Simulation of the Effect of Demand Side Management to the Power Consumption of Households

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Abstract--**A simulation model was developed in order to answer the questions that arise especially in the household sector with an implementation of Demand Side Management (DSM). This model can reproduce the behavior of household devices on the one hand and the effects of various DSM-systems on their power consumption on the other hand.**

A model of the devices of a household was established for an average daily load and verified with already known load curves, measurements and additional data.

The examined DSM-systems do not require any additional communication between the devices and have a simple structure. The information on the need for an intervention in the power consumption of the devices is determined from the line frequency.

This model was used subsequently as the basis for initial investigations of three exemplary DSM-systems using various scenarios in which different frequency profiles are given. The results of these simulations are presented in this work.

Index Terms—**Load management, power demand, power system simulation**

I. INTRODUCTION

MEASURES to promote renewable energy sources in Europe have led to a massive development of renewable energy. For renewable electric power generation are currently mainly small hydro, biomass, solar and wind power taken in consideration. The forecast of wind and solar systems is, due to the high volatility of the yields, very difficult. Many new projects are currently implemented, especially in the field of wind energy, without corresponding growth of the transmission network and the capacity of control power plants because of lengthy approval processes [1].

In addition to this burden, the transmission networks in Europe are becoming, as a result of new market mechanisms, a platform for the transfer of ever increasing energy flows [2]. In particular the occurrence of large grid disturbances shows that the scope in the transmission systems becomes smaller and smaller [4]. In order to compensate the fluctuation of power generation from renewable energy sources must the consumption of energy be able to be influenced, additional to the control of the energy production. By doing so, the transmission systems will be relieved on the one hand or, on the other other hand, the transition to decentralized structures with small, autonomous energy systems will be possible.

The possibilities of load-side control interventions through so-called Demand Side Management (DSM), especially in the household sector, will therefore be discussed further in this work. What potential for power variation is available in the household area, including all electric energy consumers, has already been explored in [5] and [8].

To use this potential, the question of the costs involved in the realization of a DSM-system has to be clarified. If the system can only be realized with high technical and financial effort, only few devices can be controlled, so that the involvement of consumers with low power input is not profitable [1]. If a DSM system could be implemented very cheap, e.g. because of high volume and simple structure, it can be assumed that even more devices will be available for influencing.

One approach for a simple and cheap DSM system would be that no communication has to take place between the individual household devices and, for example, a central control unit. In this case the costs of building an appropriate communication infrastructure are eliminated. Each device has a DSM-unit installed, which independently determines the need of influencing the power consumption due to the current energy supply situation. The information about the supply situation is expressed particularly in the frequency of the transmission system [6]. Some realizations of DSM follow this approach, e.g. [3] and [6].

In a further step it could be assumed, that in an island network, which is either independent from the transmission network or connected to it via an inverter unit, the frequency can be varied in a broad framework in order to inform all devices about the current supply situation. The goal of this particular configuration is to ensure the supply with electrical energy as autonomous as possible at all times.

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The use of such an only frequency-based DSM system arise other questions, like:

- What are the effects when this system is used in many devices, e.g. to the grid stability?
- Can the expected potentials even be utilized?
- How much will be the user behavior affected?
- What features must a possible DSM-unit provide? Can these be realized using simple, standardized components?
- What requirements must be met by the devices in order to integrate them into the DSM system?
- How much a DSM-unit must be integrated into in the device? Is it necessary or practically to define standardized interfaces between the DSM-unit and the controlled device?
- What requirements must be met by the hardware of the DSM-unit (accuracy, switching capacity ...)?
- Can such a system be used to support or to enable small autonomous island networks?

The access to answer these and further questions led to the need for a prior simulation of possible implementations of various DSM systems. The simulation should provide the opportunity to be as flexible as possible in the setup of the DSM systems. Furthermore, the behavior of devices in the household should be reproduced as closely as possible to reality to make reliable statements from the simulation results. In addition, it should be possible to add new, not now considered devices such as e.g. electric cars or decentralized power generators like PV installations.

With these requirements for a simulation of DSM, in [7] corresponding functions and models were developed to thereby perform initial investigations. Using the results from these simulations, implications and requirements for DSM systems will be worked out to support a real implementation of the previously described DSM system. In this work, additional results are presented, which arose due to the extension of the simulation model.

II. IMPLEMENTATION OF THE SIMULATION

In this section it is intended to show how the simulation was implemented to indicate the way how the simulation results are derived.

The simulation was implemented in MATLAB. An object-oriented approach was chosen due to the structure of the devices to be simulated. This has the advantage that the user devices and DSM-units can be developed separately.

