An Improved Fuzzy Inference System for Voltage/VAR Control

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***Abstract*—This paper describes the concept of a voltage/VAR controller based on an interaction of fuzzy Mamdani controllers, with the main objective of keeping voltages at all busbars inside an admissible band while avoiding line flows to exceed admissible limits. Estimation of sensitivities via fuzzy clustering of load profiles is proposed. A complex rule base interacts with a Newton-Raphson power flow routine in iterative steps until a terminating criterion is met, following a basic min-max approach. Tests to the method reveal it as one order of magnitude faster than a competing simulated annealing routine.**

***Index Terms*—Fuzzy inference systems, voltage/VAR control.**

I. INTRODUCTION

THIS paper reports the development of an energy/distribution management system (EMS/DMS) module for voltage/VAR regulation in networks with a diversity of control devices, based on the cooperation of fuzzy controllers of the Mamdani type, constituting a general fuzzy inference system, in a loop with a power-flow routine that evaluates the progressive effect of control actions until a criterion is met. This is not a closed-loop controller but a system that offers advice to be used at operator discretion (although the former use could be envisaged).

This is a general-purpose application but its interest becomes relevant in DMS environments controlling distribution networks with a high penetration of distributed generation. Usually, these generators do not contribute to voltage regulation but nowadays it is possible that reactive power injection and voltage control may be accepted as an ancillary service at distribution level, allowing independent owners to negotiate with distribution system operators the handing over of reactive power control. At present, even for wind generation, this is now possible thanks to the evolution in the power electronic technologies linking generators to the grid, either synchronous variable-speed machines of dual-fed induction machine (DFIG) generators.

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The fuzzy voltage controller developed maintains also some degree of control on line currents and allows the operator to give preference to solutions that retain controllability of the system, i.e., it suggests a control vector of actions that will tend to keep the control set points well inside their possible range. This work is an evolution and an improvement from a work announced in a preliminary report [1], where no concern for line flow limits was present. Besides, new fuzzy associative memories (FAMs) were built that, after testing, have demonstrated a robustness that was not present in the work referred to. Large scale tests were performed now, dealing with 43 simultaneous control options (earlier work could deal only with 6). And this implementation has been done in C++ and in a professional commercial DMS environment, evolving from the early experiments in MATLAB.

The idea of building a fuzzy reasoning platform to organize a voltage controller had already been suggested [2], [3]. Examples of the application of fuzzy controllers in stability may be found in [4] – however, the approach of using fuzzy logic concepts in reactive power control has relied mostly in the application of fuzzy linear programming models, as early as in [5]. Other proposals have come to light since then, all trying to overcome the difficulty caused by the linearizations imposed in the model—see, for instance, [6]. Fuzzy control appears as an alternative or complement to the use of heavy methods such as simulated annealing [7], evolutionary algorithms (as early as in [8]) or other meta-heuristics [9] for the same purpose of voltage control. Tests to our model revealed it to be one to two orders of magnitude more efficient in terms of computing effort.

The method aims at correcting voltages—it is not a full reactive optimal power flow and power losses are not optimized. Also, no action on active power injections is performed. However, line limits are taken in account, The method is not conceptually organized as a classical optimization method but as a control system. However, there is an obvious equivalence between concepts. Our controller implements an optimization of a min-max Chebychev metric by following the strategy of minimizing the maximum value deviation from the admissible band—and this leads in general to a balanced voltage profile in the system by reducing voltage differences among buses.

We illustrate the efficiency of the method by applying it to an overloaded IEEE test network and to an overloaded real 60-kV network and by comparing its performance with an alternative simulated annealing model that has been used in a commercial distribution management systems (DMS) installed in a number of utilities [7].

The robustness of the fuzzy logic approach in extremely difficult convergence conditions remains to be extensively confirmed—but this is also a challenge to other approaches. However, the method quickly provides acceptable operation solutions (in most of the cases very quickly indeed, 10 to 50 times faster than meta-heuristic routines which may be competitive only in the most difficult cases). Not only are these solutions ready for the operator to use, but the speed of the method allows one to consider using it as an essential building block inside a hybrid of an evolutionary algorithm and a fuzzy controller either to achieve fine tuning in difficult cases or to propose solutions for a voltage/VAR planning problem. Developments in this way will be proposed in the future.

II. Defining Concepts

The controller will exist in a DMS/EMS environment and it will have available data about lines and network topology as well as on all the devices in the system that can be used for voltage control. The DMS/EMS database also stores data specified by the operator, such as limits for over- and under-voltage at the nodes of the grid. Furthermore, from the SCADA or from the state estimation module of the DMS/EMS the controller receives timely information on loads and voltages, as well as the position (state) of controllers in the system. For the development of the model, we have assumed that one could act on transformer taps, switching capacitor banks, static compensators or generator excitation.

