DC microgrids with energy storage systems and demand response for providing support to frequency regulation of electrical power systems

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Keywords

«DC microgrid», «electrical power system», «battery energy storage», «demand response», «frequency and active power regulation»

Abstract

Frequency regulation of electric power systems efficiency depends on response time and on power reserves for frequency regulation. As integration of non-dispatchable renewable generation in the power system results with increased need for power reserves from fast responding power units, the idea of using aggregated DC microgrids in frequency regulation is presented. Model proposed in this work is based on using battery energy storage, combined with demand response for achieving efficient usage of battery energy storage. It is shown that large number of DC microgrids can provide sufficient

energy and fast responding power, to improve efficiency of frequency regulation of electric power system.

Nomenclature

D	Load damping constant of the power system's response to load change (p.u.)
Δf	Frequency deviation of the AC power system (Hz, p.u.)
ΔP_{PS}	Difference between consumption and power generation of all uncontrollable loads and generators in the power system and DC microgrids (MW, p.u.)
Δv	Voltage deviation of DC microgrids (V, p.u.)
f_{n}	Nominal frequency of the AC power system (Hz, p.u.)
G_{PS}	Transfer function of the power system (Hz / MW, p.u.)
G_{BESS}	Transfer function of battery energy storage system (Hz / MW, p.u.)
G_{CG}	Transfer function of conventional generators for frequency regulation (Hz / MW, p.u.)
G_{DR}	Transfer function of demand response (Hz / MW, p.u.)
k	Factor of conversion of AC frequency deviation to DC voltage deviation (p.u.)
K_{BESS}	Gain constant of battery energy storage system (p.u.)
K_{CG}	Gain constant of conventional generators for frequency regulation (p.u.)
K_{DR}	Gain constant of demand response (p.u.)
K_{EPS}	Gain constant of power system (p.u.)
M	Inertia constant of the power system response to load change (s)
P_{BESS}	Power of battery energy storage system (MW, p.u.)
P_{CG}	Power of conventional generators for frequency regulation (MW, p.u.)
P_{DR}	Total power of demand response (MW, p.u.)
P_{ESS}	Nominal power of the power system (MW, p.u.)
$P_{\mathrm{PFR\text{-}ESS}}$	Arranged power reserves of primary frequency regulation for power system (MW, p.u.)
T_{BESS}	Response time of battery energy storage system (s)
T_{CG}	Response time of conventional generators for frequency regulation (s)
T_{DR}	Response time of demand response (s)

Introduction

Power systems are developing in several directions. Effectivity of power generators is increasing, efficiency of consumer devices is improved, emissions of carbon dioxide and other pollutants produced per kWh of generated energy are being reduced. Beside safety and stability of power system, which is still the most important criteria during its operation, more importance is being given to efficient operation. Clean renewable generation, mostly wind and solar, has many advantages as clean, sustainable and cheap or free source of fuel, though it's uncertainty, volatility and limitation causes difficulties in managing electrical power systems. Achieving efficient operation of the electric power system today is more difficult because of high percentage of non–dispatchable and non-predictable generation from renewable sources in the system.

The focus of this research is frequency regulation, as it is one of the most activated ancillary services [1]. Maintaining frequency at its target value (50 Hz or 60 Hz depending on a power system) is crucial for safe operation of generators and connected loads. Therefore, it is necessary to keep the balance between power generation and consumption at all times. As percentage of renewable generation in power systems is increasing, it is important to ensure more highly dispatchable generation in the system [2], [3]. There are several solutions to reduce the impact of volatile and non-dispatchable generation on frequency regulation of power systems. Increasing conventional generation reserves for primary and secondary reserves is often the only solution, though it is not efficient and may be very expensive.

Battery energy storage is proven to be one of the most effective technical solutions to alleviate problems of non-dicpatchable generation. Additionally, battery energy storage can be financially self-sustainable and profitable if it is used in providing secondary services [4]. Battery energy storage is effective in providing several services to the system. It can easily be used in energy arbitrage as well as in providing auxiliary services to transmission system operators, like mitigating transition effects of volatile wind generation production.

The idea of using demand response in optimizing power system imposes as a very good solution to reduce uncertainties that renewable generation brings to power grid due the low investment costs and possibility of dispatching large extent of power on the consumption side of power system. DC load is considered because of small inertia factor, thus it can be used in frequency regulation due the fast response time. It can be used as a tool with the objectives of maximizing usage of renewable sources, optimizing usage of energy storage, and lowering the usage of conventional generators in frequency regulation services.

