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Improved Secondary and New Tertiary Voltage Control

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Abstract

In this paper the basic role of a secondary (regional level) voltage control in a multi-regional electric power system is reviewed. Specifically, certain limitations of presently implemented control schemes are described. Next an Improved Secondary Voltage Control (ISVC) scheme is proposed.

In the second part of the paper possible enhancements of a multi-regional system operation by means of scheduled, Tertiary Voltage Control (TVC) interactions are proposed. It is shown that the prime role of a TVC is in managing limits on voltage control devices, such as generators. The theoretical developments are illustrated on two regions of the French electric power network.

I. Introduction

While the voltage control of an interconnected large-scale power system is widely recognized as an important problem, its basic formulation and solutions are often utility specific. Most often the voltage control is viewed as a static problem, whose solution is identical to a centralized open-loop optimization-based Var/voltage management. The most common tool for solving this problem is an Optimal Load Flow (OPF) type algorithm. This approach is often referred to as the tertiary control, particularly in the European literature [1, 2]. The OPF computes changes in generator voltages to regulate load voltages on the entire interconnected system.

A second, different, approach to voltage control coordination relies on decomposition of a large system into regions and an on-line decentralized close-loop controller for regulating only a few load voltages in each region, referred to as the "pilot" voltages [1, 3, 4, 5].

For instance, in the French system a full automation of system-wide voltage regulation is achieved by employing such an intuitive reduced information structure at the regional level (the pilot busses) and regional controllers (called secondary voltage controllers) which control the pilot voltages by adjusting the terminal voltages of the regional generators. Particularly relevant is the fact that this scheme assumes negligible interactions with the neighboring regions. In this case the responsibility for coordinated voltage regulation of the entire French network is shared among regional closed-loop controllers and the operators at the national control center.

As the French power network has become increasingly meshed during the past decade and is operated closer to its transmission limits than in the past, Electricité De France (EDF) is considering the automation of the tertiary level in order to improve the security and economics of the entire system. In this paper we present some of the results of an EDF/MIT collaboration on the tertiary coordination of the secondary voltage controllers.

Addressing the issue of tertiary coordination leads to three open questions:

- The definition of voltage optimality - an interesting article documenting hidden essential questions in this area is worthwhile reading [6]. In context of hierarchical voltage control designs this issue becomes complicated even further by the questions of regional contributions to a specified system-wide performance criterion [7].
- The second question is concerned with meeting performance specifications at the regional level when interactions are not negligible.
- The third question is whether possible improvement of the voltage profile in a particular region experiencing shortage of voltage support can be achieved by optimizing a system-wide performance criterion, instead of regional criteria.

This paper is organized in the following manner :

In section II, a brief overview of a system theoretic formulation of the presently employed regional (secondary)

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voltage regulation in France is given [3, 4, 5]. Prior to proposing new solutions, critical assumptions under which the present Secondary Voltage Control (SVC) is implemented are reviewed [9, 10, 11].

In section III of this paper, an improved control design at the secondary level is proposed, which uses additional measurements to cancel the effects of the neighboring regions on a regional performance criterion. This design is defined so that a regional performance criterion can be met, independently from the voltage changes in the neighboring regions as long as sufficient voltage control reserves are available at each regional level.

In section IV, the issue of the performance of an interconnected system consisting of many electrically connected regions or utilities is studied. A tertiary level coordination scheme is proposed that optimizes this system-wide performance criterion. The actual implementation of the proposed regional voltage coordination can be decentralized (at a regional level) or centralized (at a tertiary level). The limits of a decentralized implementation are addressed from the viewpoint of classes of performance criteria that can be optimized this way.

Finally in section V, the proposed control designs are illustrated on a large network representing two electrically close regions of the French power system.

II. Survey of the EDF Secondary Voltage Control

A. Modelling

Since only the mid-term behavior of the power system is of direct interest in this paper, the transient response of generators and their primary controls are assumed stable and very fast, i.e. instantaneous relative to the slow time scale of interest. Under this assumption, only steady state load flow equations are considered. Loads are modeled as constant power devices. To review the basic model presently used in designing the secondary voltage control in France, a standard real/reactive power decoupling assumption is made.

The control problem under consideration in this paper is not a conventional one since no natural dynamics are modeled, i.e. they are assumed instantaneous. Instead, a sequence of steady state voltages is defined. The load voltages are changing in response to changes of steady state set points of generators. Changes are initiated by a load deviation away from the nominal, or by topological changes of network parameters. In order for the load flow equation to be satisfied for these new parameters, one needs to compute changes in set points of generator voltages ΔV_G which would bring the load voltage deviations ΔV_L back to zero. In this context, load voltages ΔV_L can be thought of as system state variables, which are regulated by changes in generator voltages ΔV_G. [1]. Furthermore, in the present implementation in France controls react only in response to load voltage deviations at selected nodes (pilot nodes) from their set values. The use of pilot point measurements only, instead of measurements on all load buses, is referred to in this paper as the reduced information structure at a regional level.

To introduce these control laws, let us consider the dynamics of each region.

The reactive power balance at each bus i in the region can be expressed as

$$Q_i = \Sigma_j B_{ij} V_j (V_j - V_i) + F_i \tag{1}$$

where F_i is the tie-line flow into bus i. (For non-boundary buses $F_i = 0$).

