Lab design and implementation of MAS-based active network

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G. v. d. Wolk, *Student member IEEE*, P. H. Nguyen, *Student member IEEE* and W. L. Kling, *Member IEEE*

***Abstract* - The introduction of distributed generation (DG) in ever increasing amounts into the existing electrical infrastructure challenges network operators in the way they manage the network. These DGs are often controllable but far from the present day control rooms. With the amount of generators increasing very fast, so will the number of sensors and actuators, growing to numbers way too large to handle in a single control room by human intervention. As the networks are changing from passive to active, more and more the need for automation arises. To accommodate this need the network can be divided into cells of which the borders are created naturally at places where the power flow over that border can be controlled. The cells are capable of managing tasks like protection, voltage and power control autonomously. If more power is needed they can exchange this with neighboring cells and in the worse case they can be completely decoupled from neighboring cells to ensure stability or to be operated in island mode.**

In this paper an active network is implemented on a test platform to investigate Multi-Agent control Systems (MAS), a form of distributed control to accommodate the cell structure.

Index terms – active networks; distributed generation; multi-agent system; DC bus controller; power controller.

I. Introduction

ENCOURAGEMENT to install more distributed generation (DG) challenges the distribution networks in coping with bidirectional power flows, voltage variations, fault level increases, protection selectivity, power quality and stability. The active network (AN) has recently been introduced in the electrical distribution system to adapt to the large-scale implementation of DG [1]. With one more control layer, each local area network in the AN is defined as a cell which is able to manage power inside and across cell boundaries.

To enable the AN concept, it is necessary to develop a flexible, intelligent and distributed control platform. Multi-agent system (MAS) is considered as an appropriate environment for this purpose [2]. Active elements of the AN, i.e., controllable generators and loads, will be represented by agents (software or hardware entities) that can operate autonomously with local targets or cooperate with others to achieve area tasks. A superior agent is installed in each cell as a moderator to manage autonomous actions as well as to communicate with other cells.

Application of MAS in the power system is, however, still limited because of several technical implications. There are challenges to develop scalable distributed algorithms which can be used in MAS platform. These algorithms must deal with emerging control functions, i.e, voltage regulation, power flow management. In addition, knowledge about agent design, platform, communication languages and ontology, and data standards are necessary.

In this paper, a laboratory MAS-based active network has been designed and implemented. The main objective of the research is to set up an optimal and realistic platform for further study on MAS-based AN.

II. MAS-based AN

A possible configuration of a MAS-based Active Network is shown in Fig.1 [2]. As intending to facilitate DG integration, the AN might be implemented in the medium voltage or low voltage networks. Each distribution substation represents a cell, which includes load consumption and DGs. Active components of the cell, i.e., controllable loads and generators, are managed by representative agents. Through a master agent of the cell, those agents can communicate with other cells' agents of the AN.

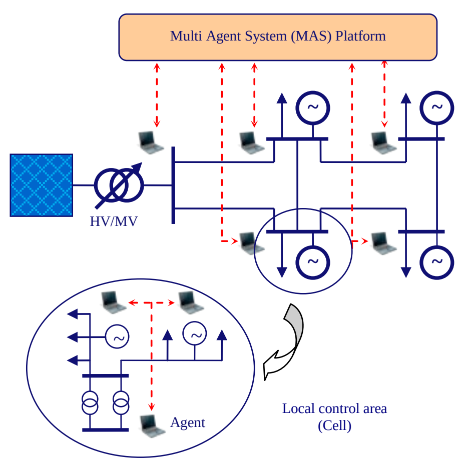

Fig. 1. Active Network managed by multi-agent system.

When an additional control level is installed for each cell component, the control architecture of the moderator of the cell has the same functions as a Distribution Management System (DMS) [3]. With the support of the MAS application, the moderator not only concentrates on the autonomous area

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but also communicates with its neighbours. The two main functions of the moderator are Distributed State Estimation (DSE) and Local Control Scheduling (LCS). The DSE can analyze the network topology, compute the state estimation, and detect bad data. Depending on the information received from the DSE, the LCS will establish the control set points for different actuators such as voltage regulation or active and reactive power control of FACTS, local generators and controllable loads. The control architecture of moderators is shown in Fig.2.