Model of frequency regulation of electric power system with support from aggregated DC microgrids is presented in this work. DC microgrids consist of battery energy storage system and demand response. The objective of usage of demand response is to optimize the usage of battery energy storage system in order to maximize its usage according to limitations of capacity, and thus decrease the number of years to payback the investment in battery energy storage system.

To the best of our knowledge, usage of demand response in optimization of battery energy storage system used to provide services of primary frequency regulation is rarely evaluated in research community, so developed model of proposed system is considered as a contribution of this paper.

Frequency regulation services in electrical power system

Frequency regulation is divided in three stages: primary, secondary and tertiary. Usual response time frame of primary frequency regulation is up to 30 seconds, secondary from few seconds to 15 minutes, and tertiary regulation is activated after several minutes.

Only primary frequency regulation is evaluated in this work, because DC microgrids with energy storage system and demand response have the ability of response in milliseconds. Also, prices of services and energy market options are not evaluated.

It is important to notice that primary regulation is activated directly in the power generators by means of turbine regulators, within aggregated limits, and provides service only for frequency regulation. On the other hand, secondary and tertiary regulations are actuated both automatically and by transmission system operators, and provide services for frequency regulation and regulation of international exchange power.

The observed time frame of primary regulation is based on [5], so response time frame of primary frequency regulation is from a few seconds to 30 seconds. Delay of activation of primary regulation until deviation of nominal frequency exceeds 20 mHz in real world, is neglected in proposed model. Maximum permitted frequency deviation is 200 mHz, which is considered as a quasi–steady state frequency limit of primary frequency regulation. Furthermore, maximum dynamic permitted frequency deviation is 800 mHz. According to [5], overall primary control reserve for the ENTSO-E synchronous area is 3000 MW. A small part of the system, in islanded operation, is modeled observed in order to highlight the influence of microgrids with battery energy storage systems and demand response on the system. Thus, modeled primary control reserve is + / - 100 MW, further in article expressed in per unit values in a system of nominal base of 4000 MW.

Configuration of model of the power system and DC microgrids

The main idea of the system is shown in Fig. 1. Modeled power system consists of ten DC microgrids that are a part of an AC electric power system, aggregated with centralized control to provide services of primary frequency regulation. Reliable communication network is established in order to ensure system safety and stability, and to maximize efficiency of the system by analyzing a large amount of information provided by all parts of the system.

The main goal of proposed model is to reduce usage of conventional generators and the need for ensuring additional conventional power reserves in primary frequency regulation of electric power system by using battery energy storage system instead. As battery energy storage system have limited capacity, demand response is used to optimize its operation and maximize its usage.

Battery energy storage system is used as energy storage system due to its cost competitiveness and mature technology. Although capacity of battery energy storage system is large, it is limited, as presented in [6]. So, it is important to plan using battery energy storage system according to weather forecast of the wind to maximize usage of batteries.

