

The interconnection in active distribution networks

Citation for published version (APA):

Nguyen, H. P., Myrzik, J. M. A., & Kling, W. L. (2008). The interconnection in active distribution networks. In *International Conference on Energy Proceedings of the Security and Climate Change: issues, strategies and options : Bangkok, August 6 - 8, 2008 AIT*.

Document status and date:

Published: 01/01/2008

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

The interconnection in Active Distribution Networks

Phuong H. Nguyen^{*1}, Wil L. Kling*, Johanna M.A. Myrzik*

Abstract – The active distribution network (AN) has been mentioned recently to adapt with a large-scale implementation of distributed generators. One of its enhancements is increasing interconnections to provide more than one power flow path among local control areas. These parallel physical connections might cause several problems for the network such as congestion and loop flow. Considering the characteristics of the AN, this paper proposes a decentralized approach to control power flow which has some analogies to the telephone networks. The implementation of this control mechanism is based on a multi-agent system (MAS) technology. A simulation of the power system and MAS is created to illustrate the possibility of the proposed method.

Keywords – Active distribution networks, interconnection, power flow control, multi-agent system, power router.

1. INTRODUCTION

Within the context of sustainable development, distributed generation (DG) has been encouraged recently to provide alternatives for better quality, more reliable and cost-effective power. However, the large-scale implementation of DG has changed distribution systems gradually from the downstream unidirectional power flow to a bidirectional power flow. The existing distribution network infrastructure designed in a passive, less intelligent manner is insufficient to adapt with these changes. An introduction of active elements in distribution networks can provide an efficient, flexible and intelligent approach to overcome those problems [1].

This so-called active network (AN) concept has been proposed with three main points: interconnection, local control areas (cells), and system services [2]-[3]. The interconnection is to provide more than one power flow path, to manage congestion by re-routing power and to isolate faulted areas effectively. The local control area is to divide the distribution network into sub-networks (cells) with one more control layer to manage and control the power inside and across the cell boundaries. The system services aim to supply different power quality levels to individual customers.

This paper focuses on the description of the interconnection between cells of the AN. With more than one power supply path, the interconnection of AN has some analogies to telephone network, i.e., the power can be re-routed when some paths are over-stressed. Thus, the AN can avoid the bottleneck phenomenon, increase system reliability and stability. However, a domino effect of interconnected networks might occur when a system failure in one part of the network can quickly spread [3].

Designing of the AN therefore needs to concern about fast acting protection mechanism and automatic reconfiguration.

In order to enable those novel functions, this paper introduces a decentralized approach based on multi-agent system (MAS) technology. MAS have been mentioned recently as a potential technology for many fields of power system applications [4]-[7]. Under framework of constructing the AN, MAS is applied for managing autonomous control actions and coordination. Within a cell, active elements, i.e., controllable generators and loads, will be represented by agents (software entities) that can operate autonomously with local targets or cooperate with others to achieve area tasks. A superior agent is installed for each cell as a moderator to manage autonomous actions as well as communicate with other cells. Therefore, power flow exchange through the interconnection of the AN can be monitored and controlled.

2. INTERCONNECTED ACTIVE NETWORKS

Designing Active Networks

The transition from the existing distribution network to the AN can start from a simple example of the radial network. The radial network consists of separated sub networks (feeders). Hence, it is possible to establish the local control area for each feeder. The MAS is setup in each cell to manage autonomous actions and coordinate with other cells. Figure 1 shows a structure of the AN with MAS control for the radial network.

As one additional control level is installed for each cell component, the control architecture of the moderator of the cell is proposed to have two main parts: the Distributed State Estimation (DSE) and the Local Control Scheduling (LCS). The DSE can work autonomously or together among moderators to analyze the network topology, to compute the state estimation, and to detect bad data. Depending on the received information from the DSE, the LCS will establish the control set points for different actuators such as voltage regulation or active

^{*} Department of Electrical Engineering, Eindhoven University of Technology, 5600MB Eindhoven, the Netherlands.

¹ Corresponding author;
Tel: + 31 40 247 4479, Fax: + 31 40 245 0735
E-mail: p.nguyen.hong@tue.nl

and reactive power control of FACTS devices, remotely controllable loads and generators. This control architecture of moderators is depicted in Figure 2.