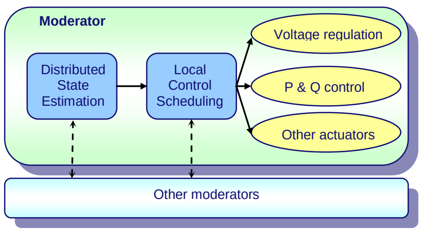

Fig. 2. Control architecture of the moderator.

III. LAB SET-UP

A. Set-up description

The proposed MAS-based controlled AN network was tested in a lab set-up, shown in Fig.3. The set-up used is composed of a grid simulator supplying feeder 1 with three controllable inverters, three loads and one uncontrolled wind turbine. A power router concept is introduced which combines an intelligent agent with the controllable inverters. This will enable the cell to manage energy flows within the cell and across the cell boundaries. With this set-up it is possible to investigate the behavior of each agent-controlled cell in the network.

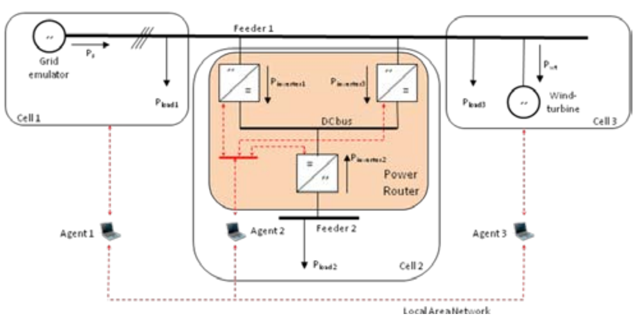

Fig. 3. Lab implementation set-up.

The wind turbine emulator consists of a 11kW motor-generator set-up. By controlling the motor speed, the variation in wind power can be emulated.

B. Inverter Control

The power router consists of three inverters with a common DC bus of which the controllers need to be designed; the inverters themselves are bi-directional and are composed of a three-phase uncontrolled rectifier followed by a three-phase voltage source inverter with a LCL output filter, Fig. 4.

Inverter 1 and 3 both are connected to the grid (feeder 1) and inverter 2 connected to feeder 2. To be able to control the power flow through inverter 3, the DC bus voltage must be boosted to well above 650V and this voltage must be maintained during operation. This is done by controlling the power flow through inverter 1, thus in turn controlling the voltage on the DC bus capacitance [4].

As only one side of the set-up is connected to the grid, one of the inverters connected to the grid must also ensure synchronization with the grid so that the remaining two inverters can generate voltages that are synchronized to the grid voltage.

Inverter 3 must be able to regulate it's output power (both active and reactive). So a controller is needed to control the inverters output current. To do this one can use Park transformation and use PI controllers to control the current components of the resulting two-phase system.

A PLL is used to generate the sine and cosine terms needed for the Park transformation and reverse transformation. Using these synchronized sine and cosine terms will ensure that the generated voltage is also synchronized to the grid voltage.

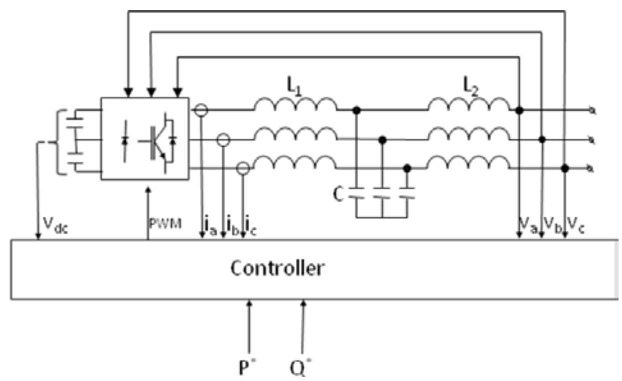

Fig. 4. Schematic representation of the inverter with controller.

