MAS-based Active Network Model for State Estimation and Beyond

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***Abstract*—In this study, a Multi-agent System (MAS) based modeling of an active distribution network is presented using cooperative agents. A method to solve a network-wise objective of state estimation is explained with the proposed model. The network component agents are defined to be cooperative to meet the overall objectives and greedy to fulfill individual objectives such as energy cost minimization. A token-ring protocol is presented for the agent communication among themselves as well as with market and network operator agents. Furthermore, a MATLAB/Simulink model of active distribution network is used to simulate the emerging stochastic loading scenario while the autonomous prosumer agents optimize their total energy cost responding to market price variations.**

***Index Terms*— demand response, distributed power generation, IEC 61968, power distribution, multi-agent systems, state estimation.**

I. INTRODUCTION

In the deregulated power systems environment, market initiated and network triggered circumstances are responded with physical and conceptual entities maximizing their optimized gains. Hence the overall network state depends up on the outcomes of individual decisions made by autonomous components. The physically distributed system of power distribution network is a natural case for application of Multi Agent System (MAS) [23]l. Individual components can be modelled so that their respective decisions will help to meet the required overall objective. In recent years there is an increasing trend of deploying this technique for various purposes such as power balance [1]-[3], voltage control [4]-[6], real-time control of distribution circuit [7], condition monitoring and protection [8]-[10] and state estimation [11]-[13]. The concept of utilizing autonomous substation agents for the purpose of state estimation was introduced by Nordman and Lehtonen [11], where the responsibility of state estimator functions such as topology analysis, observability analysis and bad data detection are delegated to local agents in secondary substation.

The type of agents selected in each study depends primarily on the objective of application of Multi-Agent system. Mostly, the physical components such as substation agent, bus agent, feeder agent, load agent and generation agent are used as agent types; for example in [1], [2], [6], [13] and [14]. Agents could also be named and modelled after their respective tasks such as communication agent, maintenance management agent, peak load frequency agent, load forecasting agent and the like as in [3], [9] and [10]. At times, agent types could be a bit detached from their power system representations and named after their software tasks such as agent expert, agent inter, terminal agents and agent communication [5], [15].

In the literature, for the implementation of MAS, authors attempted to use agent communication framework, which follows the Foundation for Intelligent Physical Agents (FIPA) standard. The widely used tool in power system communities is the Java Agent Development Framework (JADE) [1], [5] [13], [15]. Other tools such as XML (extensible markup language) in [3], Knowledge query and manipulation language (KQML) in [16], Petri-Net in [14] and Zeus in [4] are also being used to solve multi-agent systems. Together with agent development platforms for agent communication, power system simulation programs such as Matlab/Simulink in [4] and InterPSS in [1] have also been used. In most of the studies, the proposed MAS have two layers: a power system layer and a multi-agent layer (see Fig. 1).

In [24] decentralized algorithm for fault location, isolation and service restoration was proposed that fits well for the application in a multi-agent way that was subsequently demonstrated in [25] using the distributed automation architecture of IEC 61499 combined with IEC 61850. Here the concept of Intelligent Logical Node was introduced as a foundation for agents that are based on the IEC 61850 compliant data model. The reason for using this architecture

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is the need to implement agents at the standard automation platforms used in substation automation, such as programmable logic controllers (PLC). In [26], the iLN architecture, proposed in [25], was further developed and combined with the Believe-Desire-Intention reasoning pattern, popular in the agent community.

For a better integration of power dispatch and state estimation together with other network functions, MAS agents need to be clearly defined and be accessible. In this regard, there are not many studies presenting generic agents with well-defined objectives and communication protocol for the purpose of distribution network state estimation and beyond. More importantly, MAS interoperability in IEC 61850 environments did not get the required attention.

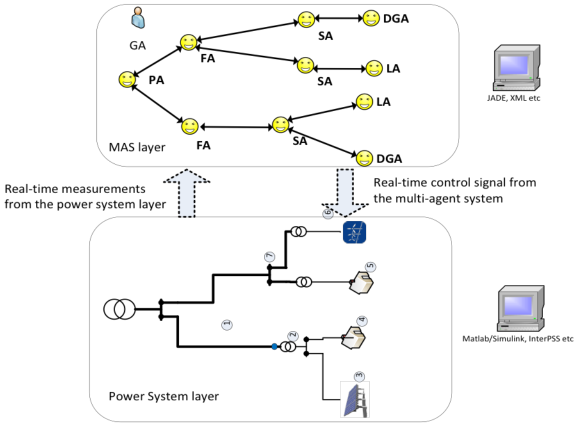

Figure 1. Multi-Agent System simulation setup.

