Journal of Energy

ISSN 1849–0751 (On–line)
ISSN 0013–7448 (Print)
UDK 621.31

https://doi.org/10.37798/EN2021704

VOLUME 70 Number 4 | 2021

70

ENERGIJA

Journal of Energy

Scientific Professional Journal Of Energy, Electricity, Power Systems
Online ISSN 1849–0751, Print ISSN 0013–7448, VOL 70
https://doi.org/10.37798/EN2021701

Published by
HEP d.d., Ulica grada Vukovara 37, HR–10000 Zagreb
HRO CIGRÉ, Berislavićeva 6, HR–10000 Zagreb

EDITORIAL

Journal of Energy

VOLUME 70 Number 4 | 2021

journal homepage: http://journalofenergy.com/

Saša Nikolić
Elmins doo
Nikole Tesle 99,
89240 Gacko Bosnia and Herzegovina
office@elmins.ba

Radoš Ćalasan
Elmins doo
Nikole Tesle 99,
89240 Gacko Bosnia and Herzegovina
office@elmins.ba

Increasing the Reliability and Availability of the Electric Motor Using Combined Static and Dynamic Diagnostics

SUMMARY

The aim of this paper is to point out the importance of early diagnostics and assessment of the condition of the electric motor in increasing the reliability and availability of the plant. Electric motors are unavoidable elements in every production process. As the complexity of the process increases, the number of electric motors involved in it increases. By increasing the number of electric motors, the possibility of cancelling and interrupting production increases. It is therefore very important to monitor the situation and detect defects at an early stage so that timely repair or replacement can be planned, without affecting the production process. Modern diagnostic methods that can be used both during the operation of the electric motor, and with the dismounted and dismantled electric motor are presented in the paper. With good organization and testing schedule and a combination of static and dynamic diagnostic methods, the reliability and availability of the plant can be significantly increased. With increased reliability and availability, a reduction in maintenance costs is achieved. In this article, some examples from the author's practice are given, when serious engine defects were discovered. These cases confirm the value of predictive testing to increase reliability of electric motor.

KEY WORDS

reliability, availability, diagnostics, MCSA

INTRODUCTION

Modern industrial plants cannot be imagined without an electric motor. They represent the driving force of most of modern industrial processes. Also, according to some estimates, in electric power consumption, electric motors participate up to 50%.

With the increasing complexity of the process, the number of engaged electric motors is also increasing. With the increase of their number in the industrial process, their importance for the reliability and availability of the plant is growing. In order to prevent unplanned shutdown and thus loss of production, the quality maintenance of electric motors plays a very important role.

Electric motors produced more than thirty years ago were mostly oversized and many of them still work.

By contrast, nowadays, manufacturers under constant cost-cutting demands, reduce the material needed for production to minimum rates. In this way, electric motors become more sensitive to operation beyond nominal parameters, even for a short time.

In addition, in modern industrial plants, electric motors are connected via frequency inverters, for better control process. In this operations mode, insulation suffers from increased stress due to large du/dt, as well as due to the existence of higher harmonics. [1]

Especially sensitive are the older electric motors that are not even designed for such a mode of operation, and very often in the process of automation of the plant, old electric motors are retained, and only the control equipment is installed. Because of this, it is necessary to monitor the condition of the electric motor from its installation in the plant and throughout the entire life time.

In order to achieve the best maintenance results, it is necessary to make a proper approach, along with defining test methods and condition assessment, the priorities and the time schedule of the test. In this way, the electric motor is monitored from its installation and its the record of its working history is kept. By doing this, it is achieved that every defect and the problem in the electric motor are noticed at the very beginning, which is followed and responded adequately before the problem becomes a serious defect that will cause huge and unnecessary costs.

After the repair, it is necessary to assess the condition to determine whether the repair was effective. Namely, in practice, it is often the case that the electric motor that was on external service breaks down again, very soon after the installation. This happens very often, because in many electric motor services shops not enough attention is given to the initial symptoms of failures.

Using a good post evaluation method will help to avoid unnecessary waste of time and shift the blame for electric motor failure from the service engineer to the owner. Also, when a defect is observed, the question that arises is whether to repair or replace the electric motor. According to a 2014 study conducted by *Plant Engineering* magazine for the Electrical Apparatus and Service Association (EASA), just more than one-half of plants have a policy of automatically replacing failed electric motors below a certain horsepower rating. While that horsepower rating varied depending upon the plant's installed motor population, the average rating was 30 hp. [2]

In the past, the decision to repair or replace an electric motor was primarily driven by the cost of energy and related potential savings. In many cases, this is still a major factor. However, a number of other elements that influence the true life-cycle cost of operating a motor should be considered.[5]

Symbols			
du/dt	- voltage change rate, V/s	f_1	- mains frequency, Hz
FFT	- Fast Fourier Transformation	%FLA	- Percent of full load, A
F_p	- Pole pass frequency, Hz	N_r	- Rotor bars number
F_{ecc}	- Frequency of eccentricity, Hz	DA	- Dielectric absorption

2.THE OBJECTIVE AND APPROACH TO THE MAINTENANCE OF ELECTRIC MOTORS

The basic maintenance goals are known:

- preventing unplanned downtime;
- reduction of costs;
- increase productivity;

Usually, only some of the goals are achieved in maintenance. This mostly depends on the approach and the way used to reach the goal.

Three basic approaches to maintenance are:

- corrective maintenance (intervention after process event);
- planned maintenance (preventive);
- maintenance by condition (predictive);

Each of these approaches produces maintenance costs. It is shown that the maintenance by condition is most favorable from the point of view of the cost. Due to good results achieved, more attention is paid to this maintenance approach. Figure 1. shows the ratio of costs of maintenance according to Schneider Electric[3].

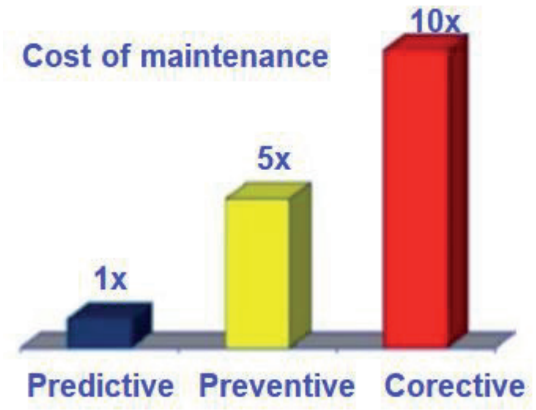

Figure 1. Cost of maintenance (Schneider Electric)

In case of maintenance by condition approach, and if there are many electric motors in the factory, a good test plan should be made and priorities defined. A decision should be made to maintain an electric motor or to let it work.

In order to define priorities, the following questions need to be asked:

- Is the motor easy to replace? If yes, is there a spare one?
- Would the purchase of a new motor cost less than repairs of the old one?
- Is the motor redundant and uncritical?

If all the answers are positive, this electric motor is not a priority for testing and monitoring. If the answer to any question is negative, it is necessary to include the electric motor in the test plans.

Three keys for quality maintenance of the electric motor can be defined. Those are:

- Quality control;
- Trending;
- Repairing;

Quality control implies that only electric motors of satisfactory quality are introduced into the production process. Therefore, it is necessary to check whether the purchased electric motor meets the defined quality criteria before installing it. It ensures that only the best electric motors are included in the production process. Trending implies that the electric motor is monitored from its installation, it is periodically examined and the trends of vital parameters are made. This achieves that any problem or deviation of the parameters of the electric motor is detected on time.

The third quality maintenance key is troubleshooting and repair. By timely detection of the defect, it can be planned to switch off the electric motor at a convenient time and to repair it at the stage when it will cause the least cost. By applying a third maintenance key, one working cycle of an electric motor is finished. After the repair and successful quality control, the electric motor can return to the production process again.

In order to achieve high quality predictive maintenance, using three quality keys, appropriate methods for testing and assessment of the condition of the electric motor should be applied. In order to avoid unnecessary stopping of the production process for testing, the best results are given by a combination of methods that enable testing of the electric motor before installation and later in operation, without disconnection.

3. METHODS OF ELECTRIC MOTORS ASSESSMENT

3.1 List of diagnostic methods

Traditional testing of the condition of an electric motor involves the analysis of very little data. Most often it is only the resistance of the insulation to the ground.

Modern diagnostic methods developed in recent years represent a comprehensive examination and assessment of the condition of all assemblies of electric motors, stator, rotor and air gap. The rating of both electric and magnetic circuits is completed. Due to the numerous data obtained, a correct estimate of the condition of the electric motor can be carried out and the need for its maintenance.[4]

The basic division of the test method is made according to whether the electric motor is tested while it is switched off and disconnected from the electric circuit, or the test is carried out in normal operation, at nominal load and in real conditions in the plant. Based on this, two methods are distinguished:

- Static (offline);
- Dynamic (online);

Static testing is performed with a deenergized electric motor, which is separated from the rest of the electric circuit. The analyzer injects currents and voltages of a precisely defined level and frequency, on the basis of which all parameters of the electric motor are determined. The advantages of this method are:

- Safety, since the test is carried out without mains voltage; - Possibility of detailed direct insulation analysis; - Possibility to evaluate electric motor condition before installation;

The disadvantages of static methods are:

- Requires motor shutdown, if already in operation; - No mechanical parts rating can be given; - No power quality rating;

Dynamic testing is carried out on an electric motor in operation, at nominal load and in real operating conditions in plant. The analyzer performs acquisition of the electric current and voltage of the electric motor and, based on the measured values, calculates the parameters necessary for the assessment of the condition. This method uses FFT to calculate the spectrum of the current. An analysis of the components in the spectrum takes place in a state evaluation. [6]

The advantages of a dynamic method are:

- Testing during work in real conditions;

- Does not require disconnection and termination of production;
- The ability to evaluate motor mechanics [7];
- Evaluation of the start-up of the electric motor (if it was switched off);

The disadvantages of the dynamic method are:

- Need to connect measuring probes to energized circuit; - There is no direct assessment of the state of insulation;

3.2 Fault zone in an electric motor

All defects and problems in the electric motor can be divided into six zones. [8] Those are:

- Power quality;
- Connection circuit;
- Stator;
- Insulation;
- Rotor;
- Air gap;

The first two fault zones include the assessment of the voltage level of both the current and the current supply circuit, which supplies electricity to the motor. Static fault zone includes insulation between turns and internal winding connection. Rotor fault zone refers to the condition of the cage and lamination of the core. Finally, the air gap as a fault zone refers to the quality of the air gap and the distribution of the magnetic field inside. Each fault zone should be analyzed to reliably assess the overall state and health of the electric motor.

The static (offline) electric motor test enables the evaluation of the electric motor in five of the six fault zones. With this method, it is not possible to evaluate the power quality.

On the other hand, dynamic (online) testing also evaluates in five of the six areas of failure. However, it is not possible to give a direct assessment of the insulation state.

An approach to the analysis of the electric motor across the error zone allows a more complete assessment of the condition and health of the electric motor.

4. TESTS TO ASSESS THE CONDITION OF THE ELECTRIC MOTOR BY FAULT ZONE

4.1. Dynamic (online) tests

Dynamic testing is based on the measurement and acquisition of all current and voltage of the electric motor. On the basis of the measured values, the FFT signal is performed, thus obtaining spectra of currents and voltages. An analysis of the current and voltage spectrum is carried out by the state estimation. This method begins to be applied extensively in recent years. The physical basis of this method is based on the fact that every defect of the electric motor modulates the flux of the motor, creating the rotation of the component as a further product of the characteristic of the components, which superimpose the basic harmonics [9]. By detecting and isolating the current components, the defect of the electric motor can be detected at the earliest stage, which allows monitoring the development of defects and reacting at the appropriate time, before serious damage is caused, which can cause great repair costs. Also, this prevents unplanned production losses and losses due to this. The advanced dynamic analyzers in a short interval of time perform a series of tests from which the state of the electric motor is evaluated by automatic or subsequent analysis.

These tests are: [6]

- Rotor evaluation test,
- Air gap assess test (Eccentricity test),
- Stator and power circuit test (Power test),
- Asses of mechanical parts (Demodulation test).

As an illustration, in Figure 2, a spectral diagram of the current is used to evaluate the rotor. This is case from TPP Ugljevik. The two components at the Fp distance from the base accordion represent the pole pass frequency [6]. Based on their value, the condition of the rotor cage is evaluated. Serious defect of rotor bars is detected at early stage and prevented catastrophic failure of electric motor.

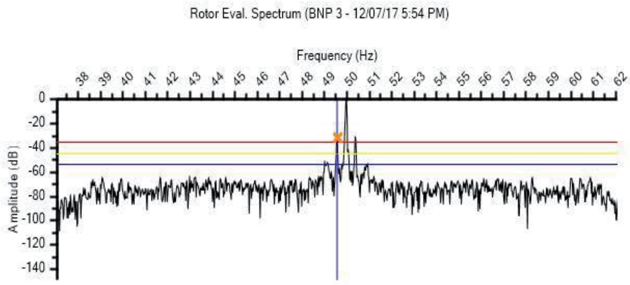

Figure 2. Rotor evaluation spectrum

Figure 3 shows a high-frequency spectral diagram of the current used to estimate the air gap.[6] This case is from Eating Oil Rafinery Bimal Brcko. Detected is air gap eccentricity which caused serious vibration and damage bearings.

