A NEW SCHEME FOR VOLTAGE CONTROL IN A COMPETITIVE ANCILLARY SERVICE MARKET

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Abstract: This paper shows how a competitive ancillary service market for voltage control/reactive power might operate and what it might look like, given the eminently local nature of the service. An automatic voltage control would dynamically manage the reactive power available in a certain geographic region and a local market in reactive power could then be developed similarly to that proposed for the load-following ancillary service. Coordination among these regions would be required.

Keywords: Automatic Voltage Control, Ancillary Service Market, Reactive Power.

1 INTRODUCTION

Voltage control is intended to compensate for voltage and reactive power demand disturbances in order to maintain a proper voltage profile along the network. Generators are equipped with an automatic voltage regulator (AVR), which operates through the excitation/voltage control system of the unit to cope with sudden and random voltage fluctuations. This is usually referred to as primary voltage control. Primary control can be fully automatic but is inadequate to handle large variations; a second level of control is required: the system operator needs to modify the input reference value on AVRs so that a satisfactory voltage profile can be achieved. On top of all this, a tertiary level of voltage control can be implemented to optimize the repartition of reactive power injections throughout the system, taking security and economical aspects into account. This is the hierarchical voltage control that several European countries have been adopting for many years, [1]-[3].

In the recent past there have been, worldwide, protracted discussions about ancillary service market in voltage control. The availability of reactive power will certainly determine such a market. However the issue is complex because of the eminently local nature of voltage control, and that reactive power can be produced not only by generators but also by static elements, by customers and by the network itself as well. Moreover voltage control does not just need supply; sometimes it may also need to pay for absorbing reactive power. All these factors bring additional complications to a competitive provision of the service, [4].

For the most part, around the world, reactive power support is still considered as a mandatory service for the generators. Both in Australia and in the UK however, in addition to the mandatory part, a generator can offer more reactive power capability to the ISO. In the UK, the National Grid Company (NGC) has formalized a new open reactive power market, [5]-[6].

A voltage control/reactive power market is usually conceived as a monopsony with the ISO, or an equivalent authority, acting as the sole buyer of the service. Most of the ideas in the technical literature utilize the optimal power flow as the main tool in handling such a competitive market, [6]-[7].

Granted that generation-based voltage control is the only voltage control recognized as an ancillary service by NERC [8], in this paper we propose a local market to provide the service in a certain geographic region that could be called voltage control area (VCA). The VCAs will often be much smaller than the classic control area and they would need to be coordinated through the supervising control center. An automatic voltage control would dynamically manage the reactive power available in a region through automatic adjustments of the voltage references at some generating units. Such an automatic secondary voltage control is analogous to the AGC and is shown to be feasible.

Thus an ancillary market for reactive power can be developed similar to that proposed for the load-following ancillary service market. This time though there may be more than just one type of reactive market per single control area since, each VCA in the area may need to introduce some peculiar features in its market, depending on the specific availability of the service in the region. For example, if in some VCA just few favorably located generators leave no possibility for true competition, the market in that region should be adjusted so that the ISO is not exposed to market power.

2 AUTOMATIC VOLTAGE CONTROL

Let us assume, for simplicity, that a control area can be evenly divided in VCAs so that no VCA lies across two or more control areas. Let us also start supposing the VCAs to be uncoupled, meaning that the reactive power supplied by a generator in one area has a negligible effect on the voltage at the buses of any neighboring area. The ISO keeps monitoring the voltage level in the whole control area.

The main idea is that, whenever the voltage at some bus falls outside a certain range, a control signal proportional to the violation is built. This signal is then sent to the controlling units through some participation factors in order to modify their voltage reference value so to bring the voltage back to an acceptable level. Given the uncoupling between VCAs, the ISO could set to zero the participation factors to all the generators outside the VCA where the voltage violation actually occurred, letting just the units inside the VCA to provide the service.

2.1 Voltage Control Areas

The first step is to divide the system in VCAs; in order to do so, considering that a node controlling voltage has a distinct influence only on its close vicinity, we need to quantify the electrical proximity of any node in the system from any generating one. The electrical distance is elected to be the quantified measurement of the concept of proximity.

