A Method for Optimal Schedule Balancing in Distribution Network using Multi Agent Control Strategy

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***Abstract*— The rising share of the distributed renewable energy sources (DRES) is posing specific challenges regarding their integration in distribution networks. They lead to overvoltages, current congestion and other issues that reduce the power quality and the security of the supply. New solutions are needed especially in the low voltage (LV) networks where the majority of the small-scale DRES are connected. In the project INCREASE (part of the FP7 program), advanced technical solutions and control strategies were developed that will allow the distribution system operators (DSOs) to maintain the secure operation of their networks despite the increased injection from DRES. This way, the DSOs don't need to resort to reinforcement of the grid or conservative approach to connection of the DRES. In the paper a concept of multi-agent control strategy is presented using the simulation results of different schedule balancing approaches with their analysis.**

***Index Terms*-- Demand response, Agent based control, Scheduling control, Economic optimization, Energy-based optimization**

I. Introduction

With the increasing penetration of distributed renewable energy sources (DRES) new control solutions and operating strategies are needed in order to maintain a safe and reliable power supply. Transmission system operators (TSOs) use ancillary services to ensure safe and reliable operation of the power system. The ancillary services are traditionally provided by the synchronous generation units and typically they control the frequency, active-power reserve, voltage and reactive power, black-start and islanding. Traditionally, large fossil-fired generation units have been covering all the needs for ancillary services in the transmission and distribution system. With the increasing share of the DRES units installed in the distribution system, their negative impact on the operation distribution-system has been increasing. In future, they are expected to help providing the ancillary-services support to DSO and potentially even to TSO, [1], [2].

In the EU FP7 INCREASE project, innovative technology solutions for the inverters were developed enabling the DRES units to provide the ancillary services. With their active power controlled through an INCREASE-developed a multi-agent control system, these inverters enable a flexible operation of the inverter-connected distributed generators (e.g. PV units). This way, more DRES capacity can be installed in the distribution network with little power quality impact and a reduced need for an additional network reinforcement. As PV units are the most common type of DRES, they are our primary focus in the paper. The key ancillary services investigated in the INCREASE are: voltage control, voltage-unbalance mitigation, line-congestion mitigation and active-power reserve provision, [3].

A large penetration of the PV generation can cause overvoltages and current congestions in the low-voltage (LV) distribution network, where most of the DRES units are located. Voltage in a distribution network can broadly be controlled either by controlling the reactive power or active power injection into the grid. Due to the reactive character of the transmission network, control of the reactive power is normally used to control the voltage. In contrast, in the LV distribution network the X/R ratio typically below 1 makes the voltage control using the active-power control through active-power curtailment a much more efficient solution, [4]. INCREASE project focuses on two ways of mitigating the overvoltage problems, the first one is active-power generation curtailment through newly developed smart inverter and the second is the optimal scheduling of local demand response (DR) units. The schedule viability is ensured via a Traffic Light System (TLS) mostly developed in the INCREASE project.

The paper focuses on different approaches for optimal scheduling of DR units implemented within the multi-agent control strategy. In Section 2, a general concept of multi agent structure and a traffic light system is presented. Different scheduling algorithms and their main features are presented in Section 3. The main parameters of DR units which were considered in the model are presented in Section 4. In Section 5, the simulation platform and the simulation scenarios used in the evaluation are described. They provide the basis for technical and economic evaluations presented in Section 6. The final conclusions are drawn in Section 7.

II. Multi Agent Structure

Within the INCREASE project, a Multi-Agent System (MAS) was devised with a hierarchical agent-based control strategy, featuring Local Control (LC), Overlaying Control (OC) and Scheduling Control (SC) that would allow for higher penetration of DRES, [8]. The Scheduling Control is the top hierarchical layer of a MAS control structure and uses flexible loads - demand response units to provide flexible energy, [5]. The Scheduling Control composes the operating schedules of the DR units according to various optimization criteria. In the process, it integrates the inputs like wholesale market price, advanced forecasting of demand, DRES generation, network topology and power quality (PQ) boundaries. This way, the DR schedules can support the operation of DRES units in the network so that they are able to generate maximum renewable energy within the boundaries set by the objectives of Local Control and Overlaying Control

Scheduling Control features the Aggregator agent that interacts with other agents within MAS architecture. This Scheduling Control Agent (SCA) interacts with many DR units in its portfolio, offering flexible energy products on the selected electricity markets. On Fig. 1 the proposed MAS control structure is shown, with the two cooperating layers: SC layer containing SCAs, performing the DR aggregator function and communicating with the agents in the OC layer, and OC layer where every feeder contains OC agents that communicate with and gather information about the DR and DRES units. Several competing SCAs can operate in the distribution network.

