Journal of Zhejiang University SCIENCE A
ISSN 1009-3095
http://www.zju.edu.cn/jzus
E-mail: jzus@zju.edu.cn

Optimal coordinated voltage control of power systems*

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Received Dec. 28, 2004; revision accepted Mar. 3, 2005

Abstract: An immune algorithm solution is proposed in this paper to deal with the problem of optimal coordination of local physically based controllers in order to preserve or retain mid and long term voltage stability. This problem is in fact a global coordination control problem which involves not only sequencing and timing different control devices but also tuning the parameters of controllers. A multi-stage coordinated control scheme is presented, aiming at retaining good voltage levels with minimal control efforts and costs after severe disturbances in power systems. A self-pattern-recognized vaccination procedure is developed to transfer effective heuristic information into the new generation of solution candidates to speed up the convergence of the search procedure to global optima. An example of four bus power system case study is investigated to show the effectiveness and efficiency of the proposed algorithm, compared with several existing approaches such as differential dynamic programming and tree-search.

Key words: Power systems, Voltage control, Immune algorithm, Global optimization
doi:10.1631/jzus.2006.A0257 **Document code:** A **CLC number:** TP202

INTRODUCTION

Voltage security control as an indispensable facility in power systems aims at mid or long term voltage quality maintenance of power systems in the presence of load and/or transmission line disturbances. Most results of earlier research have been reported on transient stabilization and network control for voltage security of power systems, with various techniques originated from modern control methodology such as dynamic programming (Popovic *et al*., 2002; Wu *et al*., 2001), model predictive control (Larsson *et al*., 2002), nonlinear control (Wang and Hill, 1996), and so-called fuzzy control (just a nonlinear control formula) (Guo *et al*., 2001). Unfortunately, as an assortment of complex dynamical systems in practice, power systems are characterized by strong nonlinearity, hybrid system dynamics, large-scale dimensional and severe model uncertainties, which lead to significant difficulties in control strategy design and parameter optimization. Global coordination control is an advanced voltage security control strategy to cope with large system disturbances, by means of sequencing and timing various kinds of voltage control actions in a power system such as capacitor bank switching, transformer tap changing, load shedding, as well as those implemented by power electronics components, e.g., SVC or FACTS, in an optimal way (Guo *et al*., 2001).

In this paper, a self-pattern-recognized immune algorithm is proposed to solve the power system global coordination control problem. A self-pattern-recognized vaccination operation is developed to make use of heuristic information to speed up the convergence of the optimization procedure. An example of a four-bus power system case study is investigated to show the effectiveness and efficiency of the proposed algorithm. Compared with differential

* Project supported by the National Basic Research Program (973) of China (No. 2002CB312200) and City University of Hong Kong (No. 9380026), China

dynamic programming (DDP) (Popovic *et al*., 2002) and tree-search (Larsson *et al*., 2002), the combinatorial explosion problem in solving such kind of complex hybrid optimization problems can be avoided to a large extent by utilizing the heuristic searching capability of the proposed algorithm.

PROBLEM STATEMENT

System model

A power system model (Popovic *et al*., 2002) is usually modelled by a set of high order nonlinear differential-algebraic-inequality formulas, for example,

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{u}); \quad (1)$$

$$\boldsymbol{g}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{u}) = 0; \quad (2)$$

$$\boldsymbol{h}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{u}) \le 0; \quad (3)$$

where $\boldsymbol{x} \in \mathbb{R}^{n_x}$ is the dynamic state vector of the power system, including the state variables of the load model and tap changer ratio; $\boldsymbol{y} \in \mathbb{R}^{n_y}$ is the algebraic constraint vector, typically the bus voltage magnitude and phase angle; $\boldsymbol{u} \in \mathbb{R}^{n_u}$ consists of adjustable system parameters such as those for load power, capacitor support and tap changers in the system as the control vector. The differential Eq.(1) describes the dynamics of the power system components and control devices. The algebraic Eq.(2) expresses the voltage, current and energy balance of real and reactive powers in the system at any time. And Eq.(3) denotes various kinds of security constraints such as static stability, transient stability and dynamic stability of the power system.