The purpose of this study is to present multi objective and generic MAS model for active distribution network. The model is explained using a distributed state estimation overall network objective. Beyond state estimation, the proposed generic MAS-based active network model can be used for both market price and network capacity based control strategies. The network wise impact of prosumer agents minimizing their energy cost is also simulated using a test active distribution network.

Section II briefly revises related studies. Besides to the presentation of agent types, the importance of compliance of agent ontology definitions with the Common Information Model (CIM) is explained in Section III. In Section IV, the distributed state estimation problem is formulated. The communication protocol for the proposed MAS based model to solve state estimation is explained in Section V. Section VI presents demonstrative simulation results of the test case and Section VII reiterate the main observations.

II. RELATED WORK

In [13], the MAS technique is utilized to improve the performance of state estimation in active distribution network. The state estimation is formulated and presented comprehensively in [13]. Nevertheless, the agent definitions are very general and are in a master-slave hierarchy format rather than cooperative distinct autonomous agents. Hence, the defined agents are not multitasking and multi-objective.

The study in [11] proposes an agent-based distributed state estimation with two approaches. The first is the distribution of the centralized task of state estimation such as bad data detection and topology processing through the cooperation of agents on the token path. The second is the undertaking of area-wise distributed state estimations locally under autonomous secondary substation agents. The concept is explained using only two agent types, the primary substation agent (PA) and the secondary substation agent (SA).

The PA has the responsibility of initiating a token in each token period, which could be 10 min. The traversing token collects switch status and information necessary for topology and observability analysis. In Fig. 2, the local state estimation at secondary substation B as presented in [11] estimates 10 min moving average current measurements of sensors. In the proposed concept, when a substation receives a token it executes the associated action, attaches the result to the token and passes it forward subsequent to each of its neighbours. If the token has reached the last substation in the chain then it recursively returns back to the primary substation.

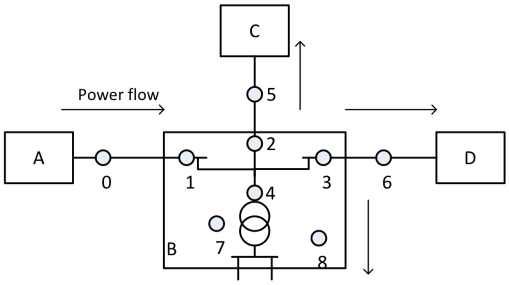

Figure 2. Substation (B) and its neighboring sensors (gray circles) and substations (A, C and D). [11]

Equations (1) and (2) show how these estimated values are attained [11].

$$\Delta I_B(t) = M_1(t) - M_2(t) - M_3(t) - M_4(t) \tag{1}$$

$$M_1(t)^* = M_1(t) - \frac{{\sigma_1}^2}{\sum_{z=1}^{4} {\sigma_z}^2} \Delta I_B(t) \tag{2}$$

Where, $M_1(t), M_2(t), M_3(t), M_4(t)$ are 10-min moving average measurements from sensors 1, 2, 3 and 4 respectively. $M_1(t)^*$ is the estimated moving average measurement of sensor 1 adjusted with $\Delta \mathrm{I_B}(\mathrm{t})$ term. σ_z is standard deviation of measurement *z*.

The presented concept in [11] doesn't explain how local estimated states are hierarchically collected for network-wise state estimations. Moreover, the limited definitions of agents inhibit the access to pseudo measurements and potential utilization of the MAS for other objectives. In this study we intend to propose expanded agent types opening up the potential for more robust state estimation and multi-objective system. Besides, the application of the MAS techniques for distributed state estimation is explained using the traditional Mean Squared Error (MSE) method. A token traversing a radial feeder twice is introduced enabling measurements and estimated states communications to solve the network-wise state estimation. Hence, this study is effectively an extension of the concept proposed in [11].

III. MAS Based Modelling of Active Distribution Network

In this study, the proposed MAS for active distribution network involves primary substation agents (PA), secondary substation agents (SA), feeder agents (FA), load agents (LA), storage agents (STRA) and distributed generation agents (DGA). The involvement of grid agent (GA) representing the market and network operator entities is also explained. These agents are generic for power systems applications and they can be mobilized for various tasks such as state estimation. This will be possible through further expansion of agent definitions to include other objectives such as dynamic demand response programs through price negotiation, incentivized DG utilization for energy efficiency, network loss reduction through real-time reconfiguration and the like. Some of the agent objectives and tasks are listed in Fig 3.

