Isochronous control of a virtual synchronous generator using inertia and excitation emulations with restoration control in a standalone microgrid

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Abstract: In this study, virtual excitation emulation (VEE) is proposed along with the virtual inertia emulation (VIE) for a virtual synchronous generator (VSG) in a standalone microgrid to improve the AC voltage and frequency profile through the control of power electronic DC–AC converter in the microgrid. The VIE emulates the inertia and damping characteristics of a synchronous generator by mimicking the swing equation. The VEE is proposed to emulate the behaviour of the field circuit and exciter system of a synchronous generator. In addition, a restoration control is also added with the inertia and excitation emulation to restore the magnitude and frequency of the output voltage at the rated value and achieve isochronous control. A linearised small-signal model of the VSG with the proposed control technique is also presented to analyse the system stability and design the control parameters. The standalone microgrid is simulated in MATLAB/Simulink environment to show the effectiveness of the proposed control technique. From the simulation results, it is reflected that the proposed control technique improves the voltage and frequency response during transient and steady-state including the frequency nadir of the microgrid.

1 Introduction

In the past few decades, the power generation from the renewable energy sources (RESs) is increasing at a very rapid rate to reduce the problem of CO2 emission and increasing fuel cost of the conventional power plants. Microgrid technology provides the best platform for the integration of RESs into the utility grid, improving the system efficiency and plug-and-play capability [1]. With the increase of power generations from renewable resources and their integration into the utility grid through microgrid technology, the amount of renewable share in the total electricity generation is increasing at a very high rate. Although high penetration of renewable power generations (RPGs) in the utility grid has many advantages such as low/no fuel cost, abundant resources, green power generation etc. However, the intermittency of the RPGs imparts certain challenges for the stable operation of a power system [2]. As the inertia of a synchronous generator (SG) in conventional (fossil fuel and hydro based) power plant plays an important role in the frequency control and stability of a power system during load variations [3]. However, such advantages are not available naturally in the inertia-less power electronic converters (PECs) dominated microgrids [4]. However, under low penetration of RPGs (10–15%) the inertia of the conventional power plants manages to maintain the stability of power system [5]. However, it will be very difficult even for conventional power plants also to maintain the stability of the power system under high RPG penetration around (40–50%) [4]. Under this situation, it is essential to enhance inertia of a microgrid to deal with the stability related problems which emerge due to the low inertia of the PECs [3]. To cope up with the situation, inertia enhancement of the PECs in the microgrid applications using virtual inertia emulation (VIE) technique is gaining research interest. The technique basically emulates the mechanical inertia characteristics of a synchronous machine in VSM [6]. To mimic the mechanical and electrical characteristics of a synchronous machine, the concept of synchroverter is proposed in [8]. Owing to the good control performance, VSG control is used in doubly fed induction generator-based wind turbines [9]; energy storage systems [10], VSC stations [11], and modular multi-level converters (MMCs) [12]. In [13], bang–bang control with virtual inertia control (VIC) is proposed to suppress the power fluctuation of VSG. In order to damp out the oscillations of DGs, an oscillation damping method using VSG is proposed in [14]. Based on dynamic performances analysis, a small-signal model and the control parameters of a VSG are designed in [15]. The dynamic characteristics of a VSG control and a droop control are analysed and compared in [16]. It is shown that the VSG control is more advantageous over droop control and it leads to the development of inertial droop control technique. VSG is also implemented to integrate a DC microgrid with the utility grid [17]. In [18, 19], the concept of VIC for a grid connected inverter of a DC microgrid is developed from the concept of VSM control to regulate the DC bus voltage. Similarly, inertia emulation techniques like VIC, virtual DC machine for bidirectional DC–DC converter is proposed in [20, 21] to regulate the DC bus voltage of an isolated DC microgrid.

