ARI and ARID control of virtual synchronous generator for frequency response improvement

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Abstract
The modern power system is progressing from a centralised generation having synchronous generators to the distributed generation having the large-scale integration of renewable energy sources. These renewable energy sources are interfaced with the system through the inverter. Due to the inertia-less nature of inverter, the system becomes prone to frequency instability. The virtual synchronous generator control is used to enhance the frequency stability by introducing virtual inertia in the inverter control. The virtual synchronous generator technique provides flexibility to the researchers to regulate swing equation parameters in real-time. Based on this concept, this paper proposes an auto-regulated inertia control as the first contribution to improve the damping effect of virtual synchronous generator control. In the literature, the primary focus is on the inertia control and negligible importance is given to the damping factor control. Therefore, to show the effect of dynamic damping factor, together with dynamic virtual inertia, on the transient stability, an auto-regulated inertia and damping factor control of virtual synchronous generator is proposed as the second contribution. Simulation results of the proposed techniques are compared with the various virtual inertia control techniques in the real-time digital simulator environment. The results show that auto-regulated inertia and damping factor control is the most effective method to provide dynamic frequency support to the microgrid.

1 INTRODUCTION

Renewable energy sources (RESs), such as fuel cells, solar photovoltaic (PV), micro-turbines, wind turbines, and energy storage elements are increasingly being deployed in modern power systems. With the rapid advancement in power electronics technology, microgrid is becoming more efficient and cleaner technology to supply the growing demand for electricity in the interconnected and islanded mode of operation. In recent years, researchers have done significant and high-impact research in the areas such as automation [1], cybersecurity [2, 3], stability analysis and control of microgrids [4]. The main objective of any control technique of a microgrid is to maintain constant voltage and frequency for stable operation. Various centralised and decentralised control techniques are suggested in the literature for the smooth operation of a microgrid [5]. The conventional active power-frequency and reactive power-voltage droop and various modified droop techniques have been reported for the autonomous control of DGs to maintain the frequency and voltage magnitude [6–8]. Since the RESs in a microgrid are intermittent, it is necessary to monitor the states continuously. The state estimation of the microgrid electrical quantity mainly depends on the communication link between the DGs and the controller [9, 10]. Hence, the failure of the communication link highly affects the microgrid operation and stability. Various state estimation techniques considering the communication link failure are reported in the literature [2, 3] to resolve the cybersecurity and stability issues for a microgrid. Similar to the conventional grid, microgrid also faces the small-signal stability, transient stability and voltage stability issues. The transient stability of a microgrid is mainly affected by the uncertain behaviour of the RESs and inertia-less nature of the interfaced converters.

In the conventional power system network, the primary source of generation is the synchronous generator (SG), with...
the inherent property of large moment of inertia. Therefore, in case of large disturbances such as a fault, substantial step change in load, and induction motor switching, the frequency oscillation is suppressed by the SG by injecting/absorbing the stored kinetic energy into/from the system, respectively. The increased integration of DG into the utility grid reduces the system’s equivalent inertia because the inverter based DG has approximately zero inertia (no rotating mass) [11]. Because of less inertia and a high share of intermittent RESs, frequency stability is a major challenge in a microgrid. In addition, the low number of RES units in microgrids put the system at high risk for disturbances such as large step change in load, fault, and generator outage. In case of large and sudden disturbances, the system frequency may experience large excursions at a high rate of change, jeopardising the system frequency instability. In standalone mode, when a static generator is operated in parallel with a rotating generator, they provide poor transient load sharing. If there is a step change in load, the static generator responds more quickly as compared to the rotating generator and shares a major portion of the load demand during the transient period. With the limited size of the static generator, this poor load sharing may diversely affect the system frequency profile during disturbances.

Various methods have been proposed in the literature to enhance the transient stability of a microgrid, such as modified droop control [11, 12], virtual synchronous machines (VISMA) [13, 14], synchronverter [15, 16], virtual synchronous generator (VSG) [17–27] etc. The idea to use virtual inertia for an inverter is given by the VSYNC project team [28, 29], but it cannot be used in an islanded mode, as it is having current controller as outer loop. Paper [14] presents both current as well as voltage source based VSIMA technique. These techniques are not suitable for parallel operation of DGs to share the load, as they do not include the droop control laws. To improve the power-sharing and transient stability, modified droop control is proposed for the inverter [11]. In this method, the droop coefficient is modified as a function of the rate of change of frequency in the transient period to provide virtual inertia. It is also observed that droop control can provide the virtual inertia for the inverter with a well-designed first order lag unit in active power droop controller [12]. The concept of providing virtual inertia for a three-phase inverter using detailed modelling of SG is proposed [15]. To improve the performance of this technique and to reduce the computational burden, a self-synchronised synchronverter method is suggested by removing the synchronisation unit [16]. To mimic the inertial property of a SG, synchronverter technique is adopted for a single-phase PV-based inverter system for improving the frequency response [30].

