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Feasibility of online collaborative voltage stability control of power systems

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Abstract: The authors present the results of feasibility study of a novel concept of power system online collaborative voltage stability control. Online collaboration between power system controllers is proposed in order to enhance their overall performance and efficiency to cope with the increasing operational uncertainty of modern power systems. The framework of the proposed online collaborative voltage stability control is first presented, which is based on the deployment of multi-agent systems and real-time communication for online collaborative control. Then, two of the most important issues in implementing the proposed online collaborative voltage stability control are addressed: (1) Error-tolerant communication protocol for fast information exchange among multiple intelligent agents; (2) Deployment of multi-agent systems by using graph theory to implement power system post-emergency control. Results of testing the proposed online collaborative voltage stability control in the case of the 10-machine 39-node New England power system are presented. Results of a feasibility study by means of a simulation are given that take into consideration low-probability cascading faults in the power system.

1 Introduction

Preventive control and emergency control are deployed in modern power systems against the loss of system stability, based on two main frameworks of decentralised and centralised control. Preventive control is decentralised and implemented locally by various controllers, such as Automatic voltage regulator (AVR), power system stabiliser (PSS) and so on. It functions online by monitoring variations of local operational performance and parameters of power systems. Rarely the actions of a local controller consider the status and needs of other local devices, even though these could be extremely important for the local controller to take the correct actions. Obviously, under the framework of decentralised control, the effectiveness and covering area of local controllers are constrained and they are not designed to be able to support each other. On the other hand, emergency control is a centralised and open-loop control involving generation and load shedding as well as islanding control. In normal operation, power system stability is maintained by closed-loop decentralised preventive control against usual fault conditions. As soon as preventive control fails to sustain stable operation of

the power system, emergency control is called in to shed generation and/or load as well as to implement islanding control, in extreme cases, in order to maintain system stability.

Recently, a different category of power system control based on multi-agent collaboration has attracted interests of many power system researchers. Actions of semi-autonomous agents to implement power system control are between those implemented by decentralised and centralised power system controllers. They rely on the collaboration among multiple agents through online communication in order to enhance overall control performance and efficiency or to handle unexpected contingent operation of power systems [1, 2]. In [3], a novel scheme of robust wide-area power system damping control is proposed based on multi-agent theory. Wide-area damping control is implemented through agent communication on a framework of communication network. In [4], a multi-agent secondary voltage control is presented for system voltage controllers to cope with power system contingent operation. A protocol of agent communication is proposed and tested in the example of the 10-machine 39-node New England power system. In [5], an online learning

framework to enhance the decision-making capability of multiple agents is proposed and tested in the example of the power system for thyristor controlled series compensator. In the proposed learning framework, agent communication is an essential part for the effective operation of multi-agent systems. In [6], a multi-agent stabilisation control system is proposed, and agent communication is based on computer network. In [7, 8], the special issue of the realisation and physical configuration of agent communication is discussed in detail, and it is reckoned that, technically, agent communication is a realistic solution to evolve for modern power systems to become stronger and more robust.

The loss of power system stability is often develops under unpredictable operating conditions, such as cascading incidents that have extremely low expected probability. Those operating conditions are difficult to be foreseen and considered by the centralised offline open-loop emergency control. Hence, in [9], an online collaborative power system control is proposed based on the multi-agent systems and agent communication. The online collaborative control is to enhance the overall performance and efficiency to handle unexpected operating scenarios of the power system. The proposed framework of online collaborative stability control is illustrated in Fig. 1. In the framework, a local controller still takes a local feedback signal and controls only its connected local device (grey part of Fig. 1). However, each local controller is a part of an information synthesis station, and online action of the local controller is guided by algorithms of information synthesis. Fast exchange of information between different local information synthesis stations is required for local controllers to know each other's status and needs as well as for them to 'talk' to each other urgently in contingent operation. The objective of fast information exchange is for local controllers to respond to

unexpected incidents and to take correct actions in a collaborative way. Furthermore, the mechanism of information synthesis and fast information exchange are managed by an information management centre through slow information exchange between the information synthesis station and the information management centre that takes into account the slow evolution of power system operation. Hence, in the proposed framework, as far as the flow of physical feedback and control signals is concerned, it is decentralised control that guarantees fast and accurate control actions. However, the flow and management of information is regional or even, possibly, global. This ensures that decentralised control has a wider impact. Hence, as far as information flow is concerned, it is centralised.