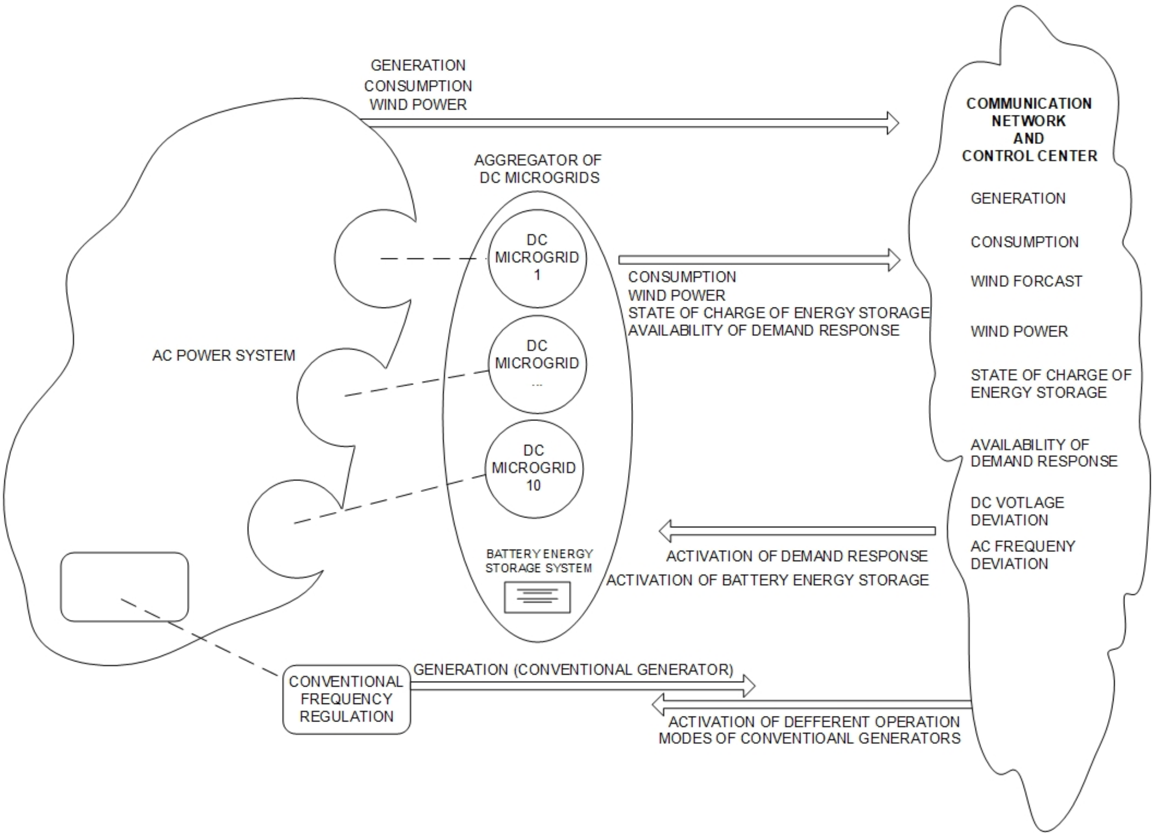

Fig. 1. The idea of AC power system and aggregated DC microgrids

Demand response is used as assistance to battery energy storage system and is replacing the role of battery energy storage system in frequency regulation when weather forecast proposes saving the capacity of battery energy storage system for another time.

Characteristics of demand response loads are presented as characteristics of controllable refrigerators because these devices are the only thermostatically controlled loads with the ability of storing energy during whole year, independently on weather conditions or seasons. Therefore, the model is simpler to implement and understand, and the results should be satisfactory due the possible integration of large number of observed units.

In order to use thermal energy stored in the refrigerators and not to ruin predicted conditions vital for its purpose, it is important to understand the logic of controlling the temperature conditions of the refrigerator cool chamber [7]. The standard refrigerator operates in cycles, turning the compressor on when the temperature inside the chamber reaches the set upper limit, and cools the chamber until the temperature reaches the set lower limit. As one cycle period is around three hours, it provides valuable amount of controllable energy. So, demand response is modeled as thermostatically controlled load. Cycles of turning a thermostatic load on and off are depending on proposed temperature, as it was explained in [8]. Modeling the behavior and control of thermostatically controlled load has been done in several studies. In [8] authors developed a model of thermostatically controlled load with ability of adapting to disturbances. The idea of predicting refrigerators temperature in order to evaluate and use the information about expected power consumption is presented in [9]. Authors in [10] use model predictive control to predict the behavior of refrigerator based on behavior of consumers in order to get the predicted information about cycles of refrigerator. Information from all of these models can be used in various scenarios of planning, optimizing and reducing the cost of consume.

However, in this work a simple model of simulation of thermostatically controlled load cycles is used. The only information the thermostatically controlled load sends to the communication network is the availability of interrupting its usual cycle and turning on or off. It is assumed that the thermostatically controlled load have their own regulation based on measurements of temperature. As proposed system uses demand response in order to optimize battery energy storage system, the only information that is important is the availability of the device. Usual uninterrupted cycles of turning the described model of the thermostatically controlled load on and off are shown in Fig. 2.