Instead of using detailed modelling of an SG, the idea to emulate the inertia using swing equation is developed in [17, 18]. In the virtual synchronous generator (VSG) control, the controller solves the swing equation in each control cycle to emulate the virtual inertia. Kawasaki Heavy Industries (KHI) project group developed the VSG control in the $a-q$ frame for three-phase and single-phase inverter, respectively [31, 32]. Small signal modelling and parameter sensitivity analysis are carried out for a virtual synchronous machine, to observe the effect of different parameters on eigenvalues of the system [26]. To improve the ability of an inverter to perform in the case of symmetrical and unsymmetrical voltage sags, a modified VSG is suggested in [23]. Virtual inertia control together with primary frequency regulation is used to provide dynamic frequency support to the grid with high wind power penetration [33]. In [22], particle swarm optimisation (PSO) technique is used for online tuning of the parameters of the VSG units in a multi-VSG microgrid to improve the transient stability. A multi-loop control structure based VSG control scheme is presented in [34] to ensure the smooth operation of RES in grid connected as well as in islanded operation. In [35], a self-tuning of the virtual synchronous machine is proposed to support the dynamic frequency control. The techniques presented in [22, 35] require large memory size and computational time for continuous search of optimal parameters. The effect of inertia, damping factor, load and impedance of the line on the small signal stability of parallel operated VSG units are discussed in [24]. For accurate transient active and reactive power sharing between the parallel operated VSG units and to damp out the oscillations, an enhanced VSG controller is proposed in [25]. VSG technique is also adopted for electric vehicle (EV) charging station (CS) to support the frequency response of the islanded microgrid [36]. [37] presents a comprehensive control scheme of VSG to improve the performance under unbalanced condition because basic VSG control technique does not consider the negative sequence components and cannot eliminate them. Thus, it will lead to current unbalance and power oscillations. Inertial response characteristics analysis for permanent magnet synchronous generator (PMSG)-based VSG-controlled wind energy conversion system (WECS) is given in [38]. It is observed that coupling between the VSG control loop and the other control loops cannot be ignored in VSG-controlled WECS. This coupling would result in the change in equivalent inertia constant and damping coefficient, and it will affect the frequency response of the WECS-VSG. Therefore, an optimal WECS-VSG control strategy is proposed to enhance the inertial response [38].

In the VSG control, it is observed that with a large value of the moment of inertia, the peak overshoot in the output power of VSG unit is significant and frequency will oscillate for a longer time before settling. VSG controlled RES may not be able to function properly if the power excursion is beyond its tolerance limits during the transient. Virtual moment of inertia and virtual damping of the VSG controlled RES can be regulated in real time for the smooth operation. Based on this concept, an alternating inertia control is suggested to improve the settling time and to reduce the peak overshoot in power oscillation [19]. In this method, the inertia constant is altered between high and low values in real time by continuous monitoring of frequency deviation and it’s rate of change. High and low values of inertia are adopted in acceleration and deceleration mode of operation, respectively. However, it is not desirable to use the constant high value of inertia in all the acceleration segments, because a high value of inertia is needed just after the disturbance to reduce the rate of change of frequency and frequency
deviation. Therefore, after the first acceleration segment, one can use different values of inertia (less than high value) in proceeding acceleration segments. Similar concept is adopted in [20] to support the frequency response in the microgrid. A bang–bang control strategy is used in [20], to vary the inertia in transient as well as in steady state periods. A pre-synchronisation control technique of VSG with alterable inertia is given in [21]. However, this paper does not consider the effect of the filter impedance on the VSG output voltage, and power oscillation may appear at the VSG terminal after grid connection. The effect of virtual damping factor, together with virtual inertia, on frequency response of the system has been introduced [39, 40]. The values of virtual inertia and virtual damping factor are regulated using a regulation coefficient in transient periods. However, the process of selection of design parameters is not well explained. Unlike an SG, in VSG controlled distributed generator, one can monitor and regulate the swing equation parameters in real-time to enhance the performance of VSG. Based on this concept, this paper highlights ARI and ARID control techniques.

The main contributions of this paper are mentioned below:

1. In the VSG control, the use of large value of virtual inertia improves the frequency response at the cost of large peak overshoot in the output power with large settling time. Therefore, conventional VSG control operated DG may not be able to function properly if the power excursion is beyond its tolerance limits during the transient. To resolve this issue, this paper proposes an auto-regulated inertia (ARI) control of VSG as the first contribution to show the effect of variable inertia on transient stability.

