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Power Flow Management in Active Networks

P. H. Nguyen, W. L. Kling, *Member, IEEE*, and J. M. A. Myrzik

Abstract--This paper proposes a new method to manage the active power in the distribution systems, a function under the framework of the active network (AN) concept. An application of the graph theory is introduced to cope with the optimal power generation (DGs/Cells dispatch) and interarea power flows. The algorithm is implemented in a distributed way supported by the multi-agent system (MAS) technology. Simulations show how the method works in cases of optimal operation, congestion management, and power generation cost change.

Index Terms--active networks; distributed generator; multi-agent system; graph theory

I. NOMENCLATURE

AN	Active network
DG	Distributed generation
FACTS	Flexible AC transmission systems
IPR	Intelligent power router
JADE	Java agent development framework
MAS	Multi-agent system
PFC	Power flow controller
$G(V,E)$	Directed graph model
A_i	Agent i
c_{ij}	Cost of edge (i,j)
r_{ij}	Residual capacity of edge (i,j)
π_i	Potential of node i
u_{ij}	Capacity of transmission line
α	Power generation cost
β	Transmission cost
γ	Load priority cost

II. INTRODUCTION

THE term of active network (AN) has been introduced for a distribution system to adapt to the high penetration of distributed generation (DG) [1]. With one more control layer, each local area network can be defined as a cell which can manage power inside and across cell's boundaries. By doing this, the power flow can be controlled in an efficient, flexible and intelligent way in order to overcome problems of existing distribution systems.

As the AN might be meshed, multi-agent system (MAS) technology can be applied for managing autonomous control actions and coordination amongs cells. Within a cell, active elements, for example controllable generators and loads, will be represented by agents (software entities) that can operate

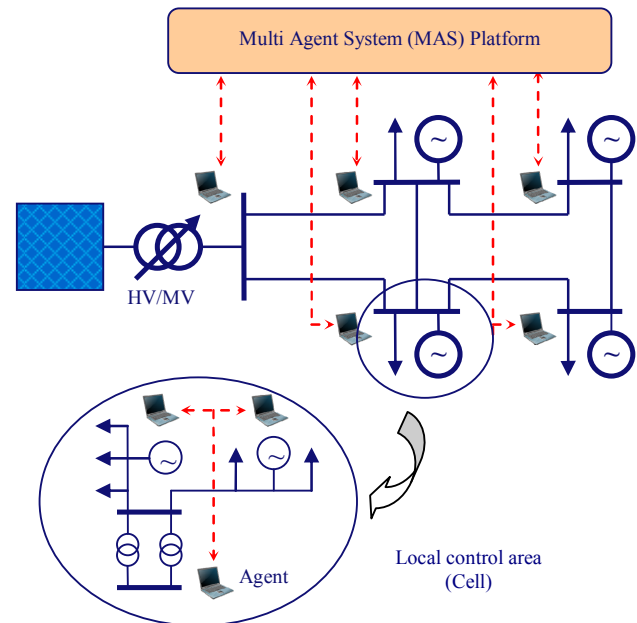


Fig. 1. Active Network managed by multi agent system

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 to communicate with other cells. This control architecture is illustrated in Fig.1.

In case of more than one power supply path, the interconnection of cells allows for power flowing through alternative paths when certain paths are over-stressed. Thus, the AN can avoid congestions when the power flow is controlled in flexible way. However, a domino effect might occur when a system failure in one part of the network can quickly spread out over the rest [1]. Therefore, designing the control layer for the AN needs to concern about optimization and security handling at the same time.

In this paper, the above mentioned power flow control function will be presented in detail. A distributed control scheme will be proposed for each cell to adapt to variations in the system. Power flow controlling (PFC) devices are used as interfaces of the cells in the AN. The power routing is optimized by a successive shortest path algorithm, an application of graph theory.

III. ACTIVE POWER FLOW MANAGEMENT

A. Problems

As stated, increasing interconnection among cells of the AN can avoid bottlenecks and can improve system reliability

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and stability. However, these meshed networks might get in troubles without appropriate control mechanisms.

The power flow in an electrical distribution network is bound to physical laws. The passive power transmission can easily cause congestion on low impedance components. Another undesired issue caused by parallel interconnections is the “loop flow” which is defined as a flow through a network part not meant to supply local loads. This unintended flow can limit power transaction schedules and increases power losses in the network involved.

