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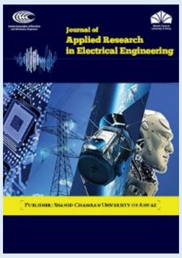

Research Article

Improving the Performance of a VSG in the Distorted Grid Using Third-Order Generalized Integrator

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Abstract: In conventional power systems, most of the power is produced by synchronous generators in the electric grid that have heavy and rotating rotors. As a result, there is an inherent inertia in the rotor of these generators. The presence of inertia in the grid prevents sudden frequency changes during imbalance situations, thus, the frequency stability of the grid is maintained. Today, with the increase of renewable energy sources that are usually connected to the network by power electronic equipment. Such resources do not have rotating materials, therefore, the overall inertia of the grid decreases and the stability of the system deteriorates. To solve the problem of lack of inertia in the power electronic-based grid, the notion of the virtual synchronous generator (VSG) technology has been introduced in recent years. This technology can imitate the behavior of traditional synchronous generators for inverters connected to the grid. In this way, the inverters connected to the grid act like a synchronous generator during imbalance. One of the problems associated with the converters-based microgrid is the existence of DC deviations and additional harmonics, which disrupt the work of the converters. Therefore, in this article, a third-order generalized integrator (TOGI) -based VSG for grid-connected inverters is employed so that the system stability is maintained in the conditions of additional harmonics and DC deviation. To show the effectiveness of the proposed method, time domain simulations have been performed in Simulink/MATLAB software. The results of the simulation verify the performance of the proposed method.

Keywords: Virtual synchronous generator, grid stability, distributed resources, dc deviations, additional harmonics.

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1. INTRODUCTION

In traditional power systems, synchronous generators with heavy and rotating rotors are commonly used to generate power. The rotational motion of these rotors is primarily responsible for providing the inertia for the entire power systems inertia, which is crucial for maintaining stability. When there is an imbalance between power generation and consumption within the grid, the speed of the rotor adjusts to accommodate this imbalance, resulting in frequency deviations. However, due to the inherent inertia of these rotors, sudden changes in speed are prevented, ensuring the stability of the network's frequency. Besides inertia, another key factor is the damping coefficient resulting from mechanical friction and electrical losses in the motor of synchronous generators. This can significantly impact the stability of the electrical network. Currently, there is a global shift toward utilizing more renewable resources in power systems. As distributed energy sources are increasingly connected to grids via power electronic devices, which usually do not have inherent inertia, the overall rotational inertia of the network is decreasing. This is because renewable resources are usually interfaced through electronics that lack of the physical spinning components compared to traditional synchronous generators that have rotational masses.

As inertia levels decrease across the grid, it becomes more sensitive to disturbances and imbalances. The network reacts faster to these disturbances, posing greater stability challenges for the system. Even minor imbalances causes cascading failures, widespread blackouts, and the need for power outages. One solution to enhancing stability under these conditions is providing virtual inertia from non-inertial resources. Recent work has acknowledged virtual synchronous generators as an approach that can mimic the behavior of a synchronous generator using power inverters connected to the network. By emulating synchronous generator characteristics, non-inertial sources act similarly to high inertia synchronous machines, compensating for the lack of physical rotating masses. This helps stabilize grid frequency in the cases of electrical disturbance [1].