In most of the literature, VIE is implemented for the grid-connected microgrid operating as a VSG to provide an inertial response to the grid. Although inertia enhancement for a load-connected VSI in a standalone microgrid is equally important [22], it is not much focused on the literature. Moreover, implementation of VIE mainly ensures better transient performance, but not the steady-state performance. Therefore, when VIE is used for a load connected VSI in a standalone microgrid supplying AC loads, restoration control (RC) is much needed feature to ensure better steady-state performance. The implementation of VIE helps to regulate the frequency of a microgrid. However, emulation of the excitation system of a SG to regulate the AC voltage at the load terminal of the microgrid is not emphasised in the literature. The emulation of excitation system, referred as virtual excitation emulation (VEE) is proposed in this paper to regulate the AC voltage of the microgrid, shown in Fig. 1. The proposed VEE is integrated with the VIE to improve the overall transient performance of the VSG in the microgrid. In addition, an RC is
proposed and designed for both VIE and VEE to improve the overall steady-state performance and achieve the isochronous control operation of the VSG in the isolated DC microgrid. Further, a small-signal model of the VSG along with the proposed control technique is developed to analyse the stability and determine the parametric values of the proposed control technique.

The implementation of the proposed control gives the following contributions of the paper:

- The rate of change of the voltage and frequency response, and the deviation of the voltage and frequency at the output of the VSG is lesser for the proposed VSG control as compared with its non-VSG counterpart.

This paper is organised as follows. The structure of the microgrid is demonstrated in Section 2. The concept, modelling and control structure design of the VSG is elaborated in Section 3. The performance analysis and parameters selection are given in Section 4. Section 5 shows the simulation results and its discussion. Advantages/disadvantages and usefulness of the proposed control technique is given in Sections 6 and 7, respectively. Finally, the conclusions are presented in Section 8.

2 Structure of the microgrid

The complete structure of the considered standalone microgrid consists of RPGs (wind turbine with permanent magnet SG (PMSG) and solar photovoltaic (PV) panels), energy storage with backup supply unit (battery and fuel cell (FC) combination) and local AC loads is shown in Fig. 1. They are connected to a common DC bus using various types of PECs as shown in Fig. 1. The wind turbine with PMSG and PV sources are operated in maximum power point tracking mode to extract the maximum power. PMSG is a self excited generator that operates at high power factor with higher efficiency. In addition, due to low speed of operation it can be used in direct drive without using gear box. This reduces the losses in the gear box. Control of PMSG is simpler because there is no need of controlling the excitation of PMSG. The storage device (battery) and backup unit (FC) are used to maintain power balance of the standalone microgrid. The VSI connected to the AC loads is operated as a VSG.

3 VSG: concept, modelling and controller structure

3.1 Concept of a VSG

VSG is basically an inverter which is controlled and operated in such a way that it can mimic the behaviour of a SG. Therefore, a VSG has the ability to provide inertial support to the grid by automatically changing its active and reactive powers according to the change in frequency and amplitude of grid voltage, respectively [5]. In addition to the grid-connection mode, a VSG can also be operated in standalone mode to ensure the load sharing among the inverters and transient stability enhancement of the system. By the implementation of VSG, the well-established theory used to control SGs in a power system may be used for inverter-based RPGs. However, in a VSG, the dynamic equations of the inverter remain same; only the mechanical power exchanged with the prime mover is replaced with the power exchanged with the DC bus. The parameters which include the droop coefficients and virtual inertia of a VSG can be set arbitrarily and they are not constrained by any physical design like a real SG. Therefore, the parameters of a VSG can be tuned freely to achieve the desired performance.

3.2 Modelling of the VSG

The VSI is the main component of the VSG. The VSI with LC filter in Fig. 2 can be considered like an imaginary SG connected in parallel with the capacitors connected to its output terminal. The sources and the storages along with the DC link capacitor (Cdc) connected on the dc bus represent the imaginary prime mover and the inertia of the imaginary rotating part of the SG. In Fig. 2,

\[ P_c = \frac{3V_e V_i}{X_e} \sin \delta \]

\[ Q_c = \frac{3V_e V_i}{X_e} \cos \delta - \frac{3V_d^2}{X_e} \]

\[ \nu_{abc} = [v_{a}, v_{b}, v_{c}]^T \]

\[ i_{abc} = [i_{a}, i_{b}, i_{c}]^T \]

\[ v_{abc} = -r_i i_{abc} - L_i \frac{di_{abc}}{dt} + e_{abc} \]  \hspace{1cm} (1)

and

\[ i_{abc} = C_i \frac{dv_{abc}}{dt} + h_{abc} \]  \hspace{1cm} (2)

where \( r_i \) and \( L_i \) represents the resistance and inductance of the stator windings of the imaginary SG. Using PWM technique, the switches of the inverter is operated in such a way that the average inverter output voltage \( e_{abc} \) over a switching period can be represented by the EMF in the average sense which is generated in the stator windings due to the movement of the imaginary rotor of