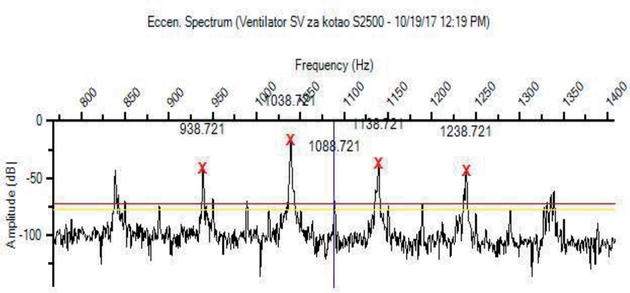

Figure 3. Eccentricity spectrum

One of the novel techniques for air gap asymmetry detection, especially for static eccentricity, is using measuring coils that are installed on the stator teeth.[12] This is an efficient method, but requires additional coils that must be installed during the manufacture of the electric motor.

For the difference, current spectrum analysis does not require additional part and additional cost of electric motor. The estimation of the state of the air gap, that is, the detection of the gap asymmetry is performed on the basis of the level of the four characteristic components in the spectrum, located at a distance of 1x and 2x from the eccentricity frequency $f_{ecc,}$ given by the expression (1).

$$f_{ecc}=N_r \cdot n/f_1 \quad (1)$$

Similarly, in other tests, identification of components in the spectrum is characteristic of certain defects. Power test, as a result, in addition to the spectrum, provides numerous numerical data with the interpretation of the state of the stator and the connecting circuit.

The estimation of the state of the electric motor by spectral current analysis is based on the IEEE and NEMA standards and also on the EASA Standard AR100-2020. [11]

4.2 Static (offline) tests

For static testing it is necessary to ensure that the motor is disconnected from the power supply and that the shaft does not rotate.

The static analyzer generates DC voltage and current signals or an AC signals of defined frequency, and it injects them into an electric motor.[10]

Measured parameters are:

- Resistance to ground,
- Capacitance to ground,
- Resistance of winding,
- Inductance of winding.

Based on the measured parameters, the assess is made in five of the six error zones:

- Insulation,
- Air gap,
- Power circuit,
- Stator,
- Rotor.

There is no direct assessment of insulation.

Tests carried out are:

- AC Standard test,
- Polarization index,
- Rotor influence check,
- Step voltage test.

AC Standard Test is a short but detailed analysis of the electric motor and its current circuits in five of the six fault zones.

Polarization index PI is the insulation test. Continuous measurement of insulation resistance and resistance ratio are performed after ten minutes and after one minute under voltage.

At the same time, the Dielectric Absorption DA is calculated, which represents the ratio of the insulation resistance after one minute and after thirty seconds.

In Figure 4. a PI test diagram is shown.

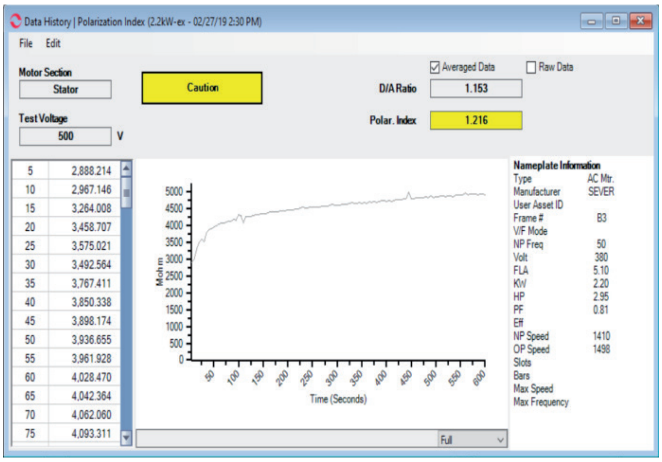

Figure 4. Polarization Index diagram

Step Voltage is ***Overvoltage test*** of insulation system and is not intended as a routine test

It is used to determine the insulation performance when the results of the AC Standard test and the PI are not consistent and sufficient.

Figure 5 shows the Step Voltage test diagram.

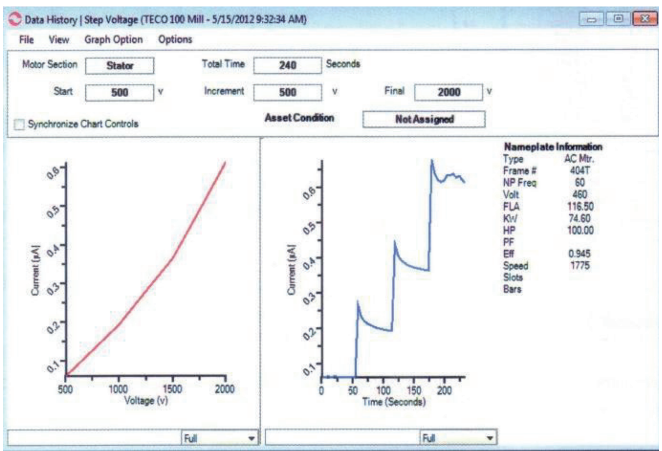

Figure 5. Step voltage test

The Rotor influence check RIC is test performed to obtain a graphic representation of the influence of the residual rotor magnetism on the Stator winding Inductance. This test is used to assess stator, rotor and air gap.

Figure 6 shows one RIC test.

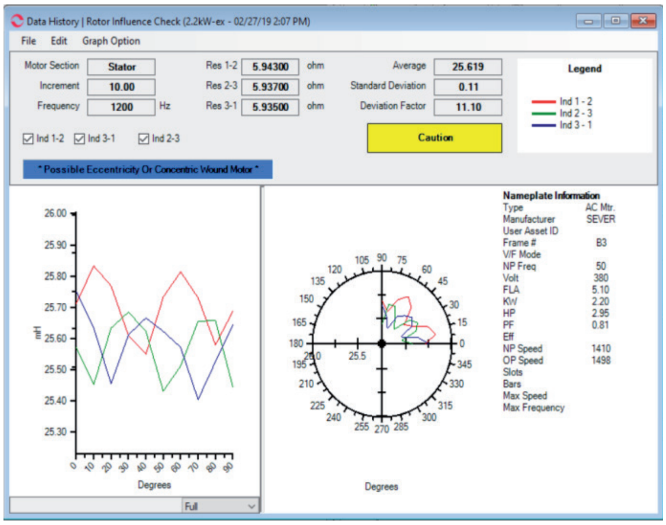

Figure 6. RIC test

5. CONCLUSION

Due to the importance of electric motors in automated industrial processes, it is very important to have a good maintenance strategy for these equipement. Some cases from practice are shown that predictive maintenance gives the best results in terms of cost reduction and increased reliability of the plant. To this end, it is necessary to monitor the electric motor from its installation and commissioning for the entire duration of its lifetime. By installing only those electric motors that meet quality criteria, periodic testing during operation, and the trend of data obtained by testing, any deviation of the parameters from the normal can be detected at the earliest stage.

Further, this defect can be monitored and reacted in time before the motor failure causes the loss of production and the large repair costs. In practice, it is shown that the best results in the predictive maintenance of the electric motor provide a combination of static and dynamic test methods. Advanced analyzers have already been developed.[10] By performing a series of tests both off and on the energized motor they provide a comprehensive and reliable assessment of the condition. Based on this assessment, maintenance activities are planned, which will contribute to increasing the reliability and availability of plants, while minimizing maintenance costs.

REFERENCE

[1] Fonstad K., *Variable Frequency Drives and Motor Insulation Stress*, ABB, MilwaukeUSA, 2011

[2] Mike Howell, *Motor maintenance trends*, Electrical Apparatus and Service Association (EASA), 2018

[3] Maling S., West B., *Solving the Maintain vs Modernization Equation*, Schneider Electric, 2013

[4] Penrose H.W., *Evaluating Motor Condition With Advanced Diagnostics,* Success by design, Old Saybrook, CT, USA, 2013

[5] Austin H. Bonnett, Helmuth M. Glatt, Ten Things You Should Know About electric Motors, IEEE Industry Application Magazine, p. 25-36, 2018

[6] S. Nikolić, R. Ćalasan, Motor Current Signature Analysis in Predictive Maintenance, Journal of Energy, vol. 67 Number 4, Special Issue, p. 3–6, 2018

[7] Fossum D., *Identifying Mechanical Faults With Motor Current Sigfnature Analysis*, Allied Services Group, USA

[8] K. Arttama and C. Jettanasen, (2022), The six electric fault zone analysis for predictive maintenance on motors of the continuous production, International Electrical Engineering Congress (iEECON), pp. 1-4,

[9] Penrose H.W., (2006), *Evaluating induction motor rotor bars with electrical signature analysis*, Success by design, Old Saybrook, CT, USA

[10] PdMA, (2017), *MCEGold – Product Support Manual*, PdMA Corporation, FL, USA

[11] EASA Inc., (2020), EASA Standard AR100-2020 Recommended Practice For The Repair of Rotating Electrical Apparatus

[12] S. Tvorić, M. Petrinić, A. Elez, M. Brčić, (2020) Static eccentricity fault detection method for electrical rotating machines based on the magnetic field analysis in the air gap by measuring coils, Journal of Energy, vol. 69 Number 4, p. 3–7

Journal of Energy

VOLUME 70 Number 4 | 2021

journal homepage: http://journalofenergy.com/

Leila Luttenberger Marić[1]
KONČAR – Digital Ltd.
leila.luttenberger@koncar.hr

Vesna Bukarica[2]
Energy Institute Hrvoje Požar
vbukarica@eihp.hr

[1] Statements expressed in the paper are author's own opinions, they are not binding for the company/institution in which author is employed nor they necessarily coincide with the official company/institution's positions.

[2] Statements expressed in the paper are author's own opinions, they are not binding for the company/institution in which author is employed nor they necessarily coincide with the official company/institution's positions.

Combined Effort Opportunities of Aggregated Demand Response Flexibility and Energy Savings in Households

SUMMARY

This paper analyses possible synergies between demand response flexibility programmes and energy savings delivered by households. In the framework of the energy transition, European Union (EU) directives are endorsing energy consumers to become full-fledged participants of the energy market, mostly via independent aggregator intermediaries. The flexibility aggregators have a very arduous role in collecting, optimising and settling aggregated flexibility delivered from heterogenous sources on the energy market. Novel business models incorporating both flexibility and energy savings opportunities from household consumers could deliver revenue diversification for flexibility aggregators and support them in overcoming technical and motivational challenges for activating consumers in the energy market. This paper discusses the main pillars for a sustainable flexibility aggregator business model which sums up the potential for flexibility placement on energy, ancillary services and energy savings markets. The main challenge identified in this work are the requirements for programme establishment, allowing the recognition and proper interpretation of energy savings triggered by short-term events and obtained by an aggregator via explicit demand response actions. This paper proposes possible solutions for a joint venture of a flexibility and energy savings aggregator, thus alleviating possible data collection problems. Collaborative efforts have been recognised in the establishment and maintenance of information and communication technologies and infrastructure, therefore facilitating continuous monitoring and verification of flexibility programmes which are able to deliver energy savings.

KEYWORDS

flexibility, energy savings, demand response, ESCO, P4P, monitoring, verification

1. INTRODUCTION

In order to set in motion EU long-term carbon neutrality, the Clean Energy Package [1] is launching ambitious energy and climate targets for 2030. The integration of renewable energy sources in the transmission and distribution energy grids are changing the landscape of the energy system. Flexibility aggregation opportunities are particularly interesting for soothing the effects of volatile production in real-time system balancing, although they could be valuable tools for network operators in long-term grid planning, as well as demand and supply balancing.

Energy consumers, which could be led by various motivational factors [2], should become enablers of energy system democratisation [3] with their capabilities to produce, store and consume energy. The technological changes which are increasing the smart readiness level [4] of buildings are occurring rapidly and the introduction of such solutions is becoming more affordable for consumers. Along with the empowerment of flexibility opportunities in the energy market, the Clean Energy Package [1] endorses energy efficiency as a priority through "energy efficiency first" principle [5]. At the EU level, buildings account for 43% of final consumption[6], therefore obvious emphasis is dedicated to the building sector and improvement of its energy performance: the target is to increase the efficiency of EU energy use by almost one-third (at least 32.5%) by 2030.

The Energy Efficiency Directive [7] defines aggregators as "demand service providers that combine multiple short-duration consumer loads for sale or auction in organized energy markets"; while the Electricity Market Directive [8] defines independent aggregator as " a market participant engaged in aggregation who is not affiliated to the customer's supplier".