There are many issues to be discussed and investigated for the full implementation of the proposed framework of Fig. 1, such as concerning the technology and details of realisation of agent communication, as discussed specially in [7, 8]; data structure of information exchange among multiple agents [10, 11]; online prediction of system instability [12] and so on. All these cannot be addressed fully in a single paper and are also dependent on progress in the respective fields. Hence, this paper presents the results of a feasibility study of the proposed online collaborative voltage stability control, focusing on two of the most important issues: (1) Error-tolerant communication protocol for fast information exchange among multiple intelligent agents; (2) Deployment of multi-agent systems by using graph theory to implement power system post-emergency control. In the paper, the proposed online collaborative voltage stability control is tested using the example of the 10-machine 39-node New England power system. Results of the feasibility study through a simulation are given that take into consideration the low-probability power system cascading faults.

Figure 1 Framework of power system online collaborative stability control

2 Error-tolerant communication protocol for online collaborative stability control

In the framework shown in Fig. 1, one of the key issues in the implementation of online collaborative control is the real-time communication among multiple agents. Agent communication is based on communication protocol, and one particular protocol, proposed in [4], is shown in Fig. 2. In Fig. 2, 'listen' is a standby status of agents waiting to send or receive communication signals; 'multicast' is the state of agents sending a signal seeking help from other agents; 'indication' is the state when a supporting agent sends a signal to offer support; 'request' is the state when the agent being supported asks the selected supporting agents to provide the help and 'reply' is the status of the supporting agent to confirm that the requested support is provided. Operational mechanism of agents in Fig. 2 is between decentralised and centralised control. As illustrated in Fig. 2, agents intend to solve their own problems whenever it is possible via local actions. Otherwise, they seek help from other agents through a properly designed protocol of communication that every agent should abide by to avoid confusion and mistakes. Correctness of a communication protocol can be checked, such as the one in Fig. 2 examined by the finite-state machine [13].

However, in communication protocol, automatic correction of communication errors caused by such factors as data corruption or interruption of physical communication channels is not considered in this paper. In real-time operation of online collaborative control, those errors could be fatally detrimental. Hence, we propose an essential improvement to the communication protocol of Fig. 2 by classifying messages sent and received into 'direct' and 'indirect' messages

and adding a re-multicasting stage of indirect messages into the protocol in Fig. 2. This improved error-tolerant communication protocol is shown in Fig. 3. Basically, at stages of multicast, request, indication and reply, whenever an agent receives a 'direct' message, it marks it as an 'indirect' message and re-multicasts it immediately. In Fig. 3, agent who finally provides the support is assumed to be supporting agent 1. Automatic correction of communication errors caused by data corruption and interruption of physical communication channels is performed by the algorithm of information optimisation, as introduced here:

According to information theory, if we assume that messages are sent and received through a certain media, x is the real state of a message sent (input), whose probability distribution is

$$\begin{bmatrix} X \\ p(X) \end{bmatrix} = \begin{bmatrix} X_1 & X_2 & \cdots & X_N \\ p(X_1) & p(X_2) & \cdots & p(X_N) \end{bmatrix}$$

and y is that of a message received, whose probability distribution is

$$\begin{bmatrix} Y \\ p(Y) \end{bmatrix} = \begin{bmatrix} Y_1 & Y_2 & \cdots & Y_N \\ p(Y_1) & p(Y_2) & \cdots & p(Y_N) \end{bmatrix}$$

From $y = y_j$, the implied information of $x = x_i$ is

$$I(x_i, y_j) = \log_2 \frac{p(x_i, y_j)}{p(x_i)p(y_j)} = \log_2 \frac{p_{ij}}{\sum_{i=1}^N p_{ij}p(x_i)} \quad (1)$$

From (1), we can see that $I(x_i, y_j)$ is associated with only $\{p(x_i)\}$ because transfer probability $\{p_{ij}\}$ is fixed with fixed media. The bigger $I(x_i, y_j)$ is, the higher the implied information of $x = x_i$ from $y = y_j$. Hence, $x = x_i$ obtained from observed data $y = y_j$ with a higher $I(x_i, y_j)$ is more reliable.