![Fig. 1 Structure of a standalone microgrid](image1)

![Fig. 2 Circuit diagram of the VSG connected to AC load](image2)
the imaginary SG. The inverter output voltage or EMF vector $\mathbf{v}_{abc} = [e_{abc}, e_{d}, e_{q}]^T$ can be expressed by

$$e_{abc} = E_{max}\sin \theta_o.$$  \hspace{1cm} (3)

where $\theta_o = \omega_o t$ is the virtual rotor angle, $\mathbf{E}_{max} = [\sin \theta_o, \sin(\theta_o - 2\pi/3), \sin(\theta_o + 2\pi/3)]^T$ and $E_{max}$ is the maximum value of the EMF vector. It is assumed that there is only one pair of poles per phase in the VSG and hence $\omega_o$ is the virtual mechanical speed of the VSG which is the same as the electrical speed of the virtual electromagnetic field.

Now the dynamic (1) and (2) can be expressed in term of the $dq$-axis components as

$$\begin{align*}
e_d - v_d &= L \frac{di_d}{dt} + r i_d - \omega_o L i_q,

\epsilon_q - v_q &= L \frac{di_q}{dt} + r i_q + \omega_o L i_d,
\end{align*}$$

and

$$\begin{align*}
i_d - i_d &= C_1 \frac{dv_d}{dt} - \omega_o C_1 v_q,

i_q - i_q &= C_1 \frac{dv_q}{dt} + \omega_o C_1 v_d,
\end{align*}$$

where $v_{d}$ and $v_{q}$ and $i_{d}$ and $i_{q}$ are the $d$- and $q$-axes components of the voltage $\mathbf{v}_{abc}$ and current $\mathbf{i}_{abc}$, respectively, $i_d$ and $i_q$ are the $d$ and $q$-axis components of the load current $\mathbf{i}_{abc}$, $\omega_o L d L d$ and $\omega_o L q L q$ are the $d$ and $q$-axis decoupling terms.

The generated real and reactive power ($P_e$ and $Q_e$) of the VSG is defined as

$$P_e = \epsilon_{d} i_{d} + \epsilon_{q} i_{q} = E_{max} i_{d} \sin \theta_o = \omega_o T_e,$$

$$Q_e = \epsilon_{d} i_{q} - \epsilon_{q} i_{d} = E_{max} i_{q} \cos \theta_o = \frac{d \epsilon_{d} i_{q} - d \epsilon_{q} i_{d}}{d t},$$

where $\epsilon_{d}$ has the same amplitude as $\epsilon_{abc}$, but with a phase delay from that of $\epsilon_{abc}$ by $\pi/2$. The operator $(\ast, \ast)$ denotes the conventional inner product in $\mathbb{R}^3$. Therefore, from (6) it is clear that reactive power has a differential relationship with the excitation voltage and it can be used in the VSG control to emulate the excitation characteristics of an SG.

The real and reactive power output of the VSG can be computed in terms of the $dq$ components and is given by

$$P_e = \frac{3}{2}(v_d i_d + v_q i_q),$$

$$Q_e = \frac{3}{2}(v_q i_d - v_d i_q).$$

The power angle ($\delta$) becomes very small when the impedance between the VSG and the load becomes inductive. The virtual inductance introduced through control techniques makes the inductive impedance for the distribution system. Now, the real and reactive power flow through the synchronous link ($X_L$) or power output of the VSG can also be expressed as

$$P_e = \frac{3}{2} v_d i_d \sin \delta,$$

$$Q_e = \frac{3}{2} v_q i_q \cos \delta - \frac{3}{2} v_d i_d \sin \delta,$$

where $V_p = v_d \cos \delta$ and $V_q = v_q \sin \delta$ represent the phasors of the VSG output voltage and the voltage at load terminal, respectively, and $\delta$ is the power angle, which is expressed as

$$\delta = \int (\omega_o - \omega_m) dt.$$  \hspace{1cm} (9)

3.3 Control structure design of the VSG

Fig. 3 demonstrates the complete control structure of the VSG proposed in this paper. The control structure is described in following subsections.

