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Frequency Response Improvement in Microgrids: A Fuzzy–based Virtual Synchronous Generator Approach

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ABSTRACT

The use of renewable energy sources in microgrids has grown dramatically in recent years. The absence of a rotational mass in these microgrids and their interfaces leads to a lack of inertia and consequently, frequency and voltage instability. To cope with these dilemmas, the virtual synchronous generator (VSG) has been introduced as an effective solution. This paper first focuses on modeling a VSG using basic electrical equations. It, then, proffers a transient fuzzy controller augmented on virtual inertia's topology. Inspired by the FACTS' performance, the privileged specifications such as STATCOM fluctuation damping ability for major perturbations at transient times are appended to the VSG scheme by a fuzzy controller. This controller is implemented with a difference in voltage angle and its derivative, as well as in frequency and its derivative. The modified coefficients of both active and reactive powers are outputs of the fuzzy system. Using the proposed fuzzy controller, the transient response of VSG-based microgrids is improved. Simplicity and ability to improve the transient response are the principal specifications of the proposed configuration. Simulation results confirm the improvement of the presented method by the introduced augmented VSG control mechanism.

Article Info

Keywords:
FACTS, Fuzzy Controller, Microgrids, Transient Performance Improvement, Virtual Inertia, Virtual Synchronous Generator (VSG).

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I. Introduction

Cost-effective and eco-friendly aspects of renewable energy sources (RESs) have motivated the growing rate of their use in recent years. The RESs usually use inverters to connect to a grid. Certainly, to avoid the micro-grid instability, the phase and frequency output of inverters must be synchronized with the phase and frequency of grids. It means that the inverters of RESs are usually controlled via a specified device such as a phase-locked loop (PLL). If a drastic disturbance occurs in a micro-grid, then the PLL may slack the latched position. At this moment, owing to excess voltage/current of dc/ac and power deficiency, the inverters may cease the operation. Due to the lack of rotational mass in RESs and their converters/inverters, microgrids are encountered with a lack of inertia. Thus, the concept of virtual synchronous generator (VSG) is proposed as a control solution, which a llows an inverter to mimic the behavior of a synchronous generator, containing the inertia specifications and droop structure[1]. In other words, pursuant to the magnitude of a grid frequency and voltage, the VSG can change its active and reactive power respectively to protect the grid. Simultaneously, VSG imitates the inertial specifications as well as aids to increase transient frequency stability using the increment of total grid's inertia. VSGs can work in both grid-connected and standalone modes. Various schemes and technical reviews of VSGs and their control algorithms have been studied in[2–13]. The main structures of VSGs are introduced in [2–4]. Due to the decentralized specifications of microgrids, it is preferred to

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use the communication-less methods in microgrids and their control strategies. One of the most effective and successful basic control methods in microgrids is droop control. VSGs are controlled by using both virtual inertia and droop control-based loops. Since the VSG structure is based on software, the selection of VSG parameters such as droop and inertial coefficients can be freely compared to SG parameters, and this has restricted choices due to physical limitations. Thus, favorable performance in case of VSGs can be achieved. Due to some equivalencies between droop control and VSGs, the parameters layout procedures of droop control give a deep insight into VSG parameters selection lately. The VSG parameters layout has been considered in some papers [8], [10], [14], [15]. In order for parameter designing and system analysis, power loop with droop control was investigated using an analysis of a closed-loop characteristic equation in [16–18]. The design and parameters control of both active and reactive power loops are much harder due to the close correlation of two aforementioned loops. By exerting the improved droop and VSG, active and reactive power sharing between various distributed generators in an isolated microgrid is conceivable [7], [19]. A detailed evaluation to analyze inertial function for a power electronics based DG is proposed such that selected the inertial features of virtual synchronous generator (VSG) which employed practical limitations of energy storage unit [20]. Although a simultaneous control strategy for inertial support between the inertial loop and energy storage power injection, but there is no any large signal analysis or verification such as islanding ride through. Authors in [9] aimed to investigate the frequency performance of multiple DG units in both grid-connected and islanded mode while considers inertia interaction. A detailed transfer function based model of paralleled inverters with emulated inertia has been proposed for theoretical analysis. Then, the frequency response is studied under several cases, which shows the interactive frequency performance of power electronics based DGs. Furthermore, inertia interaction among different inverters is analyzed in detail, which indicates the reaction from grid to inverter, however, there is still coupling issues among multi DG units in modelling. In order to improve the inertial response, a simple control strategy based on bang-bang control mechanism is proposed in [21], however, the authors merely study the performance for the frequency model, not the MG system. The concept of virtual inertia is implemented for a charging station with a set of electric vehicles. Analogy between the electric vehicles and energy storage systems makes a feasible solution for inertial improvement, however, complexity burdens are a main challenge in [22]. An adaptive Neuro-Fuzzy inference System (ANFIS) based inertial response improvement has been proposed for frequency model of a MG in [23]. In other word an ANFIS controller is mounted on the Double-Fed Induction Generator (DFIG), which contains a rotating-mass-based virtual inertia to support a frequency control as secondary control.

To better investigate the influences of parameters uncertainty on the active power and frequency for a VSG, the small signal model of an MG is derived and the dynamic performances are analyze in [24]. Then, an adaptive control strategy is proposed, which by introducing new indices, the optimal damping ratio is maintained throughout the whole process of operation to suppress the oscillation of power and frequency. A modified droop which is the result of interpreted droop curves and changed droop coefficient is introduced in [25].

In [26], a linear and desired model of a VSG is equipped with an algorithm to modify small perturbation and voltage quality improvement of transient response in the microgrid. Categories of frequency, voltage, and active/reactive power flow are investigated by an almost comprehensive solution [27]. A few papers have compared the existing VSG algorithms [15], [28]. Considering the plainness of both implementation and treatment of the converter with balanced AC voltages, the discrepancy among the implementation of two high-order synchronous generator patterns is studied in [28]. Virtual inertia injection as the specification of VSG is studied in [5], [11], [29]. It seems that both frequency and voltage reactions for load disturbances are improved by a delayed droop controller. For major perturbations such as nonlinear load switching and temporary faults, the existence of constant inertia may not suffice. Thus, adaptive virtual inertia procedures have recently been taken into consideration [5], [11], [29–33]. According to changing droop gain as a function of frequency and rate of frequency variation, the improved virtual inertia manner is discussed in [29], [30]. Since the controller efficiency can be affected by acute disturbances, so in the design discussion, over/under deflections of frequency should be considered. Although the mentioned references provide a suitable solution to improve frequency response in the presence of disturbances, over/under deflections of frequency are not considered. This restriction does not exist in [11] although there is no frequency derivative section in the mentioned schemes. In addition, within acute disturbances, the controller performance is reduced by estimated binary inertia. To solve this problem, some researchers have used adaptive inertia [31–33]. In [31], both constant and changing inertia are added together as adaptive virtual inertia based on frequency variations. Based on the rate of change of frequency (RoCoF), a self-adaptive inertia procedure is introduced in [33]. It is necessary to note that the methods used in [5], [11] and [22–26] are merely concentrated on the modification of transient frequency response; and voltage response subjects are not discussed. The modified droop control based on the rate of variations of both active and reactive powers was introduced in [34]. When a small perturbation or lower load change happens, it may not be possible to detect small rates of frequency and voltage signals. The VSG control concept is presented as a solution in [35].