By adjusting key parameters such as virtual inertia and damping rate, the output reaction of a VSG can be altered. The experts have examined different control setups with the goal of eliminating fluctuations in both power and frequency. A variety of control architectures have been evaluated as a way to reduce variations and keeping stability through the VSG response. By modifying the virtual inertia and damping emulated by the inverter, the VSG output response can be tailored to best maintain system frequency and power transfer under varying conditions of the electrical network. The virtual inertia and damping have been modeled by the inverter can allow the VSG to adapt its behavior by changing grid situations [2, 3]. A general overview and detailed investigation of various VSG designs and their structures have been given in [4], that has outline different VSG models as well as an in-depth discussion of their architectures. The concept of adaptive virtual inertia has been introduced in [5], which can effectively suppress the power and frequency fluctuations in VSGs. A small signal model of the VSG control loop has been analyzed to tune parameters in [6], obtaining optimal inertia (J) and damping (D) values. Also, in [7], the problems of designing VSG parameters have discussed and a method based on Lyapunov has been presented for designing VSG parameters. A VSG-based approach has been presented in [8] to address the reduced inertia challenge in distribution grids. In this reference a virtual inertial control has been developed to increase the inertia of a DC microgrid and reduce voltage fluctuation rates. The VSGs can produce significant damping torque to eliminate low-frequency oscillations in grids [9]. The inertia response characteristics of permanent magnet wind energy conversion systems using VSG control have been evaluated and comparing them to synchronous generators in in [10]. While virtual resistance helps synchronous resonance suppression, it has negative impacts on VSG transient stability [11]. As a result virtual resistance effects on transience has been investigated in this reference and has been proposed a method for suppressing transient fluctuations using virtual resistance. Aa microgrid model with several VSGs and real synchronous generators have been used in [12] to define the voltage angle deviations from the center of inertia angle to analyze transient stability. Also, in [13], a control method has been presented to improve transient power angle stability (TPAS) and suppression fault current when a fault occurs in the grid.

As mentioned earlier, in recent times, there has been significant growth in grid-connected microgrid systems driven by the need to improve renewable energy availability and reliability during high demand periods. To ensure accurate synchronization of renewable sources with the main grid, Phase-Locked Loop (PLL) controllers have emerged as a key solution [14]. The PLL technique is one of the most widely used and established methods for synchronization in power systems [15]. However, if DC deviation components exist in the voltage and current signals, they can induce frequency and phase fluctuations estimated by the PLL. Eliminating these low frequency oscillations has posed a challenge [16].

The novelty of this paper is to use a VSG-based control method for grid-connected inverters is which can provide virtual inertia for new microgrids, it can also maintain the stability of the system and enhances the stability of dynamics of the system in the presence of DC deviation component and additional harmonics in the voltage and current VSG signals. In this design, instead of the voltage and current signals being used directly to calculate the power, first they pass through a TOGI and the harmonic and DC deviation removal operation takes place, and then the signals without DC deviation and additional harmonics are used to calculate the transmitted power.

The remaining Sections of the article are organized as follows: Section 2 provides a concise conceptual description and overview of the general structure of a VSG. Section 3 introduces a proposed method aiming at eliminating the DC deviation component from VSG signals, ensuring that its performance remains unaffected. Section 4 focuses on carrying out the time domain simulations based on the principles outlined in Section 3, validating the effectiveness of the proposed approach through simulation results. Finally, Section 5 concludes the article, summarizing the key findings and implications of the study.

2. GENERAL CONCEPT AND STRUCTURE OF A VSG

Fig. 1 illustrates the concept of a VSG. Based on the information depicted in this figure, it can be inferred that distributed energy sources like solar and wind energy can be regarded as providing the necessary energy that is an analogy to the rotor of synchronous generators. Additionally, inverters can be viewed as analogous to synchronous generators within the framework of VSG, according to the principles of VSG, when the VSG control method and theory are implemented in all grid-connected inverters, they can be treated collectively as an equivalent synchronous generator [17]. VSG is comprised of three primary components. An inverter, an energy storage system typically utilizing capacitors, and VSG control, as depicted in Fig. 2. When an imbalance in power occurs within the grid, the capacitor is utilized to either release or store energy. Thereby preventing frequency deviations. If power consumption exceeds generation, the required power is drawn from the capacitor. Conversely, if generation surpasses consumption, the surplus energy is stored in the capacitor. This process is controlled by the VSG control. The VSG control Section incorporates the oscillation equation of synchronous generators, which can be expressed as follows:

$$P_0 - P_\mathrm{e} + D(\omega_0 - \omega) = J\omega \frac{d\omega}{dt} \tag{1}$$

where, P_0, P_e, D, J, ω and ω_0 are the active power reference, VSG active power, damping coefficient, virtual inertia, VSG angular frequency and nominal frequency, respectively.

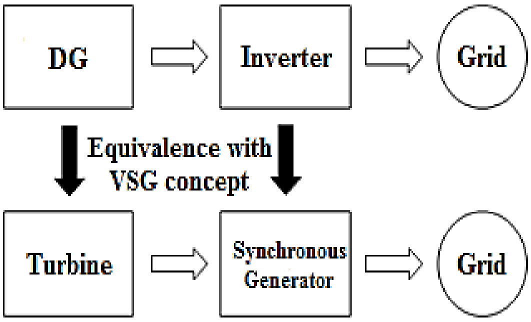

Fig. 1: Concept of a VSG.