When considering a correcting action, the factors that must be taken into account are as follows.

- The identification of the most violated constraint and its "evaluation of severity"—this will be the one that the controller will act to eliminate first. When in the presence of voltage violations and line flow violations, the most severe violation will always be a line flow constraint violation.
- The "efficiency" of a control action—depending on the nature of each device (generator, transformer, capacitor ...) and its location in the network, the impact of each action will be different and more effective actions will be preferred.
- The "availability for control" of the control action—actions that will lead controls closer to the nominal value will be preferred (made more available) to actions that push controllers to their limits, so noting "controller status" Π_j (.) at a node j becomes important.

Once their universes of discourse defined, all these factors are interpreted as variables with linguistic grades (the usual labels being NB—Negative Big to NS—Negative Small, ZE—Zero, PS—Positive Small and PB—Positive Big).

A. Efficiency Related to Voltage and to Current Control

The classical way to evaluate the influence of a change in a control device on a certain system value (voltage or current) is by means of sensitivity coefficients $\mathrm{S}_{\mathrm{kj}}^{\mathrm{V}}$ for voltage V_{k} and $\mathrm{S}_{\mathrm{kj}}^{\mathrm{F}}$ for line flows F_{i} obtained from partial derivatives relative to controller j status Π_j

$$\mathrm{S}_{\mathrm{kj}}^{\mathrm{V}} = \frac{\partial \mathrm{V}_{\mathrm{k}}}{\partial \Pi_{\mathrm{j}}} \text{ and } \mathrm{S}_{\mathrm{ij}}^{\mathrm{F}} = \frac{\partial F_i}{\partial \Pi_{\mathrm{j}}}.$$

However, partial derivatives describe the effect of infinitesimal changes and if the control devices are of discrete nature these derivatives may not translate correctly the actual effect of a "status" change (like switching on another capacitor or changing taps in a transformer). This is why the authors in [2] had already suggested a scheme based on "Experiment Planning" to derive more adequate sensitivities, based on imposing $\Delta\Pi$ variations in controls and checking the impact on the nodal voltages. We did not follow the suggestion of [2] but we nevertheless build sensitivity matrices by organizing a series of experiments with discrete step changes one at a time in each possible controlling variable.

The sensitivity values may be negative or positive; they are scaled into an interval $[-1, 1]$ generating therefore a signal that becomes associated with a linguistic variable "efficiency" on a fuzzy partitioned domain with values ranging from NB to PB.

The sensitivities are calculated separately for the effects on voltage and current.

B. Fuzzy Clustering of Load Profiles

Sensitivities may also depend on load level and therefore it is important to adopt a quick method to evaluate sensitivities. In fact, we have two approaches: one requires the direct evaluation of sensitivities at the load profile under analysis, and the other uses pre-calculated values of typical load profiles to derive approximate sensitivities.

In the first case, when the need to act is triggered by some violation signal, before initiating the control sequence the algorithm runs the power flow routine changing controller positions in discrete steps one at a time and from the incremental changes it builds the necessary sensitivity matrices.

As an alternative, to avoid this pre-calculation phase (which demands a number of runs of the power flow routine that are a linear function of the number of available control devices), a set of matrices may be organized and stored as data, to be selected for use depending on the loading condition of the power system.

Let us define a Power Profile as a vector $\mathbf{L}(\mathrm{t})$ of nodal generations and loads at a certain time t. From the history of the system, a number of typical power profiles (such as at the peak, at low load, etc) may be defined and stored, from several days at distinct hours. These profiles will then act as anchor points for some kind of "interpolation method" allowing the estimation of actual sensitivities in an intermediate case.

We have selected the Bezdek's Fuzzy c-Means [10] fuzzy clustering algorithm in order to estimate the level of similarity of the actual power profile with the anchor profiles. This method allows us to associate to each Power Profile a membership value to each anchor profile, which is interpreted as representing a cluster of similar profiles.

If we define

- $\mathbf{V}_{\mathrm{i}}$: vector denoting the anchor profile i;
- $\mathbf{L}(\mathrm{t})$: vector of the power profile at time t;
- d_{i}: distance between $\mathbf{L}(\mathrm{t})$ and the prototype of cluster i, with $\mathrm{d}_{\mathrm{i}} = \|\mathbf{L}(\mathrm{t}) - \mathbf{V}_{\mathrm{i}}\|$ (usually calculated with an Euclidean norm);
- c : number of anchor profiles;
- μ_{i}: membership of profile $\mathbf{L}(\mathrm{t})$ to anchor i;
- $\mathrm{m} \in [1, +\infty[$: weighting exponent, a parameter defining the more "fuzzy" or "hard" character of the clustering; adopted values for m are close to 2.