The individual agents are granular in such a way that they represent individual components. They are also intelligent enough to conduct their own thermal state and time series local load and generation forecasting. The dynamic thermal models of the specific components are integrated with equipment agents to give real-time thermal ratings of the components. The FAs, SAs and PA transformers use their respective thermal models and measurements from weather stations to define their real-time capacity limits.

The proposed model in Fig. 3 could perform state estimations locally with few computations and increased speed. The faster the state estimation, the faster control possibilities would emerge. The more distributed the state estimation and monitoring task, the more local solutions for load balancing and other problems would emerge. Local weather stations are assumed to relay their real-time measurements to electronic power processors (EPPs) with the equipment. Besides to being communicable, the EPPs are assumed to store certain level past time series measurements to conduct a very short-term load and generation forecasting.

Agents need explicit specifications of conceptualization called ontologies to know something about the domain they are operating in and to communicate with other agents. The multi-agent system in this study is entirely defined by equipment agents whose controllability, functions and measurement capabilities are defined. Nevertheless, the ontologies, at least upper ontologies, need to be designed and be expansible to tally with continuously developing smart grid environment and application areas such as balancing power market and network reconfiguration. For instance, the price negotiation in LAs and controllability of DGAs are such expansion capabilities requiring careful ontology definitions as shown in Fig 3. The compatibility of ontology definitions with existing standard energy management systems is another pertinent issue.

There are two IEC standards crafted to facilitate data exchange among and within power companies, the IEC 61970 and the IEC 61968. These standards are collectively called the Common Information Model (CIM) for power system and are used to facilitate the exchange of power system network data between companies and to allow the exchange of data between applications within a company. The IEC 61970 describes the power system components at an electrical level while the IEC 61968 extends the former model to include other aspects such as asset tracking, work scheduling and customer billing. As it is stated in [18], the CIM has the constructs necessary to represent knowledge about the complete power system that the agents need for optimized decision-making. Hence, the CIM is favourable platform to define upper ontologies.

Except for the Grid Agent (GA), the agents defined in this study are tangible. The GA uses the upper ontology, which is needed to share information about what it sees on the network and also it describes the relationships among the application specific agents. The lower level ontologies are defined for the rest of the agents (PA, DGA, SA, STRA, FA and LA) to conduct the specific task, for instance state estimation, and communicate with the GA. The FIPA compliance of agent definitions is not discussed as the software implementation is left for later phase of this study. Nevertheless, using the tangible physical agents, a solution for distributed state estimation is formulated. In addition, emerging behaviours on MAS-based model of active distribution network populated with self-fulfilling agents is demonstrated using a test case scenario.

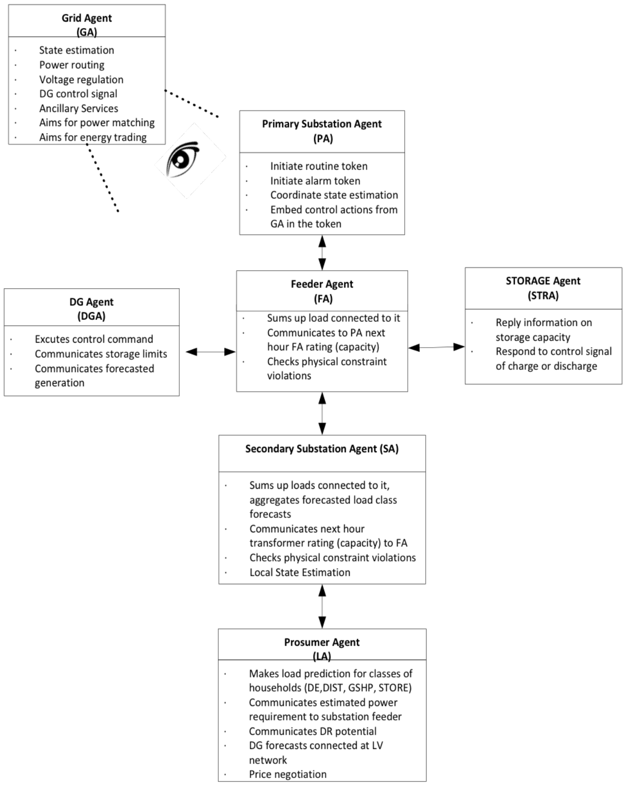

Figure 3. Active distribution network agent based modeling, agent definitions and tasks

IV. DISTRIBUTED STATE ESTIMATION

To maintain a power system in the normal secure state as the operating conditions vary during the daily operation, a continuous monitoring of the system conditions and identification of the operating state is required [19]. When the network model and complex phasor voltages at every system bus are known the operating conditions can be determined. A state estimator mainly consists of functions such as topology processing, bad data detection and state estimation. Since the secure state of underground cables, overhead lines and transformers mainly depend on the conductor and hotspot temperatures, thermal state is also included in the MAS based state estimator.