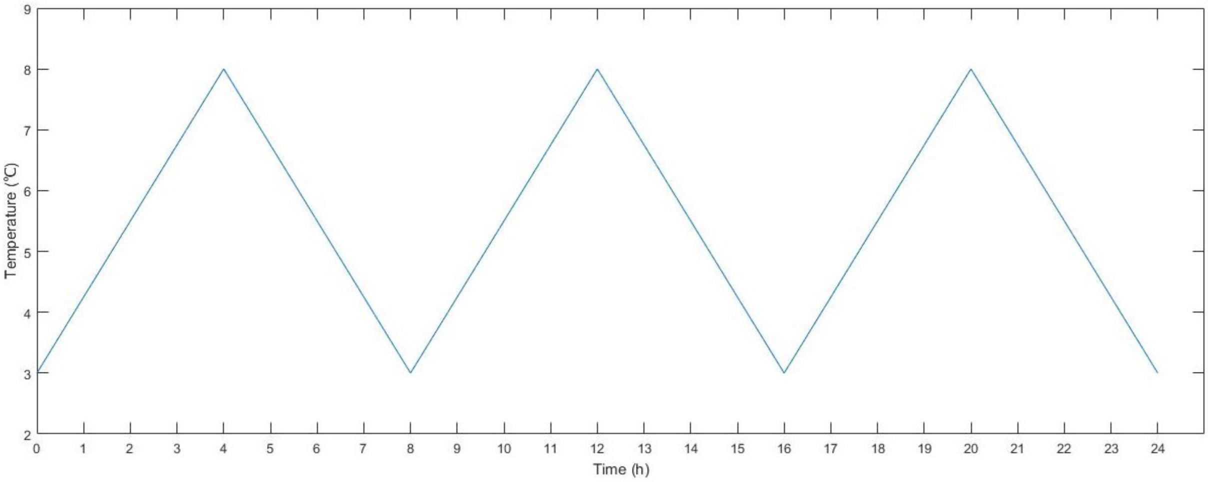

Fig. 2. Cycles of turning the thermostatically controlled load on and off in uninterrupted mode of operation

Configuration of model of the system is shown in Fig. 3. Connections of AC power system and DC microgrids are achieved by bidirectional AC/DC converters. DC microgrids consist of different conventional generators, renewable sources, battery energy storage, thermostatically controlled loads capable of providing demand response services.

The detailed converter operation and the distribution losses are neglected, due the simplicity of modeling and analysis of the system, and all uncontrollable generators and load in DC microgrids and AC system are represented as one generator and one load. Only controllable load and energy storage systems are represented individually in DC microgrids. Furthermore, all conventional generators that participate in frequency regulation of AC power system are represented as one generator.

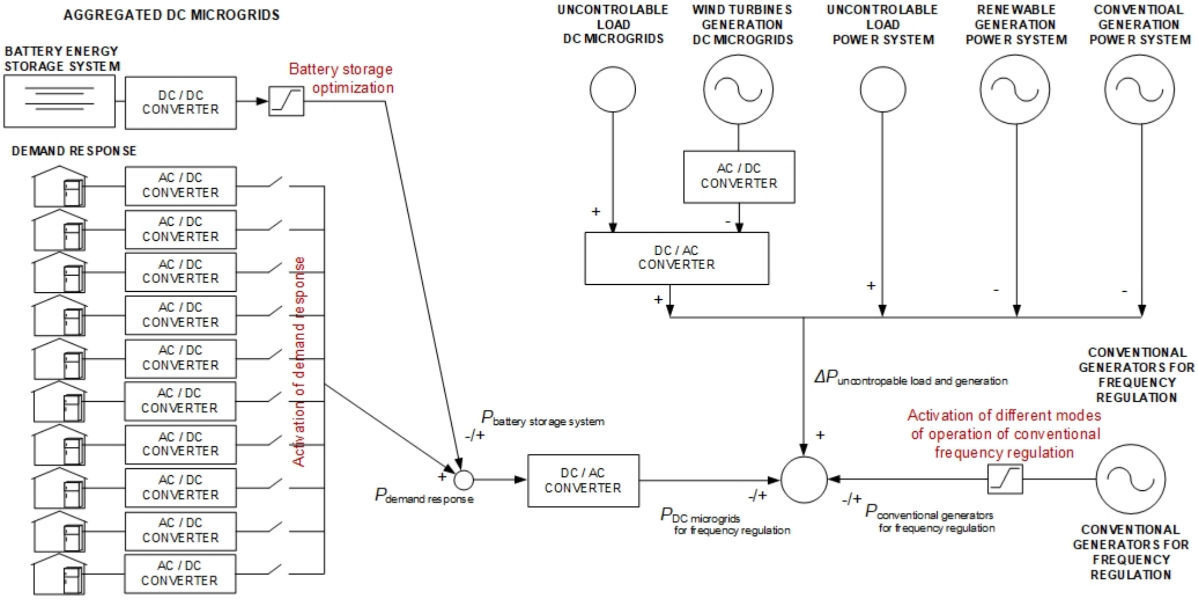

Fig. 3. Configuration or proposed model of the power system

All measurements, controls and communication are established over centralized communication network [11]. Every controllable unit within DC microgrids is controlled through a centralized communication network. In control centers, all collected data is being processed and the instructions to all the components are being sent according to integrated algorithms, constraints and evaluated prediction renewable generation. Although reliability of communication is crucial for centralized control of power system, communications are considered ideal.