The elements of the sensitivity matrix $[\partial V/\partial Q]$ reflect the propagation of the voltage variations, following a reactive power injection in a given node, throughout the system. Matrix $[\partial V/\partial Q]$ is the inverse of matrix $[\partial Q/\partial V]$, which is a part of the Jacobian. The magnitude of the coupling, in terms of voltage, between two nodes, can be quantified by the maximum attenuation of voltage variation between these nodes. These attenuations can be obtained dividing the element of each column of $[\partial V/\partial Q]$ by the diagonal term, so for example the attenuation of voltage variation between nodes i and j is:

$$\alpha_{ij} = \frac{\partial V_i}{\partial Q_j} \Big/ \frac{\partial V_j}{\partial Q_j} \tag{1}$$

The electrical distance between nodes i and j is then defined as, [10]:

$$D_{ij} = D_{ji} = -\ln(\alpha_{ij} \cdot \alpha_{ji}) \tag{2}$$

In practice, instead of using $[\partial Q/\partial V]$ to calculate the sensitivity matrix $[\partial V/\partial Q]$ and, consequently, the electrical distances, the susceptance matrix $[B'']$ is used.

The boundary of each VCA may then be traced excluding all the nodes whose electrical distances from every generating bus in the area are larger than a fixed threshold.

The partition of the area in VCAs is topology dependent and, when dealing just with small disturbances which do not alter the system topology as in our case, it does not necessitate any update.

2.2 Implementation of the automatic voltage control

The ISO, or an equivalent authority, must make sure that the voltage profile in the control area is constantly kept at an appropriate level.

Whenever the voltage V_{Li} at some PQ bus falls outside the admissible range, a control signal proportional to the voltage violation can be generated, and an automatic voltage control can be implemented as shown in the flow chart in Fig.1.

If the voltage hits either the limits at more than just one PQ bus at the same time, the largest, in absolute value, among all the violations will set the control signal. Supposing the largest voltage violation happened at the ith bus, the control signal will be:

$$\text{Contr\_Sig} = V_{limit} - V_{Li} \tag{3}$$

where V_{limit} is the limit that was struck at the ith bus; either a V_{max} or a V_{min}. The control signal is then sent to the generators to adjust their voltage references through the participation factors K_j:

$$V_{ref_{new}j} = V_{ref_{old}j} + K_j * \text{Contr\_Sig} \tag{4}$$

Equation (4) gives the new value for the voltage reference at the jth bus, with j=1,…, N_G. N_G is the total number of controlling units in the whole control area.

From equation (3), if V_{Li} has fallen below V_{min}, the Contr_Sig will clearly be greater than zero so that the new voltage references will be greater than the old one in order to raise the voltage level. Vice versa, if V_{Li} has risen above V_{max}, Contr_Sig will be less than zero so to lower the new voltage references and, consequently, the voltage level.