The control scheme used to control the output current of inverter 3 and thus the output power is shown in Fig. 5. For the current controller, PI controllers are used. PI controllers, with their limited amount of design parameters, are well known and are easily designed. The PI controllers in the current control loop are designed by considering an LCL output filter. To do this the LCL output filter is modeled in the s-domain, see (1), [6].

$$H(s)=\frac{I_1(s)}{V_1(s)}=\frac{L_2Cs^2+1}{L_1L_2Cs^3+(L_1+L_2)s}. \qquad (1)$$

The LCL filter has the following component values: L_1=6.4mH, L_2=2.1mH and C=2.2μF. Converting (1) to the z-domain using the zero-order hold method and the component values given above, leads to the following transfer function:

$$G(z)=\frac{0.01665z^2+0.01145z+0.01665}{z^3+0.04296z^2-0.04296z-1}. \qquad (2)$$

The transfer function of the PI controller in the z-domain is:

$$C(z)=K\left(1-\frac{1}{\tau_i}\frac{T_s}{z-1}\right), \qquad (3)$$

which can also be written as:

$$C(z)=K\frac{z-a}{z-1}, \qquad (4)$$

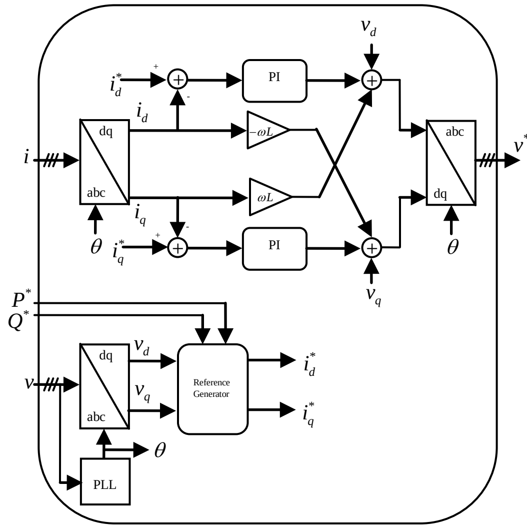

Fig. 5. Inverter control scheme

where $a = 1 - (T_s / \tau_i)$ is the position of the controller's zero. The position of the zero and the gain were first determined using the root locus tool included in the control systems toolbox in Matlab with the only criteria being stable and a damping ratio of 0.707, leading to the following controller parameters:

$$K = 17.551 \qquad \tau_i = 1.1\,ms, \tag{5}$$

however this controller turned out to be unusable because it continuously tripped the inverter set-up's protection systems. To overcome this problem the parameter values were tuned on the inverter set-up, resulting in a reasonable controller with the following parameter values:

$$K = 0.08 \qquad \tau_i = 40\,ms. \tag{6}$$

The open loop pole zero map and the closed loop root locus of the controller used are shown in respectively Fig. 6 and Fig. 7 and the step response of the compensated system in Fig. 8.

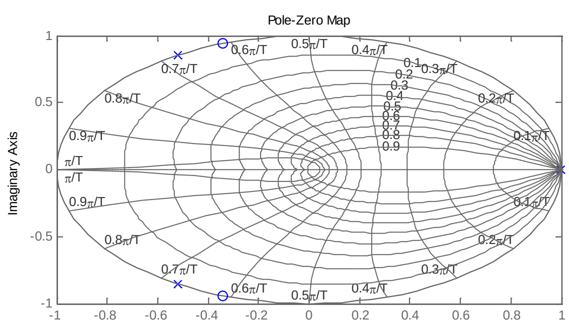

Fig. 6. Pole zero map of the LCL inverter output filter

As can be deducted from Fig. 6, a descent PI controller is hard to design. As mentioned earlier faster controllers were designed using the root locus method, but these would trip the inverters protection systems. In this case more complex, higher order controllers would have been more suitable.