Energy consumers are on one hand expected to become active participants on the energy market [8], and on the other hand to improve their energy consumption efficiency [7] via interventions in performance of their buildings, purchasing energy efficient products [9], improving energy consumption management, etc. Obviously, for achieving such ambitious targets, consumers should be provided with adequate tools, incentives and know-how. Business models which allow aggregation of such scattered

Leila Luttenberger Marić, Vesna Bukarica,Combined Effort Opportunities of Aggregated Demand Response Flexibility and Energy Savings in Households, Journal of Energy, vol. 70 Number 4 (2021), 7–12
https://doi.org/10.37798/2021704257

potential trapped in households have a unique opportunity to perceive their potential in both energy market through flexibility provision and energy savings market by delivering energy savings. Offering energy savings programmes through aggregators, as a part of flexibility service, creates more awareness of their benefits as consumers become more aware of the energy costs and impacts of energy use [10].

This article provides an overview of possible solutions and limiting factors enabling this particular cohesion.

2. METHODOLOGY AND APPROACH

The first step in the research is the analysis of existing business models which are based on flexibility aggregation, energy performance contracting, and their possible synergies. In a second step, revenue creation opportunities derived from energy savings obligation schemes have been analysed. In a third step, possible synergies in monitoring and verification techniques for a programme settlement and continuous alignments used in both flexibility and energy savings programmes have been elaborated.

2.1. Analysis of business models and possible synergies

In the following section, an overview of possible business models for an independent aggregator where flexibility provisions are dissociated from the supply contract are elaborated. Models for energy savings and flexibility aggregation are analysed, and a model is proposed to integrate both flexibilities and savings opportunities of household consumers.

2.1.1. The independent flexibility aggregator

The Electricity Market Directive [8], published with the Clean Energy Package, states that independent aggregators should be introduced in European electricity markets [11]. Independent aggregators are market participants performing demand-side aggregation and are not affiliated with the consumer's retail suppliers. More precisely, the role of the independent aggregator is to operate in the opposite direction of the energy supplier. The independent aggregator purchases the flexibility from the end users (or consumers) and offers its aggregated value to a Balance Responsible Party (BRP) on the energy market or to the system operators on the ancillary service markets. In order to regulate imbalances between energy purchased for supply and actual consumed, caused by flexibility activations from the independent aggregator, several market models could exist [12]. If flexibility provisions are dissociated from the supply contract - which is the case for the independent aggregator – ENTSO-E proposes three types of market models:

1. bilateral agreement model;
2. supplier settlement model and
3. central settlement model.

The bilateral model allows the independent aggregator to operate with a low degree of complexity on the energy market, ensuring fairness as there is a consent between involved stakeholders (supplier and aggregator). However, in this model, the participation of the independent aggregator on the energy market is highly dependent on the willingness of BRPs and suppliers, thus the economic efficiency of such model depends on the contracted conditions. Market design without bilateral contracts provides a higher degree of confidentiality for consumers and allows independent aggregators to operate without the consent of the BRP or the supplier. As stated in [12], economic efficiency is ensured if the prices to settle the transfer of energy with suppliers are cost-reflective. Such market design requires a higher degree of complexity which could take time to develop. In a supplier settlement model, the energy sold on the market by the independent aggregator is invoiced to the consumer by the supplier as if it had been consumed, which is not desirable in terms of consumer motivation. In the central model, the settlement of the transferred energy is performed by a neutral entity, which could be a system operator or a third party. Such model would allow consumers to receive a single bill, exposing the amount of consumed energy minus the transferred as flexibility via an independent aggregator. This model might be one of the most advantageous for consumers because the benefits for participation in flexibility programmes would be directly reflected in the energy bill.

Apart from supplier/BRP imbalance settlements, the independent aggregator could deliver ancillary services to the system operator under contracted conditions [13]flexibility can be provided to operators using home-appliances with the ability to modify their consumption profiles. These actions are part of demand response programs and can be utilized to avoid problems, such as balancing/congestion, in distribution networks. In this paper, we propose a model for aggregators flexibility provision in distribution networks. The model takes advantage of load flexibility resources allowing the re-schedule of shifting/real-time home-appliances to provision a request from a distribution system operator (DSO , which could add more complexity to the business model (Figure 1).

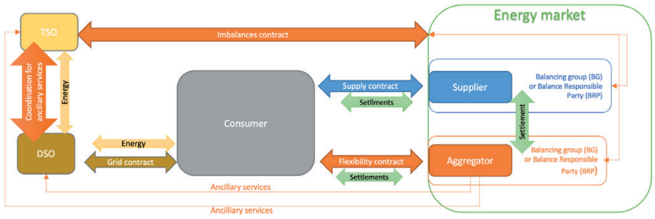

Figure 1 Independent aggregator business model

An important backbone for the introduction of independent aggregators as ancillary service providers to system operators is the introduction of a coordination platform to exchange flexibility activation information between transmission system operators (TSOs) and distribution system operators (DSOs). More precisely, the DSO should timely receive the insights of the flexibility activation schedule planned for distribution network users and purchased by the TSO. The creation of a common platform for the trading of ancillary services would increase the coordination between purchased services and would probably improve the network management efficiency.

Therefore, even if the regulatory framework eases the introduction of the independent aggregator to the energy market, its existence is highly dependent of the level of maturity of the market and willingness to establish novel contracting relationships between traditional market participants.

2.1.2. Energy saving models

Citizen or renewable energy communities offer consumers the possibility for participation in production, consumption and local energy sharing [14] to fully unleash their potential, they require a coordinated operation and design that the community itself may be ill-equipped to manage. Aggregators and Energy Service COmpanies (ESCOs. Such initiatives facilitate the integration of new technologies, advance energy efficiency at household level and support the mitigation of energy poverty through reduced consumption and lower supply tariffs [15]. The same applies for independent aggregators, oriented toward local household consumers, because they can contribute to the same goals. Business models enabling synergistic action to ensure energy savings and activation of demand side flexibility in households are interesting to observe in this context.

Through an Energy Performance Contract (EPC), which is based on achieving client's or consumer's energy savings, an energy service company (ESCO) implements a project to improve energy efficiency or integrate renewable energy sources, by using financial savings obtained from energy savings (as income) to cover investment costs. The ESCO company finances and implements energy efficiency measures for its clients and guarantees them energy savings. If the implemented project does not result in the planned energy savings, the ESCO company does not achieve the planned income [16]. The approach is based on the transfer of technical risks from the client (who concludes the EPC) to the ESCO company that guarantees energy savings, while procedures for assessing and verifying energy savings are based on the standardized procedures for monitoring and verification of energy savings. One of the most important characteristics of the EPC is that it dispenses the client (electricity consumer or network user) with permanent savings even after the contract expires, which is when the ESCO company exits the EPC financing model.

Contracts on energy performance mostly find their application in renovation projects of industrial plants, commercial or public buildings [17]. The progressive digitalization of the energy sector with the integration of automation and management systems in buildings will provide the means to ESCO companies for better data collection and analysis opportunities of their customer's portfolio. This also contributes to a better assessment of energy savings through the application of information and communication technologies as well as adequate protocols for measurement and verification [18].

In this context of combined effort opportunities between flexibility and energy savings in a real-time environment, the Pay for Performance (P4P) financial scheme is interesting for monitoring energy savings in direct consumption through actual measured data. The amount of cash payments made by the company that offers the P4P service depends on the measured consumption data, i.e., the normalization values of energy consumption for the associated weather conditions [19].

The P4P scheme can facilitate investments in the energy efficiency of buildings by continuously verifying energy savings through smart metering and transparently calculating the investment return period. One of the more important, but not key, prerequisites for the introduction of P4P schemes is the integration of smart (interval) meters. Smart meters would facilitate the collection of data of the desired granularity through standardized protocols and could enable simpler monitoring of consumption. Given that consumption is observed in relation to, for example, climatic parameters, the P4P model needs to be adapted to local conditions and characteristics of consumption [19]. Choosing an appropriate method for monitoring and verifying energy savings that can be dynamically calibrated according to the collected input data is also crucial. The basic difference between classic schemes for co-financing energy efficiency projects and P4P schemes is shown in Figure 2. In classic subsidy schemes, the payment of the subsidy for achieving savings by means of energy efficiency measures occurs at the beginning of the project, usually in one payment. The P4P scheme could ensure greater and more persistent energy savings by continuously financially compensating energy efficiency resources through a comparative analysis of actual and baseline consumption (which would occur without energy efficiency interventions). Energy savings are used as the main indicator for the performance of the energy efficiency project, and payments are made continuously based on the calculated savings [20].

The P4P schemes used for financing energy efficiency projects do not necessarily imply the stipulation of EPC. If energy savings are linked to payment, it gives more certainty to investors that energy efficiency measures will really improve the performance of a building or a system, therefore reducing their investment risk [21]. The P4P schemes require a more dynamic system for calculating savings then the usual ESCO schemes. Methods applied for monitoring and verification of energy savings should grant continuous calibration of the calculated savings, minimising errors in assessments.

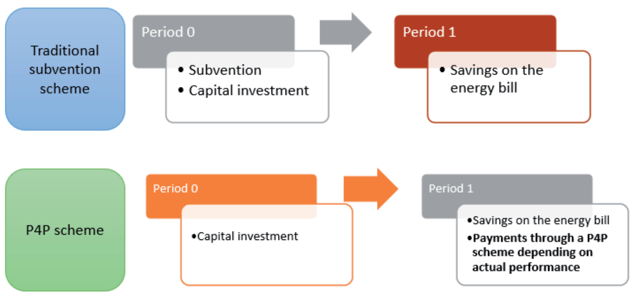

Figure 2 Difference between traditional energy efficiency and P4P subsidy schemes

The business model of the energy savings aggregator, which uses P4P schemes, is based on periodic payments which are calculated according to the obtained savings in the observed time interval. Moreover, it is not necessary that all stakeholders participating in the value-chain are part of the P4P scheme: if the scheme is more comprehensive, the complexity of the P4P programme increases.

2.1.3. Possible synergies

Figure 3 represents energy savings and flexibility aggregator combined business model, based on the model developed in the framework of the research project and adapted to European conditions [22].

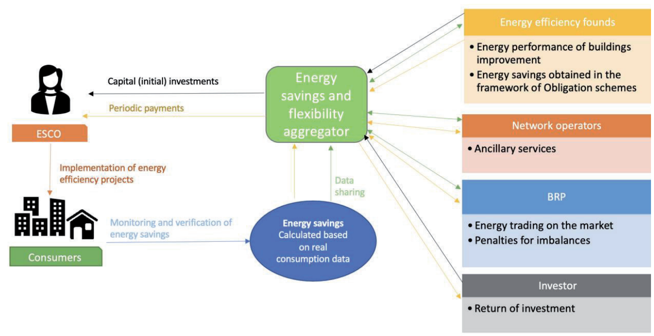

Figure 3 Energy savings and flexibility aggregator combined business model

Network operators could, for example, take part in the P4P scheme, by co-financing energy efficiency projects for network users, via energy savings aggregators for long-term congestion management in distribution networks. The aggregator of energy savings could also be included into ancillary services provision, in the same fashion as the independent aggregator, but should take special attention to the short-term activations (e.g., for peak-shaving) that could deliver permanent savings. One of the main goals of a combined business model (flexibility and savings aggregator) should be to ensure permanent savings of short-term flexibility activations. With continuous consumption monitoring, it is possible to valorise savings through short-term activation with proper monitoring and verification techniques. Additionally, special attention should be given to the imbalances that consumers could cause to the suppliers by participating in such schemes.

The combined effort of a flexibility aggregator that actively monitors, analyses consumption data of its users, and optimizes the derived flexibility on the market, along with an entity that must provide savings to those same users, opens the spot for the creation of new business models.

2.2. Revenue opportunities on the energy savings market for flexibility aggregators

Apart from traditional revenue creation opportunities for an independent aggregator on the energy market as ancillary services provider, this chapter analyses additional opportunities for a combined energy savings-flexibility aggregator business model.

According to the Energy Efficiency Directive [7], mainly Article 7, Member States shall achieve cumulative end-use energy savings. Member States shall achieve the amount of energy savings by establishing an energy efficiency obligation scheme or by adopting alternative policy measures. Energy efficiency obligation schemes (EEOS) are schemes setting an obligation on energy companies to achieve energy savings targets. By year 2020, new energy savings were set as 1.5% of annual energy sales to final customers by volume, averaged over the most recent three-year period prior to 1 January 2013, while for the 2021-2030 period, the amount has been set to 0.8% of annual final energy consumption. The obliged parties under EEOS are energy suppliers or/and energy distributors. Several Member States have implemented or are considering the introduction of an energy efficiency obligation scheme [23]. For example, in the Republic of Croatia, according to the current Energy Efficiency Law [24], the obliged parties are energy suppliers of electricity, natural gas, heat and oil products. The obliged parties could fulfil their obligations by:

- investing in energy efficiency improvements and encouraging energy efficiency in final consumption, in such a way that investments are realized as new energy savings in accordance with the Ordinance on the System for Monitoring, Measuring and Verifying Energy Savings [25], not excluding investments in electricity production equipment and self-supply, small and micro-cogeneration, smart meters for customers, i.e. energy consumers and all other investments and incentives for which the obliged party proves new savings;
- purchase of energy savings from third parties;
- payment of a prescribed fee to the Environmental Protection and Energy Efficiency Fund in case of non-compliance with the annual target; the Fund is obliged to use the gathered financial means to co-finance alternative measures and the fee is calculated annually, based on costs encountered by the Fund to achieve savings with alternative measures.