Linearizing (1) around $V_i^0 = V_j^0 = 1p.u.$ (or any other nominal operating point) one obtains

$$\dot{Q}_i = \Sigma_j B_{ij} (\dot{V}_j - \dot{V}_i) + \dot{F}_i \tag{2}$$

Using [2] vector form to denote all load and generator variables in the region of interest, one obtains

$$Q = \begin{bmatrix} Q_L \\ Q_G \end{bmatrix} \text{ and } V = \begin{bmatrix} V_L \\ V_G \end{bmatrix} \tag{3}$$

$$F = \begin{bmatrix} F_L \\ F_G \end{bmatrix} \tag{4}$$

Equation (2) can be written as

$$\dot{Q} = D\dot{V} + \dot{F} \tag{5}$$

Notice that Equation (5) is written for each region separately, i.e. D is the sensitivity matrix of the *disconnected* region from the rest of the system. Equation (5) expressed in terms of variable changes at load buses ("states") and generator buses ("controls") separately becomes

$$\begin{bmatrix} \dot{Q}_L \\ \dot{Q}_G \end{bmatrix} = \begin{bmatrix} D_{LL} & D_{LG} \\ D_{GL} & D_{GG} \end{bmatrix} \begin{bmatrix} \dot{V}_L \\ \dot{V}_G \end{bmatrix} + \begin{bmatrix} \dot{F}_L \\ \dot{F}_G \end{bmatrix} \tag{6}$$

under the constant load modeling assumption $\dot{Q}_L = 0$, resulting in

$$\dot{V}_L = -D_{LL}^{-1}(D_{LG}\dot{V}_G + \dot{F}_L) \tag{7}$$

The control variable u is defined as the **rate** of change of generator voltages and the state variables x are actual load voltages V_L. Then (7) written in a system-theoretic setting takes on the form

$$\dot{x} = C_v u - D_{LL}^{-1}\dot{F}_L \tag{8}$$

where

$$C_v = -D_{LL}^{-1} D_{LG} \tag{9}$$

One should interpret (7) as a relationship at each regional level between its own load voltages and own generator controls, whereas the effect of the interactions

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[1] In the rest of the paper for simplified notation Δ symbol is omitted

[2] Throughout this paper an approximate notation is used for $\dot{x} = (x((i+1)T) - x(iT))/T$, where the ith value represents the ith steady state solution in the sequence of solutions of interest. Here T stands for sample time of the process control computer.

with the rest of the system is only seen through the second term proportional to the reactive flow changes $\dot{F}_L$ into the area. This is a fully **decentralized**, exact interpretation of small signal changes at the regional level.

The flow changes can be also interpreted in terms of slow aggregate variables as defined in [14]. In [14] the aggregate variables relevant for the inter-regional effects are defined to be any linear combination of load voltages which does not change if the tie-line flows are kept constant, *under any form of secondary control law.* Translating this definition into mathematical relations, one obtains an intriguing relationship between the aggregate variables and the tie-line flows. This relationship is considered to be a direct rationale for proposing a reduced information structure for system-wide voltage coordination in terms of individual tie-line flows in addition to the existing regional measurement structure.

This leads to the dynamics of the aggregate variables as

$$\dot{y} = PC_v u - PD_{LL}^{-1}\dot{F}_L \qquad (10)$$

which, in order to meet the above definition requiring that whenever $\dot{F}_L = 0$ this implies $\dot{y} = PC_v u = 0$, is defined as $y = Px$, where matrix P satisfies

$$PC_v = 0 \qquad (11)$$

Following the same derivations as in [10], it is straightforward to show that

$$\dot{y} = S\dot{F}_L \qquad (12)$$

Relationship (12) states that the aggregate variables defined as above are simply linear combinations of tie-line flows into the load buses only. These variables are shown to be essential in forming a reduced-order model for centralized TVC [14].

B. Presently Implemented Secondary Voltage Control (SVC)

In this section relations among relevant variables and controls described above are simplified assuming negligible connections to the neighboring regions. Equation (8) becomes

$$\dot{x} = C_v u \qquad (13)$$

since the term $\dot{F}_L$ is neglected. This model is identical to the model used for the SVC in France at present time [3].

A particularly important feature of the model given in (13) is that it is not fully controllable since the sensitivity matrix C_v whose dimension is $(n \times g)$ is not of full rank for $n > g$, where n is the number of all loads, and g is the number of generators. Because the system is not fully controllable, and because it is not desirable to measure all load voltages, a measurement (output) feedback z to the control signal u is introduced, instead of a feedback to all variables x. To model this output feedback, suppose measurements (for example, pilot node load voltages) are defined as

$$V_P = CV_L \qquad (14)$$

Assume the feedback is proportional to the deviation measurements from their set values

$$u = \dot{V}_G = K(V_P - V_P^{set}) \qquad (15)$$

where V_P^{set} denotes the set (desired) values of critical load voltages in the region. For selection of K see [4]. With this output feedback control, the closed-loop model describing pilot point load voltage changes can be written as

$$\dot{V}_P = A(V_P - V_P^{set}) \qquad (16)$$

where $A = C_v K$.

Note that the success of an incoordinated secondary control for each region briefly reviewed here strongly depends on a good choice of a voltage control region. A region is well defined [4] if the following three assumptions hold:

- **Assumption 1:** When the voltage of pilot node is maintained at a steady level, the variations of the other load voltages in the region remain small even with the load variations.
- **Assumption 2:** The control actions in a given zone do not cause significant voltage variations in the other zones.
- **Assumption 3:** The zone has sufficient voltage control to keep the pilot point voltages steady in each region, in both normal and emergency conditions.

For the purposes of this paper the first assumption considering closeness of pilot and non-pilot load voltages in a region of interest is not discussed further, it is considered to hold. The "best" pilot point nodes can be chosen for instance using the mathematical measures introduced in [9, 12, 13]. The validity of the second and the third assumptions and ways of improving the present design when they do not hold are studied in the following sections.

III. A New Improved Secondary Voltage Control (ISVC)

A. Limitations of the Present SVC

The proposed Improved Secondary Voltage Control (ISVC) design is discussed under Assumption 1 of well defined voltage regions.

It was proven in [14] that, with the present SVC [4] under certain assumptions, typically valid for wide ranges of voltage changes, no slow persistent inter-regional voltage oscillations can take place as a result of strong effects of voltage changes in the neighboring regions; indeed, this can not occur as long as all the generators are operating within their limits and the coupling with the real power changes is negligible.