The use of flexible AC transmission systems (FACTs) in electric systems is increasing day by day owing to the special application of some FACTs equipment to enhance the efficiency and stability of systems as an effective technology. Power fluctuation damping [36], analysis and cancelation of harmonics [37], voltage sag mitigation [38], and flexible control characteristic to control wind farms [39] are some attractive aspects of STATCOM. Compensation for reactive power and unbalanced load, and power quality improvement in the distribution systems are known as features of the D-STATCOM [40], [41]. In [42], a VSM is applied to STATCOMs to improve the active and reactive power flow. The control design of VSM based-STATCOM for microgrids is studied in [43]. The use of functions of the FACTs on inverters as a virtual function has been less studied in the inverter-based microgrids [44]. Recently, the use of fuzzy methods in the VSG category has appeared in some papers [45–47].

This paper presents the concept of virtual inertia to improve the frequency response especially at transient states in MGs via VSG equipped with a fuzzy controller. This idea is inspired by one of the duties of FACTs as a virtual inertia function. In other words, the outputs of the fuzzy controller modify both the outputs of swing equation and droop blocks as an appropriate virtual inertia function. Thus, the provided signal for PWM is pure. As a result, the frequency response is improved. Several studies based on optimization methods have introduced the frequency control in microgrids. In [25], based on minimization of the errors in the current and voltage controllers, the parameters of the microgrid controller in islanding mode are optimized by using the particle swarm optimization (PSO). In [5], [21], [24], [25], [31], [33], [46], [48], the optimization methods are applied on both inertia and damping coefficients J and D. At any given time, the objective function is minimized and a better answer is obtained through a wider search space, which means spending more time. Therefore, the transient frequency response in these methods is not fast enough. In addition, in all optimization-based methods, the controller design parameters change. Therefore, by changing the structure of the system, the controller design parameters must also be changed and their changes are problematic. It should be noted that the controller design parameters are weights of the cost function elements. Hence, to achieve the optimal answer, there is usually a trade-off between these weights, which in some modes leads to high or low sensitivity to one of the controller design parameters. So, it can be said that in these optimization methods, the controller has a lot of dependency on the design parameters.

But in the fuzzy method, there are no such challenges. In other words, in the fuzzy method the control signal changes to improve the inertia response. The input signal is changed online and the method is based on data. Therefore, there is no optimization and with system change, there is no challenge to change the controller parameters. The non-linearity of the system, the adoption of the control strategy, simplicity in designing, being quick in tracking dynamics and the rest of the process lead to the use of a fuzzy controller. In fact, a suitable controller that can match the mentioned conditions is a fuzzy controller. Unlike some researches [7], [12], [20], [22] the fuzzy control does not require system linearization around the stabilized equilibrium points. Usually, some of the system dynamics disappears in the linearization. It is also free from the system model. Furthermore, the fuzzy control synthesis method is much simpler than other robust model-based methods. Moreover, the fuzzy controller works online on the specified data (fuzzy input system signals), with a series of fuzzy rules based on the designer's knowledge of the system. If the knowledge of the system behavior is correct and fuzzy rules are applied properly, it can be said that the system has the characteristics of robustness, adaptiveness and flexibility. A difference in voltage angle and frequency with their derivatives are used by the fuzzy controller to amend the frequency response. The validity of the performance of the model presented in this paper is confirmed by applying the proposed model to the case study available in[7]. Using a mentioned control strategy, the transient frequency response of [7] is improved.

The paper has been organized as follows. Section 2 briefly expresses the VSG concept via a simple schematic. Modeling the MIMO nonlinear VSG system by swing and some basic electric equations is performed in Section 3. The validation model efficiency is corroborated by using this model on a determined case study. In Section 4, the concept of transient stability improvement by phase angle regulators is briefly expressed. This concept applies to a VSG-based microgrid via a fuzzy controller as an enhanced VSG. The fuzzy controller is designed in Section 5. Simulation results are presented in Section 6 to confirm the given idea in Section 5 and fuzzy controller performance. Eventually, the paper is concluded in Section 7.

II. PRINCIPLE OF VSG

Any distributed energy resource such as photovoltaic panel, fuel cell, and gas engine, which called primary source, have an inherent uncertainty and fluctuation in their output power, which is unavoidable. Thus, in the absence of a rotating mass in DGs, the existence of energy storage is obligatory to attract or offer excess /deficiency mentioned fluctuation, especially in transient state. The structure and control scheme of a classic VSG [10]–[12] is illustrated in Fig. 1. The iterative procedure is applied to the swing Eq. (1) to yield ω_m is obtained. The swing equation block as the heart of VSG has three inputs and one output. Grid frequency, grid active power and governor output active power constitute inputs and phase of target voltage is output. The PWM target voltage is composed of magnitude and phase of target voltage.

$$P_{in} - P_{out} = J\omega_m \frac{d}{dt}\omega_m + D(\omega_m - \omega_g) \quad (1)$$

Fig. 1(b) is a subsequent version of the past basic VSG control structure, which was equipped with two considerable modifications. The bus voltage estimator and the stator reactance adjuster are shown in Figs. 1(c) and 1(d), respectively. The stator reactance adjuster, which was achieved by adjusting virtual stator inductor l_{1s} (2), plays the role of virtual impedance and tunes the output reactance of the DG independently. Sharing the transient load without fluctuation and incrementing active power damping ratio are the result of the above approach. As illustrated in Fig. 1(d), in a similar process with stator reactance adjuster, the bus voltage estimator is expressed. First, by line impedance data and measured output current, the voltage drop is calculated in a stagnant frame. The bus voltage is approximated by the difference of the output voltage and the calculated line voltage drop. As considered in [3], to illuminate the explication for the cases with different power ratings, per unit values are considered based on respective power ratings of DGs.

$$X_i = \frac{S_{base\,i}\,\omega_{mi}(L_{1si} + L_{fi} + L_{linei})}{E_0^2} = 0.7\,PU \quad (2)$$

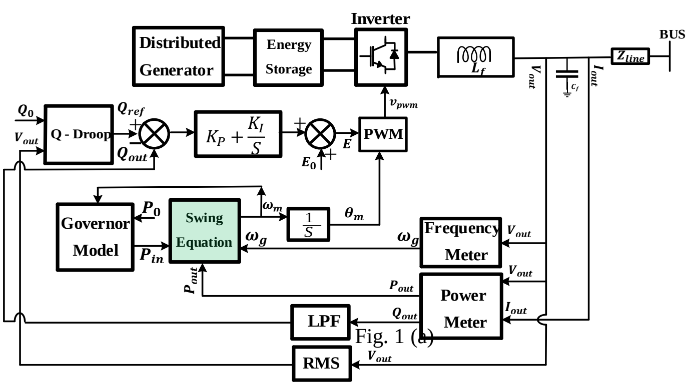

Fig. 1 (a)