A. *Simulation of the Devices*

To replicate the power consumers in a household, they were initially classified according to their properties in device classes. Each device class describes the behavior of a particular device type as close to reality as possible.

Among others, the following classes of devices have been implemented:

- Thermal storage: This class is used for the simulation of refrigeration equipment, boilers and heaters. Thereby a simple thermal model is used.
- Devices with stochastic behavior: The operation of a device of this class is purely coincidental, as it is e.g. for a TV-Set or lighting equipment.
- Devices, which are executing a program: the power consumption follows a fixed sequence, such as in washing machines. The start of the program is random, similar to the consumers with stochastic behavior.

Fig. 1 shows an example of one of the developed device classes. Parameters to be specified for this device-class describe the behavior of a collective of many of the same devices owned by different Persons. Given Parameters are here for example average power input and stand-by consumption, typical start times, average operating times, and starting probabilities.

Through the distribution of those parameters each instance of a device shows individual behavior, easily seen in Fig. 1 with reference to the graph of the single device (blue graph in Fig. 1). The more consumers are considered, the more the cumulative sum approaches a desired load profile (black graph “10,000 devices” in Fig. 1).

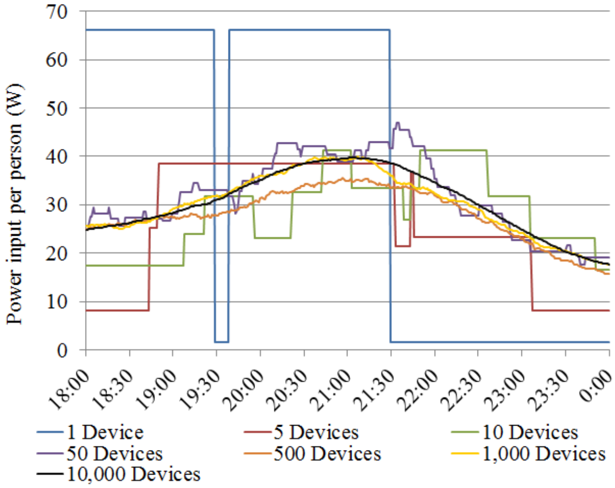

Fig. 1. Example of one of the implemented device classes - with stochastic consumer behavior (audio-video equipment shown here)

For the other classes similar different descriptive parameters are given, e.g. for thermal storages the values of the thermal resistance and the thermal capacity.

In section III it is shown, how these device classes are used to form a model of the devices of an average household.

B. *Simulation of the DSM-units*

As previously mentioned, it is the objective of this work to investigate the requirements and impacts of a simple DSM system. For this purpose several functions have been developed which a possible DSM system could be equipped with.

The DSM-functions are implemented by a "chip", the DSM-unit, which is located either before the device or in the device itself. For this purpose an interface was defined through which the DSM-unit responds the need for a service interaction to the respective device.

Programmatically the DSM-unit is implemented as separate class “`DSM_Device`” with two main parts: the DSM-input and the DSM-output (see Fig. 3).

The DSM-input determines from the line frequency the need for influencing the device. In addition to different frequency levels as threshold for the response and the variation of this levels it is also possible to define so-called priority groups, so that not all devices respond at the same frequency value.

Also there is the option to extend the period of influencing a device by delaying the response to an unfavorable network condition beyond the occurrence of this condition. This should also help to prevent the simultaneous reaction of many devices. The DSM-input therefore represents the actual DSM-unit, the “chip”, with its functions.

The information about the network status determined by the DSM-input-unit is transferred to the DSM-Output via the properties “`Warning`” and ”`Output`”, which form the previous mentioned interface (shown in Fig. 3). The DSM-Output has to be considered as a part of the controlled device. This separation is necessary because each device class has individual opportunities for power reduction.

At a critical situation, the various power consumers react according to their means. These are not the same for all device types, so different types of reactions have been developed:

- Switch off: In the event of a critical network status the device is disconnected from the mains.
- Switch off stand-by consumption: In the event of a critical network state the standby consumption is reduced, the normal function will not be affected.
- Power reduction: The power consumption of the device is reduced for the duration of an unfavorable network condition through appropriate means, e.g. by dimming of lamps.
- Set-temperature change: In the case of a thermal storage the power consumption is reduced by affecting the desired temperature for the duration of the critical network state. After the recovery of the line frequency the normal storage level must be restored by increased or prolonged power consumption.
- Postpone program start: In case of devices which are running a program (such as washing machines or dishwashers) the program start is postponed in the event of a critical system state. A maximum delay time can be defined in order for the program start to be in the foreseeable future.
- Interrupting the program: In case of devices which are running a program, the program is suspended in the event of an unfavorable network condition at a suitable moment. Again, a maximum time period for the disruption can be specified.