However, because the interconnections are becoming stronger, the settling time could deviate significantly from the anticipated response under the presently implemented SVC, which basically assumes no changes in the near-by voltages. Therefore, it is expected that the improvements of any type of ISVC over the presently implemented SVC which depend on this assumption will only be seen in the guaranteed performance criterion defined at a regional level, independently from the level of voltage deviations in the neighboring regions. One such new design for ISVC is described and illustrated by simulations on two regions of the French network in Section V.

B. ISVC Design

The present state of secondary voltage regulators is based only on the regional measurements, i.e. regional pilot point voltages. We are proposing in this section possible ways to improve the secondary level, by taking into consideration the effect of interconnections, while preserving its decentralized nature. The proposed control laws will be such that they cancel out the effect of interactions based on additional feedback signals which use the reactive power tie-line flow measurements. To introduce these control laws, we start with the regional model which does include effects of flow deviations given in Equation (10) above. An improved control law of the form

$$\dot{V}_G = K(V_P - V_P^{set}) + G\dot{F}_L \tag{17}$$

is proposed. It can be seen that this control law has an additional term relative to the presently implemented SVC (15) which is intended to respond to deviations in line flows in such a way that their effects are canceled out as seen at the secondary level. This will lead to the secondary voltage regulation according to exact specifications at the regional level. It was shown that if the gain G in (17) is chosen so that

$$G = (CC_v)^{-1}CD_{LL}^{-1} \tag{18}$$

the closed-loop pilot point response will be according to

$$\dot{V}_P = CC_vK(V_P - V_P^{set}) \tag{19}$$

Gain K is now chosen at the regional level, for known C and C_v of this region, so that the desired response is achieved. For example, it is very simple to choose K so that the regional pilot voltages reach their steady state within 3 minutes, no matter what else is happening on the system. [2]

Notice that this control scheme would be extremely simple to implement by enhancing an already existing secondary controller by an additional feedback signal $G\dot{F}_L$, which would use measurements of line flow changes into the region.

In conclusion, the advantage of the ISVC over the SVC lies in that it ensures a guaranteed time-response (3 minutes in the French implementation) at the secondary control level independently of the disturbances which occur in the neighboring regions and no matter how tightly the regions are connected.

IV. Coordinated Voltage Control of a Multi-regional Electric Power System

It can be seen from the previous section that an ISVC scheme is possible to introduce at a regional level, and that the main purpose of such improvement would be to guarantee a regional performance independently from the voltage changes in neighboring regions. This is true as long as the operating ranges are such that the system matrix C_v in Equation (13) remains positive definite and as long as no constraints on voltage controls are reached, nor secondary units tripping takes place.

The situation becomes qualitatively more complex when a control design is required for re-scheduling system-wide reserves by changing reactive power tie-line flows among the regions in order to manage the reactive power/ voltage constraints in specific regions within an inter-connected system. Two crucial questions could be asked in this context: Is it realistic to rely on reactive power/ voltage support from electrically distant areas, and if so, when is this needed? While the most economic real power tie-line flow scheduling is routinely done at many systems in order to optimize a system-wide cost of real power supply, it is not obvious that a similar concept would be meaningful and feasible for voltage scheduling, particularly because of the fundamental property of reactive power not "traveling" far [8].

It is only when voltage constraints begin to be approached that the effect of neighboring regions could become significant. Otherwise, as it was shown in the previous section, it is only an issue of time constants and the quality of regional response at which the interconnected system would settle.

In principle one could implement a coordination scheme relevant for a system-wide performance criterion in either an entirely decentralized setting (at a regional level), or one could have a centralized scheme. The later implementation is often referred to as a tertiary level. On the French power network, the centralized scheme would be associated with the national control center in Paris. A new framework for system-wide coordination and the conditions under which it could be implemented in a decentralized way are discussed next.

A. Proposed Decentralized Implementation of System-wide Voltage Controls

To start with, since the main objective of reactive power/ voltage inter-regional coordination is to manage most effectively voltage control constraints that can not be avoided by using only regional reserves, any potentially useful system-wide criterion for voltage manage-

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[2] This statement is qualified in the sense that it strictly holds only under the assumption that the sensitivity matrix of the interconnected system remains positive definite. If this is not met, more complicated control strategies are needed.

ment has to include voltage control constraints. Denoting by u^i vector of voltage control deviations from their most desired, optimal values, in region i

$$u[K] = V_G^{set}[K] - V_G^{opt} \tag{20}$$

the simplest effective system-wide performance criterion would be of the form

$$J = \sum_{i=1}^{r} J_i = \sum_{i=1}^{r} u^T R u \tag{21}$$

where r is the total number of regions and control vector u consists of control subvectors of all individual regions. The basic task of the coordination scheme is to compute system-wide voltage control set values V_G^{set} so that the system-wide performance criterion (21) is optimized, i.e so that the voltage control settings on active generators and the corresponding pilot point set values deviate least from their optimal values. Recall that the regional controllers attempt to reach these set values according to the feedback law (15). As long as all voltage controls are within their acceptable constraints

$$V_P^{opt} = V_P^{set}[K]. \tag{22}$$

This claim will be clearly illustrated in the section on numerical simulations.

Next, we use a conjecture, which is rigorously proven in [14], that for a wide class of system-wide performance criteria which are additive in terms of regional performance criteria of the same type, and which are functions of control vectors only, an entirely decentralized coordination of voltage controls is possible which leads to a system-wide optimum. The basic scheme of such a decentralized approach is described next. [3]

Consider an administratively separated region i within an interconnected system. The task is to determine controls u^i, in order to minimize a cost function of the form (21), where $i = I, II, \ldots r$. The relevant voltages and controls in each region are related via system constraints given in (7). A discrete-time version of this constraint is obtainable by integrating the model (7) between two successive implementation steps K and $(K+1)$ of coordinating controls and is of a general form

$$V_P^i[K+1] = A^i u^i[K] + B^i F^i[K] + L_0^i[K] \tag{23}$$

where A^i, B^i, L_o^i are constants, F^i is the vector of tie-line flows into the region i. The result of this decentralized optimization process is :

$$u^i[K+1] = f(F^i[K]) \tag{24}$$

One can then compute the system-wide pilot-nodes set points using Equation (23) at each regional level for the next implementation at step $(K+1)$. These new set-points are solely based on regional flow measurements at current step K.

