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Secondary voltage control system based on fuzzy logic

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ABSTRACT

This paper discusses the problem of secondary voltage control in power systems. This problem is of deep interest for researchers and engineers, since it imposes serious restrictions to system's operators. In general, this problem is resolved by selecting pilot buses representative of a region. Instead, in this paper, modal analysis is used to identify a coherent group of buses to be monitored. The set of information collected by modal analysis is considered by a fuzzy logic-based algorithm, so a voltage control policy is implemented. The academic IEEE 118-bus system is employed with all its limits considered, so the results may be reproduced.

1. Introduction

Large interconnected power systems pose a complex reactive power control problem for operators in general. Unlike the frequency control, the problem of voltage control must be locally addressed, since reactive power cannot travel far. Hence, an effective voltage control depends on the availability of generators and synchronous condensers and tap changers.

The Secondary Voltage Control (SVC) has the purpose to control the transmission-side voltage by adjusting generator AVR (Automatic Voltage Regulator) setpoints, synchronous compensator, transformers taps, etc. [1]. The studies for application of the SVC on power systems were firstly addressed in the late 1980s [2]. From then on, many papers have discussed and proposed different approaches on SVC. References [3] and [4] present the results of the SVC applied to the Spanish and Italian power systems, respectively. In [5], the authors present the benefits that can be achieved by using a coordinated secondary voltage control applied to a transmission and subtransmission system of an electric power utility in South of Brazil. A decentralized SVC methodology is employed in [6] by using an effective adjustment at the joint line drop compensator to control the voltage level in a point far from the power plant.

In order to realize a better coordination scheme of the control elements, many papers have employed Artificial Intelligence (AI). The authors in [7] propose a coordinated voltage control by using several FACTS spread over the New England system in contingencies scenarios. A fuzzy logic approach is used to enhance a successful coordination. Similarly, in [8], a fully decentralized SVC is proposed by using an Artificial Neural Network (ANN) trained from optimal power flow results. In references [9–11] AI tools to support the decisions of the Brazilian system operators are presented. The first uses an ANN approach while a Fuzzy Inference System (FIS) is applied in the others.

References above drive one to conclude that an effective reactive power control is obtained by adopting correct control actions. Large power systems require extensive analysis and communication systems for this sake. This may be overcome by subdividing the power system into areas and subareas. In [12], two techniques for system reduction are proposed in order to reduce the computational burden to trace bifurcation diagrams. First, tangent vector information is used to eliminate system variables that suffer little changes along the bifurcation path. The second technique creates an area formed by the buses around the critical bus. Modal analysis is used in [13] to identify coherent buses and form control areas.

This paper proposes a new methodology for developing a secondary voltage control system that meets the voltage operating criteria while not compromising the voltage stability margin. However, unlike the classic concept of SVC, which uses only the pilot bus information, the methodology assembles the information about all the load buses within a specific region of interest. For this sake, the mode-shape analysis is used to identify subareas of control and to provide coherent control actions information. Then, a fuzzy inference system is established for each of the subareas based on mode-shape information. This decentralizes the voltage control

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and enables one to visualize the most effective control actions. Actually, the methodology proposed here follows the structure presented in [14], which considers capacitor/reactor switching, tap changers and adjustment of Automatic Voltage Regulators setpoints. This paper proposes a novel approach for the latter topic and the SVC proposed is applied to the IEEE 118 bus system.

2. Modal analysis for voltage control areas identification

The voltage stability is essentially a dynamic process. This implies in extended transient simulations which are time consuming and do not promptly provide access to sensitivity information or voltage stability indexes. Meanwhile, due to its slow dynamic response, static methods are suitable to approach voltage stability information [15–17].

The modal analysis affords sufficient information for the evaluation of the voltage stability. Furthermore, by an appropriate choice of the Jacobian matrix formulation, the modal analysis can provide the reactive power sensitivity for all the system buses, including that with generating units. Herewith, it permits the proper identification of coherent load buses and, accordingly, the establishment of voltage control areas, which are helpful in the definition of the control hierarchy required for the design of a fuzzy control system.

2.1. Extended power flow Jacobian

The traditional power flow formulation describes the power system by a set of equations which can be written in the matrix form, as in (1).

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & N \\ M & L \end{bmatrix} \cdot \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} \tag{1}$$

where ΔP and ΔQ represent the mismatch vectors for the active and reactive power equations, respectively. $\Delta\theta$ and ΔV are column vectors of the angular and magnitudes variations of the buses voltages. Finally, the H, N, M and L are submatrices that form the power flow Jacobian matrix or J_{ca}.

The traditional J_{ca} includes solely the reactive power equations of the load buses in the formulation. Therefore, for further analysis, an extended formulation of the power flow Jacobian also providing the voltage–reactive power relationship of the generators buses is required [13,18].