In the implementation of these functions care was taken to ensure that the definition of DSM systems is very flexible and also other additional functions can be easily incorporated in the simulation environment. With these functions now different DSM systems can be put together.

C. *Structure of the Simulation*

Fig. 2 shows schematically how the individual instances are created before the simulation. From the parameter file, in form of a MS EXCEL spreadsheet, the respective parameter values are read in for each device type. Each type of device is modeled with that device class that simulates the behavior of these devices best. In the next step, the parameter values are first subjected to a distribution to obtain for each Instance an individual set of parameters. The procedure for the `DSM_Device`-instances is similar, except that in addition also a selection of appropriate input and output functions takes place.

After the devices and the `DSM_Device`-instances were generated, they are “coupled” together. One could say that the DSM-unit is "built in" to the device. In Fig. 2 the dashed connection of the instances represents this coupling.

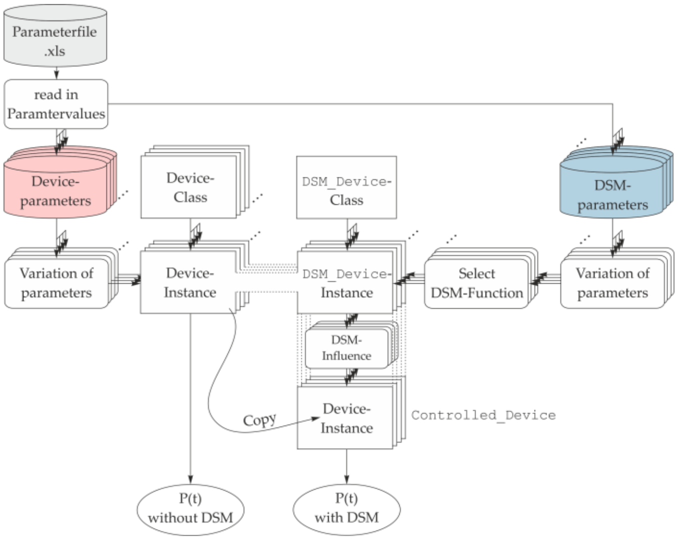

Fig. 2. Scheme of the Interaction of the implemented classes in the simulation

To allow the examination of the device group with and without the use of DSM at a simulation run, the `DSM_Device`-Instance is provided with a copy of the instance of the device (“`Controlled_Device`”). During the simulation the DSM unit influences only this copy and so the original device instance is not affected.

After the devices and `DSM_Device`-instances were created, for each simulation time-step and for each device its reaction is determined. In most cases, the calculated data consists of the current power input of the device for each simulation time-step with and without the effects of DSM (see Fig. 3). For this purpose the simulation program provides in the current simulation step any instance with all for the determination of the reaction necessary information.

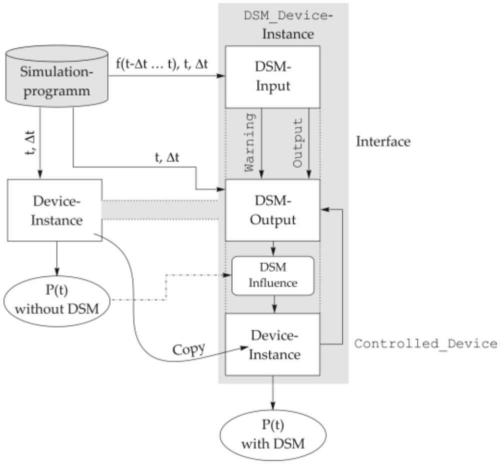

Fig. 3. Structure of the DSM_Device-Instance and sequence of the determination of the input power for a simulation step

First, the unbiased device is simulated. Then die DSM-input determines from the frequency data the network state. Via the interface (“`Warning`” and “`Output`” in Fig. 3) the DSM-output is controlled, which subsequently is influencing the copy of the device instance, depending on the requirements. After this, the actual power consumed is determined. For this often the already existing result of the original device instance can be used and thus the simulation effort be reduced.

The result is summarized after the simulation to a MATLAB structure, automatically displayed and stored.

III. USED SIMULATION MODEL

In [5] and [8] attempts were made to provide an estimation of the potential of DSM in households. As part of this effort also the daily load of different consumer groups had been identified. With the help of statistics and data collection a daily load profile could be given, which is shown in Fig. 4.