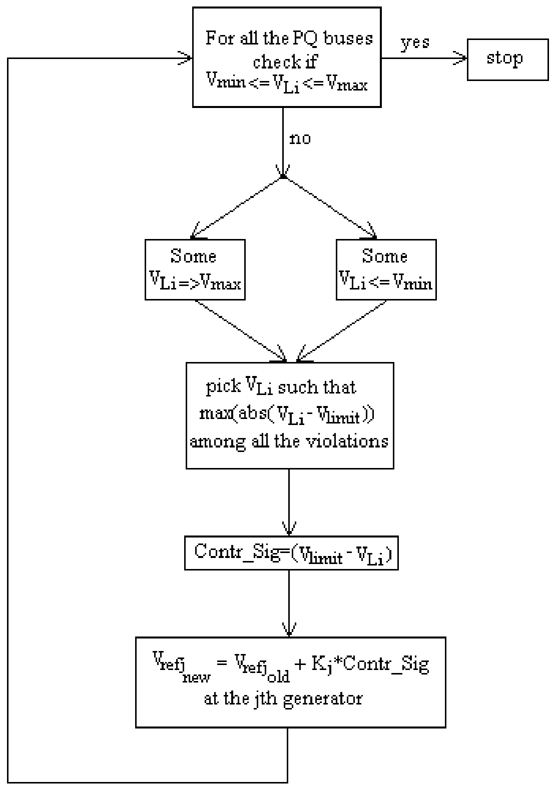

Fig.1: Automatic adjustment of the voltage references

The participation factors K_j can be chosen in different ways. In particular, assuming the VCAs in the control area are completely uncoupled, any action taken by a controlling unit outside the VCA which experienced the limit violation, would have a negligible influence on the voltage level in that VCA. The K_j to all the generators outside the VCA where the limit was hit could then be set equal to zero. In this case, just the generators belonging to the specific VCA will inject/absorb reactive power to bring the voltage profile back to an acceptable level. Also, the participation factors to the controlling units inside the VCA do not need to be set all at the same value; they can be fixed differently by the ISO so to keep various factors, even economic ones, into account.

Of course this uncoupling assumption may not be valid all the time, for example there may be the case when some buses are under the influence of two or more VCAs. Whenever one of these buses hits a limit, the ISO will always be able to set the participation factor in the most appropriate way and share the voltage control among more VCAs.

2.3 Simulation results

We tested the proposed model on the IEEE 39bus-system. The system is considered as a single control area. Partitioning it with electrical distances brings to the definition of four VCAs as shown in Fig.2.

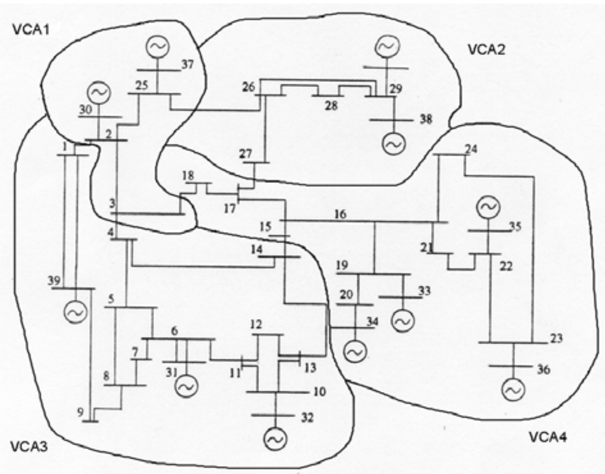

Fig.2: IEEE 39bus-system partitioned in VCAs.

The initial condition sees all the voltages at the PQ buses in between the maximum admissible voltage value chosen to be $V_{max} = 1.015\text{pu}$, and the minimum one, $V_{min} = .985\text{pu}$. Table 1 shows this steady state condition: V_{Li} are the voltages at the PQ buses, V_{ref} and Q_G are, respectively, the voltage references and the reactive power injections at the controlling buses. In all the tables just the voltage values at the PQ buses belonging to VCA3 are shown. Bus #37 is considered as the slack bus.

Suppose now a load S=150MVA with $\cos\varphi = .9$ lagging is connected to bus #9 in VCA3. The voltages at buses #7 and #8, both in VCA3, drop below the V_{min}.

#	V_{Li}
01	1.005
04	0.991
05	0.995
06	0.998
07	0.987
08	0.989
09	1.010
10	0.999
11	0.998
12	0.996
13	0.996
14	0.990

#	V_{ref}	Q_G
29	1.0265	72.48
30	1.0400	166.43
31	1.0200	128.52
32	1.0100	93.64
33	1.0100	99.68
34	1.0123	109.98
35	1.0400	249.30
36	1.0500	212.37
38	1.0500	164.63
39	1.0300	195.92

Table 1: Steady state condition

Table 2 shows the new system's condition after the disturbance occurred but before the voltage control is implemented.