Under certain conditions on the chosen criterion a decentralized up-dating of regional voltage controls in terms of their measured reactive power tie-line flows according to Equation (24) leads to a system-wide optimum of the performance criterion (21) which is the sum of all regional performance criteria [14]. These conditions reflect mutual dependence of the scheme on the performance criterion chosen, strength of electrical interconnections among the regions and the rate at which the coordinating control is implemented. When these conditions are met a tertiary, centralized implementation becomes unnecessary. Moreover for more general criterion a partially decentralized scheme can be used for tertiary voltage coordination as shown in [14].

The system-wide optimization should not be implemented at any rate T_t higher than the rate associated with the settling time needed at the secondary level T_S to respond to the newly scheduled set points. For typical present implementation of the automated secondary controllers this implies that T_t should not be shorter than 3 minutes, which is present settling time of the SVC on the French network.

B. Proposed Optimization at the Tertiary Level

In the most general case, when the constraints on some relevant output variables are hard, a general system-wide performance criterion of the type

$$J = \begin{array}{l} (y[K+1])^T R y[K+1] \\ +(V_p[K+1])^T N V_P[K+1] \\ +(u[K+1])^T M u[K+1] \end{array} \tag{25}$$

needs to be used for which a decentralized implementation is out of the question. The most typical example of such performance criterion is the total transmission loss [7]. This is computationally a much harder problem, since a centralized information structure is needed about the inter-connected system level. Using similar modeling for the entire system as for individual regions, a centralized implementation, again in terms of minimum system-wide information structure, is possible.

The model

$$y[K+1] = y[K] + PC_v K_s (CC_v)^{-1} (V_P[K+1] - V_P[K]) \tag{26}$$

represents the algebraic relationship between the deviations in set points of flows and pilot point voltages on the interconnected system. We refer to it as an **aggregate model** since it suppresses constraints which are not of direct interest for the coordination. However, this model is *centralized* since it requires full knowledge of the inter-connected system matrices C_v, P and C.

For notational simplicity we denote

$$L = PC_v K (CC_v)^{-1} \tag{27}$$

This matrix L is computed using the inter-connected system Jacobian.

Equality constraint (26) is essential for the efficient optimization of the interconnected system.

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[3] It is worth recognizing that this conjecture is the basis for the present decentralized real power tie-line flow scheduling in the United States.

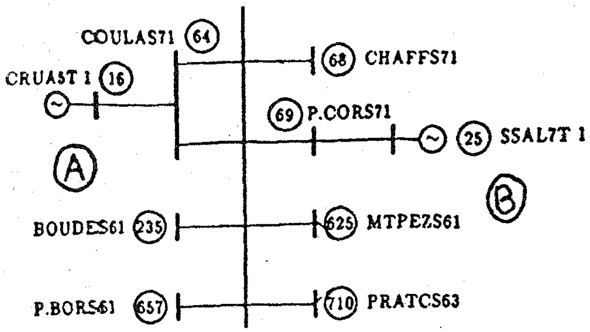

Figure 1: Tie lines on the studied network

The coordination problem, at a tertiary level now becomes the problem of optimizing (25) with respect to $(V_P[K+1] - V_P^{opt})$ subject to the system-wide constraint (26). The closed-form solution to this problem for a particular case when $M = 0$ and $N = 0$ is [4]:

$$V_P[K+1] = V_P[K] + (R + L^T L)^{-1} L^T L_0[K] \qquad (28)$$

In this equation vector $L_0[K]$ is a function of mismatches at the K-th implementation step of TVC. Formula (28) can be implemented in closed-loop setting every 3 minutes in response to whichever changes take place on the inter-connected system. These changes are seen through the measurements of variables V_P and y, which directly enter the formulae above.

A further generalization of the optimization function (25) was pursued next in [10]. This step is motivated by the fact that in the past one of the practices in regulating pilot points at the secondary level has been to do so subject to maintaining aligned reactive power outputs from the generators. In the approach proposed here this function can be moved to the tertiary level, enabling more degrees of freedom in regulating load voltages at the secondary level. Various optimization strategy could be chosen based on relative values in matrices M, N and R depending on the type of regulation desired.

V. Numerical Simulations

The numerical examples are given on a two-region portion of the French power network.

A. Network Characteristics

This portion of the network is summarized in Table 1 and Figure 1. These two regions of interest consist of 205 nodes, are located in the eastern and south-eastern parts of France and are highly interconnected.

Reg.	Pilot Nodes	Units	Units
		Sec. Contr.	Prim. Contr.
A	COULAS71	CRUA5T 1	TRICAT 3
A	TRI.PS61	TRICAT 1	TRICAT 4
A	TAVELS71	ARAMOT 1	TRICAT 5
A	SEPTES61	M.PONT 1	
B	CHAFFS71	BUGEYT 2	BUGEYT 4
B	P.CORS71	SSAL7T 1	SINAH 5
B	GIVORS61	LOIRET 3	G.ILH 1
B	CPNIES61	VAUJH 7	
B	ALBERS71	S.BIH 4	

Table 1: Pilot-nodes and units in the studied regions

Reactive flow	Region B	Region A
1	P.CORS71	CRUAST 1
2	CHAFFS71	COULAS71
3	MTPEZS61	BOUDES61
4	PRATCS63	P.BORS61

Table 2: Aggregate variables

B. Improved Secondary Voltage Control

In the secondary voltage control practiced by EDF, the control gain parameter is chosen such that the network will settle to a steady state in 3 minutes. However, this is not truly guaranteed if there are interactions among neighboring regions that are not taken into account. The ISVC adjusts the secondary regulation of the system taking the change in the tie-line flow into consideration.