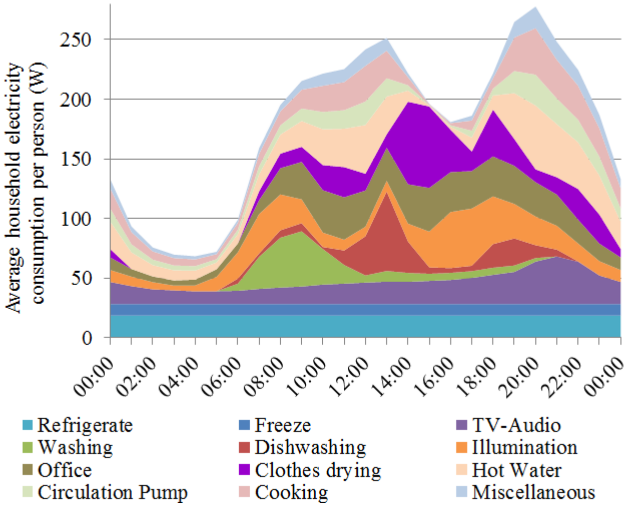

Fig. 4. Total load curves of the different sectors of a household (according to [5])

Using these data and additional statistics and measurements, a first model for the devices of a household has been obtained for the simulation, but in which not all in [5] mentioned sectors were taken up.

Those sectors that are treated are refrigerating, freezing, TV-audio, washing, dishwashing, clothes drying, illumination and office (dark areas in Fig. 4). With these sectors 70% of the electrical energy demand of an average household is covered. An integration of the other sectors in the simulation is easily possible, as all necessary classes for these device groups have already been defined.

Fig. 5 shows the result of a simulation run with the devices operated by 50,000 people and compared with the comparative data from which the consumer model has been obtained. It is easy to see that the identified model reproduces the required profiles well.

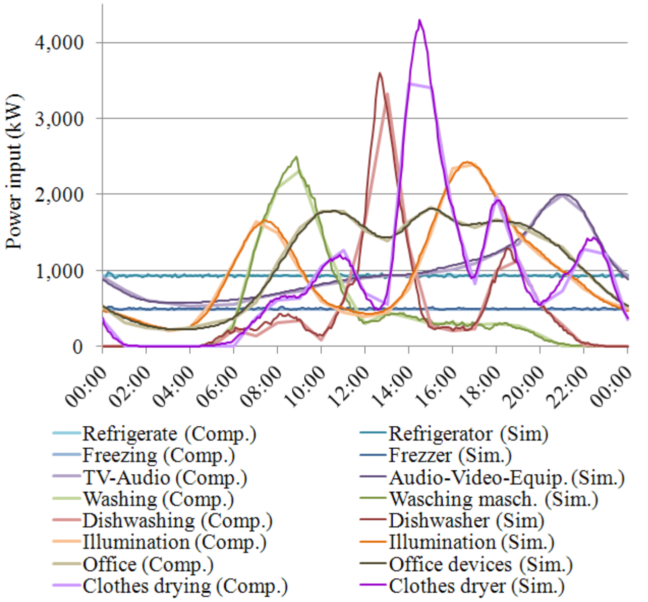

Fig. 5. Simulation results (Sim.) of the power consumption of 50,000 people and comparison to the comparative data (Comp.) by sector.

In the consumer model presented here, only one average device was defined per sector for simplicity. Thus, for example, in the sector audio-video equipment, all the devices (TV-Set, stereo systems, radio, game consoles, video recorders, etc.) are combined into one device. Through this simplification, the simulation result is at low numbers of individuals not representative. For improvement of the model, the finer division of the individual sectors of consumption is intended. In the simulation of many devices this simplification is acceptable.

In Fig. 6 the total consumption of the considered sectors is presented. In addition, also the relative deviation from the maximum value of the comparative data is illustrated. The deviation is never higher than 2.5% of the maximum value, indicating a reasonably good accordance between simulation and comparison data.

With the determined consumer model and the developed DSM-functions now initial simulations can be carried out.

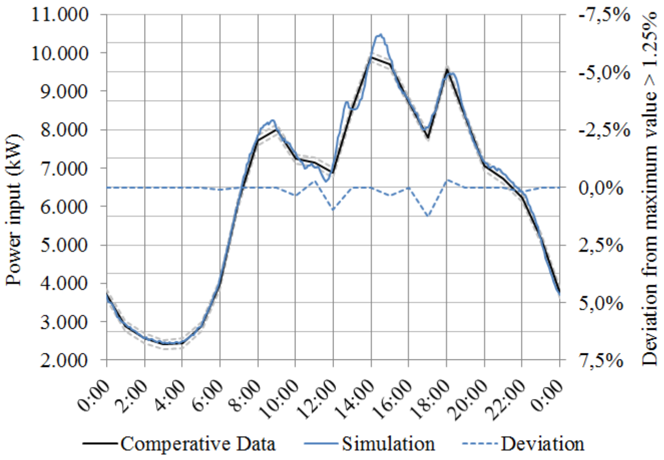

Fig. 6. Result and Deviation of the simulated total consumption of 50,000 people from the comparative data

IV. RESULTS

In this work, three different exemplary DSM systems, which use the developed features, are analyzed based on various scenarios. In [5] already initial estimates were formulated on the reduction potential of various sectors of consumption. It was assumed that the function of all devices will be affected only so far that it will be hardly noticed by the user, e.g. by slightly dimming the lights or turning off the standby consumption. These potentials are also the basis for the settings of the here used DSM systems. In all three DSM systems the Refrigerators increase their set-temperature to a maximum allowable value.