3.3.1 Virtual inertia emulation: In VIE, the inertia characteristics of the SG is emulated virtually through the control of VSG to regulate its output angular frequency $\omega_o$. In VIE, $\omega_o$ is regulated by controlling the virtual electromagnetic torque of the VSG. The VIE is done by mimicking swing equation of conventional SG which is given in

$$\begin{align*}
J_e \frac{d\omega}{dt} &= T_m + \frac{1}{2} T_e \omega - \frac{1}{2} T_e \omega - B \omega \\
T_m &= \frac{1}{2} T_e \omega + B \omega \\
\omega &= \frac{1}{2} T_e \omega - \frac{1}{2} T_e \omega - B \omega
\end{align*}$$

where $J_e$ is the virtual moment of inertia, $B_e$ is the virtual damping coefficient, $T_m$ is the virtual mechanical Torque input to the VSG, $T_e$ is the virtual electromagnetic torque output of the VSG and $\omega_m$ and $\omega_o$ are the nominal and measured value of the virtual angular frequency of the VSG rotor, respectively. Multiplying both sides of the (10) by $\omega_m$ the power equation can be established and is given as

$$P_{inv} = P_e = T_m \omega_o = J_e \omega_m \frac{d\omega_o}{dt} + B \omega_o (\omega_o - \omega_m)$$

where $P_{inv}$ is the virtual mechanical power input and $P_e$ is the electrical power output of the VSG. Under stable condition $\omega_o$ does not vary considerably. Therefore, (11) can be modified as

$$P_{inv} = P_e \approx J_e \omega_m \frac{d\omega_o}{dt} + B \omega_o (\omega_o - \omega_m).$$

Fig. 3 Block diagram of the proposed control structure of the VSG
where \( o_n \) is the nominal value of the angular frequency, \( M_p \) is the angular momentum and is also called virtual inertia constant and \( D_p \) represents the imaginary mechanical-friction damping coefficient plus the active power frequency droop coefficient.

The reference angular frequency (\( o_{o} \)) of the VSG output voltage is generated from the \( P \) – \( \omega \) control as given in Fig. 4a. The control equation is derived with the help of (13) and it is given as

\[
(P_{set} - P_o) = M_p \frac{do_o}{dt} + D_p (o_o - o_n)
\]  

(13)

where \( a_n \) is the nominal value of the angular frequency, \( M_p \) is the angular momentum and is also called virtual inertia constant and \( D_p \) represents the imaginary mechanical-friction damping coefficient plus the active power frequency droop coefficient.

The reference angular frequency (\( o_{o} \)) of the VSG output voltage is generated from the \( P \) – \( \omega \) control as given in Fig. 4a. The control equation is derived with the help of (13) and it is given as

\[
(P_{set} - P_o) = M_p \frac{do_o}{dt} + D_p (o_o - o_n)
\]  

(14)

3.3.2 Virtual excitation emulation: In the VEE, the excitation characteristics of the SG is mimicked to control inverter output voltages by controlling firing pulses so that the VSI can behave like a VSG. In order to regulate the voltage magnitude of the VSG with the variation of the reactive power demand of the load, the VEE in the reactive power (\( Q \)) voltage control loop is proposed.

In analogues to the VIE, the relation of VEE can be established with the help of (6) and \( Q-V \) control concept and can be expressed as

\[
(Q_{set} - Q_o) = N_q \frac{dE_m}{dt} + D_q (V_o - V_n)
\]  

(15)

where \( V_n \) is the nominal output voltage of the VSG, \( N_q \) is the inverse of the integration constant that incorporates the VEE in \( Q \) - \( V \) loop. The reference voltage magnitude (\( V_{o}^* \)) of the VSG output voltage reference is generated from the \( Q \) - \( V \) control as given in Fig. 4h. The control equation is established with the help of (15) and it is given as

\[
(Q_{set} - Q_o) = N_q \frac{dV_{o}}{dt} + D_q (V_o - V_n)
\]  

(16)

3.3.3 Inner loop voltage and current controllers: The inner loop control is basically a vector control scheme that includes a current controller and a voltage controller to control the output voltage and current of the VSC [23]. The \( d \) - and \( q \)-axis inner current controllers are expressed by

\[
e_{i_{id}} = (k_p + k_d/s)(i_{id}^* - i_d) - o_n L_i dq + v_{id}
\]

\[
e_{i_{iq}} = (k_p + k_d/s)(i_{iq}^* - i_q) + o_n L_i di_d + v_{iq}
\]  

(17)

where \((k_p + k_d/s) = G_i(s)\) is the PI current controller transfer function. The output of the current PI controllers is \( e_{id_{dq}} \) which is divided with the DC link voltage \( v_n \) to get modulation indices \( \{m_d \text{ and } m_q \}\). \( e_{id_{dq}} \) is the \( d-q \) component of the reference pole voltages of the inverter.