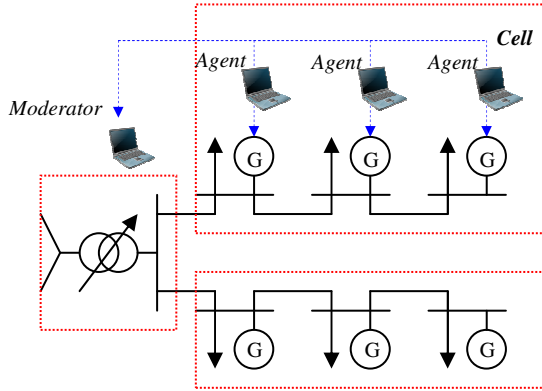


Fig. 1. Active Network managed by MAS

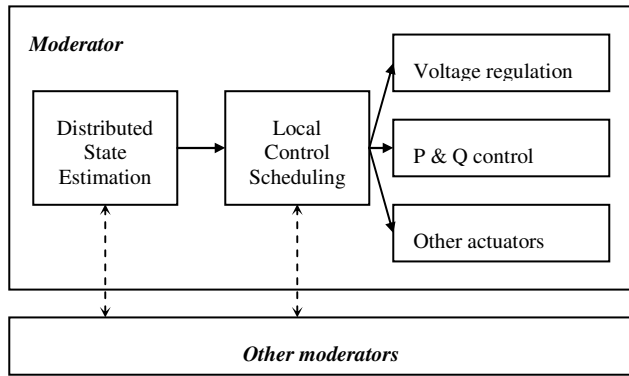


Fig. 2. Control architecture of the moderator

The interconnection

As aforementioned, the AN is based on increased interconnection between cells to avoid the bottleneck phenomenon and improve system reliability and stability. However, these meshed networks might get some following troubles without appropriate control mechanisms.

The power flow is distributed in the network according to Kirchoff's Laws. The passive transmission can easily cause over-stressed for low impedance lines. This so-called congestion problem limits available transfer capacity of the network. Another undesired issue caused by parallel physical interconnections is "loop flow" which is defined as a circulating current. This unintended flow can contribute to limit power transaction schedules and increase power losses.

In order to deal with the above problems, several solutions have been proposed. In the high voltage networks, Flexible AC transmission (FACT) is one of the effective means that can regulate power injection independently [8]. Another popular means, optimal power flow (OPF), is a centralized control way that affects overall network. Its objective functions can be adjusted to deal with different targets, i.e. minimize production cost, congestion management. In a liberalization market, price-based control mechanisms proposed by converting the system limits to correct market signals [9].

However, the implementation of these solutions

The influence of FACT devices is just in a limited area of the system. OPF requires a large-scale control measures that is not feasible for the distribution networks such as the AN. Although price-based control solutions have developed recently for decentralized purposes, they focus on economic layer of the system and still depend on market scheduling. That is not suitable for control targets of the AN, especial for fast acting protection scheme and automatic reconfiguration.

Recently, a concept of Intelligent Power Router (IPR) is proposed as a new generation of power delivery system [10]. By connecting to generators, power lines, and customers, one IPRs not only observe current network condition but also cooperate with others to active alternative power flow path in necessary cases. This approach is quite similar with the ideas of the interconnection in the AN, that the power can be re-routed via the power router. Its implementation in distributed control area is compliance with the design of the AN. In the next section, the decentralized control solution based on this concept and MAS technology will be presented in detail.

3. DECENTRALIZED CONTROL SOLUTION

Mathematical Model

For the AN, the power flow exchange among cells is controlled to minimize the production cost, maximize the using of reliable transmission components, and maximize the serving for high-priority loads. These criterions can be converted to similar type of data, i.e., the label costs that will be used for the control objective function. The centralized optimal decision for the power flow exchange among cells in the AN can be formulated as follows:

$$\min A = \sum_{i \in S} \alpha_i \Delta P_{gi} + \sum_{i \in T} \beta_i \Delta P_{ti} + \sum_{i \in D} \gamma_i \Delta P_{li} \quad (1)$$

$$s.t. \quad \sum_{i \in S} \Delta P_{gi} = \sum_{i \in T} \Delta P_{lossi} + \sum_{i \in D} \Delta P_{li} \quad (2)$$

$$P_{ti} + \Delta P_{ti} \leq P_{ti \max} \quad (i \in T) \quad (3)$$

where

- $\Delta P_{gi}, \Delta P_{ti}, \Delta P_{li}$ change in power generation, transmission, and load.
- $\alpha_i, \beta_i, \gamma_i$ label costs present for production cost, device reliability, and load priority.
- ΔP_{lossi} power loss on component i
- $P_{ti}, P_{ti \max}$ available power and power limit of component i
- S, T, D supply, transmission, and demand area sets.