The first system responds immediately to changes in the line frequency. In case of washing machines and dishwashers the program is stopped immediately. At recovery of the frequency all devices return very quickly back to their normal operation. This system will be referred as "DSM undelayed".

The system "DSM delayed selective" has the same behavior as the non-delayed, but by other choice of parameters the immediate restart of washing machines, dishwashers, clothes dryers and refrigerators is postponed here at the recovery of the grid frequency.

The last system is based on the assumption that in each device the same DSM-unit is installed with the same functions. These units provide a uniformly distributed delay time to ensure that after a critical network condition the devices return to normal operation spread gradually over four hours. In addition, this system limits the maximum delay of program starts or program interruptions to 2 hours in dishwashers and washing machines. This system is subsequently referred to as "DSM-units identical".

These three DSM systems should constitute the first steps for the implementation of DSM in households. On the basis of different scenarios, these three systems are examined and compared with respect to the frequency profile.

The grid frequency is considered in the context of the simulation as a predetermined input from the outside, which is not influenced by the consumer behavior. This assumption reflects that the overall power of the considered devices is assumed small compared to the available power in the network. A second possibility could also be an island network with a in the network installed controller that tries to control the consumer behavior with the help of the power frequency.

In the simulation are devices considered, which are used by 5,000 persons and it was assumed that all devices are full equipped with DSM-units regardless of any implementation problems. The reaction threshold of the devices is at an average frequency difference of 0.5 Hz and a standard deviation of 20% from that value.

A. Scenario "shifting peak loads"

The scenario assumed in the frequency profile shown in Fig. 7 try's to shift the tips of the total power consumption of the considered sectors. This is achieved for all three DSM systems. In case of the instantaneous system, greatly increased power consumption happens because of the simultaneous start of many washing machines, dishwashers, clothes dryers and refrigerators.

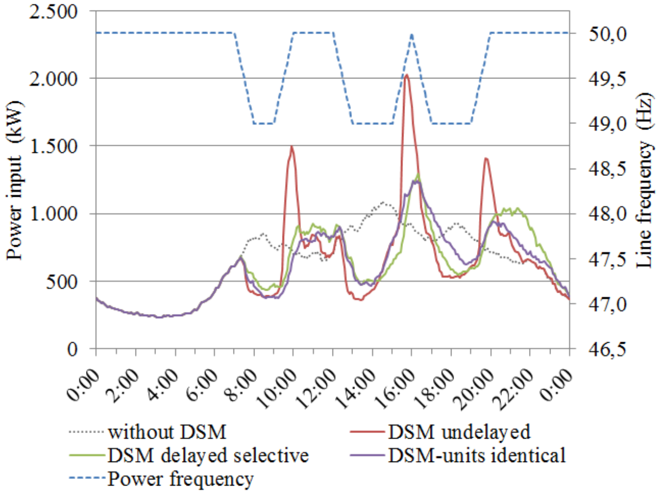

Fig. 7. Comparison of the total power consumption of the exemplary DSM systems for the scenario "shifting peak loads"

A better result is obtained by the two other DSM systems. The peak loads are shifted well from the periods with low frequency values into those with normal frequency without causing much higher power consumption.

In Fig. 8 the simulation result is shown as a load duration curve of the consumption per person. Based on this curve it can clearly be seen that although the instantaneous DSM system offers a higher reduction of the input power, this occurs at the expense of greatly increased power consumption at other times. In comparison, the other two DSM systems are closer to the power curve without DSM, but can also achieve a reduction in a similar magnitude. The DSM system with identical units even manages it to achieve a load curve that is, except for two hours, lower than or equal to the device constellation without DSM. This is substantiated in the power reduction of audio-video equipment, office equipment and lighting, which takes place here for a longer period than the in the other DSM systems.

