide approach would necessarily require algorithms like the one discussed here because of the practical impossibility to address the process of choosing pilot points as an exact optimization problem.

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Appendix A

To derive the optimal value of V, write

$$I(V,P) = \text{trace}\,[I(V,P)] =$$

$$= \text{trace} \int_{q \in D} x^T Q x \; p(q)dq =$$

$$= \text{trace} \int_{q \in D} (Mq + NVPMq)^T Q (Mq + NVPMq) p(q)dq$$

$$= \text{trace} \int_{q \in D} q^T M^T (I + NVP)^T Q (I + NVP) Mq \; p(q)dq =$$

$$= \text{trace}\,\left[(I + NVP)^T Q (I + NVP) M \left[\int_{q \in D} qq^T p(q)dq\right] M^T\right] \qquad (A.1)$$

Define the correlation matrix

$$C = \int_{q \in D} q^T q \; p(q)dq$$

$$G = MCM^T$$

Then Equation (A.1) becomes

$$I(V,P) = \text{trace}\,\left[(I + NVP)^T Q (I + NVP) G\right] =$$

$$= \text{trace}\,\left[GQ + ZQNVPG + PGP^T V^T N^T QNV\right]$$

Now, to find the optimal choice of feedback matrix V, we take the derivative with respect to V to obtain

$$\frac{\partial I(V,P)}{\partial V} = 2N^T Q^T G^T P^T + 2(N^T QN) V (PGP^T) \qquad (A.2)$$

It follows from (A.2) that

$$V^T_{opt}(P) = -(PGP^T)^{-1} PGQN (N^T QN)^{-1} \qquad (A.3)$$

which substituted back into (A.1) obtains the optimun cost as given in (2.9).

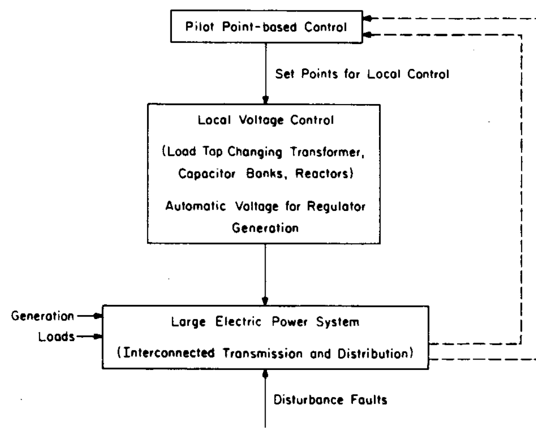

Figure 1: The hierarchical information and control structure.

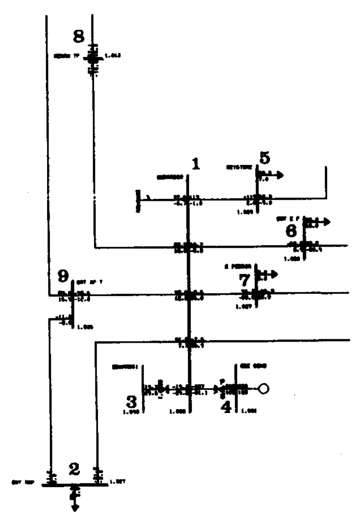

Figure 3: An Illustration of Neighboring Pilot Points N(x).

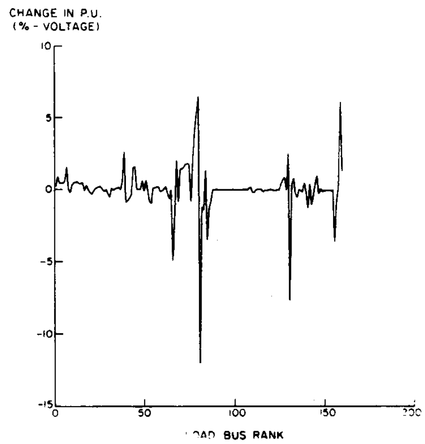

Figure 4: Load bus voltage profile (load fault on, no secondary control).