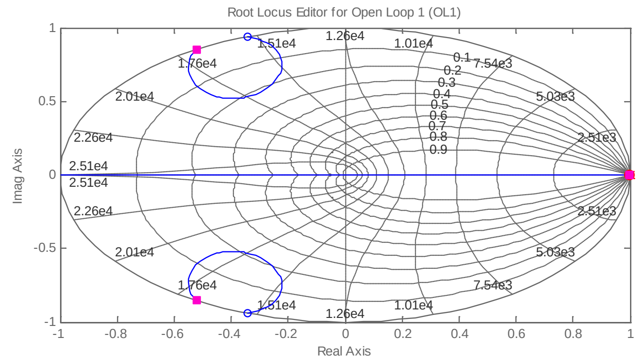

Fig. 7. Root locus of the compensated system

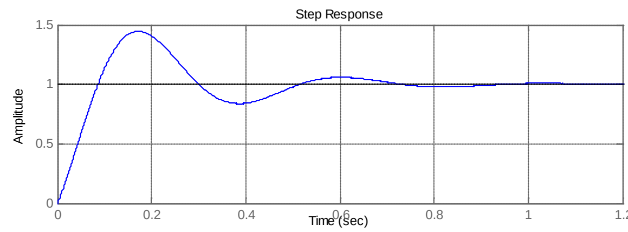

Fig. 8. Step response of the system with the implemented controller

As was mentioned earlier inverter 1 must boost the DC bus voltage well above 650V and must maintain this voltage during operation. To do this an additional PI controller is used that will add to the direct current reference, see Fig. 9.

The control parameters needed for the DC bus PI controller were again determined by tuning the parameters on the inverter set-up, resulting in the following parameter values:

$$K = 0.026 \qquad \tau_i = 12.5\,ms, \tag{7}$$

and the parameters of the current controller used for inverter 1 are:

$$K = 0.08 \qquad \tau_i = 12.5\,ms. \tag{8}$$

In principle the same current controllers can be used, but again the resulting controllers would trip the protection system incorporated in the inverter set-up.

An external DC source could be used as an alternative to the DC bus controller having in mind that the implemented active network is only used to prove the multi-agent active network control concept and not to design optimal grid coupled inverter control algorithms.

Inverter 2 that powers feeder 2 uses a feed forward voltage controller, thus cannot guarantee that the applied voltage is sinusoidal with an amplitude of about 325V. In real applications this kind of controller would not be suitable, especially in the case of non-linear loads that draw distorted currents. However in this test set-up the load on feeder 2 is a light resistive load, drawing small sinusoidal currents in phase with the voltage and the load is such that the voltage amplitude is always within the ±10% interval required by the standards.

The agent forms an upper control layer that is able to communicate with neighboring agents and to control the active and reactive power references of the device they are controlling. For the test platform the controllers do not have to be as fast as possible, because the nature of the network and grid simulator will assure that the demand and supply are always matched. This will give the agents time to negotiate and the controllers time to achieve their new reference values allowing the system to settle in a new load flow situation.

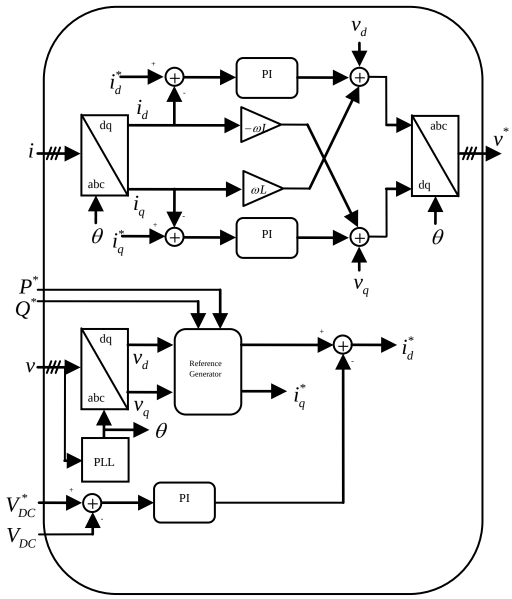

Fig. 9. Controller of inverter 1 including the DC bus controller

So to prove the concept the only real criteria posed on the controller of inverter 3 is that it should be stable and capable of controlling the output power of inverter 3, both active and reactive. The criteria posed on the controller of inverter 1 is that it ensures stability and is capable of controlling the DC bus voltage.