The objective function (1) is the total label costs for power delivery from the generation areas to the load parts. Beside the power balance condition in (2), the tranmstted power needs to be within the device's limits in (3). For simplification, this paper dose not condisder the impact of the reactive power flow.

It is difficult to cope with this centralized optimal dication in distribution networks like the AN. Therefore, a decentralized implementation will be presented in the next part.

Decentralized implementation

controlling power flow based on a so-called power routers system. The power router is a combination of an agent (software) and a power flow controller (PFC - hardware), as shown in Figure 3.

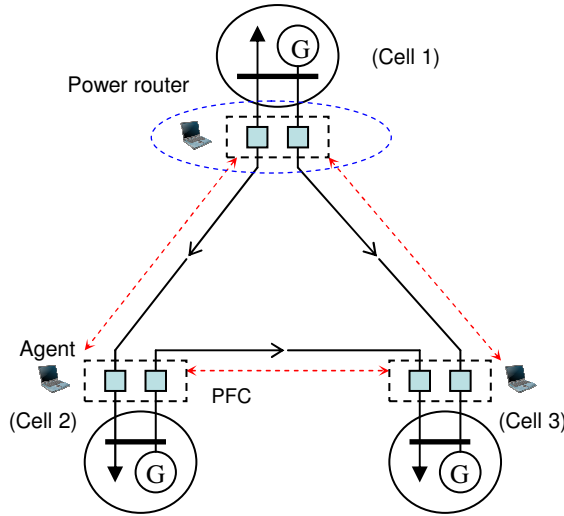


Fig. 3. The interconnection based on power routers

The agent, in this case, is the moderator of each cell, as mentioned in Section 2. It can get local area information such as power flow in incoming (outgoing) feeders, power generation reserver, power load demand, and label costs. Beside managing autonomous control actions, this agent can route message to communicate with the same level agents.

The PFC might be the application of several electronic devices that use to control power flow for its feeder based on the setting point given by the moderator. Under scope of this work, the PFC is the normal circuit breaker for simplification.

Each power router has one routing table that is updated frequently. The routing table is a ranking of predecessors based on the total label costs for power transmission to that cell. This procedure bases on the label-correcting algorithm to find the shortest path [11]. When there is a changing of the load demand, the power router of that cell will route a message to the first predecessor in the routing table to ask for power generation. If the capacity of this predecessor is lower than the amount of power demand, the power router has to ask for power from the next predecessors. This procedure does not consider a part of power losses, which is assumed to be compensated by the utility.

A simple example about operation of the power router has been shown in Figure 4 and 5. The network includes five sub areas while three of them (cell 1, 2, and 4) are generating cells (export power) and others (cell 3 and 5) are loading cells (import power). In Figure 4.a, the symbol $[x]$ denotes the total label cost (first value of the routing table), and (x) denotes the label costs (α, β, γ) of each generation, transmission, and load components.

Initially, the routing tables of all cells are null, their first value of the total costs is infinity, $[\infty]$. The updating procedure starts with generating cells first. Cell 1 updates its label cost according to its local production cost (4). Cell 2 will update its local production cost (2) although it can receive power either from Cell 1 to Cell 2 is $(4) + (1) +$

$(2) = (7)$, that will be added in the second value of Cell's routing table. For loading Cell 3, as the total label costs of its predecessors (Cell 1 and 2) are known, its total label cost will be (5) referring the total label cost of Cell 2 (2), the label cost for transmission reliability of line 2 - 3 (1), and the label cost for load priority of Cell 3 (2). Similarly, updating total label costs for other cells are shown in Figure 4.b.

