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A novel control approach for virtual synchronous generators to suppress frequency and voltage fluctuations in microgrids

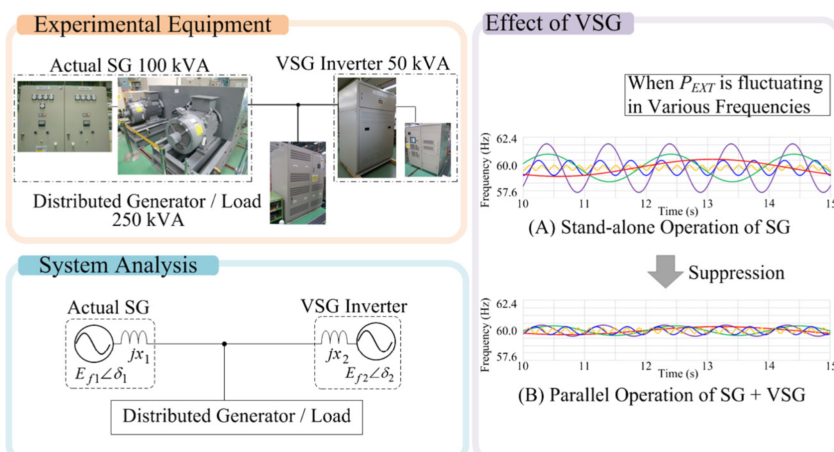
Yuko Hirase [a,*], Kensho Abe [a], Kazushige Sugimoto [b], Kenichi Sakimoto [b], Hassan Bevrani [c], Toshifumi Ise [d]

[a] Kawasaki Technology Co., Ltd., Electromechanical System Department, 1-1, Kawasakicho, Akashi, Hyogo 673-8666, Japan
[b] Kawasaki Heavy Industries, Ltd., Electromechanical System Department, 1-1, Kawasakicho, Akashi, Hyogo 673-8666 Japan
[c] University of Kurdistan, Smart/Micro Grids Research Center, Sanandaj 66177-15175, Iran
[d] Osaka University, 2-1, Yamadaoka, Suita, Osaka 565-0871 Japan

HIGHLIGHTS

- The simple algebraic-type VSG provides an intuitive and mathematical comprehension.
- The frequency/voltage deviations caused by parallel operation of SGs are analysed.
- The VSG provides the stabilization effects of the frequency/voltage deviations.
- The analytic approach has good agreement with the simulation/experimental results.
- The VSG promotes the use of renewable energies into the existing power grids.

GRAPHICAL ABSTRACT



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ABSTRACT

To achieve a more sustainable supply of electricity, consumers are expected to rely increasingly on combinations of various types of power generators. Among them, distributed generators (DGs) utilizing renewable energy sources (RESs) are a promising solution. However, introducing renewable energy based DGs into microgrids (MGs) can reduce the inertia of the whole power system, and hence, the system frequency and the voltage can be fluctuated. Furthermore, unnecessary interference occurs as the number of synchronous machines increases. To address these issues, it is desirable to develop a noble inverter control method for DGs, and to gain an intuitive understanding of the dynamic characteristics of MG power systems. In this paper, the impacts of frequency/voltage deviations in MGs are mathematically investigated using algebraic-type virtual synchronous generator (VSG). The algebraic-type VSG with a minimal number of parameters has an ability to suppress the system frequency and voltage deviations. The proposed control approach presents a suitable solution for penetration of more and more renewable energy into the existing power grids. The results of the analysis were verified via simulations and experiments.

* Corresponding author.
E-mail address: hirase-tch@corp.khi.co.jp (Y. Hirase).

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1. Introduction

The microgrid (MG) concept has proven to be an appealing alternative for overcoming the challenges of integrating renewable energy sources (RESs) and distributed generators (DGs) into power systems. Although distributed inverter-based power sources have become the main components in MGs, dynamic stability, special protection schemes, and improved control strategies remain the priority. In recent years, the large-scale integration of inverters has created significant challenges for future electric energy systems, including difficulties in achieving frequency stability due to the reduction in system inertia caused by the introduction of inverters with RESs. A general overview of existing MG control technologies and challenges is provided in [1–8]. Protection strategies for the future distribution network are discussed in [1], and a typical residential MG in the near future is predicted in [2]. Utilizing a storage battery with fast responsiveness for frequency stabilization has become popular, and one of which is described in [3]. In [4], a new master-slave DG operation was deployed, and MG-forming model of it is formulated using an advanced optimization method. Nowadays, from the viewpoint of complicated control of centralized control, new decentralized control that replaces centralized control has been studied. In [5], both centralized and decentralized frequency controls are studied, and their advantages and disadvantages are summarized. Furthermore, by boosting use of big data, a research on optimal hierarchical control has been actively carried out in [6–8].