C. MAS Control

The representative agent of each cell receives state variables which are collected from the three inverters. Besides managing autonomous control actions, this agent can route messages to communicate with the other (same level) agents. Depending on the network situation, the objectives of control coordination might be voltage regulation or power flow management.

MAS is created under the Java Agent Development Framework – JADE [5]. 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.

The agents will be programmed in simulink and by using the TCP/IP toolbox can communicate with JADE, JADE will then route the messages to the desired agents.

In this set-up only agent 2 is really controlling a power electronics device, the other two agents (agent 1 and 3) are not controlling the devices they represent but are pre-programmed with the maximum power they can supply and the per unit price of the power they supply, this is sufficient to be able to test the cell's control agent in a Multi-Agent environment.

In this test the source can supply a maximum amount of power, $P_{s,max}$, at a price, A_s p.u. and the wind emulator can supply a maximum amount of power, $P_{w,max}$, at a price, A_w. When the load on feeder 2 increases, the load will temporary be supplied by the grid (the source) while agent 2 will communicate with the other agents requesting power. Agent 1 and agent 3 will both respond with the amount of power they can supply and at what price. The power-router agent must then decide how much power it will consume from each neighboring agent, and sends a response to notify the neighboring agents about the decision made and adjusts the reference values of the power-router to accommodate the new situation.

IV. Results

To test the active network and the multi-agent system two test cases are performed. Case 1 will test the functionality of the active network by initiating the network and power-router and after that it settles changing the power references of inverter 3. Case 2 will test the multi-agent system by initiating the whole system and after that it settles changing the load power on feeder 2, after this the agents will react and adapt the load flow to accommodate the new situation.

A. Results Case 1

The network is initiated in the following state: $P_{load1}=4kW$, $P_{load2}=0W$, $P_{load3}=0.159kW$, all inverters are disconnected so $P_{inv1}=P_{inv2}=P_{inv3}=0W$, both the wind turbine and source are feeding the two loads with $P_{wt}=-0.918kW$ and $P_s=3.241kW$. Note that the wind turbine is considered to be a load, so a negative power means that the turbine is supplying power.

At $t=1s$, inverter 1 connects to the grid and boosts the DC bus voltage to 680V, Fig. 10. At $t=20s$ inverter 3 connects to the grid at which the controller of inverter 3 will drive the output power (both active and reactive) of inverter 3 to zero. At $t=30s$ inverter 2 connects to feeder 2 and starts feeding load 2. Fig. 10 validates that the DC bus controller can boost the DC bus voltage and can maintain this during disturbances caused by the changing the load flow in the network.

At about $t=35s$ the power flow settles in the second state: $P_{load1}=4kW$, $P_{load2}=0.772kW$, $P_{load3}=0.159kW$, all the inverters are connected, inverter 1 is powering the DC bus, inverter 2 is feeding the load on feeder 2 and inverter 3 is not consuming nor supplying power: $P_{inv1}=1.169kW$, $P_{inv2}=-0.773kW$ and $P_{inv3}=0W$. The wind turbine power output has remained unchanged and the extra power is being supplied by the grid: $P_s=4.410kW$.

To test the power control both the active and reactive power references are initially set to zero and at t=65s the active power reference is stepped to 500W and at t= 95s the reactive power reference is stepped to 500Var, the results of which are plotted in Fig. 10. The disturbance in the active power at t=95s is caused by the change in reactive power. The plot shows that the power controller, controlling inverter 3, acts correctly but a more optimal design would improve response times. From the results one can determine the power loss in the inverter set-up, this is approximately *397W*.

Fig. 11 shows more detailed plots of the output current of inverter 1 at the moments each inverter connects. At $t=1s$ inverter 1 connects and one second later at $t=2s$ the controller is initiated. During the time interval from $t=2s$ to $t=3s$ the DC bus voltage rises naturally to 558V after which the controller takes over and boosts the DC bus voltage up to 680V. As can be seen this boosting action causes the current to exceed 6A; these high peak currents made it difficult to design a controller that would not trip the protection system. At *t=20s* inverter 3 connects and at *t=21s* the controller initiates and drives the output power of inverter 3 to zero. At *t=30s* inverter 2 connects and starts feeding load 2.