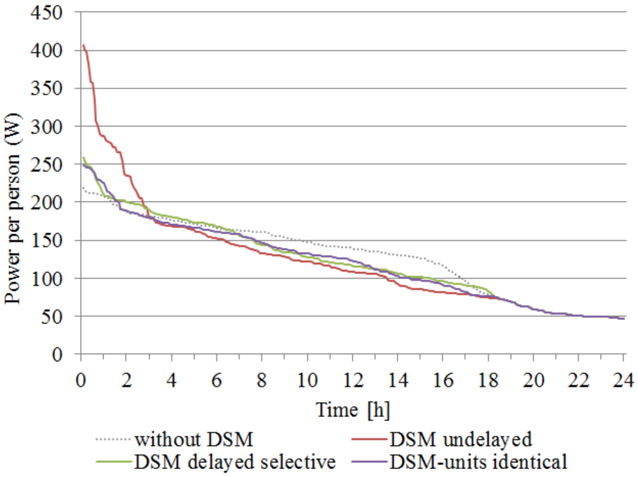

Fig. 8. Load duration curves of the Total Power per person of the various DSM systems for the scenario "shifting peak loads"

B. *Scenario "short frequency dips"*

In this scenario, the frequency breaks down at four times within 5 minutes by 1 Hz, remains on the low value for another 5 minutes and returns within 5 minutes back to the original value, shown in Fig. 9.

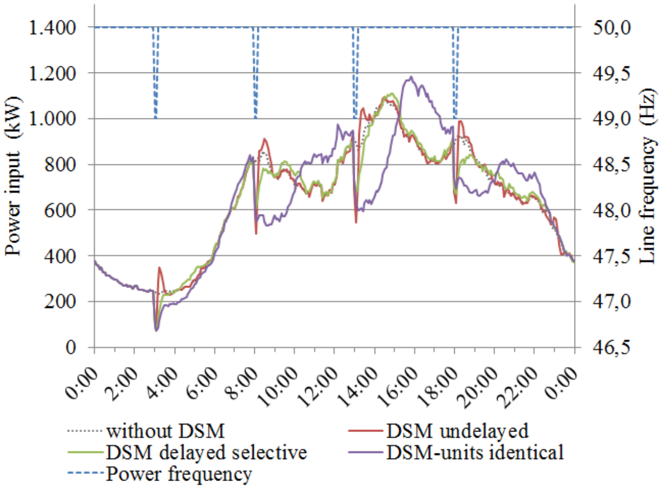

Fig. 9. Comparison of the total power consumption of the exemplary DSM systems for the scenario "short frequency dips"

The instantaneous and the DSM system selectively delayed return after each drop relatively quick back to normal power consumption. Again, the instantaneous system shows slightly increased power consumption, because of the rapid reaction. The system with identical units causes at each frequency dip a continuous reaction for up to 4 hours because of the time delay. This reaction is practically "triggered" by the frequency drop, which is an interesting behavior. If the frequency can be set freely in this system, e.g. as it could be in an island network, a control of the consumer behavior can be achieved by short frequency pulses.

C. *Scenario "long frequency collapse"*

In this scenario, a very long and lasting frequency collapse is considered. In all three systems there is a significant power reduction. The DSM systems "identical units" and "undelayed" show peak loads within the time of low frequency, because the programs of dishwashers, washing machines and clothes dryers are only postponed by up to two hours, easily to see in Fig. 10.

The system "delayed selective" allows much longer program shifts (on average up to five hours), so the power consumption of this system is nearly nine hours beneath the level without DSM. This behavior is only achieved through a strong interference in the behavior of washing machines, dishwashers, and clothes dryers. It must be doubted if this is tolerable for the user.

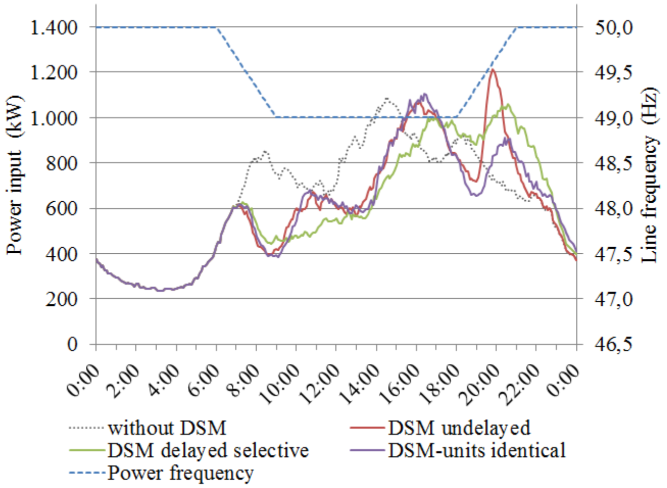

Fig. 10. Comparison of the total power consumption of the exemplary DSM systems for the scenario "long frequency collapse"

D. *Scenario "frequency curve at a big system-failure"*

Until now, the frequency profiles were assumed for the simulation as simple linear trends. However, in this scenario the system frequency should replicate the profile at a large disturbance in the European transmission network.