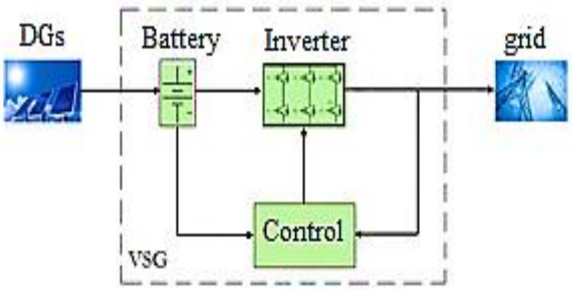

Fig. 2: General structure of a VSG.

3. PROPOSED METHOD FOR REMOVING THE DC DEVIATION COMPONENT AND ADDITIONAL HARMONICS TO IMPROVE VSG PERFORMANCE

As stated previously, the PLL plays a crucial role in the synchronization and closed-loop control of single-phase grid-connected systems (SPGCS), including photovoltaic systems, fuel cells, batteries, and wind systems [18, 19]. PLLs are responsible for accurately detecting the frequency and phase angle, which directly impacts the power quality, reliability, and stability of SPGCS [20]. The second-order generalized integrator (SOGI) algorithm depicted in Fig. 3 is considered one of the most effective PLL techniques for converters is being connected to a single-phase grid. In Fig. 3, u, K_{SOGI}, and ω_0 are the input signal, damping coefficient, and resonance frequency, respectively.

When examining the output signals u_1 and u_2 in TPGI, it is observed that they possess identical amplitudes but exhibit a phase shift of 90 degrees. Both u1 and u2 share the same amplitude and phase characteristics. However, in the presence of a DC offset component within the input signal, a notable distinction emerges. Specifically, u1 has no DC offset while u2 is significantly influenced by the DC offset. This discrepancy in behavior can pose challenges and complications in some cases.

The existence of a DC offset in PLL input is a fundamental issue due to inducing frequency fluctuations in the acquired phase and frequency [21, 22]. The detrimental impact of DC offset components in the grid voltage on synchronization unit performance is evident. It manifests as oscillatory behavior and offset errors in the estimation of grid information [23]. DC offset can arise from: voltage sensor offsets, disparities between semiconductor devices. A/D conversion and so on. To tackle this problem, this section introduces a method for eliminating the DC offset from the output voltage and current signals of VSG. Fig. 4 illustrates the general block diagram of a simplified VSG, serving as a visual representation for further discussion.

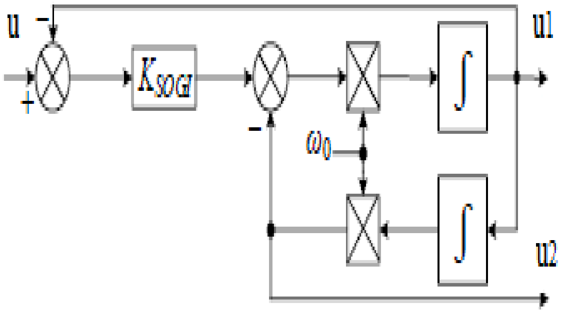

Fig. 3: General structure of a SOGI.

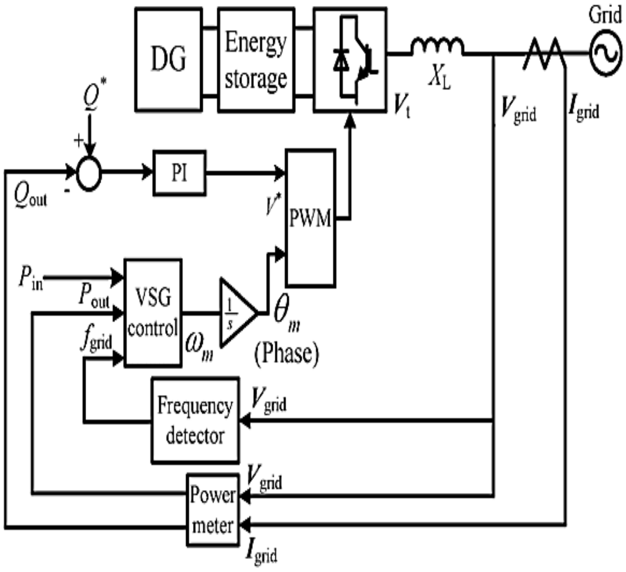

Fig. 4: General block diagram of a simple VSG.