Various kinds of control strategies corresponding to existing physical control devices are typically designed independently and assumed to be tunable. Suppose a set of different types of control strategies, such as load shedding, tap changing, capacitor bank switching, SVC control or FACTS control etc., are available and denoted by

$$\boldsymbol{u}(t) \in U = \{u_1(t), u_2(t), \ldots, u_n(t) | t \in [t_0, t_f]\}, \quad (4)$$

where each element of the control set U may be implemented by state feedback, i.e.

$$u_i(t) = f_i(x(t), t),\ \ u_i \in U; \quad (5)$$

or output feedback, such as

$$u_j(t) = f_j(y(t), t),\ \ u_j \in U; \quad (6)$$

or as a function with respect to time, e.g.,

$$u_k(t) = f_k(t),\ \ u_k \in U. \quad (7)$$

Global coordination control

Suppose the system performance can be evaluated by a set of m predetermined control objectives,

$$J_k = \varphi_k(x, y, u),\ \ k = 1, 2, \ldots, m. \quad (8)$$

Then the task of the system design is to find a global switching control scheme, consisting of a time sequence of p-stage switching control actions where p is unknown, consisting of

$$U_b(t_0, t_f) = \left(u_{b_1}(t_0, t_1), u_{b_2}(t_1, t_2), \cdots, u_{b_p}(t_{p-1}, t_f)\right), \quad (9)$$

where each control strategy $u_{b_i} \in U$ consists of a set of control actions implemented simultaneously, employed in the time span $[t_{i-1}, t_i]$ such that the system Eqs.(1)~(3) are satisfied; and the system performance indices $J = \{J_1, J_2, \ldots, J_m\}$ are called optimal when they reach their optima in the sense of Pareto or some priority-based ranking Pareto. Note that, theoretically, each control strategy $u_{b_i} \in U$ can be implemented repeatedly in the control sequence $U_b(t_0, t_f)$. Fig.1 gives a diagram of the global switching control scheme.

In the view point of system dynamics, the global coordination control problem Eqs.(1)~(9) is a hybrid multi-objective optimization problem with continuous-time decision variables and discrete-event decision variables. It includes three aspects of system design: (1) Sequencing: to decide the order of control actions in a discrete sequence domain with an unknown number of stages; (2) Timing: to decide the switching time of each control action in a real number domain; (3) Tuning: to decide the values of the adjustable parameters of each control action when it is activated. Essentially, this hybrid continuous-combinatorial optimization problem can be regarded as a multi-stage search problem in which the searching space is given by the system dynamics, control capability constraints and system stability constrains. No analytical solution can be obtained so far in the area of system science and control theories, so a suitable numerical solution procedure such as the immune algorithm proposed in this paper has to be employed.

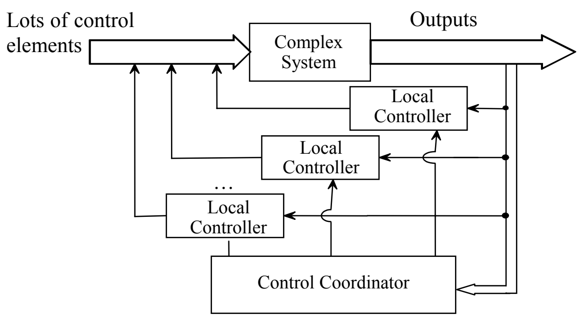

Fig.1 The diagram of the optimal coordinated voltage control

IMMUNE ALGORITHM DESIGN FOR GLOBAL COORDINATION CONTROL

Solution representation

An antibody encoding scheme with structural gene chain architecture is presented to express the solution candidates of the coordinated control problem. For example, the parameter changing time series u_i of the ith control device, is represented by an individual gene chain σ_i, and the n gene chains $\{\sigma_1,\sigma_2,\ldots,\sigma_n\}$ compose an antibody $\boldsymbol{B}_{\rm a}(x)$, representing a solution candidate $x=U_b(t_0,t_f)$ to the optimization problem.

The switching time of each control action is represented in the following implicit manner. Suppose Δt_i, i=1,2,…,n, is the minimal parameter changing time interval of the ith control device (measured by the set delay time plus the mechanical switching time of the device), then the length of the gene chain σ_i is set by

$$Length(\sigma_i)=[(t_f-t_0)/\Delta t_i]. \tag{10}$$

The gene chain σ_i is composed of a series of gene segments, $\left\{g_{i,1},g_{i,2},\cdots,g_{i,Length(\sigma_i)}\right\}$. A gene segment $g_{i,j}$ can be encoded as a binary, decimal or logical string, representing a specific value of the ith control device at the switching time $t=t_0+j\Delta t_i$.