For this, a frequency profile is used which occurred in the Ruhr region (so called "Area 1" in [2]) within the great disorder on November 4th, 2006. More detailed information about this disturbance can be found in [2]. In this frequency profile the highest frequency value is achieved with 50.19 Hz at 22:30 clock. In this scenario it is then assumed that the frequency returns within 45 minutes to the normal value of 50 Hz (see frequency curve in Fig. 11).

During the time period under consideration, almost no washing machines and dishwashers are in use, so the power reduction derives to a large part on the behavior of the cooling units. Office devices, audio-video equipment and lighting are performing a power reduction. Clothes dryers can also contribute to a network relief trough program start delays and interruption of running programs (see also Fig. 13 and Fig. 14).

The DSM system "undelayed" hastily returns after the disorder to normal operation, the selective delayed system a bit later. It occurs that the non-delayed system shows hardly increased power consumption, because of the short duration of the disorder since in this period the content of the cooling devices is only slightly warmed. In case of the system "units identical" the disorder leads to a prolonged power reduction, similar to the scenario with the short rate drops because the disorder has a very similar characteristic.

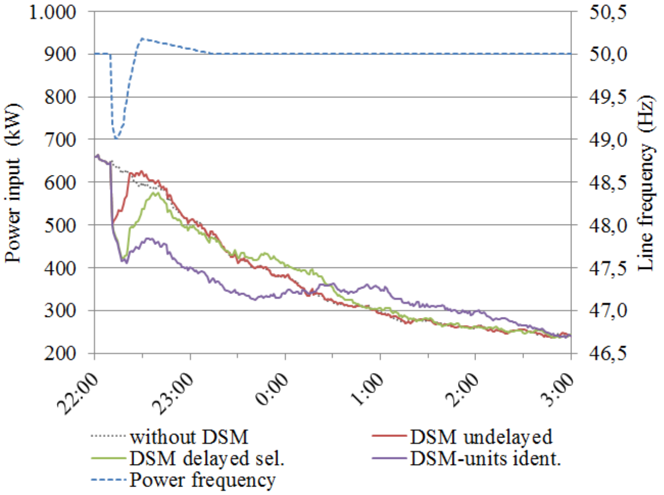

Fig. 11. Comparison of the total power consumption of the exemplary DSM systems for the scenario "frequency curve at a big system-failure"

Fig. 12 shows the duration curves of the total power. The DSM system "units identical" provides a longer power reduction than originally would be needed. However, increased power consumption after the fault is avoided for a long time. Particularly in the case of a power disruption this behavior could be of a great advantage, since so sudden load changes will not occur at the recovery of the network, which would this weigh again heavily.

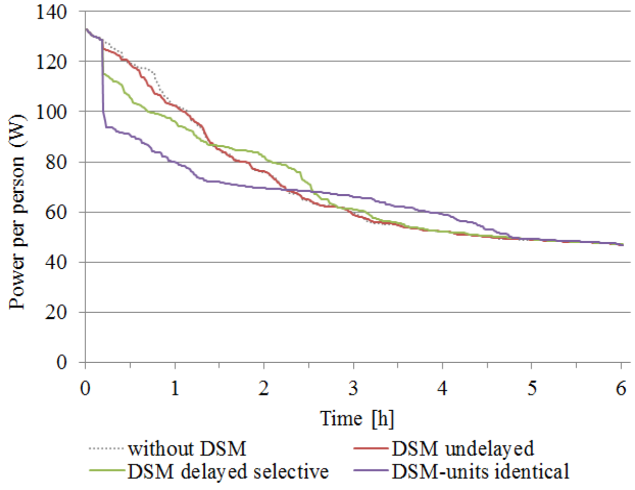

Fig. 12. Load duration curves of the Total Power per person of the various DSM systems for the scenario "frequency curve at a big system-failure"

The achieved short-term relative power reduction is for all systems already remarkable with up to 30% of the current power consumption. In order to avoid a blackout all consumers could even make a higher contribution. For e.g. could the DSM-units start a kind of "emergency program" at high and rapid frequency dips. Hereby significantly more consumers could be disconnected from the mains. Also other delay times could be valid in this operation mode of the DSM-System, in order to grant the recovery of the network more time.

Fig. 13 and Fig. 14 show for each of the DSM-systems "undelayed" and "identical units" the response of the individual device groups on the large disturbance.