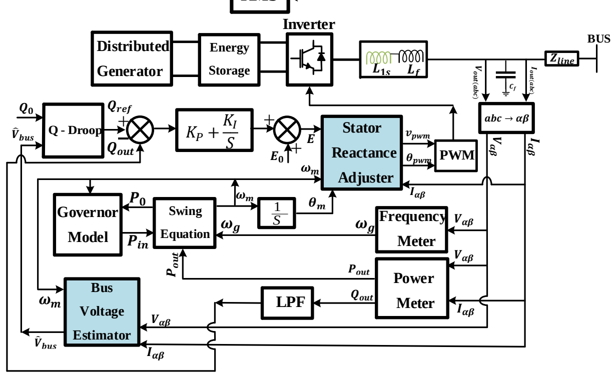

Fig. 1 (b)

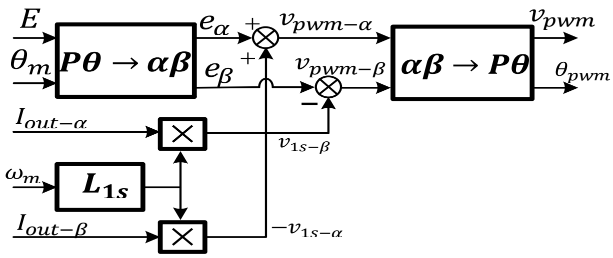

Fig. 1 (c)

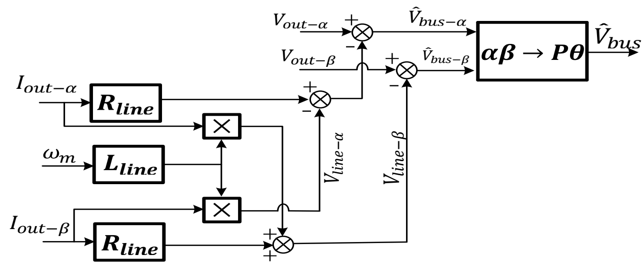

Fig. 1 (d)

Fig. 1. Block diagrams of (a) the basic VSG control, (b) the enhanced VSG, (c) the "Governor Model" block, and (d) the "*Q* Droop" block.

III. MODELING OF VSG

A. Nonlinear Modeling of VSG

The VSG model and the rest of the microgrid are illustrated in Fig. 2. Eq. (3)-(9) are related to the swing equation, active and reactive power relations and PI voltage controller, respectively. This paper introduces another model of VSG that has three inputs and three outputs. Then, an interesting model of nonlinear VSG is derived from Eq. (3)-(9). As illustrated in Eq. (3)-(9), many triangular, square and product functions increase the nonlinearity degree of this VSG model. The parameters for Eq. (3)-(9) are presented as follows: ω_r is an angular frequency of a virtual rotor (inverter frequency); $\omega_\circ$ is a nominal frequency; δ is an angle difference in VSG and equivalent Thevenin voltages; $\delta_\circ$ is an initial amount of delta; J is the virtual inertia of VSG; K_D is the virtual damping factor of VSG; P_m is the virtual mechanical power of VSG; P_e is the electrical power of VSG; ω_g is the microgrid frequency; Y_{th} is the equivalent Thevenin admittance of the rest of the microgrid; V is the output voltage of VSG; E_{th} is the equivalent Thevenin voltage of the rest of the microgrid; φ_{th} is the angle of equivalent Thevenin impedance; K_P is the proportional gain of the voltage controller; K_I is the integral gain of the voltage controller; Q_r is the reactive power reference of VSG; and Q_e is the reactive power of VSG.

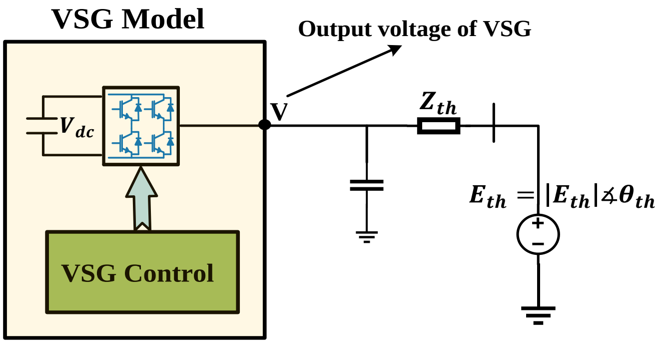

Fig. 2. The VSG model and the rest of the microgrid

$$\delta = \omega_r t - \omega_0 + \delta_0 \tag{3}$$

$$\frac{d\delta}{dt} = \omega_r - \omega_0 \tag{4}$$

$$J\omega_r \frac{d\omega_r}{dt} = P_m - P_e - K_D(\omega_r - \omega_g) \tag{5}$$

$$P_e = Y_{th}(V^2 \cos\varphi_{th} - VE_{th}\cos(\delta + \varphi_{th})) \tag{6}$$

$$Q_e = Y_{th}(V^2 \sin\varphi_{th} - VE_{th}\sin(\delta + \varphi_{th})) \tag{7}$$

$$V = (K_P + \frac{K_I}{S})(Q_r - Q_e) \tag{8}$$

$$\begin{aligned}\dot{V} &= K_P\dot{Q}_r - K_P\dot{Q}_e + K_I(Q_r - Q_e) \\ &\xrightarrow{\dot{Q}_r = 0} -K_P\dot{Q}_e + K_I(Q_r - Q_e)\end{aligned} \tag{9}$$

B. Nonlinear VSG Schematic in Mentioned Case Study

The proposed nonlinear VSG is a MIMO model, which has three inputs and three outputs as shown in Fig. 3. The nonlinear VSG inputs are both output active power from a governor and reactive power from a Q-droop block and grid frequency. The magnitude and phase of voltage and mechanical frequency are outputs. Compared with the swing equation-based VSG, instead of the grid active power, the grid reactive power is applied as a new model VSG input. The output mechanical frequency ω_m is taken as the input for the governor block.

IV. ENHANCED NONLINEAR VSG

In order to improve the nonlinear VSG performance, the concepts presented in subsections A, B, C are used.

A. Transient Stability Improvement by Phase Angle Regulators

In order to neutralize the accelerating and decelerating oscillations in the damaged machine(s), power fluctuation damping is needed. It is attained by altering the active power circulation in the line(s) [39], [49]. When the oscillating generator accelerates, and the rate of angle δ increases ($\frac{d\delta}{dt} > 0$), the transmitted electric power must be increased to compensate for the surplus mechanical input power and vice versa. The necessities of power fluctuation damping by transmission angle control are demonstrated in Fig. 4. The undamped and damped fluctuation of both angle δ and electric power P around the steady-state values δ_0 and P_0 are illustrated in Figs. 4(a) and 4(b), respectively. Fig. 4(b) demonstrates the instantaneous drop in active power, which indicates supposed perturbation initiated the fluctuation.