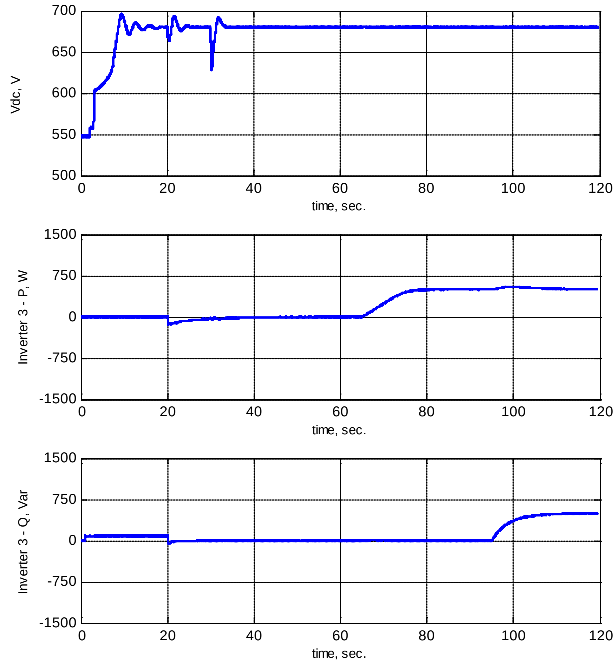

Fig. 10. DC bus voltage, active and reactive power inverter 3

B. Results Case 2

This test case was executed in three stages. First the system was initiated and at *t*=50s the load power is changed, the measurements were taken and stored in the computer's memory. The stored measurements were then used as the input to the agent system, the agent's control signals were also stored in the computer's memory. Again the power-router is initiated and the load changed at *t*=50s, the power controller then uses the stored control signals as it's reference.

Again the network is initiated in state 1 and will settle in second state at *t=35s* just as in case 1, but in this case a higher load is used on feeder 2 resulting in the following load flow situation: $P_{load1}=4kW$, $P_{load2}=0.855kW$, $P_{load3}=0.159kW$, $P_{inv1}=1.259kW$, $P_{inv2}=-0.855kW$, $P_{inv3}=0W$, $P_{wt}=-0.918\ kW$ and $P_s=5.355\ kW$.

At *t=50s* the load on feeder 2 is increased by $\Delta P=173W$ and the system will temporary be in a third state in which the extra load power will be supplied by the grid through the uncontrolled rectifier part of inverter 1. In state 3 the network is in the following load flow situation: $P_{load1}=4kW$, $P_{load2}=1.028kW$, $P_{load3}=0.159kW$, $P_{inv1}=1.435kW$, $P_{inv2}=-1.028kW$, $P_{inv3}=0W$, $P_{wt}=-0.918\ kW$ and $P_s=5.704\ kW$.

After about 5s negotiating time the agent 2 changes the active power reference of inverter 3 and at *t=80s* the load flow settles again in state 4. In state 4 the following load flow situation is achieved: $P_{load1}=4kW$, $P_{load2}=1.028kW$, $P_{load3}=0.159kW$, $P_{inv1}=1.346kW$, $P_{inv2}=-1.028kW$, $P_{inv3}=0.073kW$, $P_{wt}=-0.918kW$ and $P_s=6.408kW$. Fig. 12 shows the final results of case 2.