However, the initial conditions of the French network modeled by CODYSIL do not provide a sufficiently large change over the 3 minute time in the tie-line flow to show the effect of ISVC. Thus, tertiary voltage control is employed at $t = 200$ sec to produce this change. Due to the interactions between Region 3 and Region 4, the system does not settle to steady state in 3 minutes ($t = 380$ sec) as one can see in the reactive tie-line flows in Figure 2(a). When ISVC is applied the dynamic interactions between the two regions are settled in 3 minutes (b) and the system has once again more control reserve in the decentralized regions.

ISVC is also effective when reactive exchange support is created by a large load change. A 1667 MW and 1667 MVAR load drop is implemented in a simulation and the difference between the the case with and without ISVC is obvious (Figure 3.)

C. Tertiary Voltage Control

C.1. Basic Cases

A simulation was carried out without tertiary voltage control. It can be seen from Figure 4a, pilot node CHAFFS71 does not go to its setting (denoted by a gray line) because generators BUGEYT2 (Fig. 4b), LOIRET3 (Fig. 4c) reach their terminal voltage limits. When a tertiary control step is applied first at $t =$

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[4] More complex, similar closed-form solutions exist for any choice of M, N and R

200 sec, these generators are taken away from their constraints (Fig. 5b,c) and CHAFFS71 (Fig. 5a) reaches its new setting. In addition, generator LOIRET 3 is now producing instead of absorbing reactive power (Fig. 4d, 5d).

It is important to note that typically 2 to 3 tertiary control steps are necessary to bring the network to a steady state that gives a minimum cost in the performance criterion. It can be seen in Figure 6a that a sequence of tertiary control actions enables the pilot voltages to converge to a system optimum suggested by a particular set of nominal values, chosen such that the generator voltages would not exceed their bounds.

Figure 6b is the results of a simulation of TVC with a set of nominal generator voltages lower than that of Figure 6a. While the generators are taken away from their constraints as in the previous case, the pilot node voltages are generally lower compared to the previous case. This has the implication of preparing the system for different load change contingencies (high voltage desirable in preparation for load increase, etc).

C.2. Adaptive Weights in the Performance Criterion

If the low weight associated with a particular variable in the performance criterion does not provide acceptable regulation at a particular load or generator to recede from its constraint, adaptive tuning of the individual weight in P, Q, or R in (26) corresponding to that particular node is necessary to bring the node away from its constraint. A mechanism to increase the individual weights of those generators that approach their limits is implemented. To show this, a simulation is done first with a relatively low weight on generator voltages Since generators S.BIH4 and SSAL7T1 (Fig. 7a) are considered "too close" to their upper limits, the individual weights associated with these generators in the performance criterion are scaled by 5.0 when the first TVC is simulated at $t = 300$ sec. As a result, voltages at these generators are significantly lowered right after $t =$ 300 sec . The small ringing effect seen in this simulation means that the scaling factor of 5.0 probably excessively lowers the voltages. In Fig. 7b, a scaling factor of 2.0 is used instead, and the ringing effect disappears while both of the generators still retract from their constraints.

While this adaptive weighting mechanism might not be necessary if the criterion weights in the performance criteria are properly chosen, it provides an additional option and it may certainly prove to be useful.

VI Conclusion

In the work reported here we recognize essential importance of the choice of performance criterion with respect to which either regional and/or system-wide voltage control is done. Because of this an attempt is made to relate the performance criterion chosen and the control functions proposed at a regional and tertiary level.

Using additional measurements on the reactive tieline flows beyond the pilot point voltage structure it is shown that the present secondary voltage control scheme can be improved. This concept could become very useful as the meshing of the French network increases or to control the voltage profiles of two tightly connected utilities.

A new system-wide coordination of secondary voltage controllers is also defined. The optimization of a system-wide performance criterion is proposed as important for sharing reactive reserves when control limits are reached.

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1 Author biographies

Dr. Marija Ilić received Dipl. Eng., and M.E.E. degrees from University of Belgrade in her native Yugoslavia, in 1974 and 1977, respectively, and M. Sc. and D.Sc. degrees in systems science and mathematics from Washington University in St. Louis in 1979 and 1980. She has since been actively involved in teaching and research in the area of large scale elctric power systems at three major universities, Cornell University, University of Illinois at Urbana-Champaign and MIT. She is presently member of the MIT Department of Electrical Engineering and Computer Science, where she holds a position of a Senior Research Scientist. She is a recipient of the First Presidential Young Investigator (PYI) award for the area of power systems. Her research interests are in the areas of control and network theory applications to large scale power systems, with the specialty in voltage modeling and control.