The \( dq \)-axis current references are generated from the voltage controllers which are designed to control the AC output voltages of the VSG. Thus, the \( d \) and \( q \)-axis equation of the outer voltage controllers are expressed by

\[
e_{v_{id}} = (k_p + k_d/s)(v_{id}^* - v_{id}) - o_n C_v dv_{id} + h_{id}
\]

\[
e_{v_{iq}} = (k_p + k_d/s)(v_{iq}^* - v_{iq}) + o_n C_v dv_{iq} + h_{iq}
\]  

(18)

where \((k_p + k_d/s) = G_v(s)\) is the PI voltage controller transfer function.

The references of the voltage controllers \((v_{id}^* \text{ and } v_{iq}^*)\) are generated by using voltage reference calculation which performs the parks transformation \((T)\) of the three phase voltage reference \(v_{abc}^* = V_m \sin(o_n t)\). The three phase voltage is generated with the help of reference voltage magnitude \(V_{o}^*\) and the angular frequency \(o_n\). The \(v_{o}^* \text{ and } o_n\) are generated using VEE and VIE techniques.

With a proper design of the voltage controller, the voltage of the filter capacitors \((v_{abc})\) can accurately track the voltage references. Thus, we can write

\[
o_n \approx o_n^*, \quad \theta_n \approx \theta_n^*, \quad V_o \approx V_o^*
\]  

(19)

3.3.4 Restoration controller: The RC restores the voltage magnitude and frequency to their nominal value by reducing the steady-state errors caused the proposed emulation control approach of the VSG. The set point of the both the control loops \((P_{set} \text{ and } Q_{set})\) are derived from the error between nominal and actual value of frequency \((o_n)\) and voltage magnitude \((V_n^*)\), respectively, and are expressed as the following equations

\[
P_{set} = G_p(s)(a_n - o_n)
\]

\[
Q_{set} = G_q(s)(V_n - V_n^*)
\]  

(20)

where \( G_p(s) = k_p + (k_d/s) \) and \( G_q(s) = k_q + (k_d/s) \) are the restoration PI controller.

3.4 Governor control analogy

In the proposed control technique, the control of the DC bus voltage is analogous to the governor control. The control of the DC bus voltage to maintain the power flow to the inverter (VSG) is considered as governor control which is basically achieved by the control of the converter connected to the battery bank. This helps to regulate the frequency of the output voltage as happen in case of governor control.

4 Performance analysis and selection of control parameters of the VSG

In order to implement the VSG control techniques successfully, determining the parameter values of the inertia and excitation emulation are very crucial. To get the desired performance and the stability of the system, the parameters of the inertia and excitation emulation loops \(M_p, D_p, N_q, D_q\) play an important role. The \(D_p \) and \( D_q \) regulates the steady-state performance and \(M_p \) and \( N_q \) regulates the transient performance. Therefore, the performance analysis of the system is needed to choose their values suitably. The value of the \(D_p \) and \( D_q \) are required to decide before the determination of the \(M_p \) and \( N_q \).

Fig. 4 Detailed control diagram of the VIE with RC

(a) Virtual torque emulation with frequency restoration, (b) VEE with voltage restoration
The real power power regulation using VIE technique ($P - \omega$ control) shown in Fig. 4a has a nested structure, where the inner loop is the inertia emulation loop with feedback gain $D_p$. The time constant of the loop is given by $\tau_i = M_p/D_p$.

Similarly, like $P - \omega$ control loop, the $Q - V$ loop is also having a nested structure and the time constant of the inner loop is given by $\tau_e = N_q/D_q$.