We have then [10]

$$\mu_{\rm i} = \left[\sum_{\rm k=1}^{\rm c}\left(\frac{\rm d_i}{\rm d_k}\right)^{\frac{2}{(\rm m-1)}}\right]^{-1}$$

with

$$\sum_{\rm k=1}^{\rm c}\mu_{\rm k} = 1.$$

If one has only two anchor profiles $\mathbf{V}_1$ and $\mathbf{V}_2$ and if $\rm m = 2$, then the membership values of a power profile $\mathbf{L}(\rm t)$ to the anchors $\mathbf{V}$ are simply

$$\mu_1 = \frac{\rm d_2^2}{\rm d_1^2+d_2^2} \quad , \quad \mu_2 = \frac{\rm d_1^2}{\rm d_1^2+d_2^2}.$$

A given power profile $\mathbf{L}(\rm t)$ will have different $\mu_{\rm i}$ to distinct anchor profiles and its sensitivity estimation will reflect these measures of similarity. We calculate a sensitivity coefficient S(t) associated with a given power profile at time t from the corresponding sensitivity coefficients $\rm S_k$ for the prototypes by

$$\rm S(t) = \sum_{k=1}^{c}\mu_k S_k.$$

C. Severity in Voltage Violation

The condition to be met for voltage control is

$$\rm V_k^{min} \le V_k \le V_k^{Max} \quad \text{for all k nodes}$$

defining a "dead band" where no control action is required. Outside this band, the severity of the violation ΔV_k is proportional to its value—either $\rm \Delta V = V_k - V_k^{min}$ or $\rm \Delta V = V_k - V_k^{Max}$ · $\rm \Delta V_k$ can therefore be negative or positive.

We define a plausible interval [a,b] for violations which allows mapping violations into an interval $[-1, 1]$. Values of ΔV below a are mapped to -1 and values above b are mapped to 1. We have, therefore, created a signal $\rm S^V$ that may be associated to a linguistic variable "voltage violation severity", with values such as NB to PB as before.

D. Severity in Line Flow Violation

The constraints defining line flow violation are

$$\rm F_i^{min} \le F_i \le F_i^{Max}$$

where usually $\rm F_i^{min} = -F_i^{Max}$ for reverse line flows.

This also defines a "dead band" where no control action is required. Outside this band, the severity of the violation $\rm \Delta F_k$ is proportional to its value, either $\rm F_k^{min} - F_i$ or $\rm F_i - F_i^{Max}$.

Again, this violation is mapped into $[-1,1]$ with saturation at the limits. Like before, we have created a signal $\rm S^F$ that may be associated to a linguistic variable "line flow violation severity" with values from NB to PB.

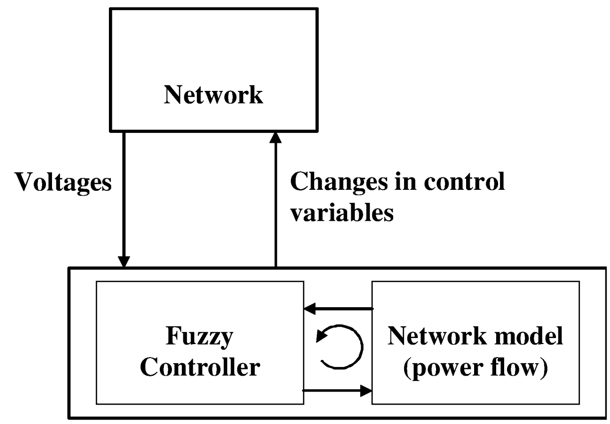

Fig. 1. General scheme of the controller action: a loop is activated between the controller and the power flow algorithm where each status change is evaluated and returns new voltage values until convergence is achieved and the changes in the control variables can be established.

E. Controller Status

A controlling variable $\Pi_{\rm j}$ is associated with a control range $[\Pi_{\rm j}^{\rm min}, \Pi_{\rm j}^{\rm Max}]$ and it's value may change within such interval, which includes in a more or less central location the nominal value $\Pi_{\rm j}^{\rm nom}$.

We buit a signal called "status" of the controller by mapping the interval $[\Pi_j^{\rm min}, \Pi_j^{\rm nom}]$ into $[-1, 0]$ and $[\Pi_j^{\rm nom}, \Pi_j^{\rm Max}]$ into [0,1].

III. Controller Action

A. Controller Algorithm

The fuzzy controller consists of a control block for each controlling device (capacitor, transformer, etc). Each control block reacts to voltage and line flow violations according to the corresponding signals and proposes a set of device status changes.

The action of the controller is iterative. Whenever a violation is detected, the controller is triggered and from the signals such as violation severity, controller efficiency, device status, etc., new device status are proposed and tested by a power flow routine (a Newton Raphson algorithm). This routine returns new voltage and line flow values which eventually trigger new status change proposals by the control blocks, which are again tested by the power flow routine. This loop continues until no violation is detected (see Fig. 1).