Along with a large-scale implementation of DGs, the power flow will gradually change from an unidirectional to a bidirectional stream. In addition, DGs’ power output is fluctuating and is hardly predictable. These uncertain characteristics cause also operational problems, such as too large voltage deviations.

B. Solution review

The most popular method for controlling the network, using the optimal power flow (OPF), is a centralized solution that affects the overall network. It is normally deployed at the economic dispatch stage to find out the optimal operation state of the network with respect to system constraints. The mathematical model of the OPF problem can be presented as follows:

$$\begin{aligned} \min \quad & f(x, u) \\ \text{subject to: } \quad & g(x, u) = 0 \\ & h(x, u) \leq 0 \end{aligned}$$

where $f(x, u)$ is the objective function that can be adjusted to deal with different purposes, i.e., power production cost or power loss minimization. The vector of independent variables u presents for the state of the system, the phase angles and load bus voltages. The vector of dependent variables x presents the control variables, for example, power generations or tap ratios of OLTC transformers. The equality constraint represents the power balance between supply and demand while the inequality constraint shows the operational limits of network components.

OPF requires a large-scale control overview that is impossible to deploy in the distribution networks such as the AN. To overcome this disadvantage, distributed OPF techniques have been proposed recently [2]. However, they still need complex input information and take relatively long time processing.

Price-based control can also be considered as a distributed OPF solution. By converting the power system parameters into desired market signals, the solution yields nodal prices for generators that can not only deal with congestion problem but also contribute to other ancillary services [3]. This can be presented in a mathematical model as follows:

$$\begin{aligned} \min \quad & \sum_{i=1}^n f(P_i, P_i^{ex}, A_i, A_i^{ex}) \\ \text{subject to: } \quad & P_i - P_i^{ex} - P_i^{load} = 0 \\ & A_i - A_i^{ex} - A_i^{req} \geq 0 \\ & g_i(P_i, A_i) \leq 0 \end{aligned}$$

where $f(P_i, P_i^{ex}, A_i, A_i^{ex})$ is the aggregated cost function of an AN i ; the equality constraint represents for power balance; the upper bound condition denotes requirements of ancillary services while the lower bound condition shows the operational limits of network components.

In high voltage networks, Flexible AC transmission (FACTS) is one of the effective means that can regulate power flows independently [4]. FACTS elements are categorized into shunt compensation (SVC, STATCOM), series compensation (TCSC), and hybrid compensation (UPFC). Regarding the distribution network having a high R/X ratio, power electronic series devices such as TCSC or UPFC can work effectively [5]. Also in [5], the concept of an intelligent node is proposed as a series controller that connects feeders based on electronic interfaces, such as back-to-back converters. These devices can be used to control the power flow and to limit voltage deviations, leading to increased utilization of network components and higher DG penetration possibilities.

However, the influence of FACTS devices is just in a limited area of the system. To obtain an optimal impact, it is necessary to coordinate with other controllable components of the system.

Recently, the concept of an Intelligent Power Router (IPR) is proposed as a new function in power delivery systems [6]. By connecting to generators, power lines, and customers, an IPR not only observes the current network condition but also cooperates with others to find alternative power flow paths in necessary cases. This approach is quite similar with the ideas of the interconnection of ANs. However, the objective function for making decisions is just on minimizing load shedding while satisfying the operating constraints. This simple algorithm can not reach the optimal operation of the complex system. The application of FACTS devices for control purposes makes the performance much better.

C. Proposed technique

This section proposes a solution based on the application of graph theory and the use of power flow controllers (PFC). The method is implemented with support of multi-agent (MAS) technology, which is mentioned in designing the AN.

In general, the power flow control can be formulated mathematically as an optimization problem including equality and inequality constraints as follows.

Objective function is:

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

subject to:

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

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

where,

$\Delta P_{gi}, \Delta P_{ti}, \Delta P_{li}$ Present a change in power generation, transmission and load.

$\alpha_i, \beta_i, \gamma_i$ Label the costs for production, reliability and load priority.

ΔP_{lossi} Gives the power loss on component i .

$P_{ti}, P_{ti \max}$ Are the available power and capacity limit of component i .