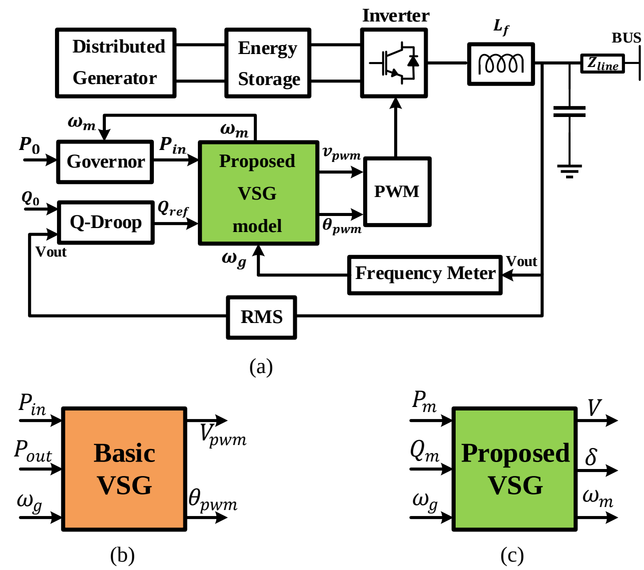

Fig. 3. Block diagrams of (a) the proposed VSG control, (b) the basic VSG model, and (c) the proposed VSG model

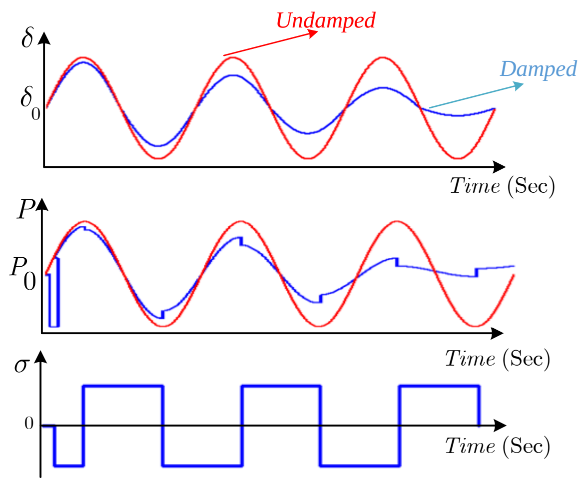

Fig. 4 Waveforms illustrating power oscillation damping by phase angle control: (a) generator angle, (b) transmitted power, and (c) phase shift provided by the Phase Angle Regulator [49].

B. Power Oscillation Damping by Reactive Power Injection

Damping of active power fluctuation by reactive power injection is shown in Fig. 5 [49], the "Bang–Bang" method controls the reactive power output (output value of the controller is changed among minimum and maximum values). This manner of control is commonly considered as the superlative efficient and simplest method, especially if major fluctuations occur. However, for damping relatively small power oscillations, a strategy that varies the controlled output of the compensator continuously, in commiseration with the generator angle or power, may be preferred.

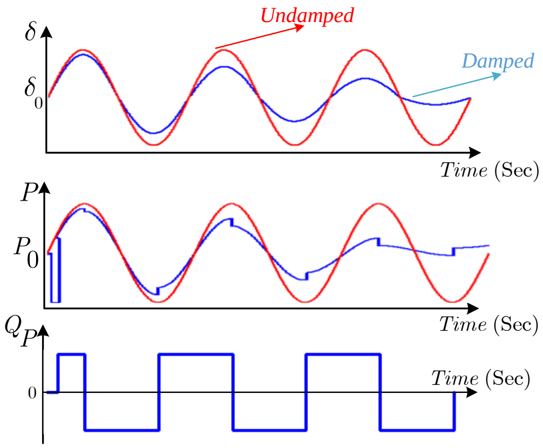

Fig. 5 Waveforms illustrating power oscillation damping by reactive shunt compensation: (a) generator angle, (b) transmitted.

C. Applying to VSG-Based Microgrids

As already mentioned, by using angle variations of δ a fuzzy controller can be proposed that is used in transient times, especially when the angle of δ exceeds its extents. For this purpose, the proposed VSG scheme is considered. To provide the inputs of fuzzy controller, it is necessary to add an angle variation detector block to the proposed VSG diagram as illustrated in Fig. 6. Indeed in the mentioned block, δ is obtained by using two PLLs. The steady state low variation of δ is filtered by a dead-bound block. The microgrid is always posed to many challenges. In this paper, challenges are islanding, load variations, and lack of power generation. Especially in transient times when large-scale variation happens, fuzzy controller satisfies the mentioned challenges by active and reactive power injections as shown in Fig. 7.

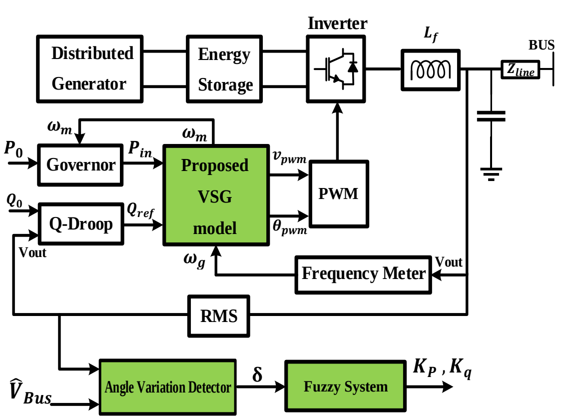

Fig. 6. Block diagram of the proposed VSG control configuration with angle variation detection.

V. Fuzzy Logic Controller Implementation

The fuzzy controller is implemented with four inputs and two outputs as shown in Fig. 7. In other words, the difference in voltage angle δ and its derivative, frequency and its derivative are inputs and modified coefficients of both active and reactive powers $K_{p-fuzzy}$, $K_{q-fuzzy}$ as the outputs of the fuzzy system are adjusted by the suggested fuzzy controller. Table I shows the proposed fuzzy rules to acquire $K_{p-fuzzy}$, $K_{q-fuzzy}$. The characteristics of input/output membership functions (MFs) such as type of MFs and training data ranges are presented in Table II.

Fig. 7 shows that the fuzzy inference system comprises the rules as determined in Table I that are used for planning the input and output functions. Proper selection of fuzzy rules has a great influence on the performance of the fuzzy controller and consequently plays an important role in modifying the transient state of frequency. As already mentioned, suitable performance is achieved by studying the behavior of the inputs. Thus, according to the specifications of the inputs within events or disturbances, the fuzzy rules are logically expanded as illustrated in Fig. 8. A significantly variated zone of responses can be divided into four sectors so that the quantity in each sector is perhaps PQ (positive quantity, implies upper perversion), ZE (zero, implies usual quantity), NQ (negative quantity, implies less perversion). As already noted, to improve the transient frequency response, rules are implemented so that in zones 1 and 3, in which the frequency response is perverting away from the nominal value (such as massive load changes, islanding and when a fault happen), a large amount of both active and reactive powers are injected through the K_P and K_q coefficients, respectively. Also in zones 2 and 4, in which the frequency response is perverting towards the nominal value, a low amount of active and reactive power are injected through the K_P and K_Q coefficients, respectively as illustrated in Table I. As shown in Fig. 9, the frequency and its derivative with delta and its derivative have 180 degrees of phase difference. For simplicity and avoidance of complexity, the number of fuzzy rules is low. By using the Fig. 9 the appropriate logic is obtained to determine the fuzzy rules. For example as shown in Table I, when the frequency and its derivative are PQ as well as delta and its derivative are NQ, this means that they are in zone 1 and zone 3 respectively. In other words, the frequency and its derivative are perverting away from the nominal values. It is the same way for delta. Therefore, the output of the fuzzy system will be such that it will confront with deviation from their nominal values. Given the knowledge of the variation in the fuzzy system inputs, the range of fuzzy input membership functions is determined.