This may happen in two ways: 1) the initial target is met (for instance, all nodal voltages fall in the admissible band) and 2) the controller does not find a solution that meets the initial target and then the admissible band is allowed to suffer an incremental enlargement to act now as a new target. In this latter case, the controller is no longer seeking a solution for the original criterion but searching for a solution that accepts the smallest possible increment in bandwidth of the nodal voltages.

This action is illustrated in Fig. 2. Once the iterative control loop is stopped because a termination criterion is met, global changes in device status are made available to the operator and may be imposed over the real network.

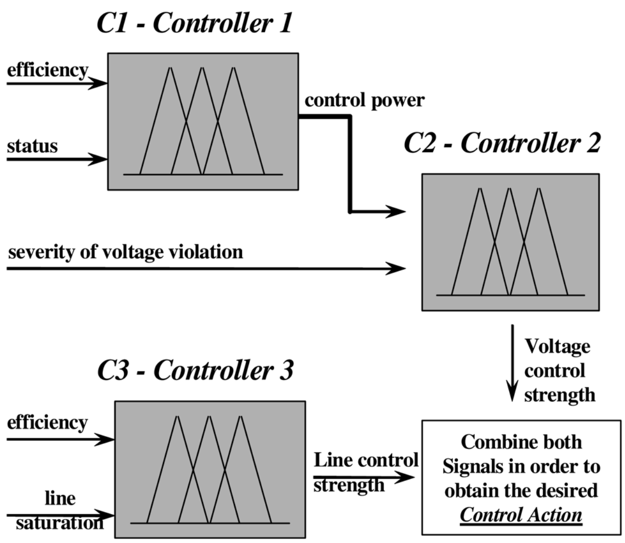

Fig. 2. Interaction of fuzzy controllers forming the control block for a controlling device.

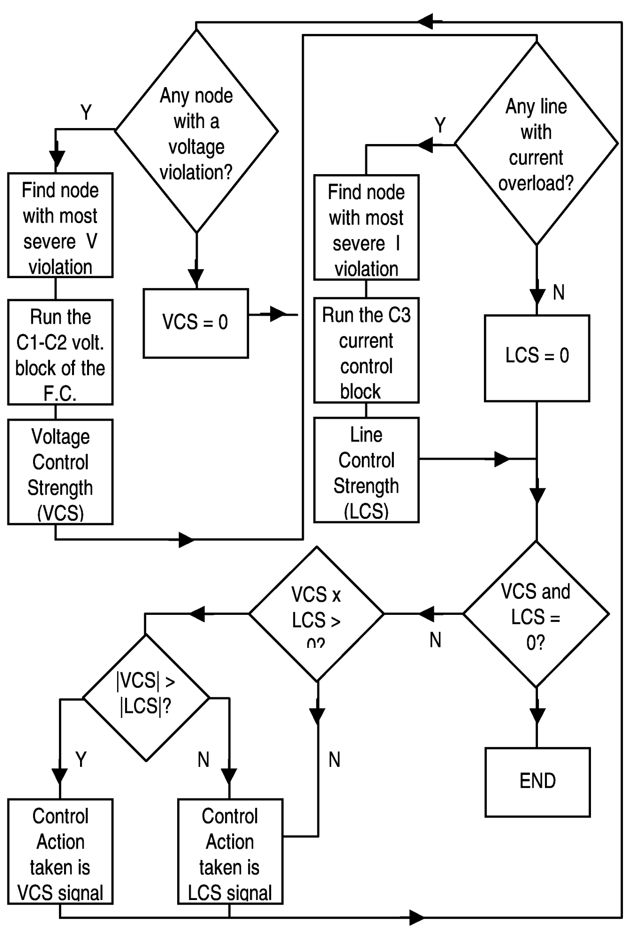

Fig. 3. Method used to combine both voltage control strength (VCS) and line control strength (LCS) signals in order to generate the control action.

B. Internal Architecture

Fig. 3 shows the internal logic of a fuzzy control block applied to each controlling device. The set of all control blocks form the Fuzzy Controller, which is a multiple input—multiple output system, because it controls voltages in all buses of the network and generates control signals for a number of control devices at the same time.

A control block is composed of three Mamdani fuzzy controllers [4] where we have used, for simplicity and with good results, triangular fuzzy sets. The defuzzification method is in all cases the center of mass. The T-norm for intersections and implications was the min operator and the S-norm for union was the Max operator.

Controller C1 produces a signal that we have called "control power". Its defuzzified value is combined with voltage violation severity in C2 to generate a control command linked to voltage violation. At the same time, if a line-flow violation is detected, controller C3 will propose a control command to alleviate it. These two commands are the combined under a set of crisp rules to produce the final block suggestion:

- if both commands from C2 and C3 have the same signal (positive or negative), the final control action will be the stronger of the two, typically moving the controller status further from the initial position it had.
- if the control signals have opposing signals, the control action will be the one suggested by C3 because a signal from C3 means that line current limits are being violated.