Representing components of AC power system and DC microgrids

The main scope of modeling and observing the impact of volatile renewable generation in electrical power system is the small signal stability, while large disturbances are not observed. Frequency deviation is considered as the most important parameter of stability on AC side of the power system. Voltage level, as the most important parameter of stability on DC side [12], is being observed as a factor of frequency deviation on AC side of converters. Components of the AC power system and the DC microgrids' models are based on small signal stability and represented by first-order lag transfer functions, as shown in following equations.

System response to a change of load [13], [14]:

$$\mathrm{G_{EPS}}\ (s)=\frac{\Delta f}{\Delta P_{\text{load-generation}}}=\frac{1}{D+sM} \tag{1}$$

$$\Delta \mathrm{v}=\mathrm{k}\times\Delta \mathrm{f} \tag{2}$$

Conventional generators [15]:

$$G_{\mathrm{CG}}(s)=\frac{K_{\mathrm{CG}}}{1+sT_{\mathrm{CG}}} \tag{3}$$

Wind generator [15]:

$$G_{\mathrm{WT}}(s)=\frac{K_{\mathrm{WT}}}{1+sT_{\mathrm{WT}}} \tag{4}$$

Battery energy storage system [15]:

$$G_{\mathrm{BESS}}(s)=\frac{K_{\mathrm{BESS}}}{1+sT_{\mathrm{BESS}}} \tag{5}$$

Battery state of charge[6]:

$$\mathrm{SOC}_{BESS}(t)=\mathrm{SOC}_{\mathrm{BESS}}\ (0)-\int_0^t \eta\frac{I_{\mathrm{BESS}}(\tau)}{C_{\mathrm{BESS}}}(\tau)d\tau \tag{6}$$

Where $\mathrm{SOC}_{\mathrm{BESS}}\ (0)$ is initial state of charge of battery energy storage, η is efficiency of charging / discharging of battery energy storage, $I_{\mathrm{BESS}}(\tau)$ current of the battery energy storage and C_{BESS} nominal capacity of battery energy storage.

Refrigerator (demand response):

$$\mathrm{G}_{\mathrm{DR}_k}(s)=\frac{\mathrm{K}_{\mathrm{DR}_k}}{1+s\mathrm{T}_{\mathrm{DR}_k}} \tag{7}$$

Components of modeled system are represented in Fig. 4.

It is important to notice that transfer functions of battery energy storage system and conventional generators are represented in phase-variable control canonical form due the need for limiting the integrators before integrated saturation of signal.