Using SC, the Aggregator can pursue two distinct goals – maximizing its profit by using economic optimization criterion to schedule flexible energy from DR units, or use energy-based criterion to help accommodating as much energy from DRES injected in the grid as possible. Depending on the goal of SCA, optimization strategy for scheduling DR units is chosen. Optimization criterion affects profit of many actors involved in scheduling control (e.g. DR unit owner, DRES unit owner, and the Aggregator). Their profit changes also depending on the remuneration scheme of DRES units.

A. *Control strategies of a smart inverter*

An inverter developed in the INCREASE project has three different control strategies for curtailing the PV unit, [7], [9]:

- Simple control – when an overvoltage is detected, an inverter shuts down the PV unit – curtails its active power to 0. This represent current business as usual case.
- Local control (LC) – in the occurrence of the overvoltage, an active power of PV unit is curtailed according to the inverters droop static.
- Overlaying control (OC) – when the overvoltage is detected, a fair curtailment level is calculated and all the PV units on the branch are curtailed according to the calculation.

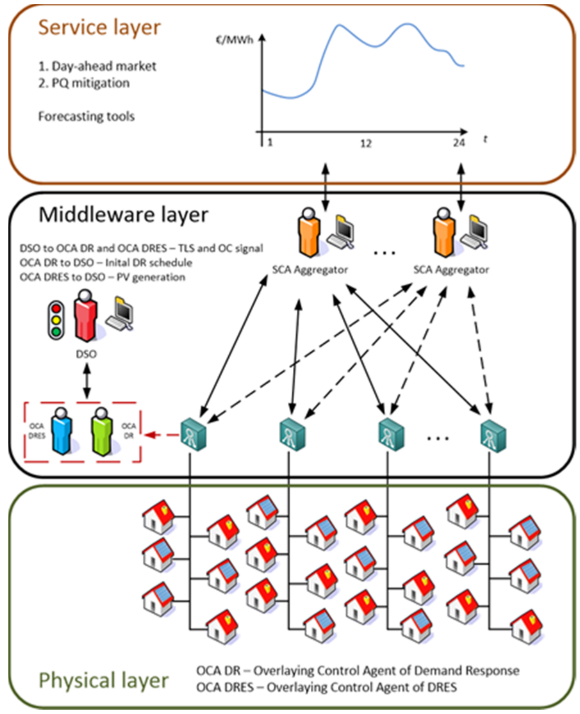

Figure 1: Scheduling Control interaction architecture

B. *Traffic Light System*

The Scheduling Control solution as well as the entire MAS control concept in INCREASE have been designed as to enable the DSO to always have control over the grid. For this purpose, a Traffic Light System (TLS) concept has been introduced that gives DSOs the ultimate control over DR unit schedules.

For the implementation of the TLS, the DSO has been equipped with an additional TLS module to check for the possible effects of the initial DR schedule on the network, in order to detect any Power Quality (PQ) violations in the system. In INCREASE, the PQ violations typically include over/undervoltages and current congestions in the feeder under consideration. The TLS module's main task is to determine whether the SC-supplied schedule of each individual DR unit causes any PQ violations. The input to TLS is the information from power flow based on the joint load schedule of DR unit and inflexible load.

TABLE I: Types of Traffic Light Systems

Action taken	**Does the joint load schedule causes PQ violations?**		**Direction: Does DR schedule help reduce PQ violations?**	
TLS Type	**No**	**Yes**	**No**	**Yes**
Simple	Accept DR schedule	Reject DR schedule	/	/
Advanced	Accept DR schedule	Check direction	Reject DR schedule	Accept DR schedule
Intelligent	Use 15-min forecasting to optimally schedule DR units.			

III. DR units parameters

In order to provide flexible energy, a DR unit model used in our research has the following technical specifications.

A. Time of use

Time of use represents the time period of DR unit availability. E.g. an electric vehicle is available to participate in DR scheduling only during the night when charging, meanwhile heat pumps are available all the time.

B. Energy constraints

Energy constraints present the amount of energy in the DR unit available to be scheduled in a particular time period of a day. The SCA needs to optimally distribute the available flexible energy during the time the DR unit is available.