4.1 Determination of $D_p$ and $D_q$

The coefficients $D_p$ and $D_q$ are generally determined based on the grid code requirements. According to [15], the allowable change of frequency is 2% of the nominal frequency corresponding to the 100% change in active power, while the 5% of the nominal voltage change is allowed corresponding to the 100% of reactive power. So, the coefficients can be obtained as

$$D_p = \frac{\Delta P_{\text{max}}}{\Delta \omega_{\text{max}}} = \frac{7500}{(2\pi \times 50) - 2\%} = 1194.3 \text{(W/s/rad)}$$
$$D_q = \frac{\Delta Q_{\text{max}}}{\Delta V_{\text{max}}} = \frac{2000}{230 - 5\%} = 173.9 \text{(VAR/V)}$$

(21)

4.2 Determination of $M_p$ and $N_q$

After determining the coefficients $D_p$ and $D_q$, the inertia and excitation emulation constants $M_p = \tau_i D_p$ and $N_q = \tau_e D_q$ are determined by properly choosing the value of $\tau_i$ and $\tau_e$, respectively. In order to find out the proper values of $M_p(\tau_i)$ and $N_q(\tau_e)$ a small-signal model of the VSG is established.

4.3 Small signal modelling of the VSG

To establish the small-signal model, any state variable $x$ in these equations can be expressed with the corresponding quiescent value $X_{on}$ plus superimposed small ac variation $\Delta X$. In order to derive the small-signal ac model of the VSG at the quiescent operating point, following (8), (9), (19), (14) and (16) are used. Following the procedure, the small-signal model of (8) can be derived as

$$P_{on} + \Delta P_{s} = \frac{3}{X_c} [V_{on} V_{in} + V_{on} \Delta V_i + V_{on} \Delta V_o + \Delta V_i \Delta V_o]$$
$$Q_{on} + \Delta Q_{s} = \frac{3}{X_c} [V_{on} V_{in} + V_{on} \Delta V_i + V_{on} \Delta V_o + \Delta V_i \Delta V_o]$$

(22)

Simplifying (22), while considering $\delta_i$ very small, we get

$$P_{on} + \Delta P_{s} = \frac{3}{X_c} [V_{on} V_{in} + V_{on} \Delta V_i + V_{on} \Delta V_o + \Delta V_i \Delta V_o]$$
$$Q_{on} + \Delta Q_{s} = \frac{3}{X_c} [V_{on} V_{in} + V_{on} \Delta V_i + V_{on} \Delta V_o + \Delta V_i \Delta V_o]$$

(23)

Simplifying (23) further we get

$$P_{on} + \Delta P_{s} = P_{on} + \frac{3}{X_c} [V_{on} \delta_i \Delta V_i + V_{in} \delta_i \Delta V_o + \delta_i \Delta V_i \Delta V_o + \Delta V_i \Delta V_o]$$
$$Q_{on} + \Delta Q_{s} = Q_{on} + \frac{3}{X_c} [V_{on} \Delta V_i + V_{in} \Delta V_o + \Delta V_i \Delta V_o]$$

(24)

Now, considering nominal voltages $V_{on}$ and $V_{in}$ equal, ignoring second and higher-order perturbation terms, (24) can be written in the simplified form given in (25).

$$\Delta P_{s} = \frac{3}{X_c} [V_{on} \delta_i \Delta V_i + V_{on} V_{in} \Delta \delta]$$
$$\Delta Q_{s} = \frac{3}{X_c} [V_{on} \Delta V_i + V_{on} V_{in} \Delta \delta]$$

(25)

Similarly, small-signal model for (9) can be derived as follows,

$$(\delta_i + \Delta \delta) = \delta_i + \int (\Delta \omega_e - \Delta \omega_i) dt$$

(26)

$$\Delta \delta = \int (\Delta \omega_e - \Delta \omega_i) dt$$

(27)

Now, small-signal model for (14) can be derived as follows:

$$(P_{set} + \Delta P_{set} - P_{on} - \Delta P_{s}) = M_p \frac{d \omega_{on} + \Delta \omega_i}{dt}$$

$$+ D_p (\omega_{on} + \Delta \omega_i - \omega_i)$$

(29)

$$(P_{set} - P_{on}) + \Delta P_{set} - \Delta P_{s} = M_p \frac{d \omega_{on}}{dt} + D_p (\omega_{on} - \omega_i)$$

$$+ M_p \frac{d \Delta \omega_i}{dt} + D_p \Delta \omega_i$$

(30)

$$\Delta P_{set} - \Delta P_{s} = M_p \frac{d \Delta \omega_i}{dt} + D_p \Delta \omega_i$$