S, T, D Define the supply, transmission and demand area sets.

The objective function of equation (1) is the total cost for power delivery from the generation areas to the load parts. It reflects overall economic dispatch regarding the security of the transmission components and load priority. The equality constraint (2) represents the power balance condition. The inequality constraint (3) represents physical operating limits.

This optimization can be solved in a distributed way by the application of graph theory. The power system, firstly, is converted to a graph $G(V, E)$, where V presents for the set of vertices (cells in the AN) and E presents for edges (interconnection lines among cells in the AN). The edge length (edge cost) c_{ij} and residual (available) capacity r_{ij} associated with each edge (i, j) is derived from the transmission cost β_i and the transmission line capacity u_{ij} . Two vertices are added: a virtual source node (s) and a sink node (t). For each cell i with generation, a source edge (s, i) is added with residual capacity r_{si} (cell generation available) and cost c_{si} (cell production cost α_i). For each cell j with load, a sink edge (j, t) is added with residual capacity r_{jt} (cell load demand) and cost c_{jt} (cell load priority cost γ_i).

In the graph model, the power flow optimization can be defined as a minimum cost flow problem that regards to both the shortest path (economy) [8] and the maximum flow (capacity) [9]. A simple and effective solution to solve the minimum cost flow problem is the successive shortest path algorithm [7].

A node potential π_i is associated with each vertex i of the graph $G(V, E)$. The source node potential is firstly set as 0. The algorithm starts updating the other node potentials until they satisfy the shortest path optimality condition:

$$\pi_j \geq \pi_i + r_{ij} ; \text{ for all } (i, j) \in E \quad (4)$$

After updating the node potentials of all vertexes, the shortest path is getting out by tracking edges from t backward s . The algorithm then augments the flow along the shortest path from s forward t until reaching the capacity of at least one edge. After updating the flow, it finds another shortest path and augments the flow again. The algorithm is ended when there is no possible path from s to t .

An example of a 5 cell system is shown in Fig.2. The graph model of the system is shown in Fig.3. The edges among cells represent interconnection lines with associated the

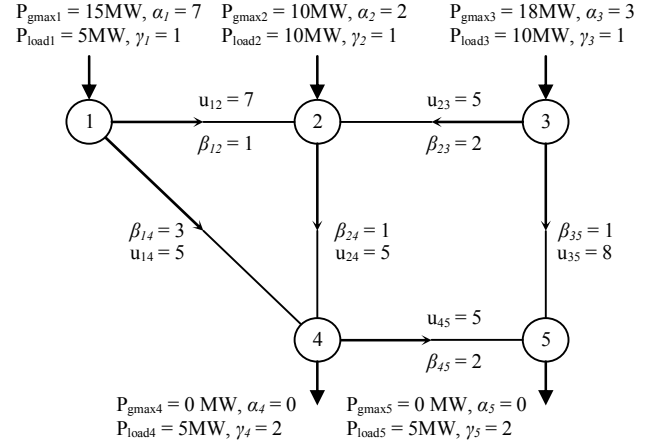


Fig. 2. An example of the Active Network.

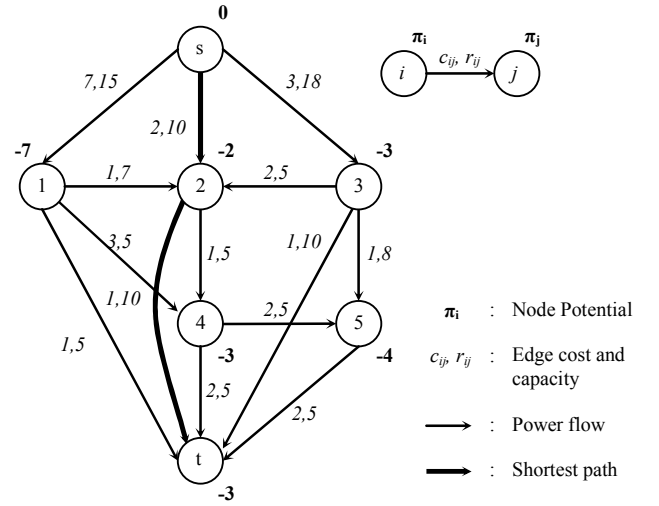


Fig.3. Augmenting power flow along the shortest path

transmission cost (β_i) and the transmission line capacity (u_{ij}). Three directed edges from s to node 1, 2, and 3 represents generation of cell 1, cell 2, and cell 3, respectively. Associated numbers of these edges are cell's power generation cost α_i and power generation capacity P_{gmaxi} . Five directed edges from 5 nodes to t represents load demand of each cell, respectively. Associated numbers of these edges are cell's load priority cost γ_i and load demand P_{loadi} . A detail implementation of the above algorithm for this example will be presented in the next section.