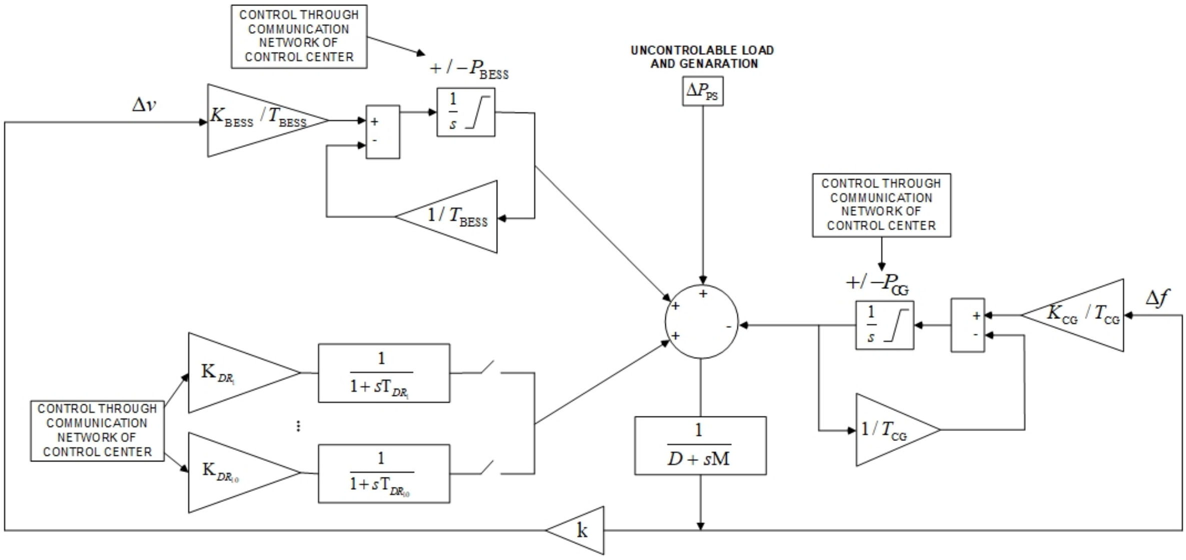

Fig. 4. Components of the AC and DC systems

Parameters of all the components of the system are explained in Table I.

Table I: Parameters of all the components of the system

Parameter	Real values	Per unit values
P_{EPS}	4000 MW	1
$P_{\mathrm{PFR\text{-}ESS}}$	+/- 100 MW	+/- 0,025
f_{n}	50 Hz	1
k		1
ΔP_{PS}	100 MW	0,025
D		0,015
M	0,2 s	
P_{CG}	+/- 100 MW	0,025
K_{CG}		40
T_{CG}	1,5 s	
P_{BESS}	+/- 50 MW	+/- 0,0125
K_{BESS}		- 20
P_{DR}	20 MW	+/- 0,005
T_{BESS}	0,5 s	
K_{DR}		1
T_{DR}	1,0 s	

Results of simulations

Four case studies are presented in the following simulations. In all four case studies, same initial conditions and disruptions during 24 hours are implemented. Initially, state of charge of battery energy storage is 100 %, states of cycles of operation of all ten loads that provide demand support are equally distributed, load is equal to generation so frequency deviation is zero.

In case study 1 primary frequency is regulated by both conventional generators and aggregated DC microgrids with battery energy storage system and demand response, and accurate wind forecast available, respectively.

Case study 2 represents the same case as in case study 1, only without services of demand response.

In case study 3 regulation is provided only with conventional generators and battery energy storage system without wind forecast information, and in case study 4 only with conventional generators.

Behavior of the system is shown in Fig. 5. In the first graph wind generation is shown. In the second graph difference between load and generation is shown, as disturbance to the system. Resulting frequency deviation is shown in the third graph. Response of conventional generators and battery energy storage system to the disturbance is shown in the following graphs. State of charge of battery energy storage system for case studies 1, 2 and 3 is shown in the sixth graph. Activation of demand response is shown in the last graph.