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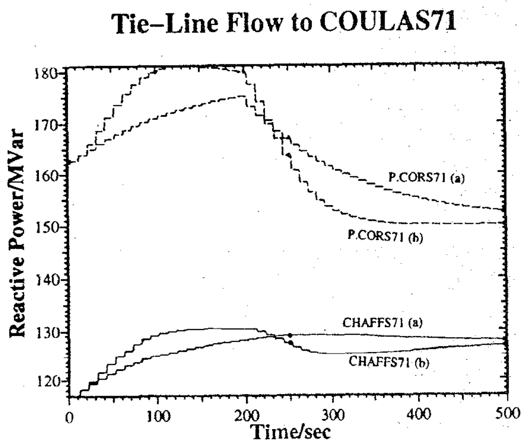
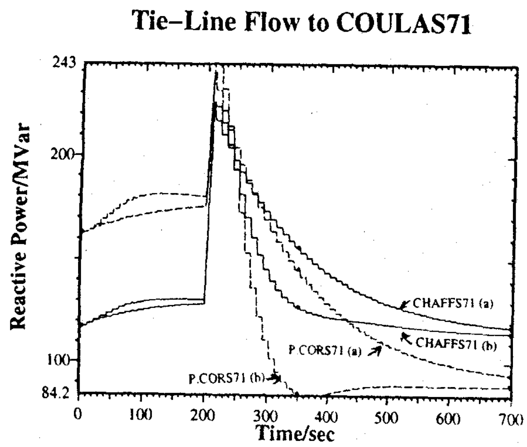
Dr. Christine Vialas received her PhD in Automatic Control in 1984 from the Institut national Polytechnique de Grenoble (France). In 1984-1985, she was a post-doctoral fellow at MIT. Since 1986, she has been a Research Engineer at Electricité de France (EDF). In 1991-1993, she was a visiting fellow in the EECS Department at MIT. Her research interests are in modeling and control of power networks.

Patrick Pruvot was born in France in 1959. He graduated from the Ecole Nationale Supérieure d'Electricité et de Mécanique de Nancy, in 1982. He has been with EDF since 1983 and is now Head of the power system control and operation group in the power system dynamics and control branch. His main fields of interest include voltage control, OPF, AGC, unit commitment and restoration techniques. He is a member of CIGRE TF 38-02-11 and 38-02-12 on voltage stability.



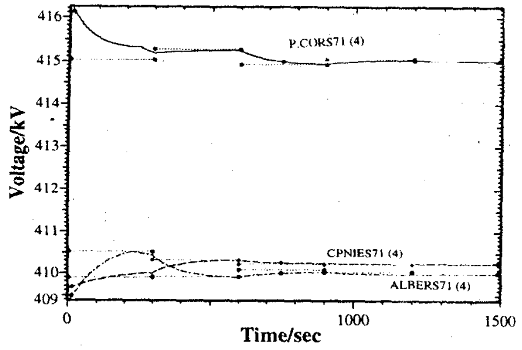
(a) Without ISVC (b) With ISVC

Figure 2: The effect of ISVC

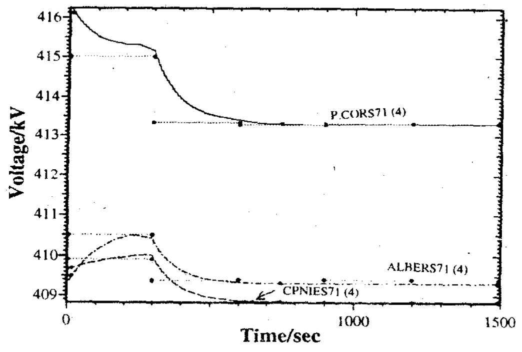


(a) Without ISVC (b) With ISVC

Figure 3: ISVC at 1667 MW and 1667 MVAR load drop

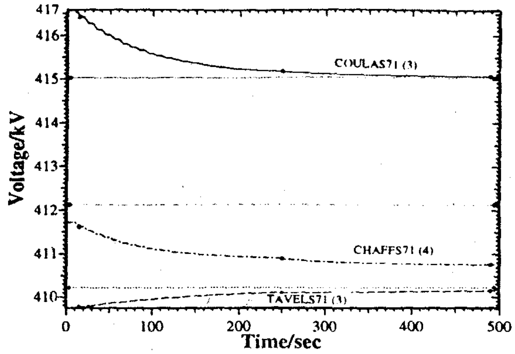


(a) Scheduling with higher voltages

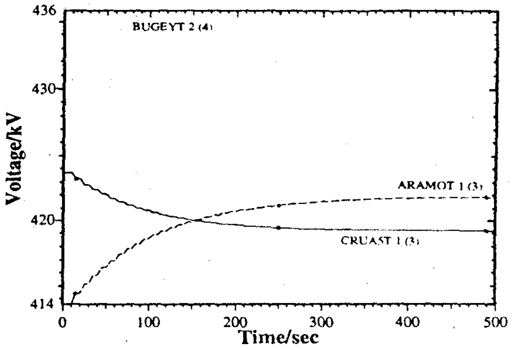


(b) Scheduling with lower voltages

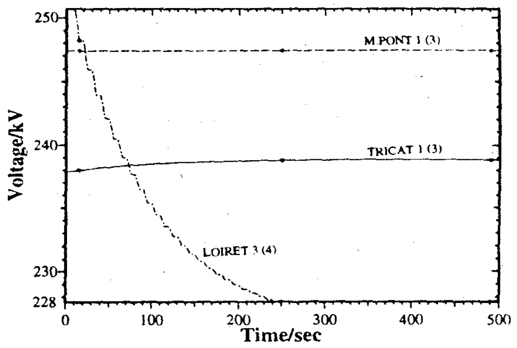
Figure 6: Pilot voltages under Repeated Tertiary Voltage Control