D. Distributed implementation

The main idea of the distributed approach is controlling the power flow based on a so-called power router system. The power router is a combination of an agent (software) and a power flow controller (hardware). An illustration of this configuration is shown in Fig. 4.

The agent, in this case, is the moderator A_i of each cell. It can get local area information such as the power flow on incoming (outgoing) feeders, power generation reserve, power load demand, and costs of production and load priority. Besides managing autonomous control actions, this agent can route message to communicate with the same level agents.

Two additional agents, A_s and A_t , are created to represent the source node s and the sink node t of the graph $G(V, E)$.

The PFC might be the application of several electronic devices, i.e., converters or an intelligent node [5], that is used to control the power flow for its feeder based on the set point given by the moderator.

Following up the above example of the 5 cell system, as the source node has potential $\pi_s = 0$, A_s sends its information to the neighbors (A_1 , A_2 , and A_3). Their nodes potential are updated regarding the condition (4) with the received information π_s and edge cost c_{si} . The potentials of A_1 , A_2 , and A_3 are then updated as -7, -2, and -3, respectively. Although A_2 receives two additional messages from A_1 and A_3 due to incoming lines 1-2 and 1-3, π_2 is still kept as -2 because it satisfies (4).

After getting all the messages, A_t identifies the shortest path according to its potential π_t . In this case, the shortest path is s -2- t with the potential $\pi_t = -3$. Then, A_t backwards message to augment power flow. The augmentation must be under the limit of the shortest path capacity (10 MW).

After getting back the confirmation message, A_s is then looking for another shortest path with updated data. The procedure is completed when A_s can not find any shortest path to A_t .

IV. SETTING-UP SIMULATION

A. Electrical Power System Model

The above example of the 5 cell system is simulated using Matlab/Simulink. Each cell (subsystem) is presented by a simplified synchronous machine, local loads, and PFCs. For the loading cell, the synchronous machine is replaced by an equivalence source. An “Embedded Matlab Function” is created for each cell as part of the power router. Local information about the subsystems is transferred through this block for being processed at the MAS platform. The block then receives control set points for the generation and the PFCs.

In this research, the PFC model is derived from a series part of the UPFC phasor model, which belongs to SimPowerSystem toolbox of Simulink [10]. The main objective of this model is to control the active power flow with respect to reference values given by MAS. Through PI regulators, error values are transferred to the V_d and V_q components of voltage that are used as control signals to the series converters. For simplicity, PFC uses a Current Source block instead of real power electronic devices to control the power flow.

B. Multi-Agent System Model

MAS is created under the Java Agent Development Framework – JADE [11]. JADE has recently been used as a popular platform for application of MAS in power engineering applications. It supports a Graphic User Interface and uses communication languages that follow the Foundation for Intelligent Physical Agents (FIPA) standard.

In this simulation, each subsystem is managed by a pair of the agents, i.e., a socket proxy agent (spa) and a server agent (SA). While the spa agent is used as the communication agent with Matlab/Simulink, the SA agent is a principal agent that

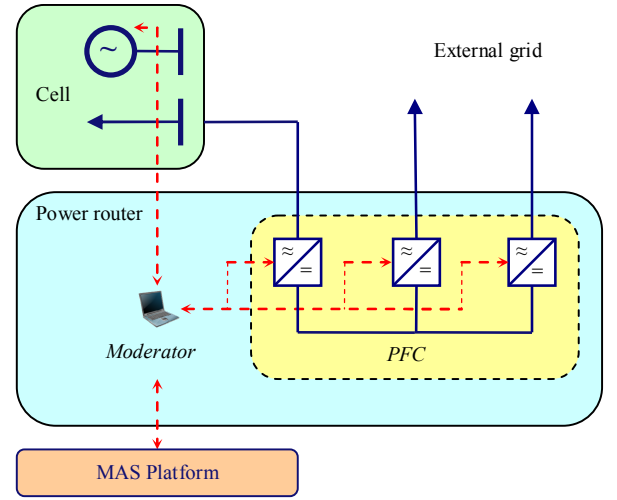


Fig.4. Power router configuration.

has all functions mentioned in the previous section. Two additional server agents, SA0 and SA6, are created to represent the virtual source node s and sink node t of the graph.