In the power calculation section, VSG power is calculated as follows:

$$P_{out} = V_a I_a + V_b I_b + V_c I_c \qquad (2)$$

$$Q_{out} = \frac{1}{\sqrt{3}} (I_a (V_b - V_c) + I_b (V_c - V_a) + I_c\,(V_a - V_b)) \qquad (3)$$

where V_a, V_b, and V_c are the voltages of phase a, b, and c, respectively, and I_a, I_b, and I_c are also the currents of phase a, b, and c. If there is a DC deviation in any of the parameters mentioned in (2) and (3), it can introduce calculation errors in power calculations. These errors can propagate through the VSG control cycle, leading to successive errors and potential instability. The dynamical coupling between frequency and voltage of a VSG a has been studied in [25]. In this reference a unified model is presented to study the voltage and frequency analysis. In reference [26], TOGI algorithm is introduced to address DC deviations in single-phase systems. The TOGI algorithm eliminates the influence of the DC offset component in u_2 by incorporating an additional loop to the SOGI. In this article, the TOGI-based

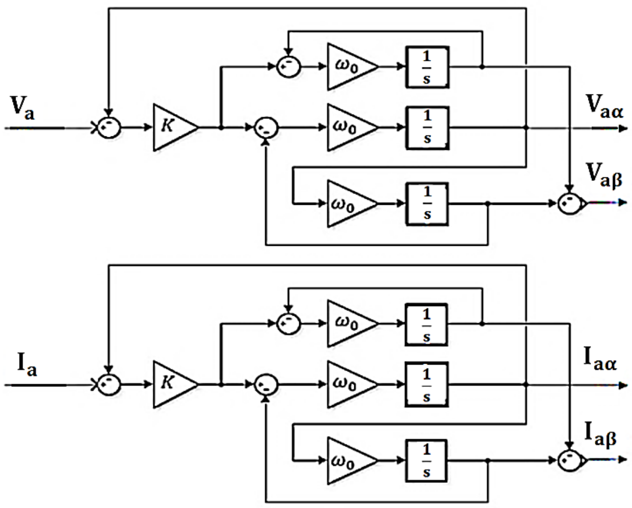

Fig. 5: Extraction of phase a αβ components by TOGI in a VSG [26].

algorithm is utilized to generate the αβ axes of voltage and current for the VSG, enabling the extraction of the fundamental components of voltage and current and facilitating power calculation. To achieve this, six TOGIs are employed, with two TOGIs per phase (one for voltage and one for current). Fig. 5 illustrates the process of extracting the αβ components of phase (a) voltage and current using the TOGI-based algorithm. Similarly, TOGI is considered in phases b and c. In this case, the VSG active and reactive powers can be calculated as follows.

$$P_{\text{out}} = \frac{(V_{a\alpha}I_{a\alpha} + V_{a\beta}I_{a\beta})}{2} + \frac{(V_{b\alpha}I_{b\alpha} + V_{b\beta}I_{b\beta})}{2} + \frac{(V_{c\alpha}I_{c\alpha} + V_{c\beta}I_{c\beta})}{2} \tag{4}$$

$$Q_{\text{out}} = \frac{(V_{a\alpha}I_{a\beta} + V_{a\beta}I_{a\alpha})}{2} + \frac{(V_{b\alpha}I_{b\beta} + V_{b\beta}I_{b\alpha})}{2} + \frac{(V_{c\alpha}I_{c\beta} + V_{c\beta}I_{c\alpha})}{2} \tag{5}$$

Using this approach, the VSG active and reactive powers are computed independent of any DC deviations, ensuring the delivery of power to the load with the desired quality and enhancing the system's stability. The modified version of Fig. 4 is represented as Fig. 6, incorporating the suggested method.