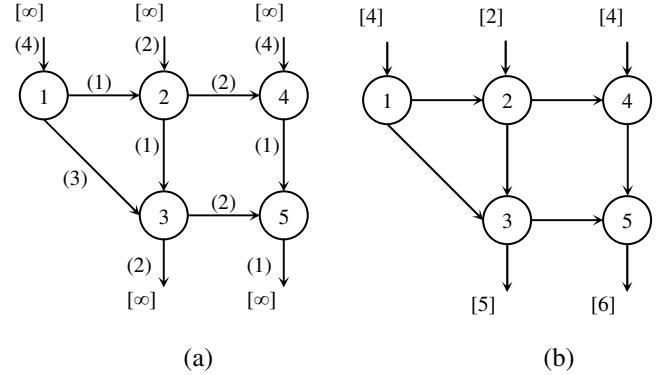


Fig. 4. Updating the routing table

In case the load demand of Cell 5 increases, its power router will send *INFORM* message including the amount of power load change (ΔP_{li}) to its first predecessor, Cell 4. Cell 4 will check its power reserve and send back *PROPOSAL* message including the amount of power generation change (ΔP_{gj}) to Cell 5. These communications have shown in Figure 5.a. If the proposed power generation is not enough ($\Delta P_{gj} < \Delta P_{li}$), Cell 5 will send *INFORM* message include a new amount of power load change ($\Delta P_{li}' = \Delta P_{li} - \Delta P_{gj}$) to the second predecessor, Cell 3. Cell 3 is not the generating area but it can route message to its first predecessor, Cell 2. The behaviors of Cell 2 will be similar as Cell 4. This procedure is shown in Figure 5.b. After meeting the power demand, Cell 5 sends *ACCEPT_PROPOSAL* message to all relevant predecessors. Then, these routers give *CONFIRM* message to their own cell to implement autonomous control actions.

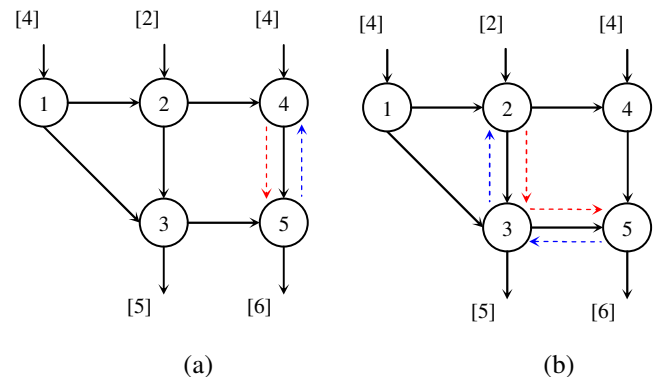


Fig. 5. Power routing procedure

In case total reserved power is not enough for load demand, the power router of Cell 5 has to decide curtailing the surplus amount of power load. This load shedding procedure is not in the scope of this work.

4. SETTING UP THE SIMULATION

This section will show how the above decentralized control implementation is simulated. The simulation is created with Matlab/Simulink and Java Agent Development Framework (JADE) as follows.

Electrical Power System Model

Five sub areas test system, similar with the above example in the previous section, is simulated under Matlab/Simulink environment, see Figure 6. Generating subsystems is presented by a simplified synchronous machine, local load, and controllabel switches. Load subsystems include only local load and controllabel switches. An “Embedded Matlab Function“ is created for each subsystem as a part of the power router.

The initial condition of test system is shown in Table 1. Label costs are similar with the example in previous section, see Figure 4.a.

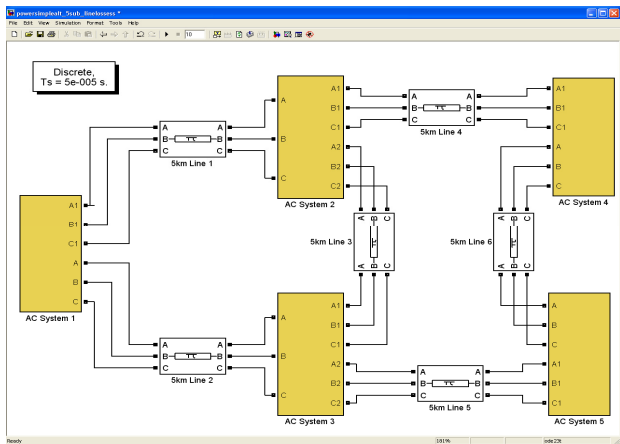


Fig. 6. Test system in Matlab/Simulink

Table 1. Power flow data

Cell	P_g , MW	P_{gmax} , MW	P_l , MW
1	13.5	15	5
2	7.2	9	10
3			5
4	15.5	19	10
5			5

Multi-Agent System Model

JADE is a popular platform for application of MAS in power engineering applications [12-14]. Agent communication languages are set by the Foundation for Intelligent Physical Agents (FIPA), an international standard.