C. The Protocol

The protocol for communication between Matlab/Simulink and JADE is based on client/server socket communication. The socket proxy agent in JADE is used as a server socket. By using the TCP/UDP/IP Toolbox, each “Embedded Matlab Function” in Matlab/Simulink can create a client socket to send data to and receive data for the spa agents. The communication time is set at 0.5 sec.

V. STUDY CASES

A. Optimal operation

The 5 cell system shown in Fig.2 has been investigated to find out the optimal operation. Table I presents variations of the power flow and the consequent cost saving before and after applying the control method. As can be seen from the table, a major part of total cost is saved from decreasing the power generation in cell 1. Mitigating the power flows on line 1-4 also reduces significantly the transmission cost. Therefore, the total flow costs (in money-based unit) before and after controlling are 208.82 p.u and 189.74 p.u, respectively. The total cost saving is 19.08 p.u.

Dynamic behaviour of the system when the proposed method starts working is shown in Fig.5. At $t = 5$ s, each agent starts collecting and sharing information across the MAS platform. At $t = 10$ s, new reference values are set for the generation and the PFC devices. The generators and PFC devices start controlling the power to reach new set points. The transient state occurs within around 10 sec and the system reaches a new optimal state.

TABLE I
POWER FLOW VARIATION AND THE COST SAVING
OPTIMAL OPERATION

From Cell	To Cell	Before control P_g , MW	Power flow, MW	After control P_g , MW	Power flow, MW	Cost diff.
1	2	9.98	1.495	6.846	1.842	-0.35
	4		3.501		0.000	10.50
2	3	9.03	-1.476	10	-3.033	-1.94
	4		2.133		4.866	-2.73
3	5	16.04	4.402	18	4.904	-0.50
4	5		0.638		0.07	1.14
Total cost difference						19.08

B. Congestion management

To see the capability of the method to cope with congestions, the capacity of line 3-5 is decreased from 8 MW to 4 MW. Although there is no change of generation dispatch, the power flows are different from the previous case due to the restriction of the lines. Therefore, the total flow cost is higher than previous case (193.62 p.u). The power flow variations and transmission cost changes are shown in Table II. The power flow in line 3-5 reaches its capacity of 4 MW.

TABLE II
POWER FLOW VARIATION AND THE COST SAVING
CONGESTION MANAGEMENT

From Cell	To Cell	Before control P_g , MW	Power flow, MW	After control P_g , MW	Power flow, MW	Cost diff.
1	2	9.98	1.495	6.846	1.001	0.49
	4		3.501		0.833	8.00
2	3	9.03	-1.476	10	-3.876	-4.80
	4		2.133		4.866	-2.75
3	5	16.04	4.402	18	4.000	0.40
4	5		0.638		0.781	-0.29
Total cost difference						15.20

C. Production cost variation

With large-scale implementation of DGs in the distribution networks, the production costs will fluctuate frequently. To see the capability of the method to deal with production cost change, power generation costs of cell 1, cell 2, and cell 3 are changed from 7, 2, and 3 to 3, 4, and 5, correspondingly. The difference in production costs establishes a new optimal operation state of the network. Those variations are presented in Table III. With new production costs, the total flow costs before and after controlling are 219.03 p.u and 209.06 p.u, respectively. Cost saving is accumulated mainly from mitigating the power flow on line 1-4 and decreasing power generation of cell 3.