2. It is observed that previous research works in this area have not well explored the effect of dynamic virtual damping factor together with dynamic virtual inertia. Also, the selection process of design parameters needs to be defined clearly. Therefore, to show the effect of dynamic damping factor on the transient stability; an auto-regulated inertia and damping factor (ARID) control of virtual synchronous generator is proposed as the second contribution. Lyapunov theory based direct method is used to verify the stable operation of the proposed techniques during large disturbances.

The basic VSG control is explained in Section 2. ARI and ARID control of VSG are discussed in Section 3; and transient stability assessment for them is discussed in Section 4. In Section 5, the simulation results for the auto-regulated inertia control, auto-regulated inertia and damping control are compared with various virtual inertial techniques in RTDS environment. Finally, the conclusion is drawn in Section 6.

2 BASIC VSG CONTROL

In the VSG control, the fundamental idea is to imitate the swing equation for the inverter [19]. The basic VSG control is implemented when the switches ‘S1’ and ‘S2’ in Figure 1 are connected at ‘a1’ and ‘b1’ positions, respectively. As the inverter is an inertia-less device, the moment of inertia and the damping factor are virtually defined parameters. For the VSG control of inverter, cylindrical rotor type of synchronous generator model is considered. The swing equation is solved by numerical integration technique to find out the virtual angular frequency, \( \omega_m \). A phase-locked loop (PLL) block is used as frequency detector to track the bus angular frequency, \( \omega_s \). The emulated swing equation is given by [19],

\[
P_m - P_o = J\omega_m \frac{d\omega_m}{dt} + D(\omega_m - \omega_g),
\]

where \( P_m, P_o, J \), and \( D \) are the input power, the output power, virtual moment of inertia, and virtual damping factor of the VSG, respectively. Here, ‘power meter’ block calculates the output real and reactive power, given by,

\[
P_o = V_\text{ref}I_\text{ref} + V_qI_q,
\]

\[
Q_o = V_\text{ref}I_q - V_IqI_{a1},
\]

where \( V_\text{ref} \) and \( V_q \) are the output voltage component in \( d \) and \( q \) axes, respectively; and \( I_{a1} \) and \( I_q \) are the output currents in \( d \) and \( q \) axes, respectively. Park transformation is used to extract \( dq0 \) reference frame signal from three-phase (abc) reference frame.

The frequency-active power \((\omega - P)\) droop of the governor and the reactive power-voltage \((Q - V)\) droop block in Figure 2 are described by,

\[
P_m = P^* - m_p(\omega_m - \omega^*),
\]

\[
Q^*/f = Q^* - n_q(V_o - E^*),
\]

where \( P^*, m_p, \) and \( \omega^* \) are the nominal active power, frequency droop coefficient, and the nominal frequency of the inverter. \( Q^*, V_o, n_q, \) and \( E^* \) are the nominal reactive power, the output voltage, the voltage droop coefficient, and the nominal output voltage of the inverter. \( Q^*/f \) is the reference signal generated by the \( Q - V \) droop, tracked by a PI controller. The virtual mechanical phase angle, \( \vartheta_m \), is produced by passing the virtual angular frequency, \( \omega_m \), through an integrator. Reference voltage, \( V^{\text{ref}} \), and \( \vartheta_m \) are used for the pulse width modulation (PWM) block to generate the pulses for the inverter to maintain the required voltage magnitude and the frequency at the inverter terminal.

For realising the VSG control, the main parameters to be considered are the virtual moment of inertia, \( J \), and virtual damping factor, \( D \). The value of \( J \) is given by [7], \( J = 2HS_0\omega_m^2 \), where \( H \) is the inertia constant of the VSG; \( S_0 \) is the rated apparent power of the VSG, and \( \omega_m \) is the system nominal frequency. The parameter \( D \) can be calculated as, \( D = P_0\omega_m \), where \( \Delta\omega_m = \omega_m - \omega_g = \delta\theta_m/dt \) [4]. Higher value of \( J \) improves the stability, but with large response time and high peak overshoot in the active power of the inverter.
In this section, ARI and ARID control of VSG are discussed to improve the system’s response time, frequency response, and to suppress the power oscillation. In ARI control, the virtual moment of inertia is adjusted, while the value of virtual damping factor is kept constant. The virtual moment of inertia regulation block will be effective when \( \frac{d\omega_m}{dt} \) exceeds a predefined threshold value \( C_1 \) and \( (\frac{d\omega_m}{dt})(\Delta\omega_m) \) is positive. Whereas, in ARID control of VSG, both virtual moment of inertia and virtual damping factor are regulated. In ARID control, the virtual moment of inertia is regulated similar to ARI control. Whereas, virtual damping factor block will be in action when \( \Delta\omega_m \) exceeds a predefined threshold value \( C_2 \) and \( (\frac{d\omega_m}{dt})(\Delta\omega_m) \) is negative. ARI and ARID control include subsystem (a), similar to basic VSG control as shown in Figure 1. The regulated virtual moment of inertia and constant value of the virtual damping factor are used in the ARI control, when the switches ‘\( S_1 \)’ and ‘\( S_2 \)’ in Figure 1 are connected at ‘\( a_2 \)’ and ‘\( b_1 \)’ positions, respectively. In ARID control, the virtual moment of inertia and virtual damping factor are regulated by connecting the switches ‘\( S_1 \)’ and ‘\( S_2 \)’ at positions ‘\( a_2 \)’ and ‘\( b_2 \)’, respectively. Switch configurations for the VSG, ARI, and ARID control are summarised in Table 1.