Affinity calculation

Generally, the antigen affinity and the antibody affinity are computed by the entropy in the information theory (Chun *et al*., 1997). Suppose an immune system contains N antibodies $x_1,x_2,\ldots,x_N$, and each antibody consists of m genes. The information entropy $H_j(x_1,x_2,\ldots,x_N)$ of the jth genes in the N antibodies can be defined as:

$$H_j(x_1,x_2,\cdots,x_N)=-\sum_{i=1}^{N}p_{ij}\lg p_{ij}\,, \tag{11}$$

where p_{ij} is the probability that the jth allele originated from the antibody x_i. Obviously, if all the jth genes in all the antibodies are the same, then $H_j(x_1,x_2,\ldots,x_N)$=0. The total information entropy $H(x_1,x_2,\ldots,x_N)$ of the N antibodies $x_1,x_2,\ldots,x_N$ is defined by:

$$H(x_1,x_2,\cdots,x_N)=\sum_{j=1}^{m}H_j(x_1,x_2,\cdots,x_N)\,, \tag{12}$$

where $m=\sum_{1}^{n}Length(\sigma_i)$.

The antibody affinity between the antibody x_1 and x_2, denoted by $A_b(x_1,x_2)$, is calculated by

$$A_b(x_1,x_2)=1/(1+H(x_1,x_2))\,. \tag{13}$$

Suppose the system performance indices J_k, k=1,2,…,l, have been ranked and integrated as a lumped objective function $f(\cdot)$ (regarded as an antigen invading into the immune system). Then the affinity between the antigen and the antibody x, denoted by $A_g(x)$, can be computed via the objective value $f(x)$ as

$$A_g(x)=(f_{\max}-f(x))/(f_{\max}-f_{\min}) \tag{14}$$

for minimization problems, where $f_{\min}$ and $f_{\max}$ are the minimum and the maximum of the objective value of the corresponding optimization problem, respectively.

Vaccine extraction and inoculation

In each iteration, a set Φ of n_r antibodies with relatively higher affinity with the antigen are extracted from the N antibodies, and are added to a memory pool. Since the capacity of the memory pool is limited, the original antibodies which have the highest affinities with the newly added antibodies are replaced. According to the aforementioned solution representation, the "vaccine" can be extracted from the antibodies with better antigen affinity values in the memory pools using a pattern recognition technique, to benefit the convergence of the immune algorithm.

Suppose there are n_r antibodies in the memory pool of the artificial immune system. The vaccine extraction is conducted against the corresponding gene chains of all the antibodies. Let $\sigma_{i,k}$ be the ith gene chain of the antibody $\boldsymbol{B}_{\mathrm{a}}(x_k)$, and $g_{i,j}^{k}$ be the jth gene segment in $\sigma_{i,k}$. All the allelic gene segments $g_{i,j}^{k}$, j=1,2,…, $Length(\sigma_{i,k})$, for the ith gene chains $\sigma_{i,k}$ of the n_r antibodies, are checked for implicit patterns. Supposing N antibodies denoted by $\Phi_{v_{j,k}}$ possess the same pattern $v_{j,k}$ at their j th alleles, then the corresponding vaccination probability values are calculated by

$$P_{v_{j,k}} = \sum_{x_i \in \Phi_{v_{j,k}}} A_g(x_i) \Bigg/ \sum_{x_l \in \Phi} A_g(x_l). \qquad (15)$$

The injection operations after the vaccine extraction are also based on the aforementioned multi-chain structure of antibodies. Each gene of the gene segment $g_{i,j}^{k}$ for j=1,2,…,$Length(\sigma_{i,k})$ in the ith gene chain $\sigma_{i,k}$ of the n_s antibodies is inoculated with a vaccine pattern in the corresponding vaccination probability via roulette method. To keep the diversity of the new generation of antibodies, a part of the individuals in the population is manipulated by a random injection of feasible patterns.

CASE STUDY

Pilot system (Larsson, 2002)

A four bus example power system was investigated for optimal coordinated voltage control design by using the proposed immune algorithm solution procedure. The reason for choosing this basic system as the object of case study is that there are three kinds of mid and long term power security control devices in this example system, where typical voltage security control problems can be tested on it in a simplified but meaningful way.

The basic power system contains two generators and three lines as shown in Fig.2. Additionally there is a transformer that can regulate the (customer) voltage at Bus 4 and a capacitor bank that can support the voltage at Bus 3. The generator G_{inf} is a model of the surrounding network which is assumed to be strong, and generator G_1 is equipped with a voltage regulator with a field voltage limit at 2.2 p.u. The transformer T_1 is equipped with a voltage regulator modelled by a state-machine. These controllers constitute a primary control layer for emergency voltage control. The optimal coordinated voltage control has the following input signals:

(1) The switching step of the capacitor bank C_3 can take the values [0, 1, 2, 3]. Each step corresponds to 0.1 p.u. of reactive compensation at Bus 3. The action delay of capacitor switching is T_{cap}=10 s.