The most popular state estimation technique is the weighted least square (WLS) method [19]. It aims to minimize the weighted square of the error between actual and functional measurement vectors as it is formulated in (3) [19].

$$min([Z - h(X)]^T \cdot W \cdot [Z - h(X)]) \tag{3}$$

Where: $X = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}, Z = \begin{bmatrix} z_1 \\ z_2 \\ \vdots \\ z_n \end{bmatrix}$ are state and measurement vectors respectively. $h = \begin{bmatrix} f_{x_1} \\ f_{x_2} \\ \vdots \\ f_{x_n} \end{bmatrix}$ is functional measurement vector and $H_{ij} = \frac{\partial h_i}{\partial x_j}$ is Jacobian matrix.

$W = R^{-1}$, where W is weight matrix and R is measurement variance vector.

The optimization problem can be solved iteratively after linearizing (3). Taylor series expansion of the equation satisfying the first order optimality condition will give the linearized form. The pseudo code for solving the WLS state estimation problem iteratively using the linearized objective function is given below.

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Step 1: Initialize state vector $X$ at $k = 0$. Usually, voltage magnitude is one and angle is 0.
Step 2: Compute $H(X^k)$ and calculate $G(X^k)$
where $G(X^k) = H^T(X^k) \cdot W \cdot H(X^k)$
Step 3: Solve $G(X^k)\Delta X^k = H^T(X^k) \cdot W \cdot [Z - h(X^k)]$
Hence $\Delta X^k = G^{-1}(X^k) \cdot H^T(X^k) \cdot W \cdot [Z - h(X^k)]$
Step 4: Update $X^{k+1} = X^k + \Delta X^k$
Step 5: Repeat from Step 2 until $\Delta X$ is small enough.
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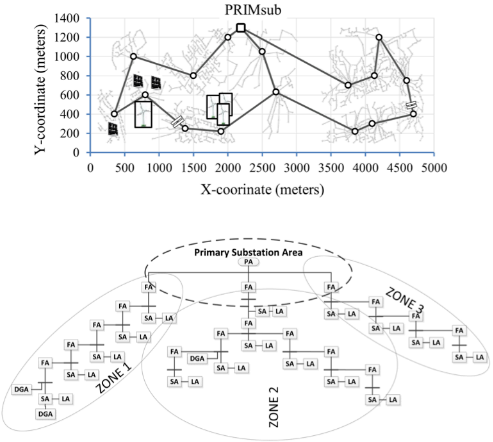
Distributed state estimation allows multi-area electric energy system while preserving the independence of each area. In formulating an area problem of a distributed state estimation, the voltage magnitude and angle estimates of neighbouring areas are treated as measurements. Hence the formulation includes the estimates of within area (area-*i*) state variables and estimates of the state variables of N_b sets of areas (area-*j*) bordering area *i* as shown in (4) [20].

$$min\begin{pmatrix} ([Z - h(X)]^T \cdot W \cdot [Z - h(X)])_i \quad + \\ \sum_{j=1}^{N_b}([Z - h(X)]^T \cdot W \cdot [Z - h(X)])_{i,j} \end{pmatrix} \tag{4}$$

A. Topology Processing and Observability Analysis

A token traverses throughout the network starting from primary substation agent (PA) in every 10 minutes time. Agents will load connecting switch states together with other measurement data and agent identification code. Once the token returns back to the primary substation using the database of component IDs, a complete network map is generated. To conduct overall network observability analysis the PA investigates locally estimated state variables and unresolved observability issues after neighbouring agents' attempts through communication. The MAS-based model of a test distribution network in Fig. 4a is presented in Fig. 4b. The detail of the Greenfield network plan is presented in [21].



(a)

(b)

Figure 4. A test distribution network plan supplying 1800 households (a) [21] and a MAS-based model of the test network using agents defined in Fig. 3(b).