Fig. 9 shows the behavior of the inputs and outputs in the absence of the fuzzy controller. Based on the amplitude of inputs and their derivative, the total ranges of inputs are determined. Also, according to the behavior of the inputs, fuzzy rules are specified.

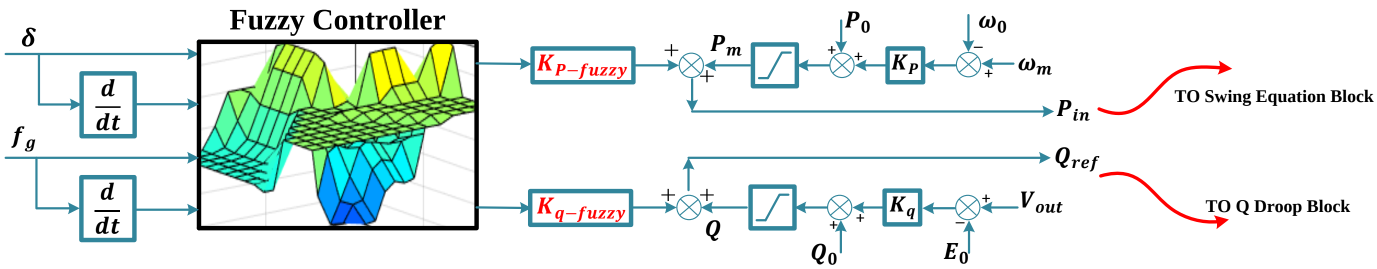

Fig. 7. The proposed fuzzy logic controller based on angle variation detection.

TABLE I.

FUZZY RULES TO ACQUIRE $K_{p-fuzzy}$, $K_{q-fuzzy}$

	$\overrightarrow{\delta}$	NQ	NQ	ZQ	PQ	PQ
	$\overrightarrow{\frac{d}{dt}\delta}$	NQ	ZQ	ZQ	NQ	PQ
PQ	PQ	NQ	ZE			
NQ	NQ					PQ
NQ	PQ				ZE	
ZQ	ZQ			ZE		
$f\uparrow$	$\frac{d}{dt}f\uparrow$					

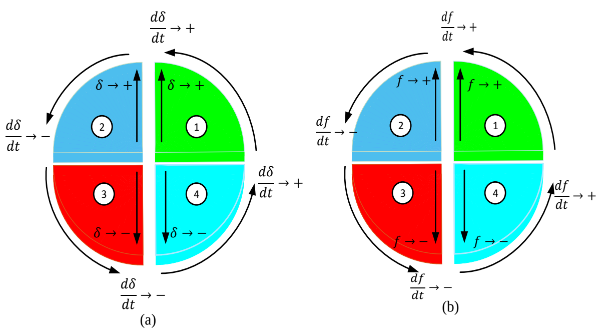

Fig. 8. Specification of (a) delta, and (b) frequency under a perturbation

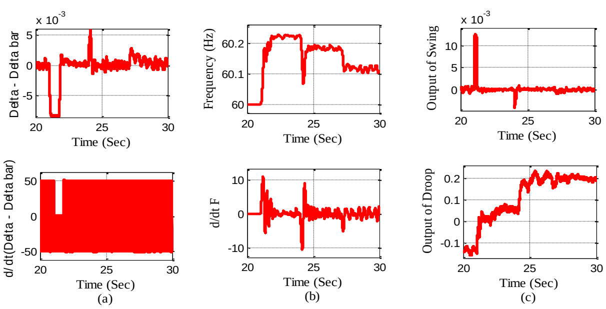

Fig. 9. The behavior of the inputs and the outputs in the absence of fuzzy controller. Left column: δ and its derivative, middle column: f and its derivative, right column: output signals.

VI. Simulation Results

In order to confirm the effectiveness of the proposed VSG control scheme, simulations are performed in MATLAB. The characteristics of the proposed VSG model and nominal parameters are listed in Table III.

TABLE II.

EXPANDED FUZZY RULES BY TRAINING DATA

Membership Function		Range		Units
Fuzzy Inputs	Variation of delta angle	NQ	nan – (-0.0084) – (-0.006)	rad
		ZE	(-0.006) - (0.00227) - (0.00582)	
		PQ	(0.00227) - (0.00582) - (nan)	
	Rate of delta angle variation	NQ	(-50.68) - (-25.27) - (0.135)	$\frac{rad}{s}$
		ZE	(-25.27) - (0.135) - (25.54)	
		PQ	(0.135) - (25.54) - (50.95)	
	Variation of frequency	NQ	(59.9) – (59.99) – (60.04)	Hz
		ZE	(60.03) – (60.08) – (60.13)	
		PQ	(60.12) – (60.26) – (60.35)	
	Rate of frequency variation	NQ	(nan) - (-10.59) - (-5.168)	$\frac{Hz}{s}$
		ZE	(-5.253) – (0.173) – (5.599)	
		PQ	(5.572) – (11 16.43) - (nan)	
Fuzzy Outputs	K_p Coefficient	NQ	(nan)-(-0.004278)- (-7.778e-05)	—
		ZE	(-0.0001) – (0.0041) – (0.0083)	
		PQ	(0.008189) – (0.01239) – (nan)	
	K_q Coefficient	NQ	(nan) – (-0.1563) – (-0.05801)	—
		ZE	(-0.0596) – (0.03875) – (0.137)	
		PQ	(0.1366) – (0.2349) – (nan)	

Fig. 10 shows the studied microgrid [7]. As illustrated in Fig. 10, an islanded microgrid containing two DGs using the proposed VSG control is investigated. In order to supply the loads inward the microgrid, two DGs are linked to a common ac bus through distribution lines. The rest of the basic parameters are specified in Fig. 10 and Table III. A set of events in the microgrid simulation [7] is demonstrated in Table IV. In Table IV, occurrences of disconnecting from the grid, loading transmission, and purposeful active power sharing alteration are simulated at 21 s, 24 s, and 27 s, respectively. Figs. 11 to 16 display the simulation outcomes. Note that in all cases, the frequency and active power of the DG1 are investigated. To verify the effectiveness of the proposed VSG system, VSG performance is compared with the basic VSG scheme [7] in the presence of mentioned scenarios. Fig. 11 shows the microgrid frequency related to the proposed and basic VSG schemes. As Fig. 11 shows, the proposed VSG performance is fully similar to the basic VSG performance. In Fig. 12, the fuzzy controller performance is illustrated. The system frequency is improved significantly in the presence of a fuzzy controller, especially in the moments of scenarios. However, fluctuation can be seen in frequency. This fluctuation is nearly omitted by using suggested fuzzy VSG control demonstrated in Fig. 7. The frequency variation rate in the presence of a fuzzy system is less than the non-fuzzy system. Especially in transient time, fluctuations in power angle and frequency can be detected. A proper and timely active and reactive power is injected to their reference values K_p and K_q factors as a virtual FACTs function via fuzzy controller by the detection of fluctuations. As a result, the above-mentioned improvements are achieved. Since the perturbation at 27 s is affected by active power alteration of DG1, this improvement is also true for active power, as shown in Fig. 14. Finally, in Figs. 15 and 16, the comparison of the frequency and active power between the main VSG and the proposed VSG equipped with and without the fuzzy controller is performed, respectively.