If $I(x_M, y_j) = \max\{I(x_1, y_j), I(x_2, y_j), \dots, I(x_N, y_j)\}$, the lost information with $x = x_i$ from $y = y_j$ will be $I_{\text{loss}}^{i,j}(x_i, y_j) = I(x_M, y_j) - I(x_i, y_j)$. Hence, we can use the following objective function for information optimisation:

$$\min \sum_{k=1}^K I_{\text{loss},k} \quad (2)$$

where K is the number of independent observed output data and $I_{\text{loss},k}$ the information loss of the k th output. To further explain the basic principle of the proposed error-tolerant protocol of Fig. 3 and the associated information optimisation of (2) above, for example, we assume that there are four agents, A , B , C and D connected in a multi-agent system. Agent A sends out a message ($X_A = 1$). The probability of the message being polluted during the transmission between agents is ε , and hence, the transfer probability matrix of transfer channel is $Q_{A-B} = \begin{bmatrix} 1-\varepsilon & \varepsilon \\ \varepsilon & 1-\varepsilon \end{bmatrix}$ for direct transfer from

Figure 2 Agent communication protocol of a finite-state machine

Figure 3 Improved error-tolerant communication protocol

agent A to B ; $Q_{A-C-B} = \begin{bmatrix} (1-\epsilon)^2 & 1-(1-\epsilon)^2 \\ 1-(1-\epsilon)^2 & (1-\epsilon)^2 \end{bmatrix}$ for indirect transfer from agent A to B through C and $Q_{A-D-B} = \begin{bmatrix} (1-\epsilon)^2 & 1-(1-\epsilon)^2 \\ 1-(1-\epsilon)^2 & (1-\epsilon)^2 \end{bmatrix}$ for indirect transfer from agent A to B through D .

Assuming the direct message is polluted, we have the output to be $Y_{A-B} = 0$. But the indirect message arrives at B correctly with $Y_{A-C-B} = 1$ and $Y_{A-D-B} = 1$. Supposing that the prior probability is 0.5, and according to the loss-information computation method [14], the loss-information for $X_A = 0$ is $I_{\text{loss}}(X_A = 0) = 2 \log_2((1-\epsilon)^2/1 - (1-\epsilon)^2)$ and for $X_A = 1$, $I_{\text{loss}}(X_A = 1) = \log_2(1-\epsilon)/\epsilon$. If $\epsilon < 0.1$, we have $I_{\text{loss}}(X_A = 0) > I_{\text{loss}}(X_A = 1)$. Hence, according to the objective function of (2), agent B receives the correct message $X_A = 1$ even if the direct message is polluted.

In the case where the physical communication channel between agents A and B is broken down, the direct message does not arrive at agent B with $Y_{A-B} = \Phi$ (empty). Hence,

$I_{\text{loss}}(X_A = 1) = 0$ that is less than $I_{\text{loss}}(X_A = 0)$. Agent B can still receive the correct message from agent A .

3 Deployment of multi-agent systems by using graph theory to implement power system post-emergency control

In the proposed framework of Fig. 1, power system voltage controllers are organised by the information management centre to form a set of multiple multi-agent systems according to the slow evolution of power system operating conditions. The deployment of the multi-agent systems is to set up a set of multiple defence lines around certain identified most important loads in the power system. In the case of failure of power system emergency control, the multiple layers of multi-agent systems are launched to prevent the sub-systems within the defence lines to collapse together with the rest of the power system and hence ultimately power supply to the identified loads is maintained. This is the ideal of power system post-emergency control [15]. We propose to deploy

the multi-agent systems by using the nesting method of α decomposition in graph theory [16, 17] as follows.