In this simulation, each subsystem is managed by a pair of the agent, i.e., socket proxy agent (spa) and server agent (SA). While spa agent is used as the communication agent with Matlab/Simulink, SA agent is a principal agent that has all functions mentioned in the previous section. Figure 7 shows the platform of MAS for the simulation.

The Protocol

The communication between Matlab/Simulink and JADE is based on the client/server socket communications [13]. The socket proxy agent in JADE is used as a server socket. By using TCP/UDP/IP Toolbox, each “Embedded

Matlab Function“ in Matlab/Simulink can create a client socket to send and receive data with the spa agents. The period time for the communication is set as 0.25sec.

Depending on different purposes, i.e., update routing table or route power, the information exchange can be asynchronous or serial [14].

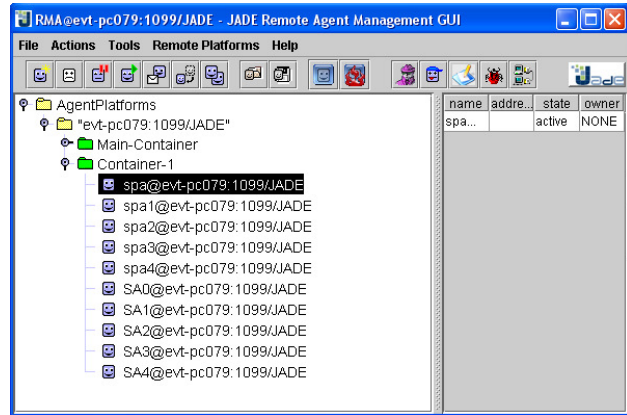


Fig. 7. Multi-agent system in JADE

5. CASE STUDY RESULTS

Message dialogue

For each communication period (0.25s), the local information of the subsystems, i.e., label costs, power reserve, and load demand will be sent to the SA agent. Figure 8 shows a list of the message which is transmitted in one communication period to update routing table of MAS.

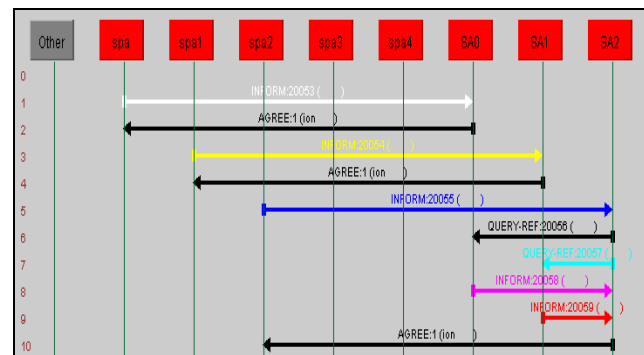


Fig. 8. MAS message dialogue

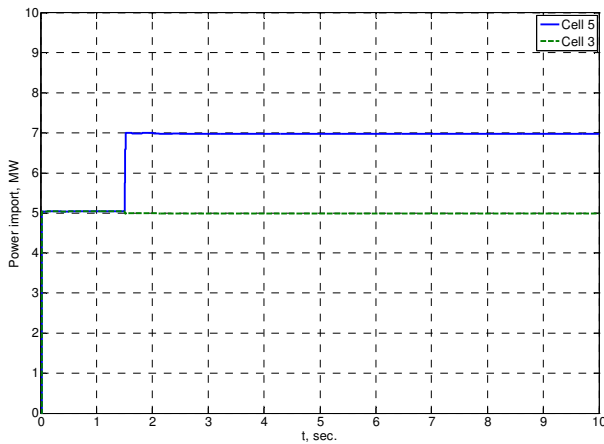
For example, after getting local information, spa2 sends an INFORM message (the 5th message) to SA2 which is represented for Cell 3. As Cell 3 has 2 incoming lines from Cell 1 and Cell 2, SA2 sends QUERY_REF messages (the 6th and 7th message) to SA0 and SA1 and receive INFORM messages (the 8th and 9th message) from them. Then, SA2 updates its data and send AGREE message back to Cell 3 (in Matlab/Simulink) through spa2.