The fuzzy associative memories or rule maps for C1, C2, and C3 have the form of Tables I–III, respectively, with the meaning already explained in the text. This design guarantees that a controlling variable near its limits will only be used if this represents moving the control variable to inside the interval—and that there will be an attempt to move it inside whenever it is beneficial.

TABLE I
RULE MAP FOR C1—ROWS: EFFICIENCY; COLUMNS: STATUS

	NB	NS	ZE	PS	PB
NB	PB	PB	PB	PS	ZE
NS	PB	PB	PS	ZE	NS
ZE	PB	PS	ZE	NS	NB.
PS	PS	ZE	NS	NB	NB
PB	ZE	NS	NB	NB	NB

TABLE II
RULE MAP FOR C2—ROWS: VIOLATION; COLUMNS: CONTROL POWER

	NB	NS	ZE	PS	PB
NB	PB	PB	ZE	NB	NB
NS	PS	PS	ZE	NS	NS
ZE	ZE	ZE	ZE	ZE	ZE.
PS	NS	NS	ZE	PS	PS
PB	NB	NB	ZE	PB	PB

TABLE III
RULE MAP FOR C3—ROWS: EFFICIENCY; COLUMNS: LINE SATURATION

	NB	NS	ZE	PS	PB
NB	PB	PB	ZE	ZE	ZE
NS	PB	PB	ZE	NS	NS
ZE	PB	PB	ZE	NB	NB.
PS	PS	PS	ZE	NB	NB
PB	ZE	ZE	ZE	NB	NB

This design favors the maintenance of control variables inside their ranges—this means that the controller system tends to keep a control margin available in every variable, which is very important and useful from an operation point of view.

C. Convergence Method

Good convergence depends on an adequate scaling of the control signal relative to the controlling range of each device, defining an iteration step size which is the maximum allowable change in status at any iteration.

The defuzzified control signal output from each block, in the range $[-1, 1]$, is mapped into the admissible iteration step size for the controlling device. If this range is composed of discrete values (such as in a transformer with taps), it is rounded to one of the nearest values, with a probability proportional to the proximity to the value. This stochastic rounding reduces the danger of having the algorithm stopped at local optima.

From our tests we observed that in mild cases with a small number of voltage violations, the controller is extremely efficient and easily corrects the bus voltages into the admissible band defined in a few iterations (less than ten calls to the power-flow routine).

In severe cases, with line overloads, multiple violations and limited control capacity (for instance, because only a small number of devices are allowed to operate to correct voltages or because the status of controllers is already close to the extreme of their range), it may not be possible to drive all voltages inside the target "dead band". Then forcing some voltage into the admissible band may drive the voltage at another bus to exceed its limit, the voltages just oscillate and no feasible solution is found.

When this condition is found, the "dead band" is enlarged step by step in increments of 0.005 p.u. until all voltages remain inside the new band. This process finds the solution with the minimum violation possible and defines the appropriate controls. This is an extension of the min-max concept because the controller is still trying at all times to minimize the maximum violation.

On the other hand, when a feasible solution exists, this procedure may be inverted. The admissible band limits are narrowed step by step while possible in order to reach a solution with the voltage profile as flat as possible or desired. It may, however, not be advisable to try to force the system into too flat a voltage profile because this may come at the cost of large voltage angles with line currents leading to greater power losses.

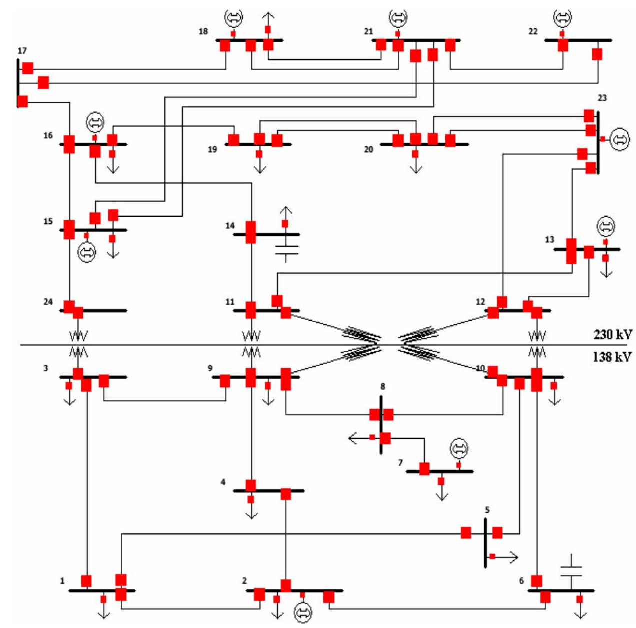

Fig. 4. Single-line diagram of the test system.