As shown in Fig. 4, if we decide to set up three layers of multi-agent system to implement the post-emergency control in a power system, the area enclosed by each layer should satisfy $A_2 \supset A_{22} \supset A_{222}$ with α to be $\alpha_1 < \alpha_2 < \alpha_3$ [16, 17]. Because the post-emergency control is to cope with the uncertainty of power system operation, it is impossible to know whether within each layer, the sub-system is stable or not. Hence, it is unlikely that the layers of multi-agent post-emergency control can be determined based on the prediction of stability. Hence, it is appropriate to determine the layers by checking the controllability of related controllers. Here, we propose to use the following sensitivity matrix, defined in [18], to implement α decomposition

$$\Delta V = S \Delta Q \quad (3)$$

where elements of vector ΔV are the deviation of node voltage, those of vector ΔQ are deviation of injection of node reactive power. Hence, the elements of matrix S are the sensitivity of voltage to the injection of node reactive power, determined by factors such as the electrical distance, controllability of node controllers and so on.

The nesting method of α decomposition mathematically is to find a transformation matrix P , to convert matrix S to a block matrix $\tilde{S} = P^T S P = \{\tilde{S}_{pq}\}$, $\tilde{S}_{pq} = \{\tilde{S}_{ij}^{pq}\}$ to satisfy $|\tilde{S}_{ij}^{pq}| \leq \alpha$. In graph theory, α decomposition is used to decompose the graph corresponding to the matrix S into sub-graphs whose elements consisted of sub-graphs not greater than α [19]. By using the nesting method of α decomposition, the deployment of multi-agent post-emergency control can ensure that the more capable controllers are closer to the identified load. Procedure of applying the nesting method of α decomposition is

1. Denote S in (3) as S_1 and obtain the graph G_1 from matrix S_1 ;
2. $k = 1$, $\alpha_k = \min(S_k)$; ($\min(S_k)$ is the minimal element of matrix S_k)
3. Let $\alpha = \alpha_k + \varepsilon$ (ε is a small number). If $\alpha = 1$ or $G_k = \Phi$ (Φ contains only the identified load), computation is completed. Otherwise, the k th α decomposition is applied on G_k and computation result is $G_k = \{G_{k1}, G_{k2}, \dots, G_{kn}\}$;

Figure 4 Nesting method of α decomposition

4. Select a sub-graph $G_{k+1} \in \{G_{k1}, G_{k2}, \dots, G_{kn}\}$ containing the identified load from $G_k = \{G_{k1}, G_{k2}, \dots, G_{kn}\}$ as the $(k+1)$ th layer of multi-agent system;

5. Calculate matrix S_{k+1} from graph $G_{k+1} \in \{G_{k1}, G_{k2}, \dots, G_{kn}\}$ and obtain $\alpha_{k+1} = \min(S_{k+1})$;

6. Let $k = k + 1$ and go back to 3.

For each agent to decide whether to offer support and how much the support to be provided, the following simple index is proposed

$$\text{Eing}_i = k_1 * k_2 * k_3 * k_4 * \Delta E_{fdi} \quad (4)$$

where Eing_i is the index used by the i th control agent. In (4)

$$k_1 = \frac{\Delta V}{|V|} \quad (5)$$

where ΔV is the deviation of voltage and $|V|$ the voltage amplitude at the busbar where the agent being supported locates. The bigger k_1 is, the more support is needed

$$k_2 = \frac{1}{1 + \Delta s_d + \Delta s_d} \quad (6)$$

k_2 considers the effect of local motor load at the place where the agent being supported locates. For motor load, slip s is an important factor to be taken account of as far as voltage stability is concerned. If s declines towards the critical slip s_{cr} continuously, it is more likely that system loses voltage stability. The faster s declines, the more dangerous it is as far as the voltage stability is concerned. Hence, we use $\Delta s_d = s_{cr} - s$ and Δs_d , the changing speed of Δs_d , in k_2 .

$$k_3 = \frac{\rho_i}{\sum_{j=1}^n \rho_j} \quad (7)$$

where ρ_i is the index of control capability of the i th supporting agent and n is the number of supporting agents. The bigger k_3 is the more support can be provided

$$k_4 = \frac{\Delta E_{fdi}}{\sum_{j=1}^n \Delta E_{fdj}} \quad (8)$$

where ΔE_{fdi} is the adjustable reserved capability of the i th supporting agent. $\Delta E_{fdi} = E_{f \max i} - E_{fdi}$, where $E_{f \max i}$ is the adjustable maximum value and E_{fdi} is that at the normal operation. The bigger k_4 is, the more support can be provided.