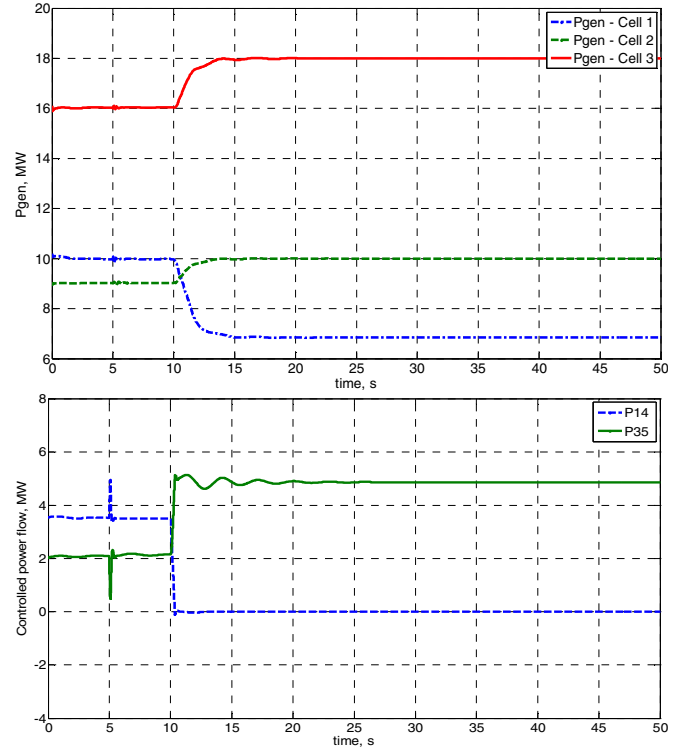


Fig. 5. Power generation and controlled power flow

TABLE III
POWER FLOW VARIATION AND THE COST SAVING
PRODUCTION COST VARIATION

From Cell	To Cell	Before control P_g , MW	Power flow, MW	After control P_g , MW	Power flow, MW	Cost diff.
1	2	9.98	1.495	10	5.000	-0.05
	4		3.501		0.000	-3.51
2	3	9.03	-1.476	10	-0.020	10.50
	4		2.133		4.870	-3.88
3	5	16.04	4.402	14.84	4.830	-2.74
4	5		0.638		0.060	6.00
Total cost difference						-0.43
						1.16
Total cost difference						9.97

VI. CONCLUSION

This paper introduces the concept of Active Networks as an effective, flexible and intelligent solution for the future. In this respect, the function of power flow management has been developed. This function is implemented in a distributed way supported by the Multi-Agent System technology. The algorithm used for distributed control comes from the application of the graph theory.

The simulations show that the method can allow both the generation and the PFC devices to operate optimally. Although the method is introduced as an application for the Active Network concept, this technique can be used for systems on various scales with similar structures. In particular, it could be applied for the transmission networks with available FACTS devices.

The directed graph model represents a power system with a certain power flow direction. It might get bad conditions when

the power flow is changed drastically. An application of undirected graph model could mitigate this problem.

As using a straightforward algorithm of the graph theory, the number of messages following among agents (the computation times) is significant. Further study is needed reduce this computation burden.

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VIII. BIOGRAPHIES



the framework of the "Electrical Infrastructure of the Future" project.

Phuong H. Nguyen was born in Hanoi, Vietnam in 1980. He received his M.Eng. in Electrical Engineering from the Asian Institute of Technology, Thailand in 2004. From 2004 to 2006 he worked as a researcher at the Power Engineering Consulting Company No. 1, Electricity of Vietnam. In the end of 2006 he joined the Electrical Power System Research group at Eindhoven University of Technology, the Netherlands as a Phd student. He is working under



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Mr. Kling is involved in scientific organizations such as Cigre and IEEE. He is the Dutch Representative in the Cigre Study Committee C6 *Distribution Systems and Dispersed Generation*.



with the Eindhoven University of Technology, the Netherlands. In 2002 she became an assistant professor and since 2008 she is an associate professor in the field of residential electrical infrastructure. Her fields of interests are: power electronics, renewable energy, distributed generation, electrical power supply.

Johanna M.A. Myrzik was born in Darmstadt, Germany in 1966. She received her MSc. in Electrical Engineering from the Darmstadt University of Technology, Germany in 1992. From 1993 to 1995 she worked as a researcher at the Institute for Solar Energy Supply Technology (ISET e.V.) in Kassel, Germany. In 1995 Mrs. Myrzik joined the Kassel University, where she finished her PhD thesis in the field of solar inverter topologies in 2000. Since 2000, Mrs. Myrzik is