TABLE III

CHARACTERISTICS OF THE PROPOSED VSG MODEL

Symbol	value	Symbol	value
E_{th}	195	Y_{th}	4.47
J	0.56	δ_0	0.04
K_I	20	V_0	200
K_P	1	Q_{r0}	1500
φ	1.95	ω_0	120π

TABLE IV.

SIMULATION SEQUENCE

Time	Grid	P_{O1}	P_{O2}	Load
$t < 21\,s$	Connected	1 pu	1 pu	Load1
$21 \le t < 24\,s$	Islanded	——	——	——
$24 \le t < 27\,s$	——	——	——	Load1 + Load 2
$27 \le t < 30\,s$	——	——	0.6 pu	——

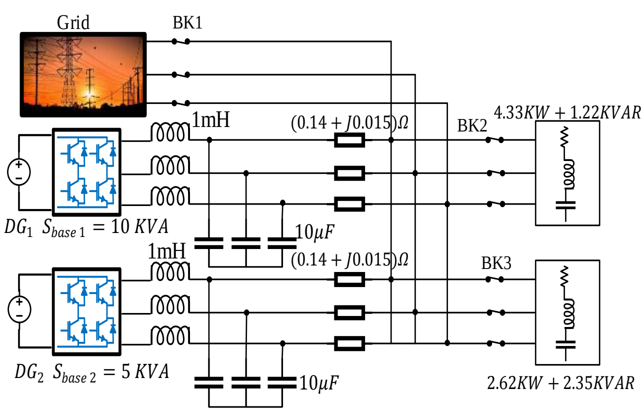

Fig.10. The microgrid case study

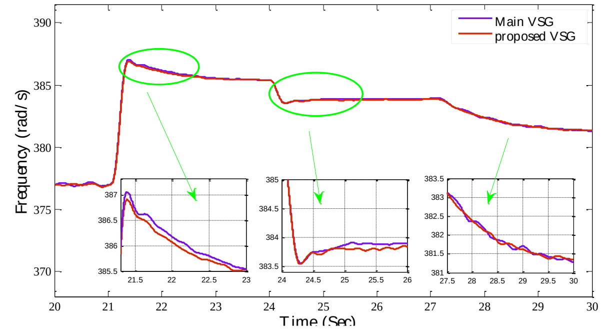

Fig. 11. Simulation results of frequency for the main and proposed VSGs

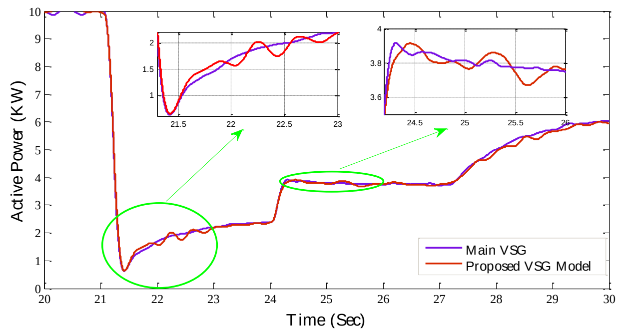

Fig. 12. Simulation results of DG1 active power for the main and proposed VSGs

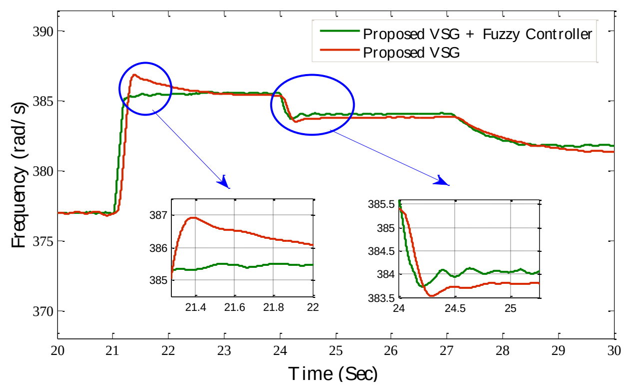

Fig. 13. The frequency response of the proposed VSG and VSG+fuzzy schemes

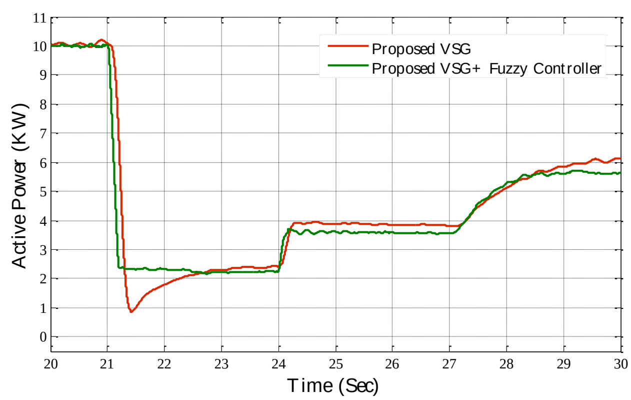

Fig. 14. DG1 active power for the proposed VSG and VSG+fuzzy schemes

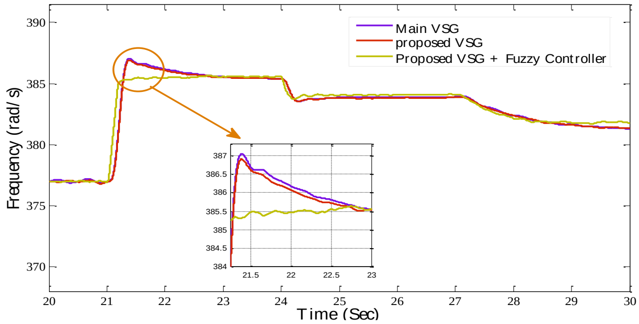

Fig. 15. The frequency response of the basic, and proposed VSG and VSG+fuzzy schemes