Case 1 - Single stage power routing

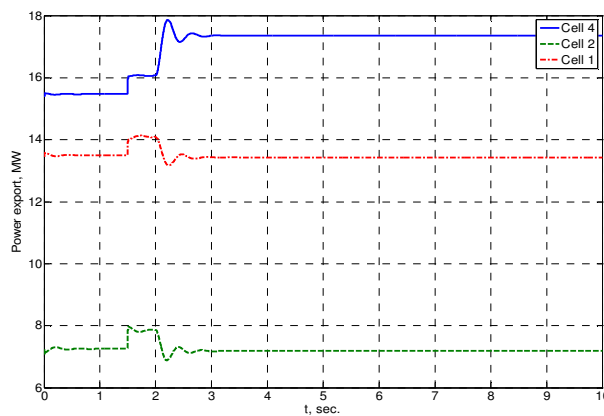
In this case, load demand of Cell 5 increases 2MW at 1.5s, see Figure 9.a. During the two first communication periods (0.5s) after changing power, the power export/import bases on the system characteristics, i.e., line impedance, inertial moment of generations. At the first communication periods (1.5 – 1.75s), Cell 5 detects the change of its power load demand. Thus, it sends a

message to its predecessors. This procedure is mentioned in the previous example of Section 3. At the second communication period (1.75 – 2s), MAS sends the decisive information to provide new setting points for generating cells. As Cell 4 is able to meet power demand of Cell 5 with the cheapest costs, the power export of Cell 4 will increase 2MW while others is kept intact. Depending on the damping factors of the system, the transient period occurs in several seconds. After that, the system reaches a new stable state with the balance between power load and supply. The power exports of generating cells are shown in Figure 9.b.

The response time for this single stage power routing is two communication periods (0.5s). It can be reduced if decreasing the communication period time. In this single stage procedure, the power demand is considered as a packet data, which is met by a single generating cell. In the next case, it is possible to divide this packet data to share with multi generating cells.



(a)



(b)

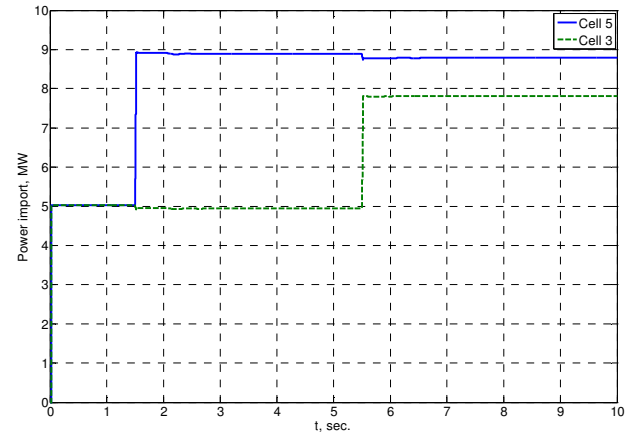
Fig. 9. Power import/export for Case 1

Case 2 – Multi stage power routing

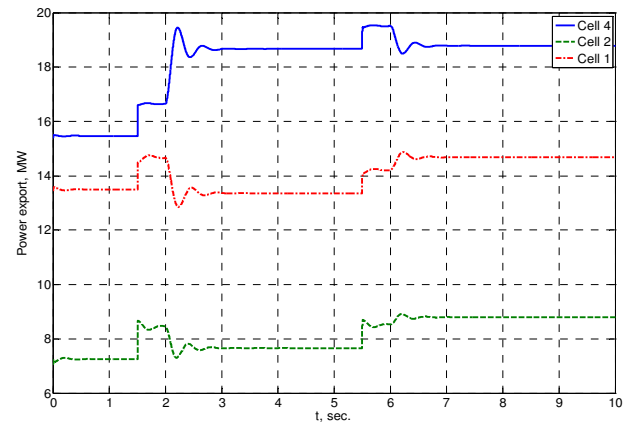
In this case, firstly, the load demand of Cell 5 increases 4MW at 1.5s. Behaviours of Cell 5 is similar as in the previous case. As the amount of load demand is larger than the power reserve of Cell 4 (3.5MW), the representing agent of Cell 5 will send message to its second predecessor. This procedure is explained in Section 3, see Figure 5.b. Finally, Cell 2 will share the responsibility for meeting power demand of Cell 5 with Cell 4. The power flow exchange for these stage is shown in Figure 10.