4. SIMULATIONS

Simulations are carried out using the Simulink/MATLAB software. This analyzes and compares the transient performance, steady state characteristics, and stability of the system in different sections, in comparison to conventional VSG control. The VSG was connected to the grid and operated alongside a local load of 15KW, with the simulation duration set for 6 seconds. Two scenarios are considered to evaluate the proposed design. The first scenario involved the presence of unwanted DC deviations in the VSG voltage and current signals. The second scenario is the connection of the studied VSG to a harmonic grid. Therefore, the proposed design should be able to perform well in both of these scenarios and maintain the stability of the system.

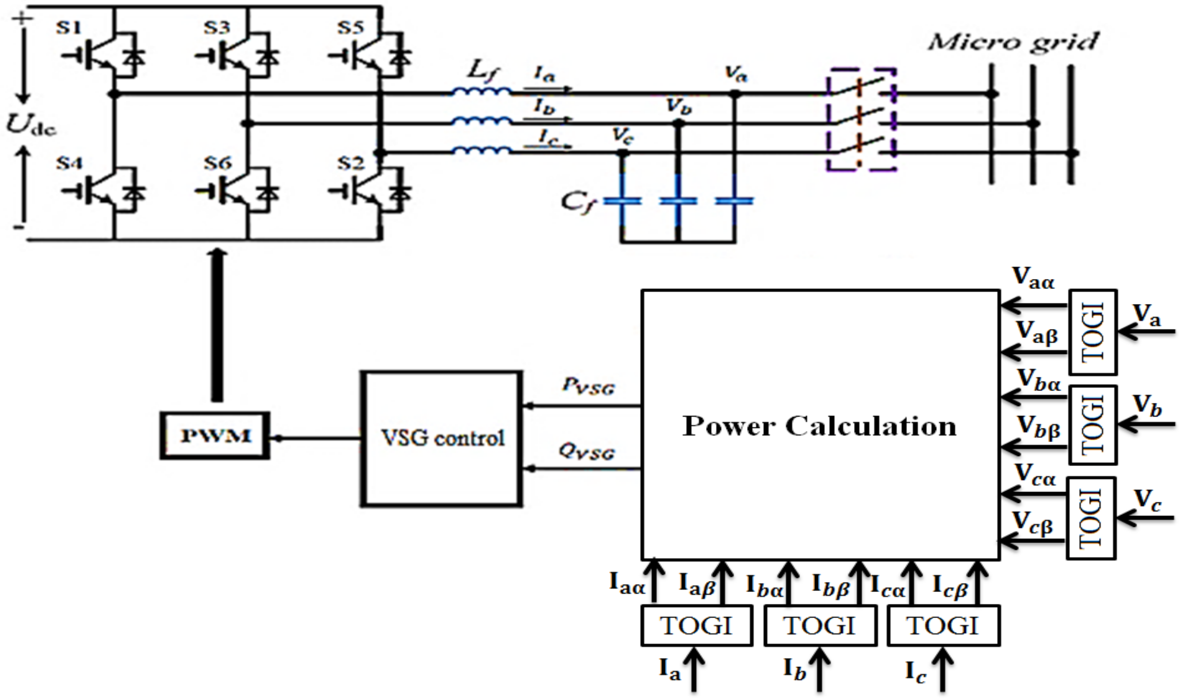

Fig. 6: Proposed VSG control scheme.

The simulation parameters for the proposed VSG are provided in Table 1. To assess the implementation and effectiveness of the proposed strategy, time domain simulations are conducted in the following under scenarios involving DC deviations in VSG voltage and current signals, as well as a harmonically distorted with harmonic content.

4.1. Scenario 1: DC Deviation in the Voltage and Current VSG Signals

In this Section, both the proposed VSG and conventional VSG are simulated while voltage and current signals have DC deviation and the results of the simulations are then compared. DC deviation can cause grid instability. Therefore, the proposed VSG should be able to reduce the effect of DC deviation. In 2.5s, a DC deviation is injected in the phase a voltage of both controllers (proposed VSG and normal VSG). The value of this deviation is 100V. Fig. 7 and Fig. 8 show the system frequency and output power of VSGs, respectively. As it can be seen from these figures, the proposed TOGI-based method removes the DC deviation value from its signals.