The effect of \( J \) and \( D \) can be analysed using power swing curve, as shown in Figure 2 [19]. For a sudden change in input power of the VSG from \( P_{in0} \) to \( P_{in1} \) at \( t = t_0 \), the system experiences power oscillations due to power mismatch between input
TABLE 1  Switch configuration

| Switches      | VSG control | ARI control | ARID control |
|---------------|-------------|-------------|--------------|
| $S_1$ (f regulation) | $a_1$ | $a_2$ | $a_2$ |
| $S_2$ (D regulation) | $b_1$ | $b_1$ | $b_2$ |

FIGURE 3  Regulation of $J$ and $D$ with change in $(d\omega_m/dt)$ and $(\Delta\omega_m)$

and output of the VSG. Therefore, the operating point oscillates from initial operating point ‘a’ to ‘c’, and then from ‘c’ to ‘d’ along the power curve, and finally settles down at the new equilibrium point, ‘b’. Four segments, $a \rightarrow b$, $b \rightarrow c$, $c \rightarrow b$, and $b \rightarrow d$ are considered in each cycle of oscillation to observe the influence of $J$ and $D$ on frequency response as shown in Figure 3. In these four segments, the values of $J$ and $D$ are regulated, as shown in Table 2.

3.1  Effect of moment of inertia

In VSG, the effect of $J$ on virtual angular frequency of oscillations can be understood by re-arranging (1).

$$J\omega_m \frac{d\omega_m}{dt} = P_{in} - P_o - D(\omega_m - \omega_i).$$

(6)

For a given operating condition described by the right hand side of the above equation, one can infer that $d\omega_m/dt$ is inversely proportional to the virtual inertia constant, $J$.

TABLE 2  Regulation of $J$ and $D$

| Segments | $(d\omega_m/dt)$ | $(\Delta\omega_m)$ | $J$       | $D$       |
|----------|-----------------|-------------------|-----------|-----------|
| $(a \rightarrow b)$ | $(d\omega_m/dt > 0)$ | $(\Delta\omega_m) > 0)$ | Regulate  | Constant  |
| $(b \rightarrow c)$ | $(d\omega_m/dt < 0)$ | $(\Delta\omega_m) > 0)$ | Constant  | Regulate  |
| $(c \rightarrow b)$ | $(d\omega_m/dt < 0)$ | $(\Delta\omega_m) < 0)$ | Regulate  | Constant  |
| $(b \rightarrow a)$ | $(d\omega_m/dt > 0)$ | $(\Delta\omega_m) < 0)$ | Constant  | Regulate  |

1. In segments $(a \rightarrow b)$ and $(c \rightarrow b)$ in Figure 3, $d\omega_m/dt$ and $\Delta\omega_m$ are of the same sign, as shown in Table 2. A high value of $d\omega_m/dt$, therefore, results in rapid frequency deviation. A high value of $J$ may be used to decrease $d\omega_m/dt$ during these two intervals [35] to reduce the frequency deviation.

2. On the other hand, in segments $(b \rightarrow c)$ and $(b \rightarrow d)$, the sign of $d\omega_m/dt$ is opposite of that of $\Delta\omega_m$ that is the frequency tries to return to the virtual synchronous speed. Therefore, a low value of $J$ is adopted, so that the frequency deviation is quickly drawn to zero.