The possibility to purchase energy savings from third parties could trigger the energy savings market, thus allowing energy suppliers to purchase verified savings from an energy savings aggregator. Energy service providers (ESCO) or savings aggregators could achieve energy savings in final consumption through the implementation of energy efficiency projects, and obliged parties could purchase these savings. In the Republic of Croatia, a bottom-up method prescribed in the Ordinance on the System for Monitoring, Measuring and Verifying Energy Savings [25] is used to prove savings. If a measure is not covered by the Ordinance, the obliged party within the report on realised savings can make a proposal for verifying new savings with the submission of appropriate evidence.

The bottom-up method consists of mathematical formulas for the calculation of unit final energy savings (UFES), which are expressed per unit relevant to the considered energy efficiency measure. Total energy savings in final consumption (FES) are calculated by multiplying the value of UFES with the value of the relevant influencing factor in the considered period and adding up all individual projects that were realized as part of a measure (e.g., a programme to encourage the renovation of the building envelope of family houses). The UFES calculation is based on the difference in specific energy consumption 'before' and 'after' the implementation of energy efficiency measures. If the value of energy consumption 'before' cannot be determined for a specific project, reference values are used [26].

The method used for monitoring and verifying energy savings within the EEOS is very often based on the calculation according to reference values, and the achieved savings are calculated for each observed year. The selection of a method for calculating savings achieved through a P4P scheme require the establishment of customized parameters for measurement and verification in a dynamic environment, which are regulated within the EU. If the energy service provider in its portfolio also offers the activation of flexibility for its users, this should be considered as a separate measure to achieve savings. In such case, it is necessary to demonstrate that the activation of demand side flexibility in a short-term event activation leads to a permanent reduction of energy consumption.

In order to include demand side flexibility as a measure for achieving energy savings, it is necessary to define an applicable methodology for monitoring and verifying the achieved savings. Additionally, special attention should be given to the calculation of energy savings to avoid double counting if the flexibility aggregator is also an energy savings aggregator.

The establishment of a trading system for energy savings would allow new stakeholders in the energy market, such as flexibility aggregators or energy communities, the possibility of income diversification. Income diversification could make it easier for aggregators to solve the problem of business sustainability in the electricity market [27]. The combined effort to sell flexibility and energy savings could certainly increase the degree of complexity of the business model for the aggregator. In practice, as an example, the requirements for flexibility activation by the distribution system operator may be in price collision with the achievement of energy savings. Likewise, it is necessary to regulate relations between different entities, i.e. suppliers and aggregators, or/and electricity consumers. If the supplier and the aggregator have a contract with the same electricity customers, and the supplier buys savings from the aggregator in order to fulfil the obligation in the framework of the EEOS, such relations must be regulated to avoid deviations and penalisation of the supplier on the electricity market. For the aforementioned reasons, there is a need to create a sustainable business model that would enable the valorisation of the flexibility in the form of energy savings.

2.3. Monitoring and verification of achieved savings in flexibility programmes

Monitoring and verification procedures (M&V) are used to evaluate the effect of certain energy efficiency measures [28] and the achievement of national energy efficiency goals [25]. They allow appropriate understanding, management and distribution of risks in energy efficiency projects [29]. Monitoring and verification procedures include programme planning, data collection and analyses, working toward reducing uncertainty energy savings estimations. ESCO usually use standardised monitoring and verification procedures to define savings within the EPC.

The first attempts to establish a protocol for monitoring and verification of energy savings have been initiated by the Department of Energy of the United States in 1994 [30], and resulted in the release of the first North American Energy Measurement and Verification Protocol (NEMVP) [31] in 1996. Considering its great international interests, a new version was issued in 1997, and the NEMVP was renamed in the International Performance Measurement and Verification Protocol (IPMVP) [32]. The application of the IPMVP is still recommended to ESCO companies [29]. The IPMVP defines guidelines, common practice in measuring, calculating and reporting of savings achieved in energy efficiency projects. It is intended to be used by experts as a base for the preparation of reports on the achieved savings. The IPMVP sets the framework for the implementation and evaluation of energy efficiency and energy management measures.

As stated in the protocol, the basic characteristic of energy savings is that they cannot be directly measured. Energy savings represent the elimination of consumption that would have occurred in the absence of a certain measure. The IPMVP gives indications about the assessment period, the reporting period and the methodology for calibrating or correcting calculations. Baseline consumption values need to be continuously calibrated and adjusted according to developing conditions (climatic conditions, number of people in the household, etc.) in order to be comparable with measured consumption values. Special attention should be given to the needs for input measurement data, e.g. the total consumption of the entire facility or a part of the facility, and the granularity of the data required to determine savings.

If demand response flexibility needs to be valorised as energy savings, adequate monitoring and verification procedures should be selected. The parameters used for the purpose of monitoring and verification of short-term flexibility are crucial for determining the effects of the flexibility programme and quantifying the achieved savings. The example is given in Figure 4.

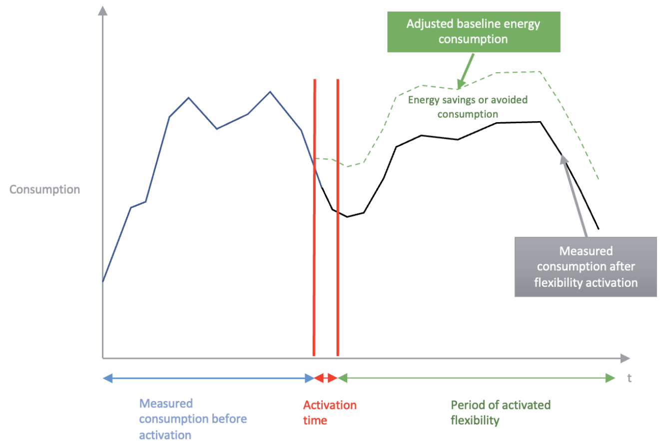

Figure 4 Example of the energy savings estimates in flexibility programmes

The methods used to quantify the estimated consumption should consider the type of user or consumer, the dependence of the observed load on variables (weather and seasonal conditions) and must be continuously adapted to changes. The result of mutual cooperation between the Department of Energy of the United States of America and the Federal Energy Regulatory Commission (FERC) is a document published in 2011 on measurement in the verification of consumption response [33], as part of the National Implementation Action Plan for Demand Response (NAPDR). The NAPDR is the product of the working group efforts and pragmatically describes the procedures which need to be followed for the establishment of a flexibility programme and continuous monitoring of its effect.

Measurement and verification of demand response flexibility defines the determination of demand reduction quantities in two broad contexts [33]:

1. Settlement – determination of demand reductions achieved by individual programme or market participants, and the corresponding rewards or penalties allocated to or from each participant.
2. Impact estimation – determination of programme level demand reduction that has been obtained or it is projected to be achieved, used for programme evaluation and planning.

It is envisioned that the measured reductions should be recognised in both contexts to ensure proper flexibility programme design and its continuous verification during operation. Settlements should be considered in programme planning, design and operation, while impact estimation should examine the appropriateness and evaluate the programme effects. M&V should ensure continuous programme calibration and impact estimation.

It is important for M&V purposes to understand the difference between ex-ante and ex-post impact estimates. The ex-ante impact estimation assesses and approximately forecasts future load reduction capabilities, while ex-post impact estimation retrospectively assesses demand reductions [34]aggregators of flexibility are expected to deliver flexibility programs rules (notification prior to a flexibility event, eligibility, rewards, penalties.

Achieved energy savings resulting as short-term flexibility activations should be observed in both contexts. Settlements should be arranged through the processes of design, planning and implementation of a flexibility programme, while performance evaluation is a continuous process through which the applied programme is examined and evaluated.

The results of M&V of consumption response are used to determine the suitability or ability of resources engaged in flexibility programmes, determining retail and wholesale settlements, predicting the effects of individual resources based on their historical performance, assessing the effect of the established flexibility programme, forecasting and planning [33]. Wholesale settlements refer to settlements between aggregators and system operators or customers on the wholesale market, while retail settlements refer to settlements between aggregators and electricity buyers or consumers.

For iterative calibration of the consumption flexibility programme, it is necessary to determine the effect of the flexibility programme in advance (lat. ex-ante) and continuously monitor the effect of the programme in retrospect (lat. ex-post). Ex-post performance analyses can be a good basis for adjusting the projections of the applied flexibility programme, but it is imperative to have the appropriate information and communication infrastructure and the correct semantic data interpretation [34]aggregators of flexibility are expected to deliver flexibility programs rules (notification prior to a flexibility event, eligibility, rewards, penalties.

The key quantities obtained from a flexibility M&V are calculated baseline load (based on historical data), calculated reduction (difference between the calculated baseline load and observed load) and financial settlement amounts (payments or penalties based on the calculated reduction). Besides the observed load, none of the mentioned quantities can be directly measured when direct load control is applied. In order to minimize the errors, both estimates and communication technologies should be properly selected and applied. For the establishment of a P4P model, which combines both short-term flexibility activations and energy savings, suitable M&V methods should be developed. Such methods should be adaptable to dynamic baseline changes and measurements with higher data granularity. Bottom-up M&V methods are not suitable for P4P model purposes.

2.3.1. Identified requirements for setting-up a programme for energy savings achieved by short-term flexibility activations

Considering the identified M&V requirements for programme settlements and their continuous calibration, authors have identified the following requirements to set-up a flexibility programme which could allow achievement of verified energy savings through a flexibility programme (Table 1).

Table 1 Identified requirements

	Requirements	Description
Initial requirements	Information and communication technologies	Set-up of a functional architecture enabling explicit demand response as well as the physical infrastructure
Ex-ante estimations	Data availability	Availability of interval metering or smart metering data
	Calculation methods for baseline assessment	Load disaggregation methods Regression analysis of key parameters influencing the consumption of flexibility assets Baseline assessment and calibration methods
	Settlement	Applying adequate strategies for consumer engagement and determination of adequate compensations
Ex-post estimations	Data availability	Smart metering data
	Calculation methods	Calibration methods of ex-ante estimates
	Information and communication technologies	Semantic data interpretation

For explicit demand response and enabling proper monitoring and verification of achieved savings, proper information and communication infrastructure should be established and installed in consumer premises.

Various techniques could be used for baseline assessment, but they are mostly dependent on the data granularity. Regression analysis on key parameters influencing the consumption of flexibility assets should be performed. Based on the assessed market potential, proper settlements should be determined for consumer compensation.

Besides data availability and the selection of proper adjustment/calibration methods, to ensure the quality of an ex-post estimate, proper semantic data interpretation should be available. Communication protocols and data models with proper message payloads should enable a comparative analysis of ex-ante impact estimates and ex-post analysis as an iterative process with continuous programme adaptation [34]aggregators of flexibility are expected to deliver flexibility programs rules (notification prior to a flexibility event, eligibility, rewards, penalties.

As an example, the OpenADR standard [35], adopted in the EU as IEC 62746 [36], specifies the data semantics only to a limited extent. The message payload interpretation does not go beyond generic types of events. However, its open specification facilitates any user to implement the two-way signalling systems, providing the servers that publish information to the automated clients subscribing to the information. Such information can serve as an immediate verification of curtailment and identification of failed or over-ridden signals. For monitoring and verification of demand response purposes, OpenADR is applicable, but needs to be enhanced with additional data semantics alignments. When the customer is paid based on the participation metrics, OpenADR is suitable for verification of such events. However, Event and Report services are not enough for impact estimation, nor are payload messages describing the assets involved in direct load control events and the interrelationship between them.

OpenADR is applicable for programme settlement purposes as part of the functional architecture for short-term flexibility activation and the related communication between the aggregator and the consumer. However, for a proper ex-post estimate and verification of achieved savings, additional semantic information for involved flexibility assets is needed. Existing data models such as Smart Appliances REFerence (SAREF) [37] offer such solutions, but a certain semantic interoperability between communication standards and ontological data models should be developed [34]aggregators of flexibility are expected to deliver flexibility programs rules (notification prior to a flexibility event, eligibility, rewards, penalties.

3. CONCLUSION

The constitution of a sustainable business model should be one of the principal goals of an independent aggregator. An independent flexibility aggregator, who optimizes the flexibility of households and therefore sells its aggregated value on the market, must either set up its own metering infrastructure for data collection and analysis or purchase the costs of a metering service.

The main challenge in identifying savings achieved through flexibility activations is the lack of proper data semantic interpretation. Interoperability must work at the technical and semantic level. Consistent and non-equivocal data interpretation is an absolute requirement for ensuring proper M&V ex-post analysis and programme impact assessment.