B. Bad data detection

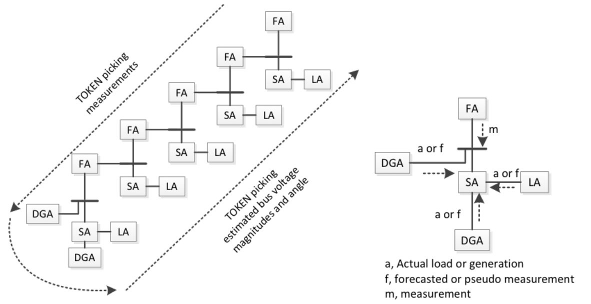
Measurements supplied by each agent are checked if they fall between their 99% confidence interval based on past measurements. In case the measurement is outlier then it is designated to be bad data and the respective pseudo measurement is used instead. Pseudo measurements can be generated from short-term time series load or generation forecasts, historical records or other similar approximation methods. The individual agents, therefore, load the actual, the estimated and the next period forecasted local measurements for every token period.

C. State Estimation

Each secondary substation conducts state estimation locally after doing local observability analysis. In case a substation is unobservable, it initiates a token addressed to the immediate neighbours so that they provide pseudo measurements to compensate for the missing measurement. Afterwards, each SA will solve its optimization problem as it is defined in (4).

V. AGENT COMMUNICATION ARCHITECTURE FOR STATE ESTIMATION

A periodic token is initiated by the primary substation. It picks measurements and switch statuses on the first traversing and it initiates and picks estimated voltage magnitudes on the returning path. The token will be received by all the agents at least once and it will be received by substation agents (SA) twice as shown in Fig. 5 (a). Based on the collected measurements on the coming path the last substation agent on the feeder will execute local state estimation to give estimates of voltage magnitude and angle of the connecting bus. On the returning path of the token, all upper level SAs will take estimates of lower level neighbouring substation agent estimates as measurements to conduct their own local estimations. The state estimations for each secondary substation will have similar formulation as in (4) and follow the expressed procedures in Section IV to solve the WLS.



(a) (b)

Figure 5. In (a), a token path for feeder in ZONE 1 of the test distribution network and in (b), a local state estimation on the last substation of the feeder.

The proposed method is different from the one proposed in [11] with the incorporation of DGA, LA and FA which are capable of doing their own measurements, local optimizations and forecasts.

The presented procedure is distributed but not parallel on radial feeder level. It means that the state estimations are done locally at substation level but sequentially starting from the substation connected at the end. Nevertheless, this approach is capable of matching boundary bus state variables between neighbouring substation agents. In addition, radial feeders sourcing from common primary substation could do the distributed state estimation in parallel, for example, the three zones in Fig. 4b. With the explained method, individual substation agents can also do local state estimations independently ignoring the matching of boundary state variables. One of the strengths of the described system is that pseudo-measurements are attained from the locally forecasted measurements. With the demand response programs induced stochastic customer behaviours and with the less predictable wind turbine generations, there is a need for high resolution and accurate short-term load and generation forecasts. These behaviours and especially their reliability can be grasped when the forecasting is performed locally [21].

VI. A CASE STUDY: DISTRIBUTION NETWORK WITH HIGHLY PRICE RESPONSIVE LOADS

The test distribution network in Fig. 4 connects households belonging to three different primary heating type classes. They are the direct electric heating system class (DE), the district heating system class (DIST) and the electric storage heating system class (STORE). The detail of the test network in Fig. 4 is presented in [21]. These three types of households have distinct load profiles; hence different DR potentials. For each type households their DR potential is attained from their disaggregated load profile of one year hourly AMR metered load data [21]. Assuming fully engaging customers, entire DR Potential of households in the network is optimized for energy cost based on hourly market price. The resulting load profile is supplied to a MATALB/Simulink model of the test distribution network in Fig. 4. The resulting component loads are used to compute the conductor and hotspot temperatures from their respective dynamic thermal models, as presented for instance in [22].

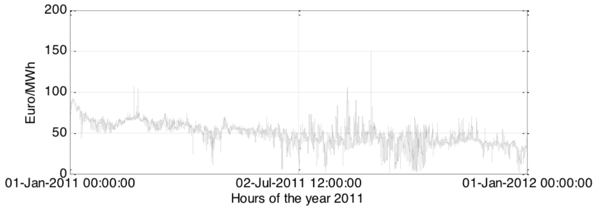


Figure 6. Elspot hourly electric energy market price for 2011.