In ARI and ARID control, the regulated value of $J$ is given as follows. For segments $(a \rightarrow b)$ and $(c \rightarrow b)$,

$$J = \begin{cases} J_{low} + \frac{(J_{high} - J_{low})}{\max(|d\omega_m/dt|)} |d\omega_m/dt|, & \text{if } |d\omega_m/dt| > C_1 \text{ and } (d\omega_m/dt) (\Delta\omega_m) > 0, \\ J_{low}, & \text{otherwise.} \end{cases}$$

(7)

For other segments, that is for $(b \rightarrow c)$ and $(b \rightarrow d)$, the value of $J$ is set as $J_{low}$.

In the above equations, $J_{low}$ and $J_{high}$ are the low and the high values of $J$, respectively. Whereas, $|d\omega_m/dt|$ is maximum rate of change of angular frequency and threshold value of $|d\omega_m/dt|$, respectively. In (7), the value of $J_{high}$ is calculated as,

$$J_{high} = 2HS_i/\omega_n^2,$$

(8)

where $H$ is the inertia constant of the VSG; $S_i$ is the nominal apparent power of the VSG, and $\omega_n$ is the system nominal frequency. The value of $J_{low}$ is taken as 10% of the $J_{high}$ [19].

3.2  Effect of damping factor

Damping control plays an important role in conventional SG; it suppresses the rotor angular frequency oscillations by providing damping power in the system. Same behaviour can be adopted for an inverter by using the damping factor, $D$, in emulated swing equation. The effect of $D$ on virtual angular frequency deviation can be understood by re-arranging (1).

$$D(\omega_m - \omega_i) = (P_{in} - P_o - J\omega_m \frac{d\omega_m}{dt}).$$

(9)

For a given operating condition described by the right hand side of the above equation, $\Delta\omega_m$ is inversely proportional to $D$.

1. In Figure 3, for the segments $(a \rightarrow b)$ and $(c \rightarrow b)$, a high value of $D$ reduces $\Delta\omega_m$; however, it also reduces the time to reach the peak of $\Delta\omega_m$, and it further increases the rate of change of frequency. The peak time is given by,
1. The system trajectory approaches the equilibrium point of
the system as time, \( t \to \infty \).
2. A continuous differentiable energy function, \( E(y) \), should exist.
3. \( \dot{E}(y) \leq 0 \), which means that the rate of change of energy
function along the system trajectory is negative.

By considering the classical model of a synchronous gener-
ator, the electromechanical dynamics for a VSG unit in grid-
connected/islanded mode can be written as,

\[
\dot{\delta}_m = f\omega_m \frac{d^2 \delta_m}{dt^2},
\]

where \( P_{in} - P_{max, \sin} \) is the maximum power that can be
transformed from the VSG to the grid/load; \( V_o, V_p, \) and \( X_T \)
are the output voltage of VSG, grid voltage in grid-connected
mode or voltage at load point in islanded mode, and the total
reactance between VSG terminal and grid/load, respectively. In
the above expression, the effect of damping is neglected.

After multiplying (13) by \( \Delta \omega_m \), the expression can be written as,

\[
\frac{J\omega_m \Delta \omega_m}{2} - (P_{in} - P_{max, \sin} \delta_m) \frac{d\delta_m}{dt} = 0.
\]

As the left hand side of the above equation is zero, its integral
is a constant. Integrating (14) from the stable equilibrium point
to any point on the trajectory, and taking the integral as the Lyap-
unov function [42],

\[
E = E_k + E_p = \frac{1}{2}J\omega_m (\Delta \omega_m)^2 - P_{in} (\delta_m - \delta_1) -

P_{max} (\cos \delta_m - \cos \delta_1),
\]

where \( E \) is the total energy, \( E_k = \frac{1}{2}J\omega_m (\Delta \omega_m)^2 \) is the vir-
tual kinetic energy and \( E_p = -P_{in} (\delta_m - \delta_1) - P_{max} (\cos \delta_m -
\cos \delta_1) \) is the potential energy stored in the VSG unit. It is
proved that (15) satisfies the Lyapunov function conditions [42].
To add the damping in the system, the ARI and ARID con-

4 | STABILITY ASSESSMENT
OF THE CONTROLLERS

The Lyapunov theory based direct method [41] is used for the
stability assessment of the controller in this work. Direct meth-
ods are sometimes preferred for the online stability assessment
because of their ability to provide stability information without
solving the differential equation set of system. A system with
a set of non-linear differential equation can be defined as:

\[
\dot{y} = F(y),
\]

where \( y \) is the state variable vector. According to Lyapunov the-
orem, the proposed controller can be considered asymptotically
stable if it satisfies the following three conditions [42]:

1. The system trajectory approaches the equilibrium point of
the system as time, \( t \to \infty \).
2. A continuous differentiable energy function, \( E(y) \), should exist.
3. \( \dot{E}(y) \leq 0 \), which means that the rate of change of energy
function along the system trajectory is negative.
TABLE 3  Parameters for Case I

| Parameters | Value | Parameters | Value |
|------------|-------|------------|-------|
| S_{base}   | 10 kVA | m_p       | 20 pu |
| \omega^*  | 376.99 rad/s | \beta^* | 0 pu |
| J_{low}    | 0.05628 | D_{low}   | 45.094 w/rad/s |
| J_{high}   | 0.5628  | D_{high}  | 450.94 w/rad/s |
| E^*        | 200 V   | Z_{1}     | 0.035 + 0.00375 pu |
| C_f        | 66.31 pu | L_f       | 0.0942 pu |
| P^*        | 1 pu    | u_q       | 5 pu |

ARI and ARID control. These adopted values of \( J \) and \( D \) do not affect the system transient energy function.

2. At point \( b' \), \( J \) and \( D \) change their values from high to low and low to high, respectively. At point \( b' \), \( \Delta \omega \) is maximum, and the change in inertia is negative for ARI control, which makes the system more damped as compared to the VSG control.

3. On the other hand, in ARID control, at point \( b' \), the change in inertia constant and damping factor are negative and positive, respectively. This positive change in the damping factor further increases the system damping as compared to the ARI control.

5  RESULTS AND DISCUSSION

In this section, the ARI and ARID control techniques are compared with conventional VSG control [13], VSG control without damping [13], inertial droop control [24], inertial droop control without damping [12], and alternating inertia control [19]. Two cases have been simulated in real-time digital simulator (RTDS) environment to validate the effectiveness of the ARI and ARID techniques. In the first case, a single VSG unit is connected to the grid, and in the second case, parallel operation of VSG and SG is considered in islanded mode. Simulation flowchart for the ARI and ARID control techniques is shown in Figure 4 for a better understanding of the algorithms.

5.1  Case I: Single VSG unit connected to the grid

The test system used for this case is given in Figure 5. A three phase 10 kVA VSG unit is connected to the grid via line impedance \( Z_{1} \) and a three-phase balanced load of 8 kVA is connected at the grid side. Case studies such as change in reference value of active power of VSG and a three phase to ground fault are considered here, for the operation of ARID control, VSG control [13], VSG control without damping [13], inertial droop control [24], inertial droop control without damping, and alternating inertia control [19] under large disturbances. The parameters for the considered system are given in Table 3 [25].

(a) Change in reference value of active power of VSG: Initially, the reference value for the active power is set to be 5 kW. To observe the performance of controllers under sudden and large disturbance, the reference value is set to 10 kW, at \( t = 2 \) s. From Figure 6, it is seen that, in VSG control the peak overshoot in the VSG output power is up to 20.08%, whereas, in VSG control without damping, inertial droop control, inertial droop control without damping, and alternating inertia control, ARI control, and ARID control, the peak overshoot of VSG output power is 29%, 20.04%, 26%, 8%, 4.2%, and 3.9%, respectively. The ARID control has settling time, \( T_s = 1.24 \) s, which is 89.14%, 89.25%, 83.73%, 84.26%, 20.51%, and 17.88% less than the settling time for VSG control, VSG control without damping, inertial droop control, inertial droop control
without damping, alternating inertia control, and ARI control, respectively.

(b) Three-phase to ground fault: In this case, a three-phase to ground fault for 6 cycles is introduced at $t = 2$ s at the VSG terminal, for determining the performance of ARI and ARID controller over various inertial control techniques under severe fault condition. In this case, the peak overshoot in the output active power of VSG unit is very large in VSG control (49.91%), VSG control without damping (49.94%), inertial droop control (49.54%) and inertial droop control without damping (49.98%) as compared to alternating inertia (11.12%), ARI (11.05%), and ARID (11.02%), as shown in Figure 7. From the frequency response, it is seen that after initiation of the three phase to ground fault, the frequency deviation is approximately same (54 rad/s) for all the control techniques. Whereas, the settling time ($T_s = 1.82$ s) of ARID control is 85.44%, 85.86%, 85%, 84.66%, 6.66% and 15.37% lesser than the settling time of VSG control, VSG control without damping, inertial droop control, inertial droop control without damping, ARI control, and alternating inertia, respectively.
FIGURE 8  A VSG unit operated in islanded mode in parallel with an SG