While, in above references, the focus was placed on the control of an MG itself, long-term predictions over wide areas are also being conducted. The United Kingdom (UK) and Ireland have set a goal to increase the introduction rate of RESs up to around 40% by 2020, and are planning to export large amounts of wind power from Ireland to the UK [9]. However, the shortage of system inertia in the power system in Great Britain (GB) was analysed in [10], and the authors of [11,12] warned that the introduction of a large number of RESs in the UK power grid could reduce the inertial constant by up to 70% by 2030.

It has also been proposed that the relevant regulations be strengthen. The British multinational electricity and gas utility company, National Grid plc (NG), is the code administrator for the grid code [13]. To maintain the frequency of the grid within the limits of the statutory range of 49.5–50.5 Hz and the operational range of 49.8–50.2 Hz, each generating unit must satisfy the minimum requirements for response capabilities that have been enacted by NG. Similar regulations have been adopted in several European islands/countries, including the Azores Islands, the Canary Islands, Crete Island, Pantelleria Island, French Islands, and Denmark, and a comparison of these regulations is provided in [14].

As described above, the shortage and reduction of system inertia is an important stability/performance issue in an MG. Detailed analyses of the inertial reduction of MGs and the appropriate countermeasures have also been conducted. In [15], the mechanisms whereby the voltage and frequency of MGs exceed the allowed variation bounds are discussed, and the authors of [16] stated that entire MG systems have lower inertial forces than those in typical commercial grids. In [17], the inertial forces of the wind turbines have been analysed, and a method for applying the associated principles to photovoltaic power generators was introduced. Similarly, since flywheels have rotational energy, their stabilizing effect on MGs has been studied [18,19]. However, because this type of equipment is usually massive and expensive, there is demand for a technique to realize these inertial forces in a pseudo manner using the inverters in DGs. When pseudo inertial forces are realized in a control program, it is called synthetic (virtual) inertia [20–22]. In [10], the frequency control of inverters is governed using a proportional gain and first order element [23]. Although this control method is similar to part of that used in algebraic-type virtual synchronous generators (VSGs) [24], which will be described later, the virtual inertia constant of the controller, reactive power control, and experimental tests were not mentioned in the study. In addition to the above referenced literature, which mostly focus on frequency control, there are also literature that discuss the unstable voltage and other voltage quality problems of MGs. When DGs are introduced into MGs, it leads to collapse of the reactive power balance and decreases the bus voltage [25]. Simulation tests show that voltage stability improves when static synchronous compensators (STATCOMs) and static VAR compensators (SVCs) are added to the grid [26]. Conversely, the problem of frequency fluctuation is not mentioned in these literature.

On the other hand, multiple synchronous generators (SGs) under parallel operation can autonomously suppress frequency/-voltage deviations with their inertial forces and automatic voltage regulators (AVRs). In doing this, they have no need to communicate with either the supervisory controller or each other. In this context, various control systems that enable an inverter to operate like an SG have been studied [24,27–41], and these systems are known as VSGs. Because the software parameters of the frequency/voltage controls can be tuned to enhance the dynamic response of the system, the VSG concept is considered to be a useful solution for improving the resilience of MG systems. Although numerous studies have focused on various types of VSGs, in each case, the VSG simulates the dynamic behaviour of an SG, and represents its fundamental swing equation by virtual inertia, which not only enables the stand-alone operation of a VSG or parallel operation of multiple VSGs, but also enhances the frequency stability of MGs. In [24,27–29], it is proven that VSGs can supply uninterruptable power between grid-connected and islanded operation modes. In addition to the frequency control, VSGs can operate to regulate the system voltage like SGs. Although the effects of voltage stabilization control in VSGs are demonstrated in [30,31], only transient responses have been focused in both research works. What should be noted here is that the consensus-based control, which requires communications among each VSG, is used in [30]. On the other hand, since VSGs have the same function as AVRs of SGs, the communication links are not used in [24,27,28]. A comparison of various VSGs and similar techniques is detailed in [32].

As the authors in [33] have already shown, system instabilities can be exacerbated by the resonance among SGs, DGs, and loads (LDs). That is, as more inverters that have the characteristics of SGs are introduced, the amount of unnecessary interference will be produced. In conventional power grids with SGs, stability analysis procedures were well established for particular classes of problems [34]. However, this may be difficult to achieve and comprehend because the wide range of power technologies were being deployed. Even though the parallel operation of VSGs was studied in [35], there was no focus on entire MG systems, which included VSGs and SGs. Furthermore, manufacturers do not normally disclose detailed device information, such as time constants, control gains, etc. Hence, it is difficult to estimate the influence caused by other equipment in advance and to prepare the necessary compensation countermeasures. Therefore, to minimize unnecessary interference and to construct an intuitive understanding of the dynamic characteristics of an MG, a straightforward design is required. Considering the above, In [33], the authors evaluated a novel two-SG model of an MG, which includes an algebraic-type VSG [24] and a conventional SG, and demonstrated that algebraic-type VSGs could be designed using a minimal number of required parameters. Although only the essential elements of the dynamic characteristics of SGs are applied in algebraic-type