In a joint venture with a company that offers energy services to household consumers for improving their energy performance, the independent aggregator could overcome technological and cost challenges that this requirement implies. For a business model where an aggregator bids into the market, there is a significant risk of not reaching scale and ending up in the so-called technological valley of death [27], where costs overburden the business model. In this context, the combined effort of an energy savings and flexibility aggregator model should become a viable option, as the revenue is primarily focused on the avoided energy costs derived from savings.

Moreover, this opens up possibilities for the flexibility aggregator to participate in the energy savings market, which could become more attractive if savings purchase market would be established on the national level. Additionally, if suppliers would be able to purchase verified energy savings from a flexibility aggregator, this could also solve the risk of imbalance between the two involved parties on the energy market.

REFERENCE

[1] Directorate-General for Energy (European Commission), *Clean energy for all Europeans*. LU: Publications Office of the European Union, 2019. Accessed: Mar. 01, 2022. [Online]. Available: https://data.europa.eu/doi/10.2833/9937

[2] R. Smale and S. Kloppenburg, "Platforms in Power: Householder Perspectives on the Social, Environmental and Economic Challenges of Energy Platforms," *Sustainability*, vol. 12, no. 2, Art. no. 2, Jan. 2020, doi: 10.3390/su12020692.

[3] J. Viitanen and R. Kingston, "Smart Cities and Green Growth: Outsourcing Democratic and Environmental Resilience to the Global Technology Sector," *Environ. Plan. Econ. Space*, vol. 46, no. 4, pp. 803–819, Apr. 2014, doi: 10.1068/a46242.

[4] "Smart readiness indicator." https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/smart-readiness-indicator_en (accessed May 13, 2022).

[5] European Comission, "Energy efficiency first principle." https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-first-principle_en (accessed May 08, 2022).

[6] "Energy Efficiency Trends in Buildings in Europe | Policy brief | ODYSSEE-MURE." https://www.odyssee-mure.eu/publications/policy-brief/buildings-energy-efficiency-trends.html (accessed Aug. 18, 2022).

[7] *Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending Directive 2012/27/EU on energy efficiency (Text with EEA relevance.)*, vol. 328. 2018. Accessed: Mar. 01, 2022. [Online]. Available: http://data.europa.eu/eli/dir/2018/2002/oj/eng

[8] *Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU (Text with EEA relevance.)*, vol. 158. 2019. Accessed: Mar. 01, 2022. [Online]. Available: http://data.europa.eu/eli/dir/2019/944/oj/eng

[9] "About the energy label and ecodesign," *European Commission - European Commission*. https://ec.europa.eu/info/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/energy-label-and-ecodesign/about_en (accessed Aug. 13, 2022).

[10] L. Luttenberger Marić, H. Keko, and M. Delimar, "The Role of Local Aggregator in Delivering Energy Savings to Household Consumers," *Energies*, vol. 15, no. 8, Art. no. 8, Jan. 2022, doi: 10.3390/en15082793.

[11] J. J. Alba, C. Vereda, J. Barquín, and E. Moreda, "Chapter 17 - Market design and regulation to encourage demand aggregation and participation in European energy markets," in *Variable Generation, Flexible Demand*, F. Sioshansi, Ed. Academic Press, 2021, pp. 393–410. doi: 10.1016/B978-0-12-823810-3.00006-6.

[12] ENTSO-E, "Market Design For Demand Response." ENTSO-E, 2015. [Online]. Available: https://eepublicdownloads.entsoe.eu/clean-documents/Publications/Position%20papers%20and%20reports/entsoe_pp_dsr_web.pdf

[13] F. Lezama, J. Soares, B. Canizes, and Z. Vale, "Flexibility management model of home appliances to support DSO requests in smart grids," *Sustain. Cities Soc.*, vol. 55, p. 102048, Apr. 2020, doi: 10.1016/j.scs.2020.102048.

[14] D. Fioriti, A. Frangioni, and D. Poli, "Optimal sizing of energy communities with fair revenue sharing and exit clauses: Value, role and business model of aggregators and users," *Appl. Energy*, vol. 299, p. 117328, Oct. 2021, doi: 10.1016/j.apenergy.2021.117328.

[15] *Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (Text with EEA relevance.)*, vol. 328. 2018. Accessed: Mar. 01, 2022. [Online]. Available: http://data.europa.eu/eli/dir/2018/2001/oj/eng

[16] T. E3P, "Energy Performance Contracting," Dec. 23, 2013. https://e3p.jrc.ec.europa.eu/articles/energy-performance-contracting (accessed Jun. 22, 2022).

[17] "ESCO Industry Trends & Analysis | Electricity Markets and Policy Group." https://emp.lbl.gov/projects/espc-trends-and-analysis (accessed Jun. 22, 2022).

[18] "ESCO contracts – Energy Service Companies (ESCOs) – Analysis," *IEA*. https://www.iea.org/reports/energy-service-companies-escos-2/esco-contracts (accessed Jun. 22, 2022).

[19] M. Santini, D. Tzani, S. Thomas, V. Stavrakas, J. Rosenow, and A. Celestino, "Experience and Lessons Learned from Pay-for-Performance (P4P) pilots for Energy Efficiency," Zenodo, Jun. 2020. doi: 10.5281/zenodo.3887823.

[20] D. Tzani, V. Stavrakas, M. Santini, S. Thomas, J. Rosenow, and A. Flamos, "Pioneering a performance-based future for energy efficiency: Lessons learnt from a comparative review analysis of pay-for-performance programmes," *Renew. Sustain. Energy Rev.*, vol. 158, p. 112162, Apr. 2022, doi: 10.1016/j.rser.2022.112162.

[21] G. Gordon, C.-H. Bourgois, S. Wuyts, and J. Coolen, "Guidelines for the design of P4P schemes," Mar. 2022, doi: 10.5281/zenodo.6367999.

[22] Grillone, "Proposal on the specifications for P4P project data," Mar. 2022, doi: 10.5281/zenodo.6367991.

[23] J.-S. Broc, W. Stańczyk, and B. Reidlinger, "Snapshot of Energy Efficiency Obligation Schemes in Europe (as of end 2019) – ensmov.eu." ENSMOV reoirt, 2020. Accessed: Jun. 26, 2022. [Online]. Available: https://ensmov.eu/snapshot-of-energy-efficiency-obligation-schemes-in-europe-as-of-end-2019/

[24] *Zakon o energetskoj učinkovitosti NN 127/14, 116/18, 25/20, 32/21, 41/21*. Accessed: May 17, 2022. [Online]. Available: https://zakon.hr/z/747/Zakon-o-energetskoj-u%C4%8Dinkovitosti

[25] *Pravilnik o sustavu za praćenje, mjerenje i verifikaciju ušteda energije NN 98/2021*. 2021, p. 4. Accessed: Jun. 11, 2022. [Online]. Available: https://narodne-novine.nn.hr/clanci/sluzbeni/2021_09_98_1772.html

[26] Ministarstvo gospodarstva Republike Hrvatske, "Metodologija za sustav obveze energetske učinkovitosti u skladu s člankom 7. i člankom 20. stavkom 6. te prilogom V. Direktive 2012/27/EU Europskog parlamenta i Vijeća od 25. listopada 2012. o energetskoj učinkovitosti." 2014. [Online]. Available: https://energy.ec.europa.eu/system/files/2014-11/article7_hr_croatia_0.pdf

[27] M. Kubli and P. Canzi, "Business strategies for flexibility aggregators to steer clear of being 'too small to bid,'" *Renew. Sustain. Energy Rev.*, vol. 143, p. 110908, Jun. 2021, doi: 10.1016/j.rser.2021.110908.

[28] "Guidelines for Monitoring, Evaluation, Reporting, Verification, and Certification of Energy Efficiency Projects for Climate Change Mitigation | Energy Technology Area." https://energy.lbl.gov/publications/guidelines-monitoring-evaluation-0 (accessed Jun. 11, 2022).

[29] T. E3P, "ESCo - Monitoring and Verification," Dec. 23, 2015. https://e3p.jrc.ec.europa.eu/articles/monitoring-and-verification (accessed Jun. 11, 2022).

[30] "Monitoring and Evaluation of Energy Efficiency Programs," Oct. 01, 2018. https://www.usaid.gov/energy/efficiency/developing-programs/evaluation (accessed Jun. 12, 2022).

[31] Natural Resources Canada's CanmetENERGY, "Overview of Different Measurement and Verification (M&V) Protocols," Econoler, 2008-069_TR_424-CONOPT, 2008. [Online]. Available: https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/canmetenergy/files/pubs/NRCan_MV_Overview_Report.pdf#:~:text=Developed%20by%20a%20volunteer%20committee%20under%20the%20U.S.,because%20of%20the%20considerable%20uncertainty%20about%20energy%20savings.

[32] D. Tanguay, "International Performance Measurement and Verification Protocol (IPMVP)," *Efficiency Valuation Organization (EVO)*. https://evo-world.org/en/products-services-mainmenu-en/protocols/ipmvp (accessed Jun. 12, 2022).

[33] M. L. Goldberg and C. Goldman, "Measurement and Verification for Demand Response," Electricity Markets and Policy Group, Energy Analysis and Environmental Impacts Division, 2013. [Online]. Available: https://eta-publications.lbl.gov/sites/default/files/napdr-measurement-and-verification.pdf

[34] L. Luttenberger Marić, H. Keko, and S. Sučić, "Semantic alignment in monitoring and verification of energy savings achieved by demand response flexibility programs," *45th Jubil. Int. Conv. Inf. Commun. Electron. Technol. MIPRO*, pp. 55–59, 2022, doi: 10.23919/MIPRO55190.2022.9803329.

[35] "OpenADR Alliance Releases 2.0b Profile Specification." https://www.openadr.org/index.php?option=com_content&view=article&id=84 (accessed Jun. 13, 2022).

[36] "IEC 62746-10-1 - Systems interface between customer energy management system and the power management system - Part 10-1: Open automated demand response | Engineering360." https://standards.globalspec.com/std/13102917/IEC%2062746-10-1 (accessed Jun. 13, 2022).

[37] "SAREF: the Smart Applications REFerence ontology." https://saref.etsi.org/core/v3.1.1/ (accessed May 17, 2022).

Journal of Energy

VOLUME 70 Number 4 | 2021

journal homepage: http://journalofenergy.com/

Matej Alandžak[1]
HOPS d.d.
matej.alandzak@hops.hr

Tomislav Plavšić
HOPS d.d.
tomislav.plavsic@hops.hr

Dubravko Franković
Tehnički fakultet, Sveučilište u Rijeci
dubravko.frankovic@riteh.hr

Provision of Virtual Inertia Support Using Battery Energy Storage System

[1] Statements expressed in the paper are author's own opinions, they are not binding for the company/institution in which author is employed nor they necessarily coincide with the official company/institution's positions.

SUMMARY

The paper presents the importance of the grid inertia constant for the frequency stability of the future high-res low-inertia power systems. Since more and more renewable energy sources (RES) are being connected to the power system via inverters, the grid inertia constant is reduced. This issue can be mitigated by applying appropriate control mechanisms through which RES can provide virtual inertia and provide rotating reserves for primary frequency control. The concept of a virtual inertia provision using battery energy storage system (BESS) is elaborated in the paper. By applying a virtual inertia concept, RES can provide support for frequency control during disturbances almost like conventional synchronous generators. The influence of virtual inertia on the stability of the part of Croatian power system was analyzed using BESSwith a control mechanism that enables its participation in frequency control.

KEYWORDS

frequency control, power system inertia, renewable energy sources, battery energy storage systems

1. INTRODUCTION

To reduce the impact of energy industry, especially electricity production, on climate change and the level of CO_2 in the atmosphere, European Parliament in the framework for achieving climate neutrality brings key goals for upcoming years. These goals include reducing greenhouse gas emissions by at least 55% compared to 1990 levels, increasing energy efficiency by at least 32.5% and at least 32% of total energy obtained from renewable sources. The long-term goals of the European Union for 2050 have an optimistic goal of achieving a climate-neutral society, that is, reducing greenhouse gas emissions to net zero. All goals and directives adopted both in the European Union and in the world encourage the use of energy from renewable sources [1,2]. The consequence of such policies is a significant increase in the installed capacity of renewable energy sources in the world, Figure 1.

It is evident from the figure below (Figure 1) that the largest increase in installed power is recorded by wind power plants and photovoltaic power plants, which are technologically very different from classic power plants that produce energy using synchronous generators.

Synchronous generators, with a governor and excitation control systems, contribute to the stability of power system after disturbances, due to their inherent inertia of the rotor, damping torque and the possibility of reactive power production. However, renewable energy sources connected to the grid via inverters are characterized by low output impedance, fast response to changes in active and reactive power, and little or no inertia and damping torque.