During online collaborative control, two types of information are sent and received among agents. They are information for communication and information for collaborative control. The data format of the information package is

{type of information, stage of communication, source agent ID, destination agent ID, middle agent ID, offer, control parameters}

where

Type of information: 1 – direct message from source agent to destination agent when source agent ID = middle agent ID; 0 – indirect message from source agent through middle agent to destination agent;

Stage of communication: 00 – multicast; 01 – indication; 10 – request; 11 – reply;

Offer: seeking or offering support, 1 – Yes, 0 – No;

Control parameters are those in (4–8).

4 Example of power system

The New England 10-machine 39-node power system installed with two SVCs at node 4 and 13 and two STATCOMs at 8 and 14 [4], shown in Fig. 5, is used as the test example power system. It is identified that in the system, L_{12} is connected to an important region and hence needs to be protected in case of system collapse. At steady state, the proposed nesting method of α decomposition is used for the deployment of multi-agent systems of online collaborative control. Results of computation of α decomposition are summarised in Table 1. From Table 1, we can see that when $\alpha = 0.01$, all nodes of the system are within one layer, hence, this layer is redundant. When $\alpha = 0.02$, the system is separated into two sub-systems. The sub-system containing L_{12} , hence, forms the first layer. When $\alpha = 0.03$, the sub-system within the first layer is divided further into two sub-systems. Again the sub-system containing L_{12} forms the second layer. So does the third layer when $\alpha = 0.04$. When $\alpha = 0.06$, although the sub-system inside the third layer is decomposed into three sub-systems, the layer cannot be formed because in the sub-system containing L_{12} , there is limited capacity of voltage support with only one voltage controller (STATCOM) and without any generator. Finally, $\alpha = 0.1$, the layer is

Figure 5 New England power system with three layers of multi-agent systems

meaningless with only the node connected to the important load. Therefore three layers of post-emergency control are formed as results of computation of α decomposition. All voltage controllers (AVRs, SVCs, STATCOMs) inside a layer and circuit breakers between each layer are control agents. In total, three multi-agent systems are formed for each layer of defence line as shown in Fig. 5.

To demonstrate the capability of three layers of multi-agent system to implement post-emergency control to maintain power supply to the identified important load in the incident of cascading faults, Fig. 6 presents the simulation results in different operational scenarios of the power system. The base scenario (BS) is system operation under a cascading fault. At 0.5 s of simulation, line 16–24 was tripped off. This was followed by a fault on line 2–30 with generator G1 out of service. The result of the simulation is given in Fig. 6a, which shows power supply to L_{12} and system stability was lost without the proposed online collaborative control being implemented.

Table 1 Results of computation of α decomposition

α Value	Set of system nodes in each sub-systems
0.01	all the nodes in the power system
0.02	$A_1 \in \{2,3,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30,33,34,35,36,37,38\}$ $A_2 \in \{1,4,5,6,7,8,9,10,11,12,13,14,31,32,39\}$ (sub-system within the first layer)
0.03	$A_{21} \in \{1,9,39\}$; $A_{22} \in \{4,5,6,7,8,10,11,12,13,14,31,32\}$ (sub-system within the second layer)
0.04	$A_{221} \in \{4,5,6,7,8,31\}$; $A_{222} \in \{10,11,12,13,14,32\}$ (sub-system within the third layer)
0.06	$A_{2221} \in \{10\}$; $A_{2222} \in \{32\}$; $A_{2223} \in \{11,12,13,14\}$
0.1	$A_{22231} \in \{11\}$; $A_{22232} \in \{12\}$; $A_{22233} \in \{13\}$; $A_{22234} \in \{14\}$

Figure 6 Simulation results

- a Scenario 1
- b Scenario 2
- c Scenario 3
- d Scenario 4
- e Scenario 5
- f Scenario 6

Fig. 6b shows the simulation result of BS but with the online collaborative control in operation. Fast voltage drop was detected by agent L_{12} and at 5 s, the first defence line was launched. From Fig. 6b, it can be seen that power supply to L_{12} was maintained (system stability outside the first defence line was lost). Fig. 6c shows the simulation when the first defence line failed to launch. The failure was caused by communication error between L_{12} and circuit breaker 1–2, which did not open until 7 s. Hence, power supply to L_{12} was lost. Fig. 6c shows the scenario to illustrate the importance of arranging multiple defence lines in comparison with that presented by the simulation result of Fig. 6d. In Fig. 6d, although the first defence line was launched at 5 s, L_{12} still detected the continuous voltage drop (it did not know that circuit breaker 1–2 failed to operate on time at 5 s). Hence, it decided to launch the second defence line at 7.5 s. From Fig. 6d, it

can be seen that with the second defence line launched at 7.5 s, power supply to L_{12} was maintained.