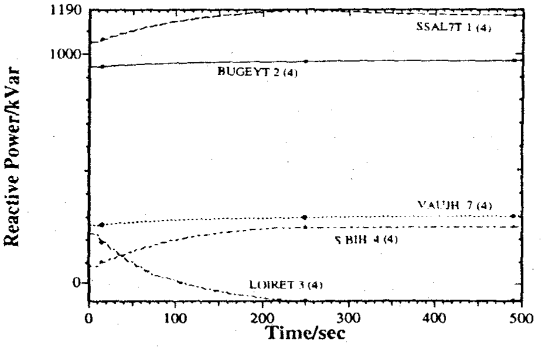
(a) Pilot voltages



(b) Unit voltages

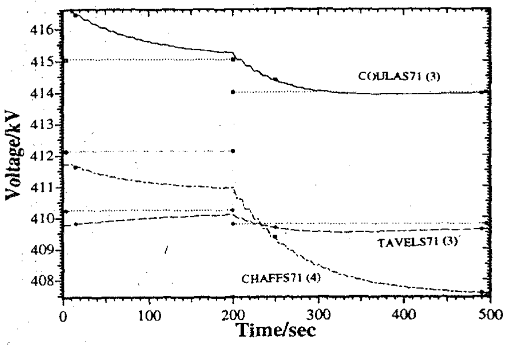


(c) Unit voltages

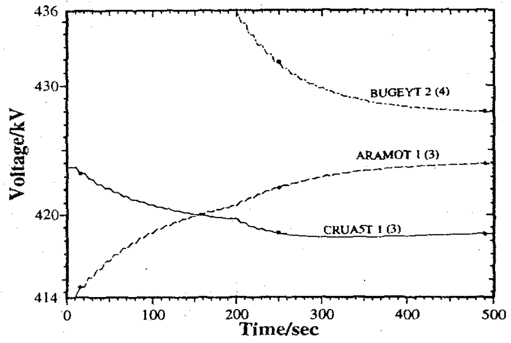


(d) Unit reactive output

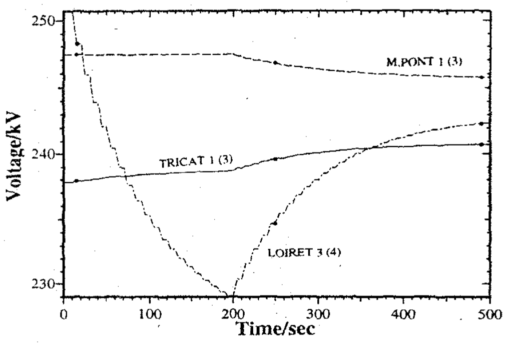
Figure 4: Plain case



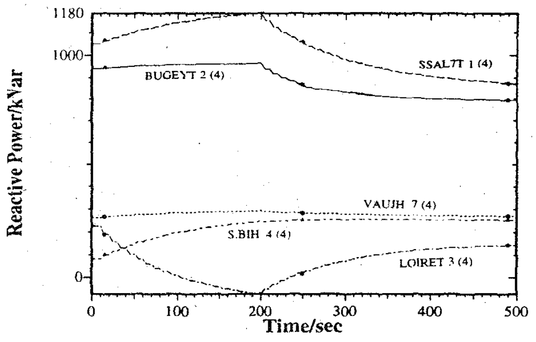
(a) Pilot voltages



(b) Unit voltages

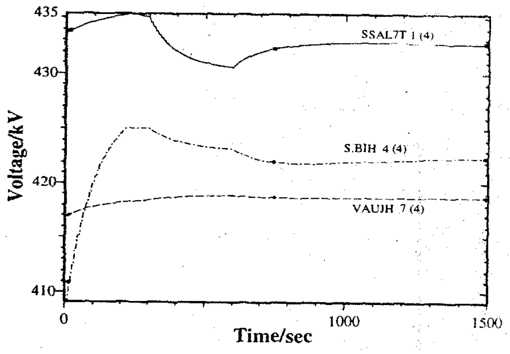


(c) Unit voltages

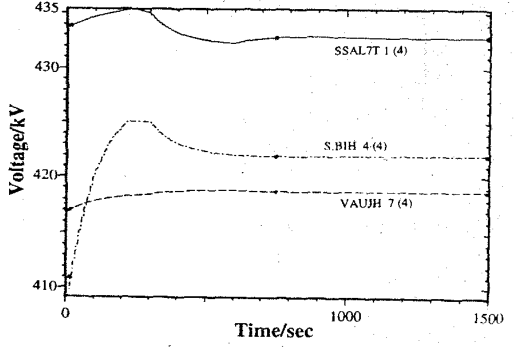


(d) Unit reactive output

Figure 5: TVC case



(a) Adaptive scaling by 5.0



(b) Adaptive scaling by 2.0

Figure 7: Unit voltages with adaptive weighting

Discussion

J.I. de la Fuente, T. Gómez (Instituto de Investigación Tecnológica, Univ. Pontificia Comillas, Madrid, Spain).

The authors are congratulated by this paper on coordination of secondary voltage controllers. We consider that some additional aspects need a further clarification.

1) One point of discussion is related to the implementation of the proposed control scheme to counteract couplings between control regions at the secondary level.

If a discrete, instead of a continuous, formulation is used to describe the control law, equation (17) in the paper becomes:

$$\begin{aligned}\Delta V_G(k) &= K(\, V_P(k) - V_P^{set}\,) \\ &+ G\,(F_L(k) - F_L(k-1)) \qquad (1)\end{aligned}$$

where

$$V_G(k+1) = V_G(k) + \Delta V_G(k) \qquad (2)$$

According to the authors notation, the relationship between voltage changes at pilot buses, generator control actions and reactive flow changes into interconnection buses is given by:

$$\begin{aligned}V_P(k+1) &= V_P(k) + CC_v \Delta V_G(k) \\ &- CD_{LL}^{-1}\,(F_L(k+1) - F_L(k)) \qquad (3)\end{aligned}$$

Substituting (1) into (3) yields:

$$\begin{aligned}V_P(k+1) &= V_P(k) + CC_v K(\, V_P(k) - V_P^{set}\,) \\ &-CD_{LL}^{-1}\,(F_L(k+1) - 2F_L(k) + F_L(k-1)) \qquad (4)\end{aligned}$$

Comparing (4) with equation (19) in the paper under discussion it is possible appreciate the existence of a new term (apart from the differences between continuous and discrete notations), which does not appear in the paper.