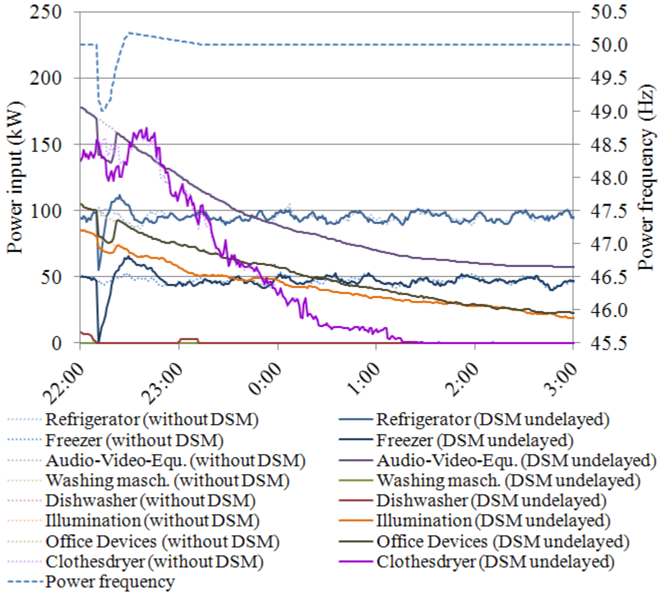

Fig. 13. More detailed illustration of the simulation results for the current scenario and the DSM-system "undelayed"

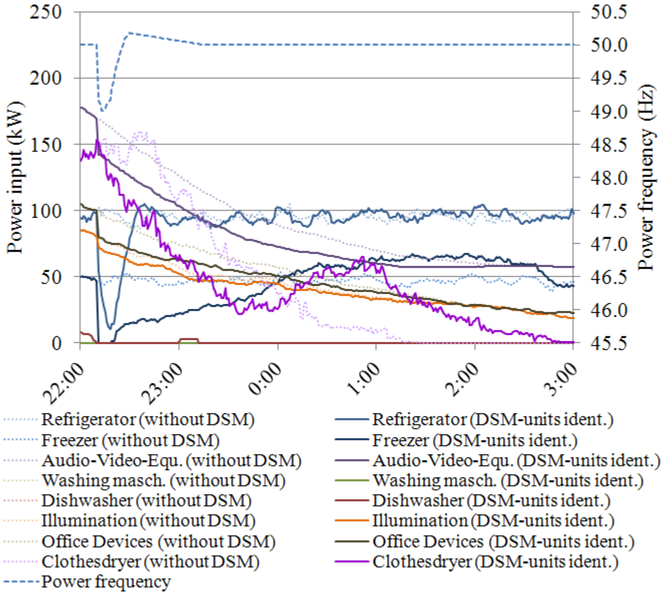

Fig. 14. More detailed illustration of the simulation results for the current scenario and the DSM-system "Units identical"

It can be seen that the DSM system "undelayed" shows a rapid response to the frequency break-in and an equally rapid return to normal operation at the recovery of the line frequency. As the duration of the power reduction is relatively short, the cooling equipment has no significantly increased power consumption. After about an hour, the power input is again the same as without DSM.

A quick reaction to the frequency drop is also performed by the DSM-system “units identical”, but in contrast, the return to the normal operation is delayed significantly (see Fig. 11 and Fig. 14). Increased power consumption of the refrigeration equipment can be noticed when the devices are setting back their set temperature to their normal value. This happens because of to the longer duration of the period in which the set temperature is altered. But it is also avoided here that the total power consumption turns too high, because the time points of returning to normal operation are distributed over a long period for each device in the DSM-system “units identical”. By shifting the starting times of the clothes dryers there is also a significant relief of the network.

V. CONCLUSIONS

With the aid of the simulation model developed in connection with the above-presented scenarios already the first requirements for DSM systems have been worked out.

Delaying the returning to normal operation of the devices after a frequency drop provided in the considered scenarios a good way to avoid peak loads. Furthermore, a simple DSM-system, which could theoretically be used in all kind of devices, led already to a good frequency-dependent load behavior.

For an appropriate implementation the definition of an interface would be effective. Over this interface a simple designed and therefore economical DSM-unit would communicate with the device. Each device would provide its potential for power reduction according to its means. But this interface and the power reducing functions can only be provided by the manufacturers of the respective devices. This requires an appropriate stimulus and a standardization of the interface to be available. The extent to which even very simple devices may also be covered depends very much on this implementation.

For further studies, the simulation model must be extended and improved. In addition to the involvement of other existing consumer groups also new consumers such as electric cars or even distributed generation plants could be considered. Also should the simulation model be more refined to make better statements. Furthermore, there are still many opportunities for other DSM functions, such as a reaction of the devices on over frequency. The developed functions and models offer the opportunities to realize the required expansions and thus enable further investigations.

Using the results gathered in this and previous works as well as from further simulations, a more accurate knowledge on the use and the effect of DSM should be obtained and subsequently support the implementation in reality.

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VII. BIOGRAPHIES

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