IV. TESTS AND RESULTS

We now present results for a system based on the 24–bus network IEEE Reliability Test System (RTS) and for a system based on the Northeast Portugal 60–kV distribution network.

A. IEEE 24 Bus System

The system consists of a network with 24 buses, including nine power injection buses and 15 load buses—see Fig. 4. It has 33 branches, five transformers, and two capacitor banks.

There are two main voltage levels in the system (230 and 138 kV), and the main power injection comes from an interface with an interconnected transmission system (bus 1). The other power injection sources are generators.

We admit that voltage may be controlled by acting at 16 places: nine generators, five transformer groups (transformers in parallel have their taps changed to the same levels), and two capacitor banks.

An application was developed in C++ interacting with a commercial DMS environment using a Newton-Raphson power-flow routine, which had a voltage/VAR control routine based on simulated annealing allowing only the transformer tap and capacitor bank control. In this environment, we have therefore prepared 16 control blocks similar to the one in Fig. 2—a block to each control variable (nine for generator voltages, five for transformer taps, and two for capacitor bank taps).

The total load is of 3000 MW, 500 MVAr in a standard load profile (base case scenario BS).

Besides BS, we built four more load scenarios:

- High load (HL) with 125% of BS load;
- Low load (LL) with 25% of BS load;
- Load transfer high-low (THL), with load transferred from the 230-kV zone to the 138-kV zone;

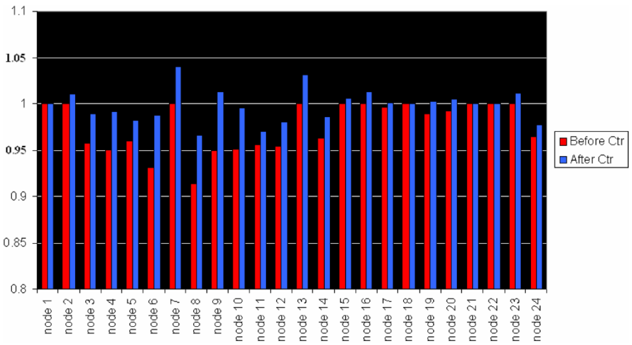

Fig. 5. Voltage profile (y axis, p.u.) in all buses before and after the control action proposed by the fuzzy controller system in case {BS-CN/LC}.

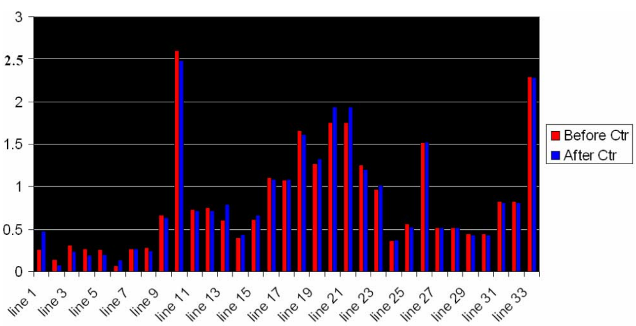

Fig. 6. Current profile (y axis, p.u.) in all branches before and after the control action proposed by the fuzzy controller system in case {BS-CN/LC}—the slight limit violation is corrected.

- Load transfer low-high (TLH) with load transferred from the 230-kV to the 138-kV zone.

The target voltage bandwidth is of 5% or [0.95, 1.05] p.u.

Line current limits were set to (1 p.u. ⇔ 100 A):

- 5 p.u.—high line capacity scenario HC;
- 3.6 p.u—moderate line capacity MC
- 3.0 p.u—small line capacity SC;
- 2.75 p.u.—relaxed line capacity RC;
- 2.5 p.u—low line capacity scenario LC;
- 2.35 p.u—very low line capacity scenario VC;
- 2.2 p.u—extremely low line capacity scenario EC;
- 0.65 p.u—absolute lowest line capacity AC.

Several studies were done, with different control options:

- CN—controllers starting at nominal positions;
- CM—controllers starting at their maximum position;
- Cm—controllers starting at their minimum position;
- CR—controllers started with random initialization;
- GO—use of generator excitation only;
- TO—use of tap-changing transformers only.

We have calculated the sensitivity coefficients for node voltages relative to the 16 controlling variables, and built the required matrices.

Before controller action, the analysis of case {BS/HC} shows that many node voltages (20%) are below the limit of 0.95 p.u. determined as the admissible threshold (see Fig. 5), with no line flow violations. An additional line-flow violation is, however, detected in case {BS/LC}—see Fig. 6.

The following tables summarize the analysis of the results obtained in all the runs for the cases listed above.