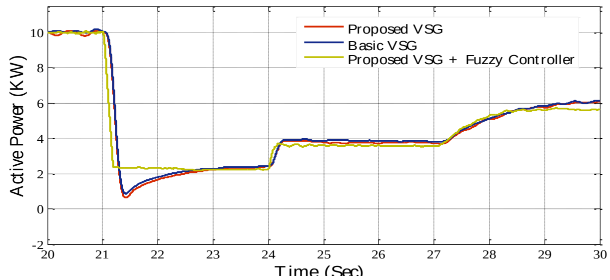

Fig. 16. DG1 active power for the basic, and proposed VSG and VSG+fuzzy schemes

VII. CONCLUSION

In this paper, based on the electrical swing equation, a nonlinear model of VSG is proposed. By applying this model to a specified case study, the validity of the proposed model performance is confirmed. Inspired by FACTs duty, the proposed VSG is equipped with a control loop, which has the tunable "virtual" parameters related to the FACTs functions by the fuzzy controller in order to obtain the transient performance improvement and many flexibility advantages. The non-linearity of the system, the adoption of the control strategy, simplicity in designing, being quick in tracking dynamics lead to the use of a fuzzy controller. In fact, a suitable controller that can match the mentioned conditions is a fuzzy controller. The fuzzy control does not require system linearization around the stabilized equilibrium points. Usually, some of the system dynamics disappears in the linearization. It is also free from the system model. Furthermore, the fuzzy control synthesis method is much simpler than other robust model-based methods. The frequency overshoot and frequency nadir are the main criteria for frequency evaluation. By comparing the proposed VSG with and without a mentioned control strategy, it was shown that the frequency overshoot and frequency nadir in presence of control strategy are less than the absence of mentioned control strategy. In islanding operation, load variations and lack of power generation scenarios, the proposed VSG performance is investigated in both cases of absence and presence of the fuzzy controller. The simulation results indicate that the proposed fuzzy controller on the considered VSG contributes to obtaining favorable performance in transient states and to some extent in steady states compared to the absence of the fuzzy controller. According to the mentioned contents, the proposed VSG with the suggested fuzzy controller is a preferable selection for the improvement of transient frequency in microgrids.

REFERENCES

[1] H. Bevrani and T. Ise, *Microgrid dynamics and control*. John Wiley & Sons, 2017.

[2] H. Bevrani, T. Ise, and Y. Miura, "Virtual synchronous generators: A survey and new perspectives," *Int. J. Electr. Power Energy Syst.*, vol. 54, pp. 244–254, 2014.

[3] M. S. Haritha and D. S. Nair, "Review on virtual synchronous generator (VSG) for enhancing performance of microgrid," *EPSCICON 2018 - 4th Int. Conf. Power, Signals, Control Comput.*, pp. 1–5, 2018.

[4] S. D'Arco and J. A. Suul, "Virtual synchronous machines—Classification of implementations and analysis of equivalence to droop controllers for microgrids," in *PowerTech (POWERTECH), 2013 IEEE Grenoble*, 2013, pp. 1–7.

[5] M. A. Torres L, L. A. C. Lopes, L. A. Moran T, and J. R. Espinoza C, "Self-tuning virtual synchronous machine: a control strategy for energy storage systems to support dynamic frequency control," *IEEE Trans. Energy Convers.*, vol. 29, pp. 833–840, 2014.

[6] Y. Cao *et al.*, "A Virtual Synchronous Generator Control Strategy for VSC-MTDC Systems," *IEEE Trans. Energy Convers.*, vol. 33, no. 2, pp. 750–761, 2018.

[7] J. Liu, Y. Miura, H. Bevrani, and T. Ise, "Enhanced virtual synchronous generator control for parallel inverters in microgrids," *IEEE Trans. Smart Grid*, vol. 8, pp. 2268–2277, 2016.

[8] C. Yuan, C. Liu, X. Zhang, T. Zhao, X. Xiao, and N. Tang, "Comparison of Dynamic Characteristics between Virtual Synchronous Machines Adopting Different Active Power Droop Controls," *J. Power Electron.*, vol. 17, no. 3, pp. 766–776, 2017.

[9] Z. Wang, F. Zhuo, H. Yi, J. Wu, F. Wang, and Z. Zeng, "Analysis of Dynamic Frequency Performance among Voltage-controlled Inverters Considering Virtual Inertia Interaction in Microgrid," *IEEE Trans. Ind. Appl.*, vol. PP, no. c, pp. 1–1, 2019.

[10] J. Liu, Y. Miura, and T. Ise, "Comparison of dynamic characteristics between virtual synchronous generator and droop control in inverter-based distributed generators," *IEEE Trans. Power Electron*, vol. 31, no. 5, pp. 3600–3611, 2016.

[11] J. Alipoor, Y. Miura, and T. Ise, "Power system stabilization using virtual synchronous generator with alternating moment of inertia," *IEEE J. Emerg. Sel. Top.*

Power Electron., vol. 3, no. 2, pp. 451–458, 2015.

[12] T. Shintai, Y. Miura, and T. Ise, "Oscillation damping of a distributed generator using a virtual synchronous generator," *IEEE Trans. power Deliv.*, vol. 29, no. 2, pp. 668–676, 2014.

[13] Y. Chen, R. Hesse, D. Turschner, and H.-P. Beck, "Dynamic properties of the virtual synchronous machine (VISMA)," *Proc. ICREPQ*, vol. 11, 2011.

[14] H. Wu *et al.*, "Small-signal modeling and parameters design for virtual synchronous generators," *IEEE Trans. Ind. Electron.*, vol. 63, no. 7, pp. 4292–4303, 2016.

[15] S. D'Arco and J. A. Suul, "Equivalence of virtual synchronous machines and frequency-droops for converter-based microgrids," *IEEE Trans. Smart Grid*, vol. 5, no. 1, pp. 394–395, 2014.

[16] J. M. Guerrero, L. G. De Vicuna, J. Matas, M. Castilla, and J. Miret, "A wireless controller to enhance dynamic performance of parallel inverters in distributed generation systems," *IEEE Trans. power Electron.*, vol. 19, no. 5, pp. 1205–1213, 2004.

[17] J. M. Guerrero, N. Berbel, J. Matas, J. L. Sosa, J. Cruz, and A. Alentorn, "Decentralized control for parallel operation of distributed generation inverters using resistive output impedance," in *Power Electronics and Applications, 2005 European Conference on*, 2005, pp. 10-pp.

[18] E. A. A. Coelho, P. C. Cortizo, and P. F. D. Garcia, "Small signal stability for single phase inverter connected to stiff AC system," in *Industry Applications Conference, 1999. Thirty-Fourth IAS Annual Meeting. Conference Record of the 1999 IEEE*, 1999, vol. 4, pp. 2180–2187.

[19] S. A. Khajehoddin, M. K. Ghartemani, and M. Ebrahimi, "Grid-Supporting Inverters with Improved Dynamics Using Enhanced Virtual Synchronous Machine (eVSM)," *IEEE Trans. Ind. Electron.*, 2018.

[20] K. Shi, H. Ye, W. Song, and G. Zhou, "Virtual Inertia Control Strategy in Microgrid Based on Virtual Synchronous Generator Technology," *IEEE Access*, vol. 6, no. c, pp. 27949–27957, 2018.

[21] J. Li, B. Wen, and H. Wang, "Adaptive virtual inertia control strategy of VSG for micro-grid based on improved bang-bang control strategy," *IEEE Access*, vol. 7, pp. 39509–39514, 2019.