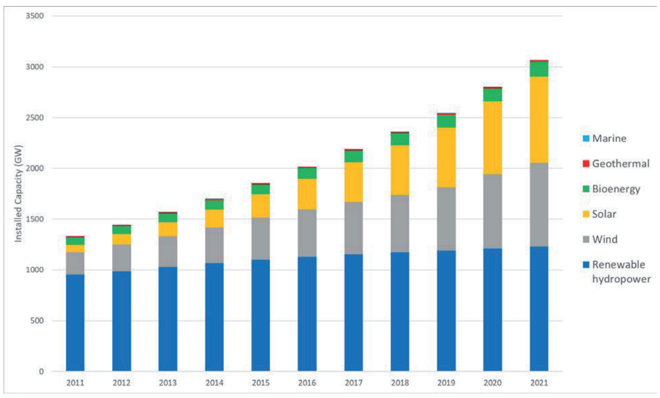

Figure 1. Yearly cumulative increase in RES installed capacities [3]

Due to the significantly lower operating costs of renewable energy sources, compared to traditional power plants, especially those running on fossil fuels, the share of renewables in the production mix is growing constantly. The number of renewable generating units in the daily operation on the grid is increasing, which consequently negatively affects the inertia and thus the stability of power system, which becomes more vulnerable to frequency disturbances.

To improve the dynamic performance and stability, it is necessary to provide additional inertia to the power system. To achieve this, the concept of a virtual synchronous generator was proposed, that is, adding virtual inertia to a renewable energy source using a short-term energy storage together with a frequency converter and a suitable control mechanism. In this way, the renewable generating units will provide inertia and damping torque like conventional synchronous generators [4].

In [5] a literature review of the current state-of-the-art of virtual inertia implementation techniques is given, and potential research directions and challenges are explored, while the major virtual inertia topologies are compared and classified.

In [6] a comprehensive review of virtual inertia (VI)-based inverters is presented and discussed, together with a provision of dynamic models for RMS studies in PowerFactory software tool.

Evaluation, comparison, and technical analysis of each VI-based inverter techniques, including virtual synchronous machine (VSM), virtual synchronous generator (VSG), and synchronverter are given. The assessment of VI emulation techniques, including the critical analysis, current challenges, and future research on virtual emulation, are presented.

The studies of future low-inertia power systems, [7,8], review the various control techniques and technologies that offset a decrease in inertia and discuss inertia emulation control techniques available for inverters, wind turbines, photovoltaic systems, and microgrids.

A comprehensive review of VSG and control system topologies for virtual inertia simulation are given in [9] and [10]. Classification of VSG based on model's order is presented, and future research directions are given.

A comparative analysis of a power system stability with virtual inertia is given in [11]. The paper presents power system modal analysis with Voltage Source Converters (VSCs) controlled as synchronverters, vector control, or Rate of Change of Frequency-based Virtual Synchronous Generator, thus comparing different approaches to VSC control. The results demonstrate the benefits of synchronverters over other control strategies.

Extensive work has been done to obtain simplified wind generator models for frequency response studies. In [12] it is proved that the coefficient K_G of wind turbines is not constant. When wind direction and speed vary, the output power changes, and this means that the actual power of the wind generator transmitted to the primary frequency control changes. As a result, the value of K_G should be determined at different wind speeds. Therefore, modifications to the wind turbine control systems are proposed to take advantage of the inertial behavior of wind farms.

The increasing penetration of wind power with static converters has led to a reduction in the equivalent inertia of power systems, which worsens the dynamic response of the system frequency (lower frequency support and frequency instability). The criteria for the allowable reduction of system inertia can be the rate of change of frequency (ROCOF) or the maximum frequency deviations [13,14].

Application of BESS for enhancement of grid inertia is studied in [15]. The paper quantitatively assesses the impact of large-scale BESSs on frequency containment for low inertia power grid and compares the performance of grid-forming and grid-following control modes. It is concluded that BESSs can provide significant value to both frequency containment and restoration services.

In [16] a virtual adaptive inertia control (VAIC) strategy for distributed battery energy storage system in microgrids is proposed, while in [17] a hybrid energy storage system (HESS) consisting of supercapacitor and battery is employed for enhancement of frequency response in a microgrid, controlled by a virtual synchronous generator strategy.

The aim of this paper is to give an overview of the inertia shortage problem in future power systems, and to simulate a simple but effective solution for improving grid inertia constant with BESS for a part of Croatian power system.

The rest of the paper is organized as follows: Section 2. presents the fundamentals of inertial response from synchronous generator, and gives discusses the inertial response in future power sytem with high RES share. General virtual inertia concept is presented in Section 3. Results of the simulation of BESS influence on Croatian power system stability are given in Section 4.

2. GRID STABILITY OF FUTURE HIGH-RES LOW-INERTIA POWER SYSTEMS

2.1. Inertial response of a synchronous generator

Inertia is one of the main parameters of power system's secure operation. Inertia of the synchronous generator and turbine coupled rotating masses, and to a smaller extent electrical drives, determines the frequency response of the power system to the imbalance between production and consumption, and thus affects frequency stability. Rotational speed of large and heavy rotating machines cannot be changed instantaneously. When frequency change occurs, the rotating masses inject kinetic energy into the power system or absorb it from the power system, in order to oppose frequency changes, and will slow down in the case of energy injection or speed up in the case of energy absorption, [18].

The ROCOF (*df/dt*) is defined by the swing equation:

$$\frac{df}{dt} = \frac{1}{2\pi}\frac{d\omega}{dt} = \frac{1}{2\pi}\frac{P_m - P_e}{2H_G} \tag{1}$$

where: ω - grid frequency in pu; Pm and Pe - mechanical and electrical powers in pu, respectively; H_G - grid inertia constant in seconds.

With higher grid inertia constant, a lower rate of frequency change is achieved, and thus the power system is more stiff in the event of a disturbance. However, in the case of a smaller grid inertia constant, the frequency response is more dynamic and oscillatory when a disturbance occurs, which can lead to a violation of power system frequency stability and finally to the loss of power system integrity, and even to complete blackout. The inertial response begins at the instant of disturbance occurrence, before the primary frequency control reaction. Synchronous generators oppose frequency change by absorbing real power from the grid or injecting real power into the grid. The real power that is injected into the network comes from the kinetic energy of the machine rotating masses, what results in a decrease in the machine rotational speed. This applies to the case of an increase in consumption compared to production, that is, in the event of a production unit outage or connection of a large load.

In the case of production increase or consumption decrease, absorption of energy from the network occurs and consequently an increase in machine's rotational speed. Figure 2 shows the inertial response and the response of frequency containment reserves (FCR) and automatic frequency restoration reserve (aFRR), after connection of a significant load. The minimum frequency that appears after the disturbance depends on the value of the grid inertia constant.

Inertial response, as an inherent property of synchronous machines operation, cannot be controlled. In thermal power plants, turbogenerators contain from 30 to 60% of the inertia in the turbine, and in the case of hydro generators, 4 to 15% of the inertia is contained in the turbine, including the inertia of the water. Incidents that significantly disrupt power system frequency stability are mainly outages of large production units and loads from the network, disconnection of HVDC links that connect different power systems, and system separation.

The value of the inertia constant affects:

- the initial slope of the frequency change curve after disturbance,
- the time when the highest frequency deviation occurs,
- maximum frequency deviation from the nominal value (frequency nadir).

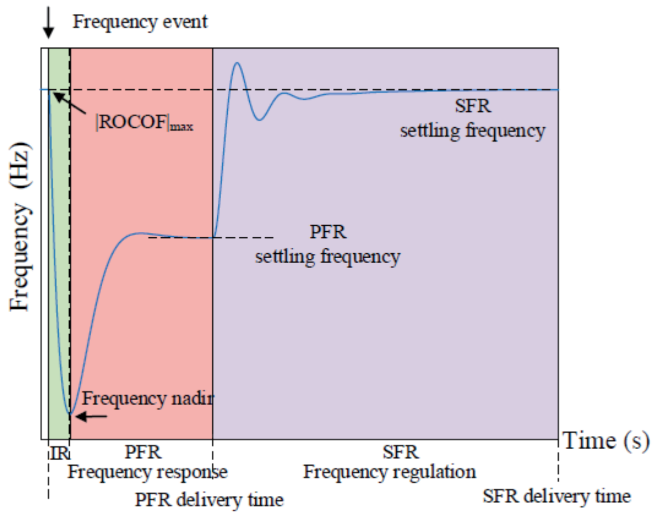

Figure 2. Inertial response and FCR and aFRR response, after connection of a large load [19]

With larger values of grid inertia constant, the frequency drop in the system occurs more slowly, but the duration of the transient is longer. When the ROCOF is slower, the turbine controllers have a longer time for reaction, and therefore the maximum frequency deviation will be smaller. The inertia constant does not affect the value of frequency at which the frequency stabilizes after the disturbance.

In contrast, lower values of the grid inertia constant will allow very fast frequency changes and large frequency deviations, whereby the response of the turbine controller will be faster, which will result in larger and faster frequency oscillations, which is undesirable. The initial slope of the frequency change curve after the disturbance will be very large for systems with a small value of the grid inertia constant.

2.2. Inertia in high RES power systems

In future power systems, with a high RES share, conventional power plants will be often replaced in favor of RES units with lower marginal costs, thus reducing grid inertia. RES operate very differently from conventional power generating units. RES are connected to the grid via power electronics devices, i.e. converters, what results in partial or complete electrical separation of the power generating units from the grid. As a result, the relation between the rotational speed of the generator and the frequency of the system is not relevant anymore. Therefore, the generating units connected to the grid via inverters do not contribute to the overall grid inertia. Then, the kinetic energy reserve present in conventional energy sources is often missing in RES. For example, photovoltaic power plants have no rotating parts, and a very small amount of energy can be stored in capacitors.

The lack of grid inertia results in higher rates of frequency changes and maximum frequency deviations from the nominal frequency during sudden changes in production and consumption, which can lead to system instability, as well as relay protection triggering and thus disconnection of generating units from the network, or even underfrequency load shedding. Reduced grid inertia also affects other elements of power system operation, such as voltage stability, system protection, control reserves, etc.

The inverters that electrically separate RES generating units from the grid are not set to act on system frequency changes. However, by measuring the frequency deviations, the inverter can be adjusted to exchange energy with the grid in a controlled manner. This kind of energy exchange is called the virtual inertial response.

If the inertia constant of a classical machine with a synchronous generator is expressed as:

$$H = \frac{E_k}{S_n} = \frac{J\omega_0^2}{2S_n} \tag{2}$$

where: H - inertia constant $[MJ/MVA = s]$, E_k - total kinetic energy of the rotating mass $[MJ]$, S_n – machine nominal power $[MVA$, J - machine total moment of inertia $[kgm^2]$, ω_0 - synchronous speed of the rotor $[rad/s]$.

then the contribution to the grid inertia constant of conventional generating units and generating units connected to the grid via inverters can be expressed as, [20]:

$$H_G = \frac{\sum\frac{J\omega_0^2}{2}+\sum\frac{J_V\omega_0^2}{2}}{S_G} = \frac{\sum E_k+\sum E_V}{S_G} \tag{3}$$

where: H_G – total grid inertia constant $[MJ/MVA = s]$, J_V - total virtual moment of inertia $[kgm^2]$, EV - total virtual kinetic energy $[MJ]$, S_G – total system nominal power $[MVA]$.

Figure 3 shows an illustration of the effect of the added virtual inertia on the inertial response when disturbance occurs in the system compared to the inertial response without the added virtual inertia. Primary control cannot act fast enough to stop the frequency change instantaneously. It can be concluded from the figure that systems with low inertia have higher maximum frequency deviations and a higher ROCOF.

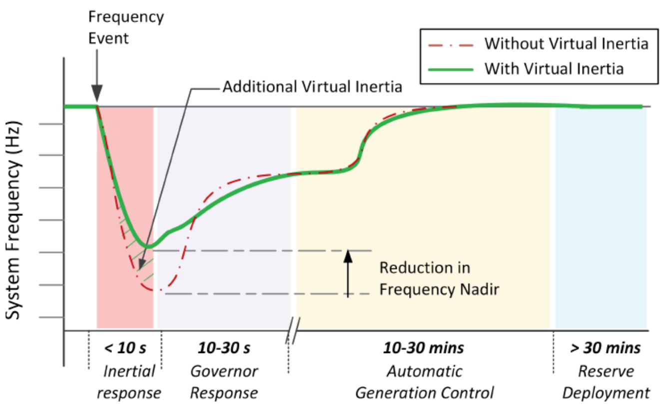

Figure 3. Time response of frequency control to load increase including virtual inertia [21]

Since inverters electrically separate the RES generating unit from the grid, any kind of energy source or storage can be used to contribute to the moment of inertia of the system, for example flywheels, batteries, supercapacitors, etc. In wind farms, there is a large amount of stored kinetic energy in the turbine blades and generator, whose inertia constant is equal to conventional power plants and ranges from 2 to 5 s. However, since the wind power plant is separated from the grid with the inverter, it does not contribute to the grid inertia, therefore this kinetic energy could be used to provide the virtual moment of inertia.