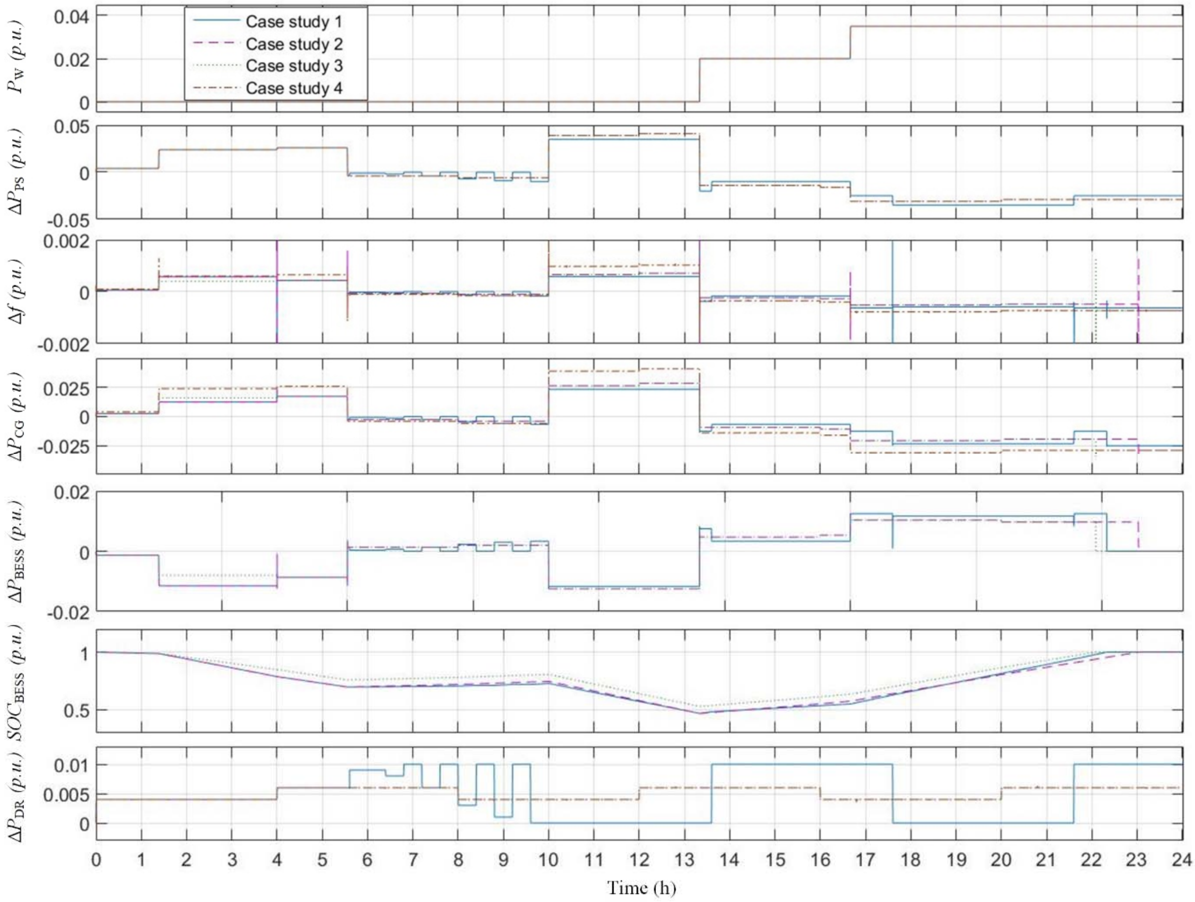

Fig. 5. Behavior of the system in case studies 1, 2, 3 and 4

Stability and effectivity are observed as the main criteria in simulations. Stability is presented as respecting the maximum dynamic permitted frequency deviation (800 mH, 0.016 p.u.) and maximum permitted quasi–steady state frequency deviation (200 mHz, 0.0036 p.u.).

Effectivity is presented in achieving the main goals of this work. Lower usage of conventional generators in frequency regulation is proven by counters of generation of conventional generators in frequency regulation during simulations with and without support from DC microgrids and wind forecasting. Also, usage of conventional generators in range higher than arranged (+ / - 100 MW, + /-

0.025 p.u.) is measured. State of charge and usage of battery energy storage is also measured, so support from demand response to battery energy storage system can also be evaluated.
Maximum dynamic frequency deviation, energy generated from conventional generators for primary frequency regulation, number of cycles of battery energy storage system and number of activations of demand response units are shown for every case study in Table II.

Table II: Results of simulations

Variable		Case study 1	Case study 2	Case study 3	Case study 4
Maximum dynamic frequency deviation	(p.u.) (Hz)	0.003778 0.1889	0.003778 0.1889	0.003292 0.1646	0.002529 0.12645
Energy generated from conventional generators for primary frequency regulation	(p.u.) (MWh)	0.3299 1319.6	0.3563 1425.2	0.3745 1498.0	0.5304 2121.6
Usage of conventional generators in range higher than arranged (> abs (100) MW, > abs (0.025) p.u.)	(p.u.) (MWh)	0.00002 0.0698	0.118977 475,909	0.146327 585.308	0.39226 1569.055
Number of cycles of battery energy storage system	(nr.) (MWh)	0.5614 673.68	0.58 696	0.5192 623.04	0 0
Demand response - number of activations	(nr.)	26	0	0	0
Total energy of controllable load that provide services of demand response	(p.u.) (MWh)	0.01199 479,96	0.01199 479,96	0.01199 479,96	0.01199 479,96

In all four case studies, maximum frequency deviations are within permitted limits, so the system is considered as stable in the given conditions.
As the main goal is to reduce the usage of conventional generation in frequency regulation it can be noticed that the least energy from conventional generators was produced in case study one, where assistance from aggregated DC microgrids (battery energy storage system and demand response) and wind forecast was provided. In this case the need for usage of conventional generation in range of power higher than the arranged power range was used for generation of only 0.0698 MWh, while in other case studies this need occurred for much longer periods during the day. Also, it can be noticed that the overall need for primary regulation was smaller in case study 1, where demand response mitigated the differences in generation and consumption by adjusting cycles of operation of according to predicted generation from renewable generators. In case study 2, as demand response is not available to help in optimization of usage of battery energy storage system in reference to wind forecast, capacity of battery energy storage system is available for usage for reduced amount of time, which resulted in higher usage of conventional generator. Energy generated from conventional generators for primary frequency regulation is higher in case study 3, where the capacity of battery energy storage was not optimized according to wind forecast. Activation of conventional primary frequency regulation can be seen in case study 4, where aggregated DC microgrids don't provide services of frequency regulation.