Similarly, Figs. 6e and 6f present the simulation results to demonstrate the function of the third defence line. Fig. 6e shows the scenario when the circuit breaker 8–9 did not operate until 9.5 s and Fig. 6f shows that with the third defence line launched at 10 s, power supply to L_{12} was maintained (although rest of the power system collapsed). A summary of scenarios and operational actions of online collaborative control is given in Table 2. From Table 2 and Fig. 6, we can see that without the multiple layers of multi-agent system, the collaborative control or the online collaborative control was not implemented successfully, power supply to L_{12} was lost together with the loss of stability of the whole power system. With the online collaborative control implemented successfully, it was

Table 2 Cascading events and post-emergency control actions corresponding to simulation results of Fig. 6

Scenario	Event or control actions	Time	Consequence	Simulation results
1	tripping off of line 16–24	0.5 s	power supply to L_{12} was lost together with the loss of stability of the whole system	Fig. 6a
1	G1 out of service due to the fault on line 2–30	1.5 s		
2	islanding control to isolate the sub-system inside the first layer was successful and online collaboration was implemented	5 s	power supply to L_{12} was maintained, although the rest of the system outside the first layer collapsed	Fig. 6b
3	circuit breaker of line 1–2 delayed until 7 s to implement the above islanding control due to communication errors	7 s	power supply to L_{12} was lost due to the collapse of the sub-system within the first layer	Fig. 6c
4	islanding control to isolate the sub-system inside the second layer was successful and online collaboration was implemented	7.5 s	power supply to L_{12} was maintained, although the rest of the system outside the second layer collapsed	Fig. 6d
5	circuit breaker of line 8–9 delayed until 9.5 s to implement the above islanding control due to communication errors	9.5 s	power supply to L_{12} was lost due to the collapse of the sub-system within the second layer	Fig. 6e
6	islanding control to isolate the sub-system inside the third layer was successful and online collaboration implemented	10 s	power supply to L_{12} was maintained, although the rest of the system outside the second layer collapsed	Fig. 6f

maintained even though the rest of the system lying outside the layers collapsed.

5 Conclusions

The major contribution of this paper is the presentation of a feasibility study of a novel concept of power system online collaborative voltage stability control. In the paper, two main issues in implementing the proposed collaborative control through the deployment of multi-agent systems are addressed. The first one is the proposal of an improved error-tolerant agent communication protocol by using information optimisation algorithm. The second is to use the nesting method of α decomposition in graph theory to deploy multiple layers of multi-agent systems to protect sub-systems around identified loads in a power system to prevent them from collapsing together with the rest of the power system when it is subject to unexpected cascading faults. In the paper, simulation results of applying the proposed scheme in the 10-machine 39-node New England power system are presented, to demonstrate the feasibility of proposed online collaborative control.

The authors would like to point out that the paper only presents the idea and configuration of proposed online collaborative control confirmed by results of a preliminary feasibility study. There are many important issues that need to be addressed and explored through further investigation. For example, in practical applications of multi-agent operation, possibility of failure or wrong actions of agents needs to be considered. This is because agents are different with

conventional controllers. They may come up with totally unexpected decisions. This paper proposes to set up multiple defence lines. Somehow, this is a strategy physically to ensure control objective to be met in the case of failure of some agent's action, as demonstrated by simulation results in Fig. 6. In the paper, relative simple indices in (3–8) are used for the feasibility study. The authors believe more work is needed to improve the control algorithm itself (including indices) to enhance the robustness and performance of the online collaborative control to agents' actions. In the future work, authors will also investigate the possibility of considering load shedding as an effective means in the proposed online collaborative control and test the proposed control algorithm in a larger power system.