TABLE 4  SG parameters for Case II

| Parameters | Value       | Parameters | Value       |
|------------|-------------|------------|-------------|
| $S_{base,sg}$ | 10 kVA     | $D_{sg}$   | 230.092 kW/rad/s |
| $E^*$       | 200 V       | $X_{d,sg} = X_{q,sg}$ | 0.219 pu     |
| $m_{sg}$    | 20 pu       | $X_{d,sg} = X_{q,sg}$ | 0.027 pu     |
| $n'_{sg}$   | 5 pu        | $X_{d,sg}'' = X_{q,sg}''$ | 0.01 pu     |
| $\omega^*$  | 376.99 rad/s| $T_{d,sg}'$ | 6.55 s      |
| $P^*$       | 1 pu        | $T_{q,sg}'$ | 0.039 s     |
| $Q^*$       | 0 pu        | $T_{q,sg}''$ | 0.85 s      |
| $J_{sg}$    | 0.16 s      | $Z_1$      | 0.035 + 0.00375 pu |
|            |             |            |             |

5.2 Case II: VSG unit connected in parallel with an SG

In this case, a microgrid, consisting of a VSG unit in parallel to a synchronous generator, is operated in islanded mode, as shown in Figure 8. Similar to Case I, three sub-cases have been considered for this case to show the effectiveness of different controllers during large disturbances. In first case, a step change in load is considered, in second case, a three phase to ground fault at VSG unit terminal is considered, and in third case, variable load profile is considered to show the system ability to improve frequency response. The parameters are given in Tables 4 and 5 for the synchronous generator and virtual synchronous generator, respectively [25].

(a) Load switching: Initially a loading of 12.5 kW is considered for the given test system, and 6.65 and 5.85 kW are the active power shared by the VSG and SG, respectively. At $t = 3$ s, an extra load of 4 kW is switched-in to see the performance of the controllers. From Figure 9, it is seen that, in VSG control, the peak overshoot in the VSG output power is 94.11%. Whereas, in VSG control without damping, inertial droop control, inertial droop control without damping, alternating inertia, ARI control, and ARID control, the peak overshoot in VSG output power is 94.88%, 93%, 90.23%, 58.29%, 55.29%, and 47.05%, respectively. The frequency deviation is approximately same for all control techniques. In Figure 9, the frequency response shows that proposed controller has settling time of $T_s = 2.2$ s, which is 30%, 38.18%, 24.54%, 35.45%, 23.63%, and 21.36% lesser than the VSG control, VSG control without damping,
inertial droop control, inertial droop control without damping, alternating inertia, and ARI control, respectively. The value of virtual damping factor and virtual inertia for the VSG, alternating inertia, ARI, and ARID control are shown in Figures 9(c) and 9(d), respectively. It is shown that the ARI and ARID control increase their virtual inertia as a function of \( \frac{d\omega_m}{dt} \) from \( J_{\text{min}} \) during transient period. Whereas, in VSG control, it is taken as constant always and in alternating inertia control of VSG, it is altered between maximum and minimum values. Similarly, the value of \( D \) is increased in ARID control as a function of \( \Delta \omega_m \) during transient case only, and it is kept constant in VSG, alternating inertia, and ARI control.

(b) Three-phase to ground fault: In this case, a three-phase to ground fault is initiated at \( t = 3 \) s. Before the fault, the active power shared by VSG and SG units are 8.5 and 7.85 kW, respectively. After the fault, it is observed that VSG controller has much larger power oscillation in magnitude as compared to the others, as shown in Figure 10. The peak overshoot in the power is minimum in case of the ARID control of VSG as compared to the other techniques. The frequency response, virtual damping factor, and virtual inertia are shown in Figures 10(b), 10(c), and 10(d), respectively. The ARID control performs well with least power oscillations (42.11%) and takes less settling time (\( T_s = 0.88 \) s) as compared to the ARI, alternating inertia, and
VSG controller. From the above case study, it can be concluded that ARID outperforms the ARI, alternating inertia, and VSG control; whereas, ARI has moderate performance.

(c) Variable load condition: In this case, a dynamic change in load demand is considered at \( t = 2, 12, 22, 32 \) and \( 42 \) s. At each point of sudden change in load, it is observed that VSG controller has much larger power oscillation in magnitude as compared to the others, as shown in Figure 11. The peak overshoot in the power is minimum in case of the ARID control as compared to the other techniques. The frequency response, virtual damping factor, and virtual inertia are shown in Figures 11(b), 11(c), and 11(d), respectively. From the above case studies, it can be concluded that ARID outperforms VSG control, VSG control without damping, inertial droop control, inertial droop control without damping, alternating inertia; whereas, ARI has moderate performance. Table 6 summarises the performance of proposed techniques. In Table 6, frequency deviation (\( \Delta \omega_m \)), settling time (\( T_s \)), and peak overshoot in power (\( P_{over} \)) are given in rad/s, s, and %, respectively.