C. Power

Each DR unit has a two-part structure of the load, Figure 2: a non-controllable part P_L which would normally be consumed by the unit that cyclically varies through time, and a controllable part P_{DR} scheduled by the Aggregator. When the controllable load part is not scheduled, the whole DR unit operates at a $P_L + ½\ P_{DR}$ level. The level of consumption $P_L + P_{DR}$ represents full power operation of a DR unit, and the P_L level the shutdown of the flexible part of the DR unit load.

D. Internal DR unit price

Internal DR unit price reflects the price of the unit's flexibility. Based on this price, the agent decides whether to use the unit in the scheduling portfolio and to which market to bid the unit flexibility. DR internal unit prices are unit-specific and stem from the consumer preferences.

E. Energy payback

Full energy payback means that the energy sum of all energy adjustments at the end of the day is equal to zero for the DR unit. This way, any increases or decreases in consumption must be fully compensated by the end of each day. By including the full energy payback with the energy consumption, no comfort loss can be assumed. In the simulations a full energy payback was assumed and it represents the rationale for our assumption of internal price of DR to be set to 0. Hence the DR unit's flexibility can be fully utilized even in the events of low market prices.

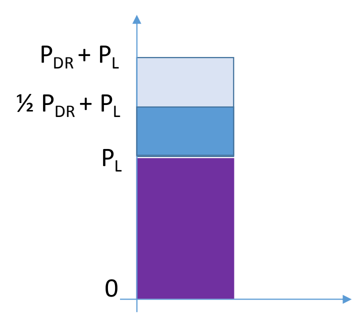

Figure 2: Load structure of a demand response unit

IV. Scheduling Optimization Algorithms

In the paper, we compare the economic outcomes of the two optimization criteria used in the Scheduling Control. The Aggregator also performs the retailer's function. The results focus on the findings of the simulations for a selected test distribution network, and compare the DR units' schedules obtained using both energy and economic optimization. The schedules are characterized through the injected green energy from DRES as well as the profits by various actors. The appropriateness of the SC optimization schemes from the Aggregator's point of view are assessed, and the conclusions used as a contribution towards the update of the regulatory framework supporting the demand response participation in the electricity markets.

A. Economic optimization of DR units

When the economic optimization is used in the scheduling algorithm, the objective is to maximize the profit of the Aggregator's DR unit portfolio schedule, [6]. The input data of the optimization include the daily wholesale market energy prices and the costs for DR unit adjustment. The objective function J_E in (1) aims to maximize the profit of the DR schedule by maximizing the income of the DR unit through using its energy flexibility on the DA wholesale market while also minimizing the cost of the DR unit adjustment. By increasing their consumption in the hours with lower energy prices and reducing it during the high price periods, the SCA realizes profit with its flexible energy product portfolio. The objective function J_E is defined as:

$$J_E = \sum_{k=1}^{N}\sum_{i=1}^{N_D} a_{ik}\left[\left(W_{ik}^{+} + W_{ik}^{-}\right)S_{Mk} - \left(W_{ik}^{+} + W_{ik}^{-}\right)S_{Di}\right] \quad \max \tag{1}$$

where W_{ik+} and W_{ik-} are upward and downward energy adjustment of i-th DR unit in hour k, where the energy adjustment is calculated as a product of hour k and power limits P_{DR} and P_L as shown on the Figure **2** . S_{Mk} represents wholesale market energy price in hour k, and S_{Di} stands for internal output adjustment price of i-th DR unit. Optimization is performed for N_D DR units over the N time interval steps.

B. Energy optimization of DR units

The energy optimization scheduling aims to achieve maximum injection of the green energy produced by the DRES, in our case PV. This is achieved by adjusting the DR schedule to minimize the difference between the total consumption and the PV production in the LV feeder. By minimizing the energy difference voltage profile deviations are reduced and fewer PV unit curtailment events are expected, thus leading to greater PV energy injection. The objective function J_W can be written as:

$$J_W = \sum_{k=1}^{N}\left(\left(W_{load,k} - W_{PV,k}\right) + \sum_{i=1}^{N_D} a_{ik}\left(W_{ik}^{+} - W_{ik}^{-}\right)\right) \quad \min \tag{2}$$

where optimization is performed over N time interval steps, with $W_{load,k}$ and $W_{PV,k}$ as total network load and consumption respectively in hour k. W_{ik+} and W_{ik-} represent the upward and downward energy adjustment of i-th DR unit in hour k.