It becomes stable with an acceptable transient and follows its reference values without any fluctuations. However, the DC deviation greatly affected the control performance of conventional VSG. The performance of this controller fluctuates greatly in these conditions and even the frequency and power fluctuate outside the allowed range. This is despite the fact that the DC deviation occurred with a relatively low amplitude and only in phase (a). If it occurs in other phases with higher amplitudes, it can worsen the situation.

4.2. Scenario 2: Performance of the Proposed VSG Connected to a Harmonically Grid

In scenario 2, the simulations are carried out for both the proposed VSG and conventional VSG in the presence of a harmonic grid. The grid to which the VSG is connected is considered to have a third order harmonic with an amplitude of 0.2pu and a phase of -25 degrees, spanning from 2s to 4s seconds. Both the proposed and conventional VSG controls are connected to this grid, enabling a comparison of their respective responses. Fig. 9 displays the system frequency, while Fig. 10 illustrates the output power of the VSGs. Both figures are for the conditions that the third harmonic is present. These simulation results provide a basis for evaluating the performance and effectiveness of each control approach in the presence of harmonic distortion.

Table 1: Simulation parameters.

Parameter	Value
Nominal frequency	50 Hz
switching frequency	14 KHz
Grid voltage	220 V
DC bus voltage	800 V
Virtual inertia J	0.023
Damping coefficient D	796
Filter inductance L_f	1.5 mH
Filter capacitor C_f	150 μF

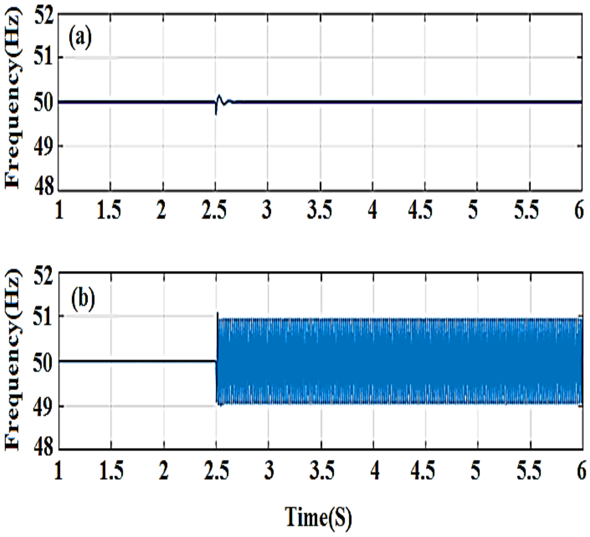

Fig. 7: System frequency: (a) proposed VSG control, (b) conventional VSG control.

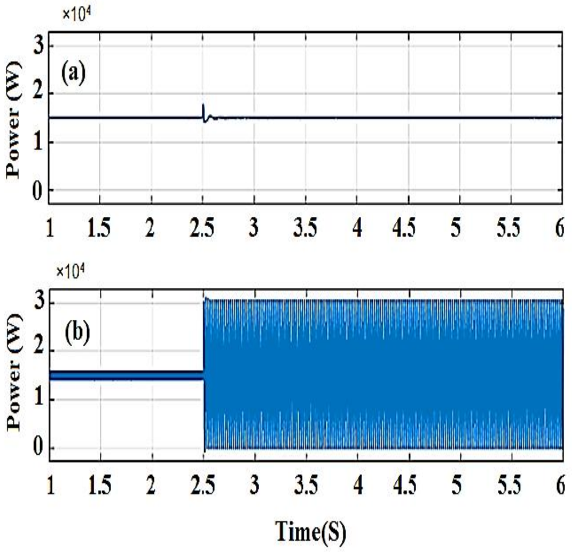

Fig. 8: Output power of VSGs: (a) proposed VSG control, (b) conventional VSG control.