## 6 | CONCLUSION

This paper proposes an Auto-Regulated Inertia (ARI) technique as the first contribution to improve the damping of a virtual synchronous generator. In ARI control, controller adopts regulated high value of inertia as a function of \( \frac{d\omega_m}{dt} \) in accelerating segments when \( \frac{d\omega_m}{dt} \) exceeds a predefined threshold value of the rate of change of angular frequency. This regulated high value of \( J \) is used to suppress the output power and frequency oscillations. The results show that regulation of inertia in real-time improves the frequency response with less settling time and less peak overshoot in power as compared to the VSG control, VSG control without damping, inertial droop control, inertial droop control without damping, and alternating inertia control. To explore the effect of dynamic damping factor together with dynamic virtual inertia on the performance of the virtual synchronous generator unit, an auto-regulated inertia and damping (ARID) control is proposed as the second contribution. In ARID control, the value of the damping factor is also regulated together with inertia to improve the damping and frequency response of the ARI control. The value of inertia constant is regulated as a function of the rate of change of angular frequency and the value of the damping factor is regulated as a function of virtual angular frequency deviation. In ARID control, the regulation of \( J \) is similar to ARI control and it adopts a low value of \( D \) when the sign of \( \frac{d\omega_m}{dt} \) and \( \Delta \omega_m \) are the same so that it does not affect the desirable impact of the high value of \( J \). On the other hand, when the sign of \( \frac{d\omega_m}{dt} \) and \( \Delta \omega_m \) are not the same, it adopts the regulated high value of \( D \) to suppress the magnitude of frequency deviation. The ARID technique is an efficient control of the frequency excursions while reducing the settling times and the peak overshoot in power.

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## TABLE 6 Performance of virtual inertia control techniques

| Method                | Case   | \( \Delta \omega_m \) | \( T_s \) | \( P_{over} \) |
|-----------------------|--------|------------------------|--------|--------------|
| VSG control           | Case I (a) | 06.61                 | 11.42  | 20.00        |
|                       | Case I (b) | 44.41                 | 12.50  | 49.91        |
|                       | Case I (a) | 22.63                 | 02.86  | 94.11        |
|                       | Case I (b) | 28.00                 | 02.12  | 96.47        |
|                       | Case I (c) | 03.23                 | 03.89  | 106.81       |
| VSG control without damping | Case I (a) | 07.6                  | 11.54  | 29.00        |
|                       | Case I (b) | 48.71                 | 12.88  | 49.94        |
|                       | Case I (a) | 23.66                 | 03.04  | 94.88        |
|                       | Case I (b) | 28.23                 | 02.29  | 97.23        |
|                       | Case I (c) | 03.63                 | 03.91  | 107.38       |
| Inertial droop control | Case I (a) | 06.72                 | 07.64  | 20.04        |
|                       | Case I (b) | 47.11                 | 10.96  | 45.17        |
|                       | Case I (a) | 23.84                 | 02.77  | 93.00        |
|                       | Case I (b) | 28.41                 | 02.27  | 97.11        |
|                       | Case I (c) | 03.27                 | 02.98  | 105.12       |
| Inertial droop control without damping | Case I (a) | 07.75                 | 07.88  | 26.91        |
|                       | Case I (b) | 49.52                 | 11.31  | 49.80        |
|                       | Case I (a) | 24.33                 | 02.98  | 93.23        |
|                       | Case I (b) | 29.51                 | 02.39  | 97.77        |
|                       | Case I (c) | 03.79                 | 03.01  | 106.91       |
| Alternating inertia control | Case I (a) | 06.81                 | 01.56  | 08.00        |
|                       | Case I (b) | 58.00                 | 02.15  | 11.12        |
|                       | Case I (a) | 23.09                 | 02.72  | 58.28        |
|                       | Case I (b) | 22.08                 | 01.98  | 74.11        |
|                       | Case I (c) | 02.95                 | 02.86  | 82.00        |
| ARI control           | Case I (a) | 06.80                 | 01.51  | 04.20        |
|                       | Case I (b) | 58.50                 | 01.95  | 11.05        |
|                       | Case I (a) | 23.01                 | 02.67  | 55.29        |
|                       | Case I (b) | 22.75                 | 01.24  | 62.35        |
|                       | Case I (c) | 02.94                 | 02.31  | 59.64        |
| ARID control          | Case I (a) | 06.80                 | 01.24  | 03.60        |
|                       | Case I (b) | 57.18                 | 01.82  | 11.02        |
|                       | Case I (a) | 22.89                 | 02.20  | 47.05        |
|                       | Case I (b) | 22.71                 | 00.88  | 42.11        |
|                       | Case I (c) | 02.93                 | 01.96  | 47.29        |
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