Adding the equations referred to the control devices to the traditional power flow formulation in (1), it can be rewritten as:

$$\begin{bmatrix} \Delta v \\ \Delta y \end{bmatrix} = \begin{bmatrix} J_{ca} & J_{vx} \\ J_{yu} & J_{yx} \end{bmatrix} \cdot \begin{bmatrix} \Delta u \\ \Delta x \end{bmatrix} \tag{2}$$

where Δv represents the column vector on the left-side of Eq. (1). Δy is a column vector which represents the mismatches of the additional equations. J_{ca} matrix is the traditional power flow Jacobian. J_{vx} is a non-quadratic matrix which represents the partial derivatives of the active power equations with respect to the new state variables. The J_{yu} and J_{yx} matrices are the partial derivatives of the additional equations with respect to the original state variables and the new ones, respectively.

The extended Jacobian allows the representation of several control devices at the traditional power flow formulation [13,18,19]. The reactive power equations of the PV buses and the Swing bus are inserted into the problem and, for each bus, a control equation is included (represented by Δy in (2)), so the Jacobian matrix is kept square.

2.2. Modal analysis of the extended Jacobian

Assuming the insertion of the reactive power equations of all PV buses and the Swing bus and neglecting the control equations in (2), the linear system can be written as:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \cdot \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} \tag{3}$$

where the submatrix $J_{P\theta}$ represents the partial derivatives of the active power equations with respect to the state variable θ of the PV and PQ buses. The submatrix J_{PV} represents the partial derivatives of the active power equations with respect to the state variable V for all system buses. The submatrix $J_{Q\theta}$ denotes the partial derivatives of the reactive power equations with respect to the state variable θ of the PV and PQ buses. Finally, the submatrix J_{QV} represents the partial derivatives of the reactive power equations with respect to the state variable V for all system buses, including the swing bus.

Assuming $\Delta P = 0$, Eq. (3) is reduced to:

$$\Delta Q = (J_{QV} + J_{Q\theta} \cdot -J_{P\theta}^{-1} \cdot J_{PV}) \cdot \Delta V \tag{4}$$

Then, it is possible to set a QV sensitivity matrix as follows:

$$J_{SQV} = J_{QV} + J_{Q\theta} \cdot -J_{P\theta}^{-1} \cdot J_{PV} \tag{5}$$

The inverse matrix of J_{SQV} gives the voltage-reactive power sensitivity information. Also, given the similarity transformation, J_{SQV}^{-1} can be written by means of the right and left eigenvectors and the system eigenvalues, leading to:

$$\Delta V = \Phi.\Lambda^{-1}.\Psi.\Delta Q \tag{6}$$

where Φ and Ψ are the right and left eigenvectors matrices, respectively, and Λ is the eigenvalues matrix of the system.

If the eigenvalues of J_{SQV} are sorted in an increasing order by their magnitudes values and assuming the first eigenvalue λ_1 to be meaningfully lower than the others, the voltage-reactive power sensitivity of the system could be assessed by its right and left eigenvectors. Accordingly, it could be written as in (7):

$$\Delta V \approx \frac{(\phi_1 \cdot \psi_1)}{\lambda_1} \cdot \Delta Q \tag{7}$$

where ϕ_1 is a column vector ($nx1$) in which its kth-element is related to bus k and ψ_1 is a row vector ($1xn$) in which its mth-element is related to bus m.

Eq. (7) could be expanded in a matrix form as:

$$\frac{\Delta V}{\Delta Q} \approx \begin{bmatrix} \phi_{11} \cdot \frac{\psi_{11}}{\lambda_1} & \phi_{11} \cdot \frac{\psi_{12}}{\lambda_1} & \cdots & \phi_{11} \cdot \frac{\psi_{1n}}{\lambda_1} \\ \phi_{21} \cdot \frac{\psi_{11}}{\lambda_1} & \phi_{21} \cdot \frac{\psi_{12}}{\lambda_1} & \cdots & \phi_{21} \cdot \frac{\psi_{1n}}{\lambda_1} \\ \vdots & \vdots & \ddots & \vdots \\ \phi_{n1} \cdot \frac{\psi_{11}}{\lambda_1} & \phi_{n1} \cdot \frac{\psi_{12}}{\lambda_1} & \cdots & \phi_{n1} \cdot \frac{\psi_{1n}}{\lambda_1} \end{bmatrix} \tag{8}$$

where the first index of ϕ is related to the system buses numbers and the second one is related to the eigenvalue λ_1 of the system. Similarly, the first index of ψ is related to λ_1 and the second index is related to the system buses numbers.

The examination of the matrix rows in (8) shows the voltage sensitivity of a bus k with respect to the reactive power injection in all system buses. On the other hand, the columns represent the voltage sensitivity of all the buses with respect to the reactive power injection at bus m.

A further and careful inspection of the formerly matrix presented in (8) indicates that the rows are composed by identical elements multiplied by their corresponding right eigenvector element. Just like the extended power flow Jacobian, the sensitivity