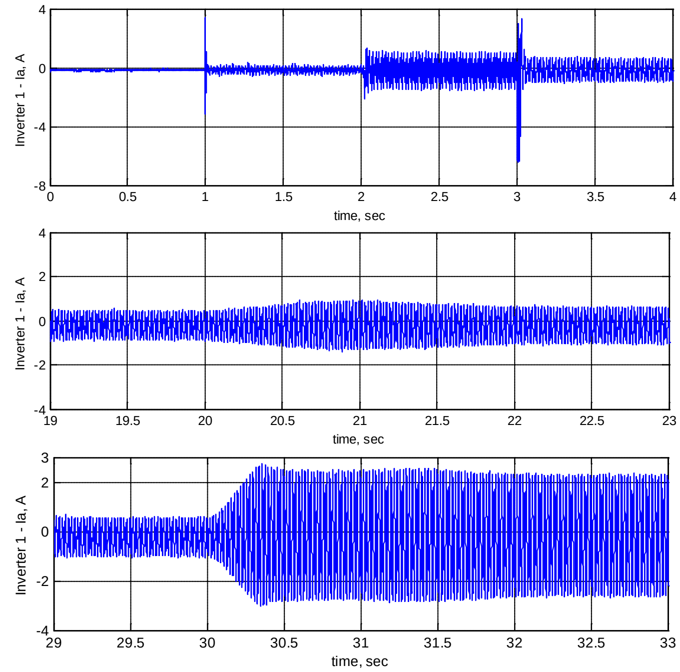

Fig. 11. Inverter 1 current through phase A

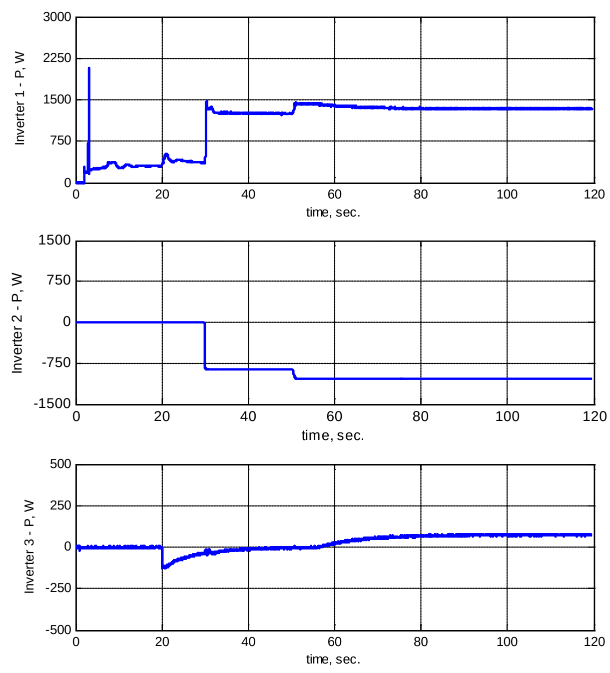

Fig. 12. Active power inverter 1, 2 and 3.

To design agents the Unified Modeling Language (UML) is often used. UML offers a standardized design procedure consisting of several diagrams. One of the diagrams used in UML is the sequence diagram; this diagram depicts the communication between the agents of a multi-agent system and is similar to timing diagrams used for designing computer communication protocols. JADE offers the possibility to visualize the communication between agents using a sequence diagram, see Fig. 13.

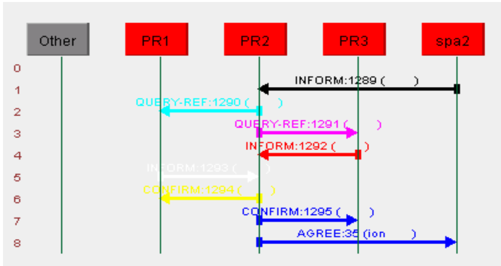

Fig. 13. UML sequence diagram .

Fig. 13 needs a bit of clarification, PR2 stands for agent 2 (the agent managing cell 2), PR1 stands for agent 1 (the agent managing cell 1) and PR3 stands for agent 3 (the agent managing cell 3). Spa 2 is an extra agent whose only function is to open a communication channel, allowing agent 2 (running in matlab/simulink) to communicate with the other agents. Along the vertical axis we see time and the arrows indicate the messages between the agents.

We see that after agent 2 detects the load change it sends a query to agent 1 and 2, requesting power. Both agent 1 and 2 send messages containing information about how much power they can supply and at what price. Agent 2 will then determine how much power it will consume from each neighboring cell and sends a message to each neighboring agent to confirm this.