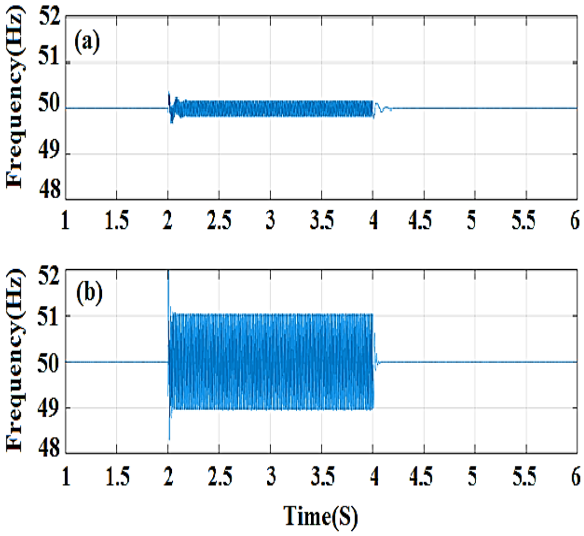

Fig. 9: System frequency: (a) proposed VSG control, (b) conventional VSG control.

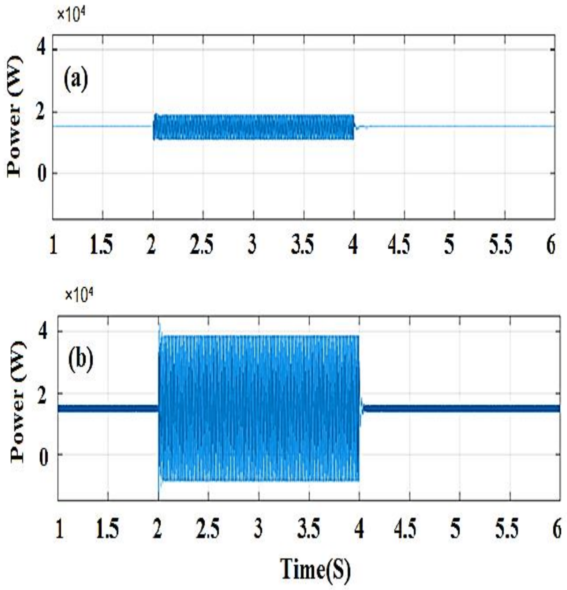

Fig. 10: Output power of VSGs: (a) proposed VSG control, (b) conventional VSG control.

As Fig. 9 and Fig. 10 show, in time interval between 2s to 4s, when the additional harmonic is injected, the proposed VSG remove the effect of the excess harmonic well and has only a very small fluctuation, which is within the permissible range. but the conventional VSG has not been able to remove the additional harmonic effect and as it is known, the system has a strong oscillation in 2 to 4 seconds. The advantages of the proposed design include easy implementation, low calculation time, improvement of VSG stability in harmonic conditions and the presence of DC deviations in voltage signal, applicable for single-phase and three-phase inverters, without the need to connect with other system components and low cost.

5. CONCLUSION

This article focuses on enhancing the stability of a VSG in the presence of harmonically distorted conditions and DC deviations in its voltage and current signals. It begins by providing a brief overview of the general and conceptual structure of a VSG. Subsequently, a method utilizing TOGI is introduced to eliminate DC deviations from the VSG's voltage and current signals. To evaluate the effectiveness and efficiency of this proposed approach, the time domain simulations are conducted in Simulink/MATLAB software, by considering two scenarios: 1) the presence of DC deviations in the VSG's voltage and current signals, and 2) the VSG connected to a harmonically distorted grid. The simulation results clearly indicate the effectiveness of the proposed design in enhancing the stability of the VSG.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Ramin Arjmandzadeh: Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Roles/Writing - original draft. **Mahdi Banejad:** Formal analysis, Methodology, Project administration, Supervision, Validation, Roles/Writing - original draft, Writing - review & editing. **Ali Akbarzadeh Kalat:** Investigation, Methodology, Resources, Supervision.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues; including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy has been completely observed by the authors.

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BIOGRAPHY

Ramin Arjmandzadeh was born in Bojnord, Iran in 1984. He finished his M. Sc in electric power engineering at Shahrood University of Technology, Shahrood, Iran. His research interested are renewable energies and microgrid control.

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Ali Akbarzadeh Kalat was born in Mashhad, Iran in 1969. He received his B.Sc. degree from Iran University of Science and Technology in 1992. He graduated in control engineering in M.Sc. and Ph.D. from Ferdowsi University, Mashhad, Iran and Tarbiat Modarres University, Theran, Iran in 1998 and 2007 respectively. He is with the Faculty of Electrical and Robotic Engineering at Shahrood University of Technology in Iran. His fields of interest include Neural, Fuzzy and Adaptive control systems and Nonlinear observer design.