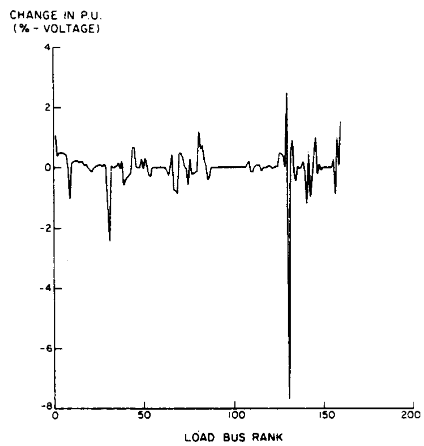

Figure 5: Load bus voltage profile (load fault on, with secondary control).

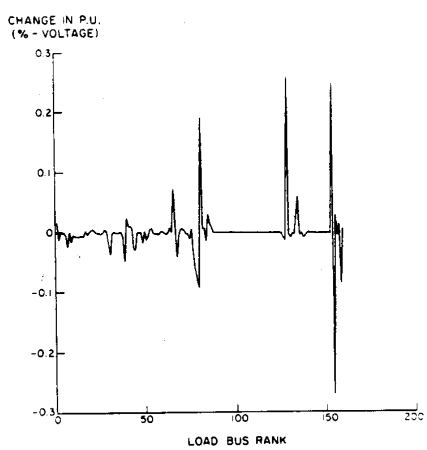

Figure 6: Load bus voltage profile (line fault on, no secondary control).