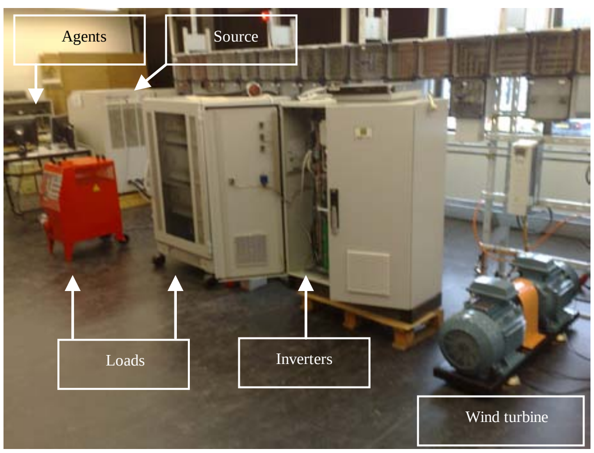

Fig. 14. Lab set-up

Fig. 14 shows a photo of the lab with the lab set-up: in the background one can see a table with three computers on which the agents are implemented, next to that the three-phase source (grid emulator) and on the foreground two of the used loads, the inverter set-up and the wind turbine emulator set-up.

V. Conclusions

With this lab implementation we have shown that the MAS concept works and can be used to manage electrical networks with distributed generation and controllable loads, the so called active networks. Although at this moment there is still a lot of room for improvements.

The controllers work sufficiently for this first test set-up, but better design procedures should be researched to optimize the DC bus voltage and output current controllers. The feed forward voltage controller should be replaced by a regulated voltage controller. Real-time interfaces are needed to test the system in real-time.

Follow-up work will be done on the controllers and further testing will be done in which the MAS control concept will be used to control a more complex active network. When controllable generation or storage is added to feeder 2, cell 2 could be disconnected and operated in island mode. During island mode voltage controllers are needed and during grid connected mode current controllers. An extra controller is needed to detect the modes and to switch to the appropriate controller. The neighboring agents (agent 1 and 3) should be replaced by real agents that can control and monitor the device they represent. More test cases should be performed in which not only power flow is managed but services like voltage regulation and protection are supplied.

VI. References

[1] F. van Overbeeke, “Active networks: Distribution networks facilitating integration of distributed generation,” In *Proc. of 2nd international symposium on distributed generation: power system and market aspects*, Stockholm, 2002.

[2] P. H. Nguyen, J. M. A. Myrzik, W. L. Kling, “Power Flow Management in Active Networks”, In *Proc.of IEEE PowerTech Conference*, Bucharest, Romania, Jun 2009.

[3] J. A. Pecas Lopes, N. Hatziargyriou, J. Mutale, P. Djapic, N. Jenkins, “Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities”, *Electric Power Systems Research*, vol. 77, pp. 1189-1203, 2007.

[4] V.Soares, P.Verdelho, “Digital Implementation of a DC Bus Voltage Controller for Four-Wire Active Filters”, In *Proc. Of 32nd Annual Conference on IEEE Industrial Electronics,* 2006.

[5] JADE – Java Agent DEvelopment Framework [Online]. Available: http://jade.tilab.com/.

[6] Remus Teodorescu, Frede Blaabjerg, “Flexible control of small wind turbines with grid failure detection operating in stand-alone and grid-connected mode” *IEEE transactions on power electronics*, Vol. 19, No.5, September 2004.

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Wil L. Kling (M’95) was born in Heesch, the Netherlands in 1950. He received the M.Sc. degree in electrical engineering from the Eindhoven University of Technology, the Netherlands, in 1978. From 1978 to 1983 he worked with Kema and from 1983 to 1998 with Sep. Since then he was with TenneT, the Dutch Transmission System Operator, as senior engineer for network planning and network strategy. Since 1993 he is a part-time Professor at the Delft University of Technology and since 2000 he was also a part-time Professor in the Electric Energy Systems Group at the Eindhoven University of Technology, the Netherlands. From December 2008 he is appointed as a full-time professor and chair of EES group at the Eindhoven University of Technology. He is leading research programs on distributed generation, integration of wind power, network concepts and reliability.

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*.