[22] K. Dhingra and M. Singh, "Frequency support in a micro-grid using virtual synchronous generator based charging station," *IET Renew. Power Gener.*, vol. 12, no. 9, pp. 1034–1044, 2018.

[23] A. Karimipouya and H. Abdi, "Microgrid frequency control using the virtual inertia and ANFIS-based Controller," vol. 2, no. 2, pp. 145–154, 2019.

[24] F. Wang, L. Zhang, X. Feng, and H. Guo, "An Adaptive Control Strategy for Virtual Synchronous Generator," *IEEE Trans. Ind. Appl.*, vol. 54, no. 5, pp. 5124–5133, 2018.

[25] P. S. Optimization, "Optimal Control of Islanded Micro grid Using Particle Swarm Optimization Algorithm," vol. 1, no. 1, pp. 53–60, 2018.

[26] Y. Chen, R. Hesse, D. Turschner, and H.-P. Beck, "Improving the grid power quality using virtual synchronous machines," in *Power engineering, energy and electrical drives (POWERENG), 2011 international conference on*, 2011, pp. 1–6.

[27] Y. Xiang-Zhen, S. Jian-hui, D. Ming, L. Jin-wei, and D. Yan, "Control strategy for virtual synchronous generator in microgrid," in *Electric Utility Deregulation and Restructuring and Power Technologies (DRPT), 2011 4th International Conference on*, 2011, pp. 1633–1637.

[28] Y. Chen, R. Hesse, D. Turschner, and H.-P. Beck, "Comparison of methods for implementing virtual synchronous machine on inverters," in *International Conference on Renewable Energies and Power Quality*, 2012, pp. 1–6.

[29] N. Soni, S. Doolla, and M. C. Chandorkar, "Improvement of transient response in microgrids using virtual inertia," *IEEE Trans. power Deliv.*, vol. 28, no. 3, pp. 1830–1838, 2013.

[30] D. K. Dheer, N. Soni, and S. Doolla, "Improvement of small signal stability margin and transient response in inverter-dominated microgrids," *Sustain. Energy, Grids Networks*, vol. 5, pp. 135–147, 2016.

[31] X. Hou, H. Han, C. Zhong, W. Yuan, M. Yi, and Y. Chen, "Improvement of transient stability in inverter-based AC microgrid via adaptive virtual inertia," in *Energy Conversion Congress and Exposition (ECCE), 2016 IEEE*, 2016, pp. 1–6.

[32] Z. Xiaobo, W. Kangda, and Z. Baohui, "An improved droop controller for eliminating control error in microgrid," in *Power and Energy Engineering Conference (APPEEC), 2016 IEEE PES Asia-Pacific*, 2016, pp. 1101–1105.

[33] D. Li, Q. Zhu, S. Lin, and X. Y. Bian, "A self-adaptive inertia and damping combination control of VSG to support frequency stability," *IEEE Trans. Energy Convers.*, vol. 32, no. 1, pp. 397–398, 2017.

[34] G. Yajuan, W. Weiyang, G. Xiaoqiang, and G. Herong, "An improved droop controller for grid-connected voltage source inverter in microgrid," in *Power Electronics for Distributed Generation Systems (PEDG), 2010 2nd IEEE International Symposium on*, 2010, pp. 823–828.

[35] J. Meng, Y. Wang, C. Fu, and H. Wang, "Adaptive virtual inertia control of distributed generator for dynamic frequency support in microgrid," in *Energy Conversion Congress and Exposition (ECCE), 2016 IEEE*, 2016, pp.

1–5.

[36] M. H. Haque, “Improvement of first swing stability limit by utilizing full benefit of shunt FACTS devices,” *IEEE Trans. power Syst.*, vol. 19, no. 4, pp. 1894–1902, 2004.

[37] S. Filizadeh and A. M. Gole, “Harmonic performance analysis of an OPWM-controlled STATCOM in network applications,” *IEEE Trans. power Deliv.*, vol. 20, no. 2, pp. 1001–1008, 2005.

[38] P. Wang, N. Jenkins, and M. H. J. Bollen, “Experimental investigation of voltage sag mitigation by an advanced static VAr compensator,” *IEEE Trans. Power Deliv.*, vol. 13, no. 4, pp. 1461–1467, 1998.

[39] B. Singh, R. Saha, A. Chandra, and K. Al-Haddad, “Static synchronous compensators (STATCOM): a review,” *IET Power Electron.*, vol. 2, no. 4, pp. 297–324, 2009.

[40] J. Shi, A. Noshadi, A. Kalam, and P. Shi, “Fuzzy logic control of DSTATCOM for improving power quality and dynamic performance,” in *Power Engineering Conference (AUPEC), 2015 Australasian Universities*, 2015, pp. 1–6.

[41] B. Singh and J. Solanki, “A comparison of control algorithms for DSTATCOM,” *IEEE Trans. Ind. Electron.*, vol. 56, no. 7, pp. 2738–2745, 2009.

[42] C. Li, R. Burgos, I. Cvetkovic, and D. Boroyevich, “Active and reactive power flow analysis of a STATCOM with virtual synchronous machine control,” in *Control and Modeling for Power Electronics (COMPEL), 2015 IEEE 16th Workshop on*, 2015, pp. 1–8.

[43] C. Li, R. Burgos, I. Cvetkovic, D. Boroyevich, L. Mili, and P. Rodriguez, “Evaluation and control design of virtual-synchronous-machine-based STATCOM for grids with high penetration of renewable energy,” in *Energy Conversion Congress and Exposition (ECCE), 2014 IEEE*, 2014, pp. 5652–5658.

[44] A. Karimi, Y. Khayat, M. Naderi, R. Mirzaee, and H. Bevrani, “Improving transient performance of VSG based microgrids by virtual FACTS’functions,” in *Smart Grid Conference (SGC), 2017*, 2017, pp. 1–6.

[45] C. Andalib-Bin-Karim, X. Liang, and H. Zhang, “Fuzzy-Secondary-Controller-Based Virtual Synchronous Generator Control Scheme for Interfacing Inverters of Renewable Distributed Generation in Microgrids,” *IEEE Trans. Ind. Appl.*, vol. 54, no. 2, pp. 1047–1061, 2018.

[46] Y. V. P. Kumar and R. Bhimasingu, “Fuzzy logic based adaptive virtual inertia in droop control operation of the microgrid for improved transient response,” in *Asia-Pacific Power and Energy Engineering Conference (APPEEC), 2017 IEEE PES*, 2017, pp. 1–6.

[47] Y. Hu, W. Wei, Y. Peng, and J. Lei, “Fuzzy virtual inertia control for virtual synchronous generator,” in *Control Conference (CCC), 2016 35th Chinese*, 2016, pp. 8523–8527.

[48] B. Rathore, S. Chakrabarti, and S. Anand, “Frequency response improvement in microgrid using optimized VSG control,” in *Power Systems Conference (NPSC), 2016 National*, 2016, pp. 1–6.

[49] N. G. Hingorani and L. Gyugyi, *Understanding FACTS : concepts and technology of flexible AC transmission systems*. IEEE Press, 2000.

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