C. Comparison of the schedules

Figure 3 compares different schedule optimization methods, where flexible part of the DR units' power output is shown. With economic optimization, the unit is scheduled to lower the consumption in hours with higher energy prices (during peak hours), while with energy optimization, the unit is scheduled at full consumption during the PV production interval instead.

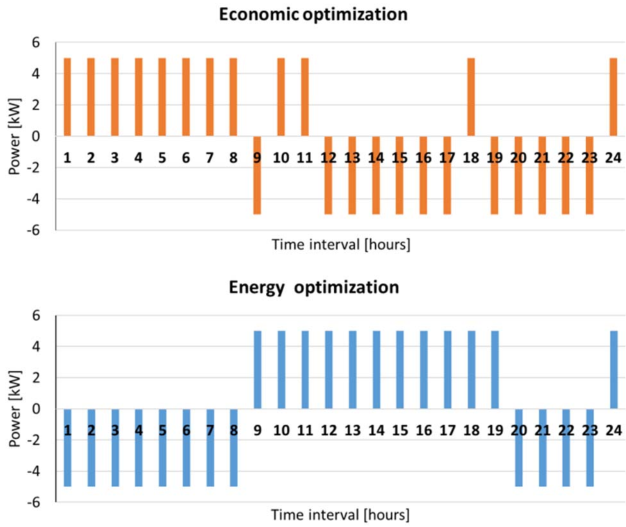

Figure 3: Schedule comparison

V. SIMULATION SETUP

The developed MAS control and implementation of DR units were tested using a simulation model with a part of the LV network modelled in the INCREASE Simulation Platform based on OpenDSS and MatLab, [10]. The model resembles a small part of the network of the Slovenian DSO Elektro Gorenjska (EG), and the basic network parameters are listed in TABLE II.

To evaluate the technical potential of the controls and economics of the proposed remuneration mechanism, simulations with different parameter settings were tested. PV production and load profiles used for the simulation of the base-case scenario were based on measurement data provided by EG. The additional load and PV profiles for the RES development scenarios were derived from the original data with a 10 % MAPE variation.

TABLE II: The parameters of the simulation network

Parameter	Value
Number of branches	10
Number of nodes	77
Number of loads	70
Number of PV base scenario	6 (already installed)
Transformer	250 kVA (21kV/420V)

Each of the control strategies was simulated with different parameters of the PV unit shares, different loads and different PV production profiles as a result of the seasonal variations. The development scenarios that were technically and economically evaluated are shown in TABLE III.

TABLE III: The DRES development scenarios

Scenario	Number of PV / DR	Installed PV power [kW]	Installed DR power [kW]
1	6 / 2	209	20
2	9 / 4	304	37
3	15 / 6	513	51
4	21 / 8	722	68
5	24 / 10	836	95
6	30 / 12	1045	115

The results of the technical analysis were node voltage levels, PV power generation levels and losses in the network. Technical results were furthermore used as an input to the economic analysis. Three PV remuneration schemes were evaluated: Market based-, Premium- and FiT remuneration. In the market based scheme, the Aggregator sells all the PV green energy production in the feeder on the wholesale market. PV unit owners pay to the Aggregator a contractual share φ_{PV} of their market revenue for this service as a broker to provide them the access to the wholesale electricity markets. The sum of PV profits PS_{PV} for N amount of PV plants in the network is defined as in (3).

$$PS_{PV} = \sum_{i=1}^{N}\left((1-\varphi_{PVi})\sum_{k=1}^{T} W_{PVik}\cdot S_{Mk} - C_{PVi}\right) \qquad (3)$$

Here the produced energy of i-th PV plant W_{PVik} in hour k is multiplied with the market price S_{Mk}, and reduced for the cost C_{PVi} of the i-th PV plant. The Aggregator covers the costs of the additional DR equipment to provide flexibility capability C_{DRe}. Sum of profits PS_{DR} for the N aggregated DR units in observed time interval T is the payment for their participation in the DR portfolio of the Aggregator in term of electricity bill reduction φ_{DR} of the joint consumption of DR unit, the flexible load W_{DRik} and the inflexible load W_{Nik}. Both consumptions are paid according to retail price S_R.

$$PS_{DR} = \sum_{i=1}^{N}\varphi_{DRi}\sum_{k=1}^{T}\left(W_{Nik}+W_{DRik}\right)\cdot S_R \qquad (4)$$

VI. RESULTS

The simulation scenarios were made for the time period of one week for each season. To present the results, we chose the summer scenario because of the high PV production, expected voltage problems and therefore the expected noticeable effect of the control strategies and the scheduling algorithm.