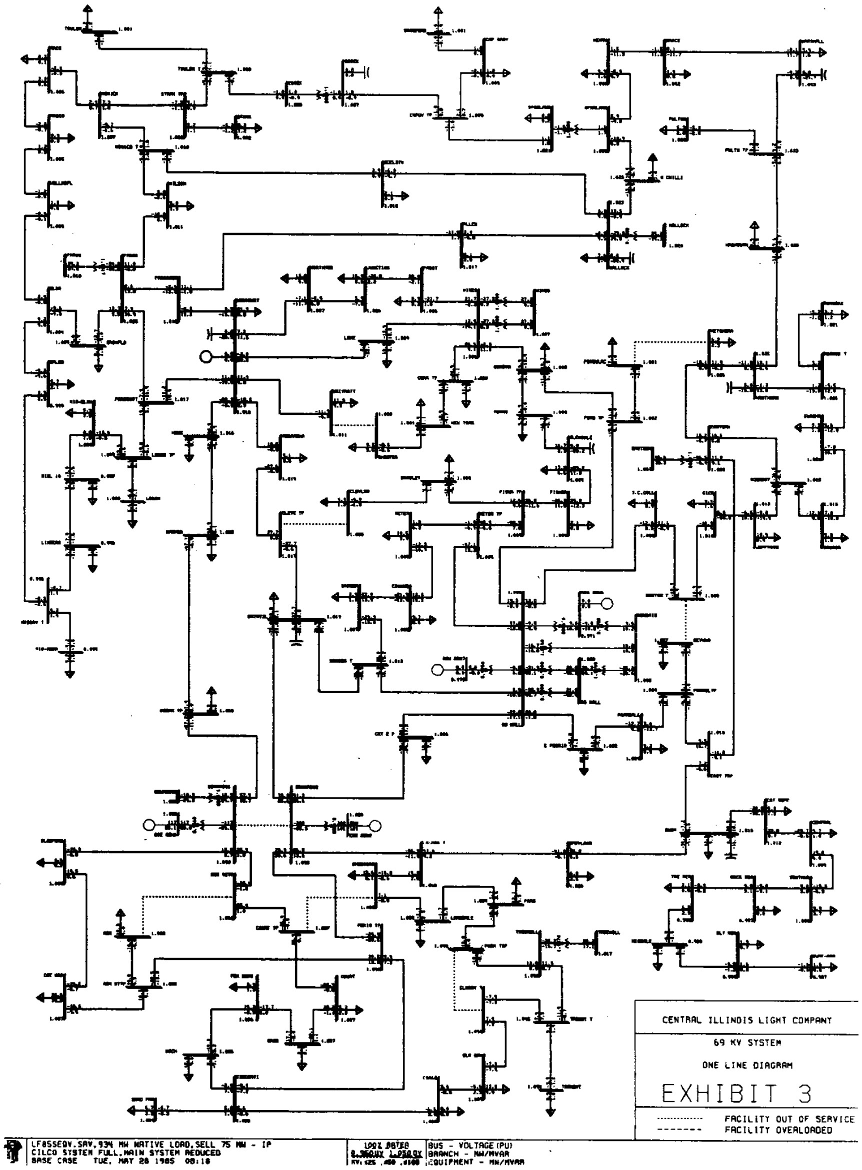

Figure 2: The CILCO 69kV System - One line diapram

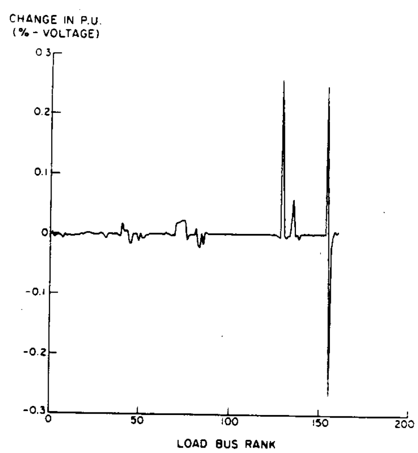

Figure 7: Load bus voltage, profile (line fault on, with secondary control).

Discussion

J. Carpentier (Electricité de France, Paris, France): The authors must be congratulated for the very ingenious way in which they settled and solved the problem of secondary voltage pilot point localization. Indeed, at Electricité de France, where such pilot points are used, it was observed that the location of these points is of prime importance for the quality of voltage control.

On the other hand, in recent studies at Electricité de France, the question to know whether a hierarchized voltage control (with secondary and tertiary levels) is necessary was reexamined. Various reasons led to the conclusion that such a hierarchization is much preferable, especially for the robustness and the dynamics of voltage control, even if the present implementation is improved. Could the authors make comments on this point of view? Moreover, do they think the annealing algorithm would be practical for a large scale system such as that of Electricité de France in a few years, with about 1000 nodes and 300 reactive sources?

M. Ilic, J. Christensen, and **K. L. Eichorn**: The authors are most grateful to Mr. J. Carpentier for providing a discussion for this paper. The input to our work from the researchers at the Electricité de France is important since this system is currently the only one with the automated secondary voltage control implemented. The original motivation for our theoretical work was definitely triggered by the practical implementation of the pilot point concept on the French power system.

The question related to the comparison of the hierarchical control, (i.e., both secondary and tertiary) versus the secondary only for the entire system is not an easy one. Depending on the communications and computing support available, the answers may be different. It is definitely true that, if the techniques for the hierarchical control are developed taking into account interactions among the subsystems, it is more feasible to deal with smaller subsystems and then coordinate them. The coordination of the subsystems controlled via the secondary control has to be done properly though, and new developments are needed for this. The solution proposed in this paper applies to the entire system with the secondary control level being the highest. No additional (tertiary) coordination is needed.

However, because of the high requirements in memory and computing time for large systems, having the tertiary control level simplifies the programming effort. The same answer holds specifically for the annealing algorithm. If a large enough computer is available, the algorithm is practical for the large scale systems, since finding the pilot points and the control low coefficients is always an off-line process. The actual signal processing involved is not complicated. We are currently at the stage of testing the algorithm for realistic systems with 550 nodes.