TABLE IV
NUMBER OF ITERATIONS (CALLS TO THE NEWTON-RAPHSON ROUTINE) UNTIL CONVERGENCE—CASES IDENTIFIED IN THE TEXT

	BS	HL	LL	THL	TLH
CN/HC	4/5	121	3	7	5
CN/MC		484			
CN/RC				1210	1210
CN/LC	4/4	3751*	3	1331	3751*
CN/VC	1210				
CN/EC	3751*				
CN/AC			2		
CM/HC	18/38	121	57	32	24
Cm/HC	19/24	121	49	605	121
CR/HC	66/100 39/45	121 121	95 63	605 605	75 121
GO/HC	726				

* no convergence – no feasible solution discovered

In Table IV, we find the number of iterations (calls to the Newton-Raphson routine) required in order to reach a solution. In the column referring to the base case scenario BS we indicate the no. iterations as x/y, with x referring to the number of iterations needed to satisfy the 5% band and y to the total number of iterations needed to narrow the bandwidth to the interval indicated in Table V. The convergence criterion demanded 50 iterations without improvement of the voltage profile; so, the actual number of iterations adds 50 to the numbers in Table I in all cases when convergence was not obtained within the band [0.95, 1.05].

We see that the method is remarkable fast in some of the cases studied.

Table V presents the final best bandwidth that was possible to reach with the action of the controller. The cases where no solution was found are marked with * and the corresponding bandwidth is the one being tried in the last iteration.

Figs. 5 and 6 present the bus voltage profile and the line current profile before and after the controller action, in the base case, with line limits set to the LC scenario (low limit of 250 A or 2.5 p.u.) and the starting position of control devices in their nominal values.

The TO studies allowed us to compare the performance of the fuzzy controller with a simulated annealing model [7]. Generators do not participate in the voltage/VAR control and the problem becomes more difficult. The studies performed are illustrated in Tables VI and VII.

The cases marked with "—" mean that no feasible solution has been found. In all cases the fuzzy controller reaches the same bandwidth as the simulated annealing method, giving reassurance about the robustness of the fuzzy control approach.

B. *Northeast Portugal 50-Node System*

This is a 60-kV meshed system supplied from a 220-kV transmission system, with elements included in Table VIII. Fig. 7 depicts the simplified schematic of the network.

TABLE V
VOLTAGE BANDWIDTH GUARANTEED—CASES IDENTIFIED IN THE TEXT

	BS	HL	LL	THL	TLH
CN/HC	[0.955, 1.045]	[0.945, 1.055]	[0.985, 1.015]	[0.96, 1.04]	[0.95, 1.05]
CN/MC		[0.935, 1.065]			
CN/RC				[0.905, 1.095]	[0.9, 1.1]
CN/LC	[0.96, 1.04]	[0.795, 1.205]*	[0.985, 1.015]	[0.895, 1.105]	[0.795, 1.205]*
CN/VC	[0.9, 1.1]				
CN/EC	[0.795, 1.205]*				
CN/AC			[0.98, 1.02]		
CM/HC	[0.96, 1.04]	[0.945, 1055]	[0.985, 1.015]	[0.96, 1.04]	[0.95, 1.05]
Cm/HC	[0.955, 1.045]	[0.945, 1055]	[0.985, 1.015]	[0.925, 1.075]	[0.945, 1055]
CR/HC	[0.96, 1.04] [0.955, 1.045]	[0.945, 1055] [0.945, 1055]	[0.985, 1.015] [0.985, 1.015]	[0.925, 1.075] [0.925, 1.075]	[0.95, 1.05] [0.945, 1.055]
GO/HC	[0.92, 1.08]				

* no convergence – bandwidth in the last iteration

TABLE VI
NUMBER OF ITERATIONS (CALLS TO THE NEWTON-RAPHSON ROUTINE) UNTIL CONVERGENCE—CASES IDENTIFIED IN THE TEXT

		BS		HL	
		Fuzzy	SA	Fuzzy	SA
TO/HC	CN	121*	395	34	484
	CM	121*	653	57	748
	Cm	121*	258	19	224
	CR	121*	471	45	608
TO/SC	CN	121*	380	–	–
	CM	121*	718	–	–
	Cm	121*	247	–	–
	CR	121*	515	–	–

* results after 120 iterations trying to enforce [0.95; 1.05]

This distribution system admits an important amount of private owned dispersed (distributed, private) generation. The composition of this dispersed generation is in Table IX.

The installed capacity in dispersed generation reaches 88% of the 220 MVA peak power consumption in the region. We have limited the number of generators contributing to voltage control to four and we have therefore 43 control options, counting generators, transformers, and capacitor banks.

Allowing the distributed generation to participate in voltage control, the Fuzzy Controller reaches a bandwidth of [0.97; 1.03] in 35 iterations, which is much better than [0.95; 1.05] as a specified target.