In the case of photovoltaic power plants, additional energy storage can be implemented in the form of batteries. It is also possible to curtail production units in order to have available power reserve. However, the problem with such solutions are some restrictions that occur: limitations of the inverter operation, minimum rotor speeds, maximum acceleration and deceleration of wind turbine blades, and dependence on the operating point. The inertia provided by the load to the system, mainly motors and fans, will decrease in the future due to the increasing use of frequency converters to control these devices [19].

Under almost all scenarios, kinetic energy from conventional energy sources will be lower in the future than today. Therefore, it is necessary to take particular measures that would compensate for the lack of conventional inertia from synchronous generators:

- Virtual inertia of generating and consumption units connected via inverters,
- Use of hydroelectric power plants operating at minimum power or in compensator mode,
- Changing the parameters of the control systems of power plants that provide frequency control services.

The challenges of electric power system operation and control will be solved by a combination of the above-mentioned measures in order to ensure the necessary stability. Providing the inertial response of wind farms is a

Matej Alandžak, Tomislav Plavšić, Dubravko Franković,Provision of Virtual Inertia Support Using Battery Energy Storage System, Journal of Energy, vol. 70 Number 4 (2021), 13–19
https://doi.org/10.377982021704250

method that is already beginning to be applied in practice and will become widely applicable for all systems with a high portion of electricity produced from wind farms. Other methods of providing virtual inertia are currently still in research stages. However, with the increasing RES integration, there should be a greater implementation of virtual inertia and thus the gradual increase of its importance in maintaining the dynamic stability of power system.

3. VIRTUAL INERTIA CONCEPT

The idea behind virtual inertia is based on implementing dynamic properties of synchronous generators to generating units that are connected to the grid via inverters, simulating this way dependency of the rotor speed and grid frequency, controllable active and reactive power output, influence of rotating masses and damping windings, and stable parallel operation, improving stability of the power system. This principle can be applied to one or a group of generating units. The latter is, of course, more economical, and better from the grid operator's point of view, but the first method is more suitable for owners of generating units.

Generation system with implemented virtual inertia, used in the simulations, consists of an BESS, inverter, and the control system, Figure 4. Virtual inertia concept is implemented between the energy source and the grid, and presents the energy source as a synchronous generator to the grid in terms of inertial and damping properties. Virtual inertia is emulated by controlling the active power through the inverter inversely proportional to the rotor speed. From the grid point of view there is no difference between an electromechanical synchronous generator and an electrical virtual synchronous generator, except for the increased frequency noises due to the switching operations of the inverter's semiconductor valves.

Since the described generation system should be able to inject or absorb electrical energy, while operating in normal state of operation, the state of charge of the BESS should be at 50% of the nominal storage capacity. Depending on charging conditions, the operating conditions can be described depending on the specified upper and lower limits which are determined depending on the energy storage technology, for example 20 and 80% of the maximum charging state. When the charging state is between these limits, the generation system works in active mode, and when there is an excess of energy in the system, it works in virtual load mode.

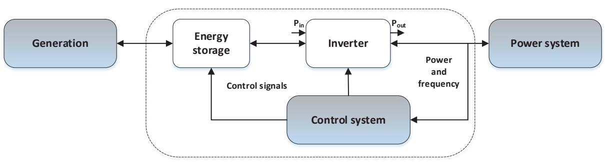

Figure 4. Structure and concept of a generation system with implemented virtual inertia

The main purpose of the virtual inertia concept is to increase the grid inertia constant H. The output power of the generation system with implemented virtual inertia can be expressed as:

$$P_G = P_0 + K_H \frac{d\Delta\omega}{dt} + K_D \Delta\omega \tag{4}$$

where: P_G - generation system output power, P_0 - initial power transmitted to the inverter, K_H - virtual inertia characteristic coefficient, K_D - virtual damping characteristic coefficient.

In expression (4), P_0 represents the power that was transferred through the inverter to the grid before the disturbance occurred. Then, the second term of the equation represents the injected or absorbed power from the network depending on positive or negative frequency deviation from the nominal frequency. Furthermore, $_H$ can be expressed as:

$$K_H = \frac{2HS_n}{\omega_n} \tag{5}$$

where: ω_n is the nominal grid frequency.

K_H acts as a gain constant, and it must be chosen in such a way that the virtual synchronous generator gives the maximum active power when the maximum ROCOF occurs, for example 1 Hz/s. The drop in frequency, i.e., rotational speed, can be reduced by increasing the virtual mass, but in this way oscillations of synchronous units can occur. By increasing inertia, i.e., the parameter K_H, the maximum frequency and rotor speed deviations will decrease, but the natural frequency and damping will also decrease.

Given that $d\omega/dt$ is by its nature an error signal, because the balance point is at zero, the power will alternate only in transient states, which does not necessarily mean that the system frequency will return to nominal value. To avoid this problem, a static part should be added, that is, the third part of the expression (4). In this way, at every moment the nominal frequency is subtracted from the measured one, thus providing an error signal whenever a frequency deviation occurs within the power system. The purpose of K_D is to imitate the influence of synchronous generator damping windings and represents a linear damping. It is chosen in such a way that the third part of equation is equal to the rated power of a generation system with implemented virtual inertiaat the maximum allowed frequency deviation.

Unlike conventional synchronous generators, which are opposing to changes in the rotor speed, or frequency, using the kinetic energy of rotating masses, generation system with implemented virtual inertia usually use energy from the BESS. Also, for the case of energy consumed during disturbance damping, the energy is dissipated on the resistances of the damper windings. However, in the presented concept, this energy needs to be absorbed by the BESS to balance the power system generation and load. The most important parameters for choosing the appropriate BESS technology for generation system with implemented virtual inertia are: maximum power system load, rated power of production units providing frequency control services, mean value of charging state in normal operation, detection time, control delay, maximum of the total response delay.

From the last two terms of expression (4), it can be concluded that power can flow in both ways, from the electric power system to the energy storage and vice versa. The result is that generation system with implemented virtual inertia can act as conventional synchronous generator, but also as a load, depending on the sign of the frequency deviation.

Essentially, virtual inertia opposes network frequency deviations, while virtual damping suppresses grid oscillations, thus obtaining equally effective features of synchronous generators. The gain constants K_H and K_D must be negative in order to provide power which will counteract the change in frequency. Increasing the value of characteristic constants means that there will be more power injected or absorbed for the same frequency change, i.e. ROCOF change. However, there is a limit to how much the constant K_H can increase. This limit depends on the rated power of the inverter and the phase synchronization mechanism precision. Namely, the inverter has no possibility of overloading like a synchronous machine, therefore a high derivative term leads to higher power overloading during transients. Then, the precision of frequency determination depends on phase synchronization mechanisms. Because of the afore mentioned, the optimum value of the derivative term K_H is determined by a compromise among the size of virtual inertia, inverter's overload capacity, and characteristics of the phase synchronization mechanism [8].

4. SIMULATION OF VIRTUAL INERTIA INFLUENCE ON CROATIAN POWER SYSTEM STABILITY

For the simulation of the virtual inertia influence on Croatian power system stability the DIgSILENT Power Factory 2020 power system analysis software was used. The aim of the simulation was to show the impact of BESS contribution to grid frequency control and grid inertia constant. BESS with nominal power of 10 MW was added to the 110 kV substation Vrataruša. The BESS was connected to the 110 kV busbars via a two-winding transformer. As previously explained, the BESS injects or absorbs active power when an imbalance between production and consumption occurs, that is, when the frequency deviates from the nominal value. The BSEE model used in simulations is shown in Figure 5.

Matej Alandžak, Tomislav Plavšić, Dubravko Franković,Provision of Virtual Inertia Support Using Battery Energy Storage System, Journal of Energy, vol. 70 Number 4 (2021), 13–19
https://doi.org/10.377982021704250

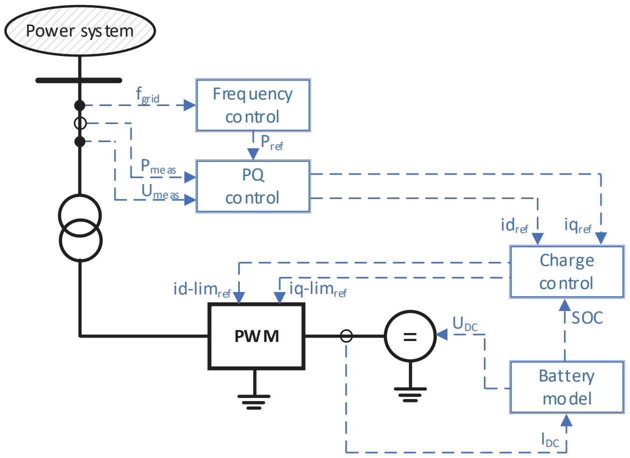

Figure 5. BSEE model used in simulations

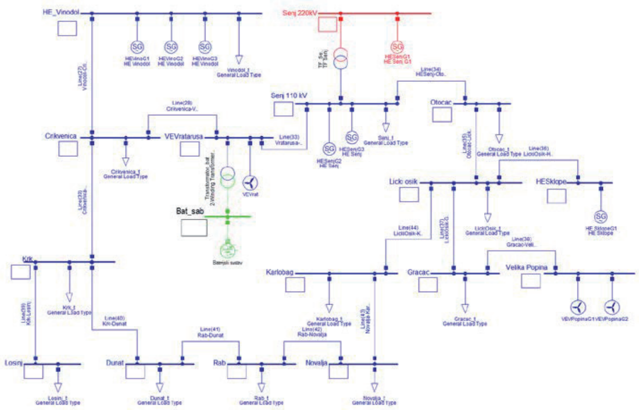

Figure 7. Power factory model of the analyzed system

The simulation is done on the part of the Croatian 110 kV transmission subsystem, shown in Figure 6. The corresponding Power factory model of the subsystem shown in Figure 6 is presented in Figure 7. Total load of the analyzed system is 231 MW.

To clearly show the influence of a relatively small BESS on the frequency transient, island mode of operation was assumed for the modeled subsystem. Generally, in the island mode of operation, the power system is more susceptible to disturbances, because the total amount of generating capacity, and thus the grid inertia constant, are smaller.

Generator G2 of the Senj hydropower plant (HPP) was set as the reference machine. Every HPP is modeled as participating in FCR. The modeled wind farms Vrataruša and Velika Popina produce only active power (unity power factor), and do not participate in frequency control, nor provide inertia to the system. Simulation of inertial response and frequency control considers four scenarios: step increase of system load by 10% and step decrease of system load by 10%, with and without BESS connection.

In the first scenario, the load increase occurs in the third second, followed by frequency drop and generation increase of generation units participating in FCR. Maximum frequency nadir (deviation) occurs in the scenario without BESS operation, when the frequency drops to 0.971 p.u. that is, at 48.55 Hz. In the scenario with BESS operation, the frequency drops to 0.983 p.u., i.e. at 49.15 Hz. Frequency response at 110 kV bus Vrataruša with and without BESS is shown in Figure 8.

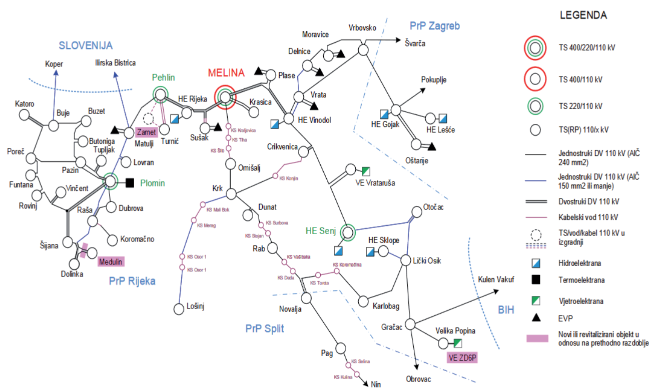

Figure 6. Part of Croatian 110 kV transmission system (Rijeka area)

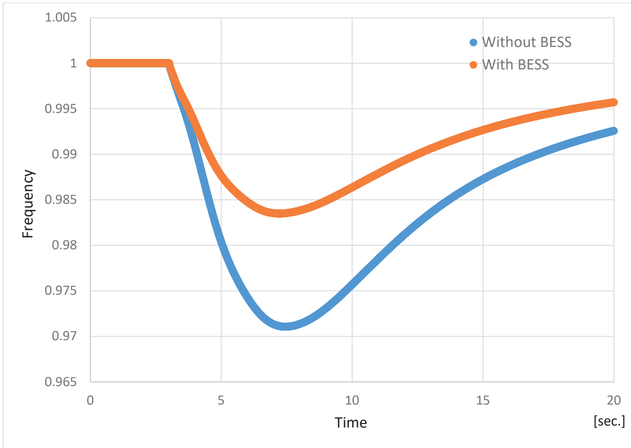

Figure 8. Frequency response at 110 kV bus Vrataruša with and without BESS when the load increases by 10%

The BESS from the simulated example provides virtual inertia to the power system, thereby reducing the maximum frequency deviation and the ROCOF. However, it also participates in FCR for a certain period of time, which depends on its total capacity and current state of charge. Therefore, for realistic application of such a technology, it is necessary to take into account these parameters. The BESS power injection is shown in Figure 9.