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7 References

- [1] REHTANZ C.: 'Autonomous systems and intelligent agents in power system control and operation' (Springer, 2003)

- [2] JENNINGS N.R.: 'Cooperation in industrial multi-agent systems' (World Scientific, 1994)
- [3] NI H., HEYDT G.T., MILI L.: 'Power system stability agents using robust wide area control', *IEEE Trans. Power Syst.*, 2002, **17**, pp. 1123–1131
- [4] WANG H.F., LI H., CHEN H.: 'Co-ordinated secondary voltage control to eliminate voltage violations in power system contingencies', *IEEE Trans. Power Syst.*, 2003, **18**, (2), pp. 588–595
- [5] ERNST D., GLAVIC M., WEHENKEL L.: 'Power systems stability control: reinforcement learning framework', *IEEE Trans. Power Syst.*, 2004, **19**, (1), pp. 427–435
- [6] HIYAMA T., OHTA T.: 'Hierarchical stabilization control with upper level multi-agent based controller and lower level local controller'. Proc. 13th Int. Conf. Intelligent Systems Application to Power Systems, 6–10 November 2005, p. 6
- [7] TONG X., LIAO G., WANG X., ZHONG S.: 'The analysis of communication architecture and control mode of wide area power systems control'. Proc. Autonomous Decentralized Systems, 2005, ISADS 2005, 4–8 April 2005, pp. 59–65
- [8] HOLBERT K.E., HEYDT G.I., NI H.: 'Use of satellite technologies for power system measurements, command, and control', *Proc. IEEE*, 2005, **93**, (5), pp. 947–955
- [9] WANG H.F.: 'The "third-category" method and multi-agent system theory in power system applications'. Invited penal paper, IEEE General Meeting, San Francisco, USA, 2005
- [10] MCARTHUR S.D.J., DAVIDSON E.M., CATTERSON V.M., ET AL.: 'Multi-agent systems for power engineering applications. Part I: Concepts, approaches, and technical challenges', *IEEE Trans. Power Syst.*, 2007, **22**, (4), pp. 1743–1752
- [11] MCARTHUR S.D.J., DAVIDSON E.M., CATTERSON V.M., ET AL.: 'Multi-agent systems for power engineering applications. Part II: Technologies, standards, and tools for building multi-agent systems', *IEEE Trans. Power Syst.*, 2007, **22**, (4), pp. 1753–1759
- [12] XUE F., CHEN Z., WANG H.F.: 'A novel criterion for online prediction of voltage collapse'. Proc. UPEC 2006, Newcastle, UK, 2006
- [13] SHIBATA K., OKAMURA K., ARAKI K.: 'Design and evaluation of dynamic protocol selection architecture for reliable multicast'. Proc. 2002 Symp. Applications and the Internet (SAINT), Los Alamitos, CA, USA, 2002, pp. 262–269
- [14] TANG L., SUN H., ZHANG B., ET AL.: 'Online fault diagnosis for power system based on information theory', *Proc. CSEE*, 2003, **23**, (7), pp. 5–11
- [15] WANG H.F.: 'Post-emergency control – the extra defense line against power system collapse'. Invited penal paper, Int. Conf. Electrical Engineering, Kunming, China, 2005
- [16] ZABORSZKY J., WANG K.-W., HUANG G.M., ET AL.: 'A clustered dynamic model for a class of linear autonomous systems using simple enumerative sorting', *IEEE Trans. Circuits Syst.*, 1982, **29**, (11), pp. 747–757
- [17] LEI F., HEN C.: 'Study of secondary voltage control (Part I)', *Autom. Electr. Power Syst.*, 2000, **24**, (11), pp. 18–21
- [18] LAGONOTTE P., SABONNADIÈRE J.C., LEOST J.Y., PAUL J.P.: 'Structural analysis of the electrical system: application to secondary voltage control in France', *IEEE Trans. Power Syst.*, 1988, **4**, (2), pp. 479–485
- [19] ZABORSZKY J., WANG K.-W., HUANG G.M., ET AL.: 'A clustered dynamic model for a class of linear autonomous systems using simple enumerative sorting', *IEEE Trans. Circuits Syst.*, 1982, **29**, (11), pp. 747–757