#	V_{Li}
01	1.006
04	0.989
05	0.992
06	0.996
07	0.982
08	0.984
09	0.997
10	0.997
11	0.997
12	0.995
13	0.995
14	0.990

#	V_{ref}	Q_G
29	1.0265	64.39
30	1.0400	166.56
31	1.0200	138.65
32	1.0100	99.22
33	1.0100	97.36
34	1.0123	108.93
35	1.0400	246.71
36	1.0500	210.91
38	1.0500	164.63
39	1.0300	245.10

Table 2: Condition after disturbance before voltage control

The automatic voltage control is now implemented so to bring the voltage level back into the admissible range. All the participation factors to the controlling units outside VCA3 are set equal to zero. It is the voltage value at bus #7, which is smaller than the one at bus #8, to set the control signal that will drive the automatic control.

Two different scenarios are considered:

Case (a) the participation factors $K_{31}\, K_{32}$ and K_{39}, to all the three generators in VCA3, are set to be equal to each other. This situation is shown in Table 3.

#	V_{Li}
01	1.008
04	0.992
05	0.995
06	0.999
07	0.985
08	0.987
09	1.000
10	1.000
11	1.000
12	0.998
13	0.998
14	0.992

#	V_{ref}	Q_G
29	1.0265	63.19
30	1.0400	163.07
31	1.0235	140.45
32	1.0135	101.77
33	1.0100	95.61
34	1.0123	108.14
35	1.0400	244.74
36	1.0500	209.81
38	1.0500	164.63
39	1.0335	250.60

Table 3: Case (a): Condition after automatic voltage control with $K_{31}\, K_{32}$ and K_{39} set all equal

Case (b) K_{31} and K_{32} are chosen to be equal to each other and four times greater than K_{39}. This situation is shown in Table 4.

#	V_{Li}
01	1.006
04	0.992
05	0.995
06	0.999
07	0.985
08	0.987
09	0.999
10	1.000
11	1.000
12	0.998
13	0.998
14	0.993

#	V_{ref}	Q_G
29	1.0265	63.45
30	1.0400	164.71
31	1.0242	142.86
32	1.0142	103.93
33	1.0100	95.63
34	1.0123	108.14
35	1.0400	244.76
36	1.0500	209.82
38	1.0500	164.63
39	1.0311	242.93

Table 4: Case (b): Condition after automatic voltage control with K_{31} and K_{32} equal and four times greater than K_{39}.

Comparing Table 2 and Table 1 it can be observed that the three generators inside VCA3 are the ones which start increasing their production of reactive power following the disturbance. The automatic voltage control will then adjust their voltage reference values and, therefore, their reactive power injections, so to raise the voltage level in VCA3.

As it can be seen from Table 3, in case (a), since the participation factors are the same, the voltage references at the three controlling buses in VCA3 increased by the same amount. All the three generating units are injecting more reactive power into the system even though not in the same proportion: bus #39 is producing more, and this was true already before the automatic voltage control action took place, (see Table 2). Bus #39 is most likely the closest, in terms of electrical distance, to the disturbance.

With this model for automatic voltage control however it is possible to maneuver the reactive power injection levels at the three generating buses, setting in different ways the participation factors K_j. In particular if, for some reasons, the ISO would rather have the two units at buses #31 and #32 to increase their reactive power productions for voltage control purposes in VCA3, this can be easily achieved weighting more the influence the control signal has on the voltage reference adjustment at these two buses.

This is shown with case (b) in Table 4. The participation factors this time are set in such a way the voltage reference values at buses #31 and #32 grow by the same amount and more than the one at bus #39. Consequently the reactive power injections at these two buses increase more than in case (a). The Q_G at bus #39 actually drops a little if compared with the value it had soon after the disturbance (Table 2), when just the local control of the different units had responded. This means that the generator at bus #39 is actually forced to produce less reactive power.

3 REACTIVE POWER MARKET

The proposed model of automatic voltage control seems suitable for the development of a local market for reactive power in each of the VCAs. It is beyond the scope of this paper to enter into cost analysis, bidding strategies or market clearing process details, (see, for example Bhattacharya *et al.*, [5]); nevertheless some general ideas of what such a market might look like are presented.