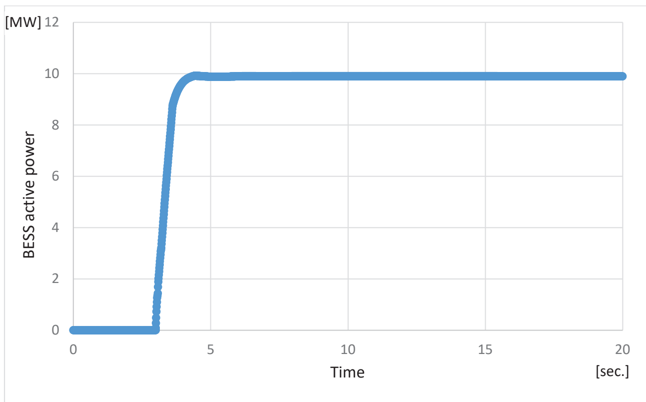

Figure 9. BESS active power injection

Furthermore, when the load changes in the third second, the generating units inject power into the grid to balance production and load. The power increase of HPP units without and with BESS is given in Figure 10. If BESS is applied, lower power of the HPP units in the stationary state can be observed.

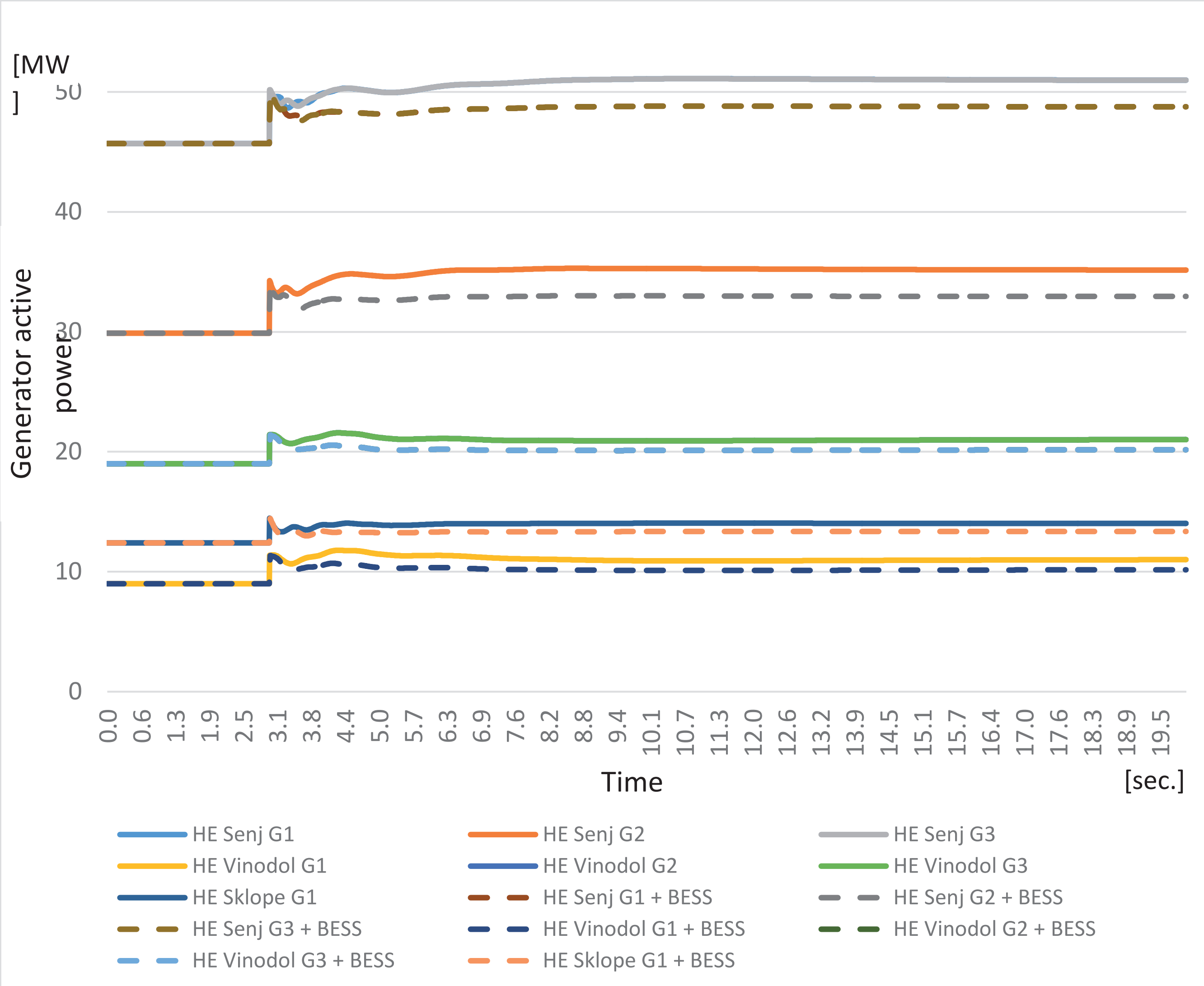

Figure 10. HPP units active power production with and without BESS

In the second scenario, when the load is reduced by 10%, the frequency increases and then generating units active power production decreases. In this case, the difference is that the BESS does not inject active power into the system, but absorbs it from the system, i.e., it acts as load. A BESS can absorb active power from the power system until it reaches the maximum allowed state of charge.

During maximum frequency deviation that occurs in the scenario without BESS, the frequency will increase to 1,028 p.u. that is, at 51.4 Hz, while in the scenario with BESS, the frequency increases to the value of 1.023 p.u., that is to 51.15 Hz, Figure 11.

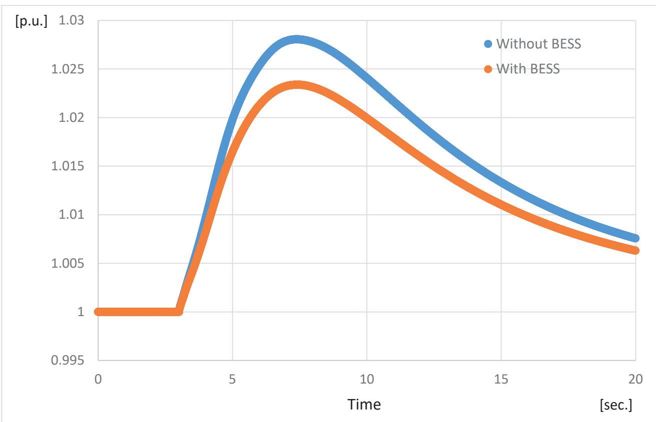

Figure 11. Frequency response at 110 kV bus Vrataruša with and without BESS with load decrease by 10%

5. CONCLUSION

The influence of virtual inertia on Croatian power system stability was analyzed in the paper. The virtual inertia is obtained using a BESS with a control mechanism that enables its participation in frequency control. The result of the simulation confirmed the effect of the virtual inertia to reduce the maximum deviation of the frequency from the nominal one, and to reduce the ROCOF.

In fact, the beneficial influence of the BESS upon frequency deviations in the simulated scenarios, prevents over/under frequency elements from tripping loads and generators. In contrast, without BESS the frequency drops below 49 Hz for a sudden step wise load increase, thus triggering the first stage of under-frequency load shedding scheme. For the scenario of a sudden load decrease the frequency increases to 51,4 Hz, just below the over-frequency limit of 51,5 Hz when disconnection of generating units occurs.

Of course, the presented simulation results are only orientational and give an insight on the possibilities for virtual inertia provision by BESS. For more accurate results, the exact type and technical parameters of the BESS should be known.

Actually, the behavior of the battery energy storage largely depends on the settings, that is, on the modeling of the battery itself. In fact, a BESS consists of two main components - a storage component and a rectifier/inverter component that transforms DC to AC and vice versa. The rectifier/inverter component is normally based on a voltage sourced converter (VSC) with a pulse width modulation (PWM). This element is well known and it's settings are known and easily obtainable. However, the storage component is a rechargeable battery i.e., an element that depends on the actual application and battery technology (Lead-acid, Ni-Cd, NI-MH, Li-ion etc.). Each type has its own assets and drawbacks.

In addition, oscillations between generators or among groups of generators may appear unexpectedly from small disturbances. These oscillation modes are inherently stable, but may get unstable by introducing feedback loops. With higher damping and lower inertia of the system the oscillations are well resolved at the cost larger transient frequency deviations in case of large disturbances. Therefore, a trade-off between improved damping and sufficient inertia against large disturbances has to be determined.

Although development and implementation of virtual synchronous generators is a good way to accelerate RES integration, it brings new technical challenges to power system operation. Therefore, further research is needed, so that virtual synchronous generators can be effectively integrated into future power systems.

REFERENCE

Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action

Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality

IRENA (2021), Renewable Capacity Statistics 2021, The International Renewable Energy Agency, Abu Dhabi. - https://www.irena.org/

H. Bevrani et all.: "Virtual synchronous generators: A survey and new perspectives", International Journal of Electrical Power & Energy Systems, Vol. 54, pp. 244-254, 2014.

U. Tamrakar, D. Shrestha, Manisha Maharjan, B. Bhattarai, T. Hansen, R. Tonkoski, "Virtual Inertia: Current Trends and Future Directions", Applied Sciences 2017, 7, 654; DOI: 10.3390/app7070654

B. Barać, M. Krpan, T. Capuder, I. Kuzle, »Modeling and Initialization of a Virtual Synchronous Machine for Power System Fundamental Frequency Simulations,« in IEEE Access, vol. 9, pp. 160116-160134, 2021, doi: 10.1109/ACCESS.2021.3130375.

K. S. Ratnam, K. Palanisamy, G. Yang, "Future low-inertia power systems: Requirements, issues, and solutions - A review", Renewable and Sustainable Energy Reviews 124 (2020) 109773

M. N. H. Shazon, N. Al-Masood, A. Jawad, "Frequency control challenges and potential countermeasures in future low-inertia power systems: A review", Energy Reports 8 (2022) 6191–6219

K. M. Cheema, "A comprehensive review of virtual synchronous generator", Electrical Power and Energy Systems 120 (2020) 106006

B. Muftau, M. Fazeli, "The Role of Virtual Synchronous Machines in Future Power Systems: A Review and Future Trends", Electric Power Systems Research 206 (2022) 107775

L. Vetoshkin, Z. Müller, "A Comparative Analysis of a Power System Stability with Virtual Inertia", Energies 2021, 14, 3277. https://doi.org/10.3390/en14113277

M. Krpan, I. Kuzle, "Inertial And Primary Frequency Response Model Of Variable-Speed Wind Turbines", The Journal of Engineering, Vol. 1, No. 1, November 2017, pp. 1-6, DOI: 10.1049/joe.2017.0449

J. Đaković, M. Krpan, P. Ilak, T. Baškarad, I. Kuzle, "Impact of Wind Capacity Share, Allocation of Inertia and Grid Configuration on Transient RoCoF: The Case of the Croatian Power System", International Journal of Electrical Power & Energy Systems, Vol. 121, October 2020, pp. 1–8, article no. 106075, DOI: 10.1016/j.ijepes.2020.106075

T. Bašakarad, N. Holjevac, I. Kuzle, I. ivanković, N. Zovko, "ROCOF importance in electric power systems with high renewables share: a simulation case for Croatia", 12th Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion, Paphos, Cyprus, 9-12.11.2020.

Y. Zuo, Z. Yuan, F. Sossan, A. Zecchino, R. Cherkaoui, M. Paolone, "Performance assessment of grid-forming and grid-following converter-interfaced battery energy storage systems on frequency regulation in low-inertia power grids", Sustainable Energy, Grids and Networks 27 (2021) 100496

W. Xing, H. Wang, L. Lu, X. Han, K. Sun, M. Ouyang, "An adaptive virtual inertia control strategy for distributed battery energy storage system in microgrids", Energy 233 (2021) 121155

M. M. Mohamed, H. M. E. Zoghby, S. M. Sharaf, M. A. Mosa, "Optimal virtual synchronous generator control of battery/supercapacitor hybrid energy storage system for frequency response enhancement of photovoltaic/diesel microgrid", Journal of Energy Storage 51 (2022) 104317

M. Brezovec, I. Kuzle, M. Krpan, "Detailed mathematical and simulation model of a synchronous generator", Journal of Energy (Energija), vol. 64, no. 1-4, pp. 102-129, 2015.

U. Tamrakar et all, "Virtual Inertia: Current Trend and Future Directions", Applied Sciences, Vol. 7, No. 7, 654, 2017.

W. Zhang et all, "Performance Tuning for Power Electronic Interfaces Under VSG Control", Applied Sciences, Vol. 10, No. 3, 953, 2020.

P. Tielens, D. Van Hartem, "The relevance of inertia in power systems", Renewable and Sustainable Energy Reviews, Vol. 55, pp. 999-1009, 2016.

ENERGIJA