Model of the complete system is developed in the environment of MATLAB Simulink [16].
Verification results of simulated models are implemented by OPAL-RT real time Model-in-Loop system [17].

Conclusion

Frequency regulation is crucial for maintaining power system safety and stability. As distributed generators and loads with unconventional characteristics are being integrated in the system, frequency regulation is becoming an increasingly challenging task. The idea of providing support to frequency control from aggregated DC microgrids is proposed. Advantages and disadvantages are subjected, and improved stability and efficiency is proven through four case scenarios. As the proposed system is highly complicated, and demands reliable communication network, future research will be focused on those subjects.

References

[1] Kirby B. J.: Frequency regulation basics and trends, Report prepared for the US DoE - ORNL/TM-2004/291.

[2] Dragičević T., Sučić S., Vasquez J. C., and Guerrero J. M.: Flywheel-based distributed bus signaling strategy for the public fast charging station, IEEE Trans. Smart Grid, Vol. 5, no. 6, pp. 2825–2835, 2014.

[3] Bradbury K.: Energy storage technology review, Technical report, 2010.

[4] Pandžić H., Kuzle I.: Energy Storage Operation in the Day-Ahead Electricity Market, 2015 12th International Conference on the European Energy Market (EEM)

[5] Supporting Document for the Network Code on Operational Security, European Network of Transmission, System Operations report, Continental Europe Operation Handbook, UCTE OH – Policy 1: Load-Frequency Control - Final Version (approved by SC on 19 March 2009), available at www.entsoe.eu

[6] Dragičević T., Guerrero J. M., Vasquez J. C., Škrlec D.: Supervisory Control of an Adaptive – Droop Regulated DC Microgrid With Battery Management Capability, IEEE Trans. On power electronics, Vol. 29, no. 2, February 2014.

[7] Lakshmanan V., Gudmand-Høyer K., Marinelli M., Kosek A. M., Nørgård P.: Energy shift estimation of demand response activation on refrigerators — A field test study, Power Engineering Conference (UPEC), 2014 49th International Universities, 2-5 Sept. 2014

[8] Crocker S. J., Mathieu J. L.: Adaptive state estimation and control of thermostatic loads for real-time energy balancing, American Control Conference (ACC), July 2016.

[9] Lakshmanan V., Marinelli M., Kosek A. M., Sossan F., Nørgård P.: Domestic Refrigerators Temperature Prediction Strategy for the Evaluation of the Expected Power Consumption, 2013 4th IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe), October 6-9, Copenhagen

[10] Khadgi P., Bai L., Evans G.: Modeling Demand Response Using Utility Theory and Model Predictive Control, Proceedings of the 2014 Industrial and Systems Engineering Research Conference Y. Guan and H. Liao, eds.

[11] Budka K. C., Deshpande J. G. and Thottan M.: Communication Networks for Smart Grids, London, U. K.: Springer - Verlag, 2014. [Online]. Available: http://dx.doi.org/10.1007/978-1-4471-6302-2

[12] Sannino A., Postiglione G. and Bollen M. H. J.: Feasibility of a DC network for commercial facilities, IEEE Trans. on Industry Applications, Vol. 39, no. 5, Sept.-Oct. 2003)

[13] Senjyu T., Nakaji T., Uezato K. and Funabashi T.: A hybrid power system using alternative energy facilities in isolated island", IEEE Trans. Energy Convers., vol. 20, no. 2, pp. 406 – 414, Jun. 2005.

[14] Xu L. and Chen D.: Control and Operation of a DC Microgrid With Variable Generation and Energy Storage, IEEE Trans. On power delivery, Vol. 26, no. 4, October 2011.

[15] Lee D. J. and Wang L.: Small - Signal Stability Analysis of an Autonomous Hybrid Renewable Energy Power Generation / Energy Storage System Part I: Time - Domain Simulations", IEEE Trans. on Energy Conversion, Vol, 23, no. 1, March 2008.

[16] https://se.mathworks.com/

[17] http://www.opal-rt.com/