It is important to underline how many different gradations a reactive power market might have; first of all one should not expect a unique market model to fit each and every VCAs. As a minimum, the availability of reactive power and the location of the controlling units in each VCA would determine some peculiarities the reactive market should have in that specific VCA.

Moreover, there are several other factors to keep in consideration; this paper is focused on the production/consumption of reactive power by generating units, ancillary to voltage control in a certain geographic area. The reactive power management involved in this “area control” is considered apart from the reactive power management related to the local control each generator operates at its site. Payments for the local control may or may not be set through a competitive market, which may or may not be joint with the area control market.

Let us consider the most generic situation in which every VCA in the control area has its own market. The ISO will coordinate all these market. Generators wishing to participate in the reactive power market for voltage control tender a bid. This bid could be composed either of capacity (i.e. some total amount of MVAr reserve offered with a price per MVAr) or of energy utilization (i.e. a MVAr-hour price curve) or of a combination of both. A market price level is established in an appropriate way in each VCA. Whenever voltage control service is required in the VCA, the ISO can set the participation factors so that only those generators which joined the market are selected to provide the service. These controlling units will then be paid, for the amount of reactive power they needed to produce/absorb, according to the market price.

A more realistic circumstance would envisage the relaxation of the voltage uncoupling assumption made at the beginning. In some situation the ISO may need to call up for help also some generating units outside the perturbed VCA. The participator factors to those generators will then be set different from zero in the automatic voltage control and, also in this case, whatever amount of reactive power was provided by those units will be paid, but according to their market price this time.

Another scenario might contemplate the possibility for the ISO to enter into bilateral contract with some controlling units to provide voltage control service. If the market allows it, and in case it is actually convenient to purchase the service from some specific units rather then from others, the participation factors could be regulated so that the service is mostly provided by those specific generators. This situation is similar to the one shown in section 2.3 for case (b). Going back to that example, suppose buying reactive power, for voltage control purposes, from the controlling unit at bus #39 is more expensive than buying it from the ones at buses #31 and #32. Even though, for that specific disturbance, bus #39 would naturally increase the reactive power injection at its site, the ISO can set the participation factors in such a way the other two units will increase their reactive power productions instead, to bring the voltage in VCA3 back to the appropriate level. In some circumstances, this may also be a way to prevent some suppliers from exercising market power.

The last consideration here addresses the lack of service providers and the consequent risk of market power that may occur in some areas. Whenever it is necessary, a payment for lost opportunity cost should be included in the market: if some units, in order to provide reactive power for voltage control, needed to decrease their real power output, they should be paid more. Sometimes, the risk for the ISO to be exposed to market power leaves no possibility for true competition in some regions. In such a case the market needs to be structured in an appropriate way; the ISO would probably need to direct generating resources more strictly, maybe asking the few units located in the area for an, at least partial, mandatory service. In this case some transmission-based voltage control might help as well.

4 CONCLUSIONS

An automatic voltage control is proposed in the paper and it is demonstrated to be feasible. Dividing the system in VCAs and managing the reactive power in each VCA through automatic adjustment of the voltage reference values at some controlling units, using participation factors, help to handle the reactive power market as a localized problem. Whenever it is possible, given the peculiar local nature of the voltage control service with all the limitations implied, the controlling units and the amount of service each of them should provide may be selected following some dictates of a competitive reactive power market. The ISO, or an equivalent authority, should be responsible for the coordination of the service among the different regions and of all the different local reactive power markets in the control area.

Further investigations are required to understand which is the best option for reactive power market in the various regions. All the peculiar features, especially in terms of availability of reactive power and location of the generating resources, of the specific area are to be taken into consideration while designing the appropriate market for that area.

Insights in other realistic scenarios are also essential; for example some VCAs are most likely going to lie across two or more AGC control areas under the jurisdiction of more than one ISO. How the ISOs should coordinate their efforts in order to handle voltage control in these VCAs, so to avoid conflicts, needs still to be addressed.

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