Notice that in (4), the third term of the right-hand side becomes zero only if changes in reactive flows into interconnection buses are monotonous:

$$\begin{aligned}&F_L(k+1) - 2F_L(k) + F_L(k-1) = \\ &(F_L(k+1) - F_L(k)) - (F_L(k) - F_L(k-1)) \qquad (5)\end{aligned}$$

i.e., only if $(F_L(k+1) - F_L(k)) = (F_L(k) - F_L(k-1))$ the mentioned term becomes zero. But this is not always warranted since, from our experience, dynamic couplings at secondary level are frequently characterized by oscillations in reactive flows among regions. The conclusion is that the compensation scheme proposed in the paper does not counteract, in general, the voltage changes at pilot buses produced by the reactive power flow changes at the interconnection lines from other control regions.

2) In our opinion is necessary to include a term in the control law of every controller which compensates the predicted changes at the pilot bus voltages produced by the control generators from the neighbouring controllers.

As an example, consider a system divided in 2 regions (denoted by subindex 1 and 2). The linear model which reflects the voltage deviations at pilot buses of region 1 due to the own control actions and to the couplings with region 2 is given by:

$$\Delta V_{P1} = CC_{v11}\Delta V_{g1} + CC_{v12}\Delta V_{g2} \qquad (6)$$

where CC_{v12} denotes a sensitivity matrix which represents the couplings of control generators of region 2 with pilot bus voltages of region 1. The proposed control law which counteract interactions between regions has a local part and a corrective term. In the case of region 1 (the same procedure is applied in the case of region 2):

$$\Delta V_{g1} = \Delta V_{g1l} + \Delta V_{g1c} \qquad (7)$$

The local term keeps the voltages at pilot buses with a specified dynamic without taking into account the couplings with other regions:

$$\Delta V_{g1l} = K_1\,(\, V_{P1} - V_{P1}^{set}\,) \qquad (8)$$

The corrective term should counteract the effect of control generators of region 2:

$$CC_{v11}\Delta V_{g1c} + CC_{v12}\Delta V_{g2} = 0 \qquad (9)$$

$$\Delta V_{g1c} = -\,(CC_{v11})^{+} CC_{v12}\Delta V_{g2} \qquad (10)$$

where + denotes pseudoinverse matrix (in general CC_{v11} is not an square matrix, as is discussed in point 3).

The problem is that region 1 should predict the value of ΔV_{g2} to compute the corrective control action. Assuming that, usually, the local action is greater than the corrective action, one simplified approximation to the control law of region 2 is to consider only its local term :

$$\Delta \hat{V}_{g2} = K_2\,(\, V_{P2} - V_{P2}^{set}\,) \qquad (11)$$

Notice that the evaluation of $\Delta\hat{V}_{g2}$ requires the availability of pilot bus voltages of region 2.

Using the equations (6) to (11), the resulting dynamic of pilot bus voltages of region 1 is given by:

$$\begin{aligned}V_{P1}(k+1) &= V_{P1}(k) + CC_{v11}K_1(\, V_{P1}(k) - V_{P1}^{set}\,) \\ &+ CC_{v12}\Delta V_{g2c} \qquad (12)\end{aligned}$$

where ΔV_{g2c} denotes the corrective action in region 2. Thus, the proposed scheme reduces the effects in region 1 due to region 2 from $CC_{v12}(\Delta V_{g2l}+\Delta V_{g2c})$ to $CC_{v12}\Delta V_{g2c}$, which, taking into account the predominant effect of the local action, constitutes an important coupling reduction.

Other coordination schemes are also possible, for instance a control law in which the corrective term is designed to minimize voltage changes at frontier buses (with other control regions). Notice that with this scheme, no information is required from neighbouring regions.

3) Another point of discussion refers to expression (18) of the paper, in which the authors consider the inversion of the matrix (CC_v), so it is assumed that the number of pilot buses is equal to the number of control generators, so that (CC_v) is an square matrix.

Usually, the required number of pilot buses is much smaller than the number of control generators. In [1] a suitable objective function to select pilot buses is proposed. It is shown that a reduced set of appropriate selected pilot buses saturates the objective function so is useless to consider a greater number of pilot buses. The same conclusion can be obtained considering an objective function such as the one proposed by one of the authors in reference [12] of the paper under discussion.

In addition, the freedom degrees between the number of required pilot buses and the number of control generators could be used to coordinate reactive power reserves to improve the security margin to the voltage collapse.

We would appreciate any comments on the previous issues.

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X. Liu:

We wish to thank the discussers for the excellent questions raised in their discussions. The following is our response.

1) Due to the static nature of the network constraints, all deviations for different quantities must be defined for the same time interval. For example, the voltage deviation is defined as:

$$\Delta V_G = V_G\ (k+1) - V_G(k)$$

as noticed in (2) of the discussions. The line flow is defined for the same time interval, i.e.,

$$\Delta F_L = F_L\ (k+1) - F_L(k)$$

With the consistent definition, the feedback control law can be explicitly written as:

$$\Delta V_G(k) = K\ (V_P(k) - V_P^{set}) + G(F_L(k+1) - F_L(k))$$

instead of (1) in the discussions. This, of course, requires measurement of the line flow at the same time instant. One would argue that this is not practical. With the line flows varying not rapidly, it does not make much difference to use a delayed version of the line flows.

2) It is true that any generator voltage changes in one area will affect the rest of the system. However, this effect is seen by any area in the form of changes in tie-line flows. This is exactly one of the motivations for the proposed control scheme. No detailed information on the controlling generator voltages of other areas is needed. If one can measure the tie-line flows, and use them in the feedback signal for controls, then any variations in the rest of the system can be completely cancelled in the pilots (not in all voltages), provided that measurements at the same instant are available.

3) It is true that the number of pilot voltages can be less than the number of controlling generators. Extra freedom can be used to control other quantities, such as reactive reserves. In our paper, "pilot" is a general concept for any quantity that is critical to the system and is to be controlled. It does not have to be physical voltages. It includes reactive reserves or any other variables that will be regulated. Because reserves or these pilot quantities, similar to the pilot voltages, are functions of generator voltages, there is no qualitative change in the formulation of the problem. The only quantity that will be different for different choices of the pilots is matrix C.

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