TABLE VII
FINAL VOLTAGE BANDWIDTH—CASES IDENTIFIED IN THE TEXT

		BS		HL	
		Fuzzy	SA	Fuzzy	SA
TO/HC	CN	[0.945 ; 1.055]	[0.945 ; 1.055]	[0.92 ; 1.08]	[0.92 ; 1.08]
	CM	[0.945 ; 1.055]	[0.945 ; 1.055]	[0.92 ; 1.08]	[0.92 ; 1.08]
	Cm	[0.945 ; 1.055]	[0.945 ; 1.055]	[0.92 ; 1.08]	[0.92 ; 1.08]
	CR	[0.945 ; 1.055]	[0.945 ; 1.055]	[0.92 ; 1.08]	[0.92 ; 1.08]
TO/SC	CN	[0.945 ; 1.055]	[0.945 ; 1.055]	–	–
	CM	[0.945 ; 1.055]	[0.945 ; 1.055]	–	–
	Cm	[0.945 ; 1.055]	[0.945 ; 1.055]	–	–
	CR	[0.945 ; 1.055]	[0.945 ; 1.055]	–	–

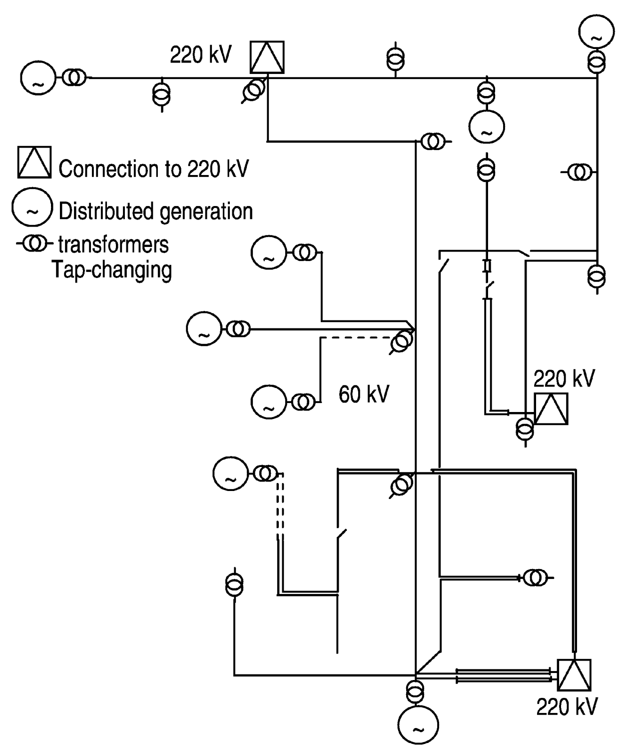

Fig. 7. Simplified diagram of the 60-kV Northeast Portugal network with three interconnection points to the 220- kV transmission system and dispersed generation.

TABLE VIII
DIMENSION OF THE NORTHEAST PORTUGAL NETWORK

Buses	**Lines**	**Gener.**	**Transf.**	**Cap.**	**Loads**
50	37	36	25	14	16

TABLE IX
COMPOSITION OF THE DISPERSED GENERATION

Generation	Type	no.	Total (MVA)
hydro generators	Synch.	16	105.6
	Asyncr.	2	1.0
wind parks	Synch.	5	34.6
	Asyncr.	8	46.6
industrial chp	Synch.	2	5.8
Total		33	193,6

TABLE X
FINAL VOLTAGE BANDWIDTH—CASES IDENTIFIED IN THE TEXT

	BS		HL	
	Fuzzy	SA	Fuzzy	SA
Band Width	[0.96 ; 1.04]	[0.96 ; 1.04]	[0.96 ; 1.04]	[0.96 ; 1.04]
Nº Iterations	102	1698	83	1678

Inhibiting the control via the generation and depending only on transformer taps and switched capacitors, we have in Table X the results of the competition between the fuzzy controller and the simulated annealing model, where again the same bandwidth is reached by both algorithms but with 15 to 20 times less effort by the fuzzy controller.

V. CONCLUSION

This paper describes an interacting set of fuzzy controllers of the Mamdani type forming a voltage control system for a DMS/EMS environment.

The new controller acts on a min-max principle, i.e., always seeking to minimize the maximum violation detected in the system. Furthermore, it regulates its action taking in account constraints related to branch power flows. There is the theoretical possibility that the controller may get trapped in local optima in difficult cases because of the gradient-type of progression it elicits, but this possibility is also real with any meta-heuristic and we did not meet any case of failure.

The controller is easily formatted to suit specific operation needs such as inhibiting the action of some devices if they have been subject to previous frequent operation. This is straightforward and does not offer any difficulty in implementing.

In all the tests we have performed, it displayed great superiority in computing effort over methods that search for optimal controls by using heavy algorithms such as simulated annealing. These ones may require hundreds to thousand of evaluations using a load-flow routine, while the fuzzy control system only requires a number one to two orders of magnitude smaller. This means that it has the potential to be integrated in hybrid models for optimal reactive power flow, a possibility to be explored in the future.

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