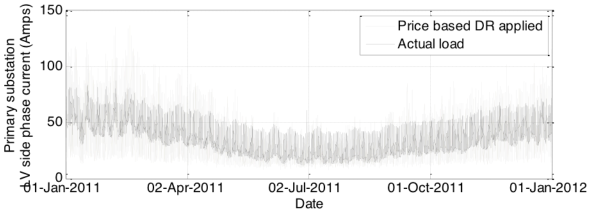


Figure 7. The cumulative effect of load shifting as seen from primary substation

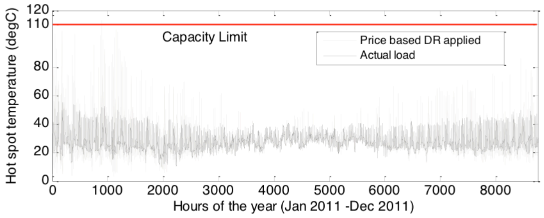


Figure 8. The corresponding primary substation transformer hot spot temperature for normal annual load peak 1pu

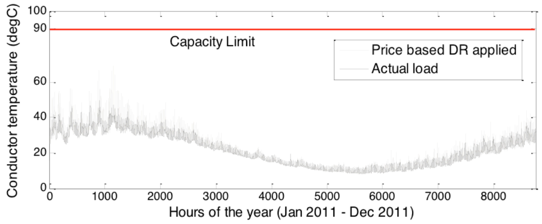


Figure 9. The corresponding MV underground cable conductor temperature for normal load peak 330A

The hourly price signal used in the simulation is presented in Fig. 6 and it is attained from the Nordic energy market system, Elspot. The simulation results show that in the worst case scenario, where all customers are responding to price signal by shifting their respective shift-able loads, the network loading will be highly stochastic. In some hours, component loadings could go beyond their capacity limit as shown in Fig. 8, for substation transformers and in Fig. 10, for overhead lines. The underground cables are the least affected by the stochastic loading, as shown in Fig. 9, and it is due to their relatively high thermal time constant. However, the highly stochastic emerging load profile will deteriorate the life of cable connection joints straining their mechanical strength. Although the incipient voltage profile in the test case is not severe as shown in Fig. 11; with higher load level, however, it may cause under voltage. The results demonstrate the emerging behaviour after self-fulfilling load agents optimize their respective objectives in MAS-based network model. These specific behaviours cannot be observed unless the MAS-based models include generic and detailed agents as in Fig. 3.

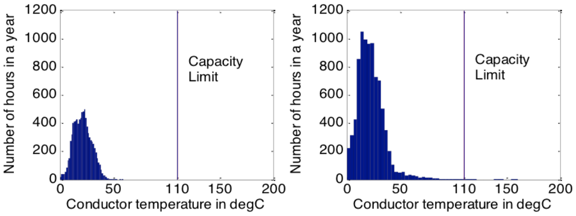


Figure 10. The corresponding MV overhead line one year hourly maximum conductor temperature distribution for the actual load peak of 430A.

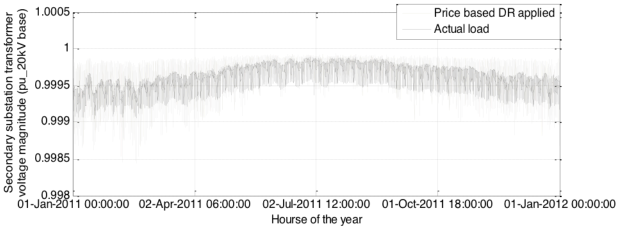


Figure 11. Hour-by-hour average voltage magnitude of the 16 secondary substations (in Fig. 4a) for one year period.

Hence, the MAS-based model enables to craft network capacity and market price based control strategies in a real-time. The demonstration also show that there is a need for communications in a common platform between the market price based demand response programs initiated by GAs and LAs and the capacity based control actions on the FAs, PAs and SAs.

VII. CONCLUSIONS

In this study, a bottom up MAS model of an active distribution network is presented based on autonomous cooperating agents. A network wise task of distributed state estimation is used to explain the MAS technique. Furthermore, the emerging network behaviuor is simulated for cost minimizing prosumer agents.

The presented MAS-based active distribution network model opens up increased possibilities and potentials. For example, the distributed state estimation can be faster because of the substation level state estimations and the reduction of massive measurement communications. The method could also increase the quality and quantity of pseudo-measurements by conducting load and generation forecasts locally. The presented method helps to set-up fast and local control strategies, such as local load balancing, energy efficiency and DR programs. The MAS technique proposed to solve the distributed state estimation could have a generic upper level ontology creating the capacity and convenience of communication with the already existing IEC 61968 based applications. The implementation and verification of some of the mentioned advantages are left for the next part of this research.

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