(2) The step of load shedding can take the values [0, 1, 2, 3]. Each step corresponds to disconnection of 5% of the load at Bus 4, and the action delay of load shedding is set to T_{load}=20 s. Load disconnection must be limited to extreme cases where it is not possible to stabilize the voltage using a combination of the other two controls.

(3) The reference voltage of the transformer tap changer T_1 can take values in the interval [0.9…1.1] and corresponds to the setpoint of the voltage regulator of transformer T_1 that regulates the voltage at Bus 4. The action delay of reference voltage changing is set to T_{tap}=10 s.

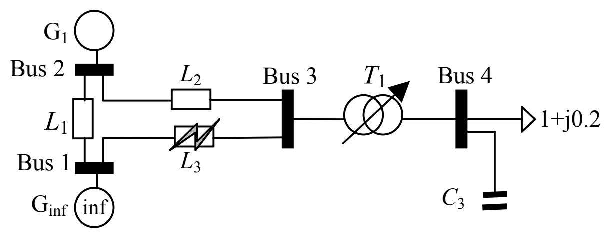

Fig.2 The 4 bus example power system

An emergent disturbance is assumed by a change of impedance on line L_3 from 0.5 to 1.5 p.u. at t=100 s. This fault inevitably leads to voltage fluctuation at all the buses, i.e., V_2 (the voltage at Bus 2), V_3 (the voltage at Bus 3), and V_4 (the voltage at Bus 4), except for the Bus 1 voltage which is supposed to be very robust against the disturbance.

Control aims

The aim of the optimal coordinated voltage control can be expressed as the following system performance objectives: J_1: Stabilizing all voltages at their steady state values above 0.9 p.u. following the fault; J_2: Minimizing the amount of load shedding; J_3: Keeping the voltage at Bus 4 as close to 1 p.u. as possible; J_4: Minimizing the voltage fluctuations at Bus 2, Bus 3 and Bus 4 due to voltage control actions; J_5: Minimizing the amount of capacitor control.

All the values of objectives J_2~J_5 are normalized into [0, 1] with 0 denoting the best case and 1 the worst case. Computational delay times of up to 30 s are acceptable though all controls are more effective when applied as soon as possible following the fault. As each control device can change its tunable parameter stepwisely on the whole control period provided the set delay time and the mechanical switching time constraints are satisfied, we usually cannot obtain an optimal control schedule by random search or empirical guess.

Algorithm parameters

The proposed immune algorithm was employed to solve the optimal coordinated voltage control problem. The antibody $\boldsymbol{B}_a(x)$ with three gene chains σ_{cap}, σ_{load} and σ_{vref} was used to represent a solution candidate x in the form of $\boldsymbol{B}_a(x)=[\sigma_{cap}\ \sigma_{load}\ \sigma_{vref}]^T$, where σ_{cap} is the capacitor switching sequence, σ_{load} the load shedding sequence and σ_{vref} the transformer tap changing sequence. In consideration of the input format of both the capacitor bank and the load shedding expressed as the step number (0,1,2,3) but not real values, a digital encoding system is employed. The simulation parameters are listed in Table 1.

In the simulation study, the system objective J_1 is used as a hard constraint for the feasibility checkup of solution candidates. The objectives J_2~J_5 are lumped as a weighted integrated performance index:

$$J=\sum_{i=2}^{5} w_i J_i\ ,$$

where $\sum_{i=2}^{5} w_i=1$. It was proved that a solution optimizing the index J is a Pareto optimum of the 4 bus system coordinated voltage control problem. The objective $J\in[0,1]$ is then used to calculate the antigen affinity $A_g(x)$ for each antibody $\boldsymbol{B}_a(x)$ according to Eq.(14), i.e.,

$$A_g(x)=1-J(x).$$

Table 1 The simulation parameters in the four bus example system voltage control

Parameter	Value
Simulation period	800 s
Control period	[110,210]
Initial value of load shedding	0
Initial value of capacitor bank C_3	2
Initial value of tap changing reference voltage	1.0 p.u.
Iteration times in the immune algorithm (IA)	50
Population size of antibodies in the IA	30
Capacity of the memory pool in the IA	15

SIMULATION RESULTS

A number of rounds of the problem solving were conducted to investigate the average performance of the proposed algorithm. Three kinds of control schemes were compared: (1) All the controllable parameters keep their nominal values unchanged following the transmission line fault (No Control); (2) The capacitor bank and the reference voltage of the tap changer shift once from their initial values 10 s after the fault occurrence (Regular Control) (Larsson, 2002); (3) All the control devices track the optimal control trajectories generated by the proposed immune algorithm (Optimal Coordinated Control).