After setting and reaching a new state, at 5.5s, the load demand of Cell 3 will increase 3MW, see Figure 10.a. In this case, the representing agent of Cell 3 will devier messages to its first predecessor of Cell 2 for asking power supply. As Cell 2 is not able to meet the required power demand, it proposes its maximum capacity. Next, Cell 3 needs to ask Cell 1 covering the rest part of power demand. That means a responsibility for meeting the power demand has been shared between Cell 1 and Cell 2, see Figure 10.b.

As can be seen from these results, the multi stage power routing can deal with the problem of optimal power flow control between cells in the active networks. With the relative short time response, it is able to keep the system stable by balancing the power demand and supply. In future works, it is possible to extend this application for different problems of the system such as thermal limit of the line, (n-1) condition, restoration, and fast reconfiguration.



(a)



(b)

Fig. 10. Power import/export for Case 2

6. CONCLUSION

In this paper, the description of the interconnection in the Active Network has been shown. A solution for active control power flow among local areas is proposed. The approach is based on decentralized implementation and multi-agent system technology. As can be seen from results of the simulation, changing of power demand in a sub area can be adapt with other sub areas by routing power. The relative time response is another interesting point of this solution since it has the possibility to cope

with other problems of the power system.

In the future work, this application will be considered with the impact of the reactive power flow. The power flow controller (PFC) will also be applied.

ACKNOWLEDGMENT

The work presented in this paper is part of the research project: Electrical Infrastructure of the Future (Elektrische Infrastructuur van de toekomst in Dutch), sponsored by the Ministry of Economic Affairs of the Netherlands. Further information at: www.futurepowersystems.nl.

REFERENCES

- [1] Ault, G. W., Foote, C. E. T., and McDonald, J. R. 2005. UK research activities on advanced distribution automation. In *Proceeding of Power Engineering Society General Meeting*.
- [2] Overbeeke, F. V., and Roberts, V. 2002. Active networks as facilitators for embedded generation, *Cogeneration and On-Site Power Production*, vol. 3, no.2.
- [3] European Commission. 2003. New ERA for electricity in Europe – Distributed Generation: Key issues, Challenges and Proposed Solutions.
- [4] McArthur, S. D. J., and Davidson, E. M. 2005. Concepts and approaches in multi-agent systems for power applications. In *Proceeding of Intelligent Systems Application to Power Systems*.
- [5] EU-EESD project. 2006. CRISP - Critical Infrastructures for Sustainable Power (No.ENK5-CT-2002-00673).
- [6] Rehtanz, C. 2003. *Autonomous Systems and Intelligent Agents in Power System Control and Operation*. Springer.
- [7] Dimeas, A. L., and Hatziargyriou, N. D. 2005. Operation of a Multiagent System for Microgrid Control. *IEEE Transaction on Power System*. Vol. 20, no. 3.
- [8] Zhang, X. P., Rehtanz, C., and Pal. B. 2005. *Flexible AC Transmission Systems – Modeling and Control*. Springer.
- [9] Jokic, A. 2007. Price-based Optimal Control of Electrical Power Systems. Phd Thesis. Eindhoven University of Technology, Eindhoven, the Netherlands.
- [10] Laurens, I. J, V. 2005. A decentralized negotiation framework for restoring electrical energy delivery networks with Intelligent Power Routers – IPRs. MS thesis. University of Puerto Rico.
- [11] Ahuja, R.K., Magnanti, T. L., and Orlin, J. B. 1993. *Network flows: theory, algorithm, and applications*. Prentice-Hall, Inc.
- [12] JADE – Jave Agent DEvelopment Framework: <http://jade.tilab.com/>.
- [13] Gualdrón, J. G. G. 2006. A multiagent system approach for a self-reconfigurable electric power distribution system. MS thesis. University of Puerto Rico.
- [14] Negenborn, R. R. 2007. Multi-Agent Model Predictive Control with Applications to Power Networks. Phd thesis. Delft University of