The simulation results of economic optimization scheduling in TABLE IV show that the PQ overvoltages occur only in the last two scenarios with higher PV penetration levels during the summer. The number of overvoltage events is significantly higher than in the simulations with energy optimization shown in TABLE VI. That also leads to the increased green energy infeed no matter what type of control strategy of the inverter is taken into account.

TABLE V shows the summer simulation results of profit calculations for DR and PV units, calculated by (3) and (4). The aggregator fee for providing the service was set to φ_{PV} = 20% for PV units and φ_{DR} = 10% for DR units. By comparing TABLE V and TABLE VII results we can see that the DR profit is lower when energy optimization scheduling is used, and PV profit is higher due to the increased energy infeed. This raises a question, which of the goals should have priority and opens a new question of compensations between DR and PV units. The answer is highly dependent on the prices of energy, but in our case the additional profit of PV could cover the losses of DR units, stabilizing the whole network with fewer overvoltage events.

TABLE IV: Green energy infeed with economic optimization (MW/week) with number of PQ violation/week

	Summer				Winter			
Sc.	**SiC**	**LC**	**OC**	**PQ**	**SiC**	**LC**	**OC**	**PQ**
1	4.16	4.16	4.09	0	1.51	1.51	1.49	0
2	5.95	5.95	5.85	0	2.17	2.17	2.14	0
3	10.00	9.86	9.64	0	3.67	3.66	3.60	0
4	14.27	14.02	13.66	0	5.22	5.18	5.10	0
5	16.41	15.91	15.48	69	6.03	5.94	5.83	7
6	19.00	19.34	18.32	2133	7.45	7.37	7.16	156

TABLE V: Results of profit calculations of economic scheduling for summer scenario (€/week)

	DR			PV		
Sc.	**SiC**	**LC**	**OC**	**SiC**	**LC**	**OC**
1	14.3	14.3	14.3	128.9	128.9	126.9
2	26.7	26.7	26.7	184.0	184.0	181.1
3	36.5	36.5	36.5	309.1	303.6	296.7
4	52.8	52.8	52.8	441.7	432.4	420.8
5	74.8	74.8	74.8	508.1	489.3	475.4
6	92.1	92.1	92.1	578.0	591.7	557.1

TABLE VI: Green energy infeed with energy based optimization (MW/week) with number of PQ violation/week

	Summer				Winter			
Sc.	**SiC**	**LC**	**OC**	**PQ**	**SiC**	**LC**	**OC**	**PQ**
1	4.16	4.16	4.09	0	1.51	1.51	1.49	0
2	5.95	5.95	5.85	0	2.17	2.17	2.14	0
3	10.00	9.99	9.81	0	3.67	3.67	3.61	0
4	14.27	14.18	13.89	0	5.22	5.21	5.13	0
5	16.46	16.15	15.79	0	6.04	6.00	5.90	0
6	19.77	19.77	18.92	868	7.54	7.47	7.28	42

TABLE VII: Results of profit calculations of energy based scheduling for summer scenario (€/week)

	DR			PV		
Sc.	**SiC**	**LC**	**OC**	**SiC**	**LC**	**OC**
1	14.3	14.3	14.3	128.9	128.9	126.9
2	26.7	26.7	26.7	184.0	184.0	181.1
3	36.5	36.5	36.5	309.1	308.7	303.5
4	48.6	48.6	48.6	441.7	438.4	429.7
5	68.4	68.4	68.4	510.1	498.8	487.7
6	83.7	83.7	83.7	608.6	608.7	580.6

VII. Conclusion

In this paper an optimal schedule balancing in distribution network using multi agent control strategy mostly developed in INCREASE project is presented. The results of the simulations between economic and energy based optimization scheduling show that the profit of DR units is better with using the economic optimization, but on the other side, less green energy is injected and PV profits decrease. The results of energy based optimization for scheduling show just the opposite results, an increase in green energy injection and PV profit as well as a decrease in DR profit. The energy optimization significantly reduces the number of PQ overvoltage violations and thus the help increase the green energy infeed.

The main conclusion is, that there is an obvious need for cooperation and coordinated actions between PV and DR units and new remuneration schemes for fair distribution. There is also a need for set of new rules and regulation which would define what is the priority of DSO and what benefits the society more. One of the main goal of the INCREASE project is to make proposals on this matter that would support the future policy making procedures.

VIII. Acknowledgment

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