In the Regular Control mode the capacitor changes once to Step 3, and the tap changer changes reference voltage once to 0.92 p.u. after 10 s following the fault without load shedding. In the Optimal Coordinated Control, 7 times of capacitor switching, 4 times of load shedding and 9 times of tap changing occur to achieve best system performance. Compared with the Regular Control mode, more capacitor switching, tap changing and load shedding take place in the Optimal Coordinated Control. At this cost, it yields the best system performance. Fig.3 shows the voltage responses at Bus 2, Bus 3 and Bus 4, resulting from the aforementioned voltage control actions. As shown in these figures, the voltages at Bus 2, Bus 3 and Bus 4 of the system collapse after the emergent disturbance occurs at 100 s without voltage security

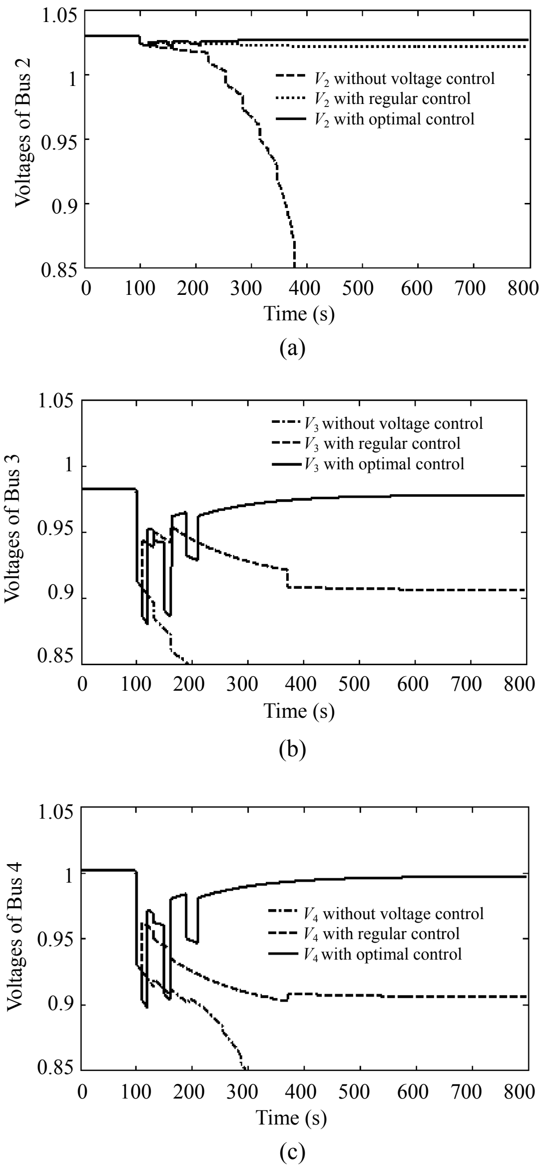

Fig.3 Voltage control results at Bus2 (a), Bus3 (b) and Bus4 (c)

control. On the other hand, both the Regular Control and the Optimal Coordinated Control recovers the system voltages well above their lower limits (0.9 p.u.) within 110 s after the emergent disturbance occurs, but the Optimal Coordinated Control yields best system performance, especially for the voltage at Bus 4 which returns to its nominal value of (1.0±0.05) p.u. within 110 s after the emergent disturbance occurs, and in the whole control horizon the three voltages are always beyond 0.89 p.u.

CONCLUSION

The proposed self-pattern-recognized immune algorithm is a general purpose framework for complex system optimization problems such as the optimal coordinated voltage control design problem investigated in this paper. With no analytical system model needed and effective heuristic information extracted automatically in the search process, it makes the solution of complex system optimal control problems more feasible and efficient. The key stage of the proposed algorithm is vaccine extraction and inoculation. With "pattern" we define the implicit modes of control action profiles which may benefit the convergence of search procedures. Simulation results have shown the promising capability of the proposed method in solving such optimal coordinated voltage control problem.

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