(31)

and the derivation for the small-signal model of (16) is given as follows:

$$(Q_{set} + \Delta Q_{set} - Q_{on} - \Delta Q_{s}) = N_q \frac{d V_{on} + \Delta V_o}{dt}$$

$$+ D_q (V_{on} + \Delta V_o - V_o)$$

(32)

$$(Q_{set} - Q_{on}) + \Delta Q_{set} - \Delta Q_{s} = N_q \frac{d V_{on}}{dt} + D_q (V_{on} - V_o)$$

$$+ N_q \frac{d \Delta V_o}{dt} + D_q \Delta V_o$$

(33)

$$\Delta Q_{set} - \Delta Q_{s} = N_q \frac{d \Delta V_o}{dt} + D_q \Delta V_o$$

(34)

Similarly, small-signal model for (19) can be derived as follows:

$$(\omega_{on} + \Delta \omega_i) \approx (\omega_{on} + \Delta \omega_i)$$

$$\theta_{on} + \Delta \theta_e \approx (\theta_{on} + \Delta \theta_e)$$

(35)

$$(V_{on} + \Delta V_o) \approx (V_{on} + \Delta V_o)$$

At steady state, the nominal value for the reference and actual quantity is equal. Now, (35) can be written as

$$\Delta \theta_e \approx \Delta \theta_i$$

$$\Delta V_o \approx \Delta V_o$$

(36)

Applying Laplace transformation, equations, (25), (28), (36), (31) and (34) can be expressed in small-signal form and they are written as
\[ \Delta P_e(s) = \frac{3V_mV_l\Delta \delta(s)}{X_c} + \frac{3V_l\delta(s)\Delta V(s)}{X_c} \]
\[ \Delta Q_e(s) = \frac{3V_mV_l\Delta V(s)}{X_c} + \frac{3V_l\delta(s)\Delta V(s)}{X_c} \]
\[ \Delta V_p(s) = \frac{3V_mV_l\Delta \delta}{X_c} = K_p \Delta \delta \]
\[ \Delta Q_e(s) = \frac{3V_mV_l\Delta V(s)}{X_c} + \frac{3V_l\delta(s)\Delta V(s)}{X_c} \]

where \( K_p = \left( \frac{3V_mV_l}{X_c} \right) \) and \( K_q = \left( \frac{3V_m}{X_c} \right) \).

As a result, the design of the control parameters of both the loops can be done independently, which greatly simplifies the design procedure.

For introducing secondary control, \( \Delta P_{set} \) and \( \Delta Q_{set} \) are generated from \( \Delta \delta(s) \) and \( \Delta V(s) \), respectively. The small-signal model of the secondary control is derived from (20), and is given as

\[ \Delta P_{set}(s) = -G_{ps}(s)\Delta \alpha_0(s) = -\left( \frac{K_p}{s} + \frac{K_q}{s} \right) \Delta \alpha_0(s) \]
\[ \Delta Q_{set}(s) = -G_{qs}(s)\Delta \delta(s) = -\left( \frac{K_p}{s} + \frac{K_q}{s} \right) \Delta \delta(s) \]

Therefore, the complete small-signal model of the VIE with RC of the VSG can be derived from (38), (40)–(42); and is given in Fig. 6.

Fig. 5  Small signal model of the VSG with VIE and RC

Fig. 6  Closed-loop block diagram of the Small signal model of the VSG without coupling along with the VIE
(a) Active PFL, (b) Reactive QVL
Fig. 7 Block diagram of the Small signal model of the VSG without coupling along with the VIE and RC
(a) PFL with RC, (b) QVL with RC

\[ T_{PFL}(s) = \frac{\Delta P_{s}(s)}{\Delta P_{set}(s)} = \frac{K_p}{M_p s^2 + D_p s + K_p} \]
\[ T_{QVL}(s) = \frac{\Delta Q_{s}(s)}{\Delta Q_{set}(s)} = \frac{K_q}{N_q s^2 + (D_q + K_q) s + K_q} \]

In order to ensure the stability of the system the value of the \( M_p \) in the PFL and the \( N_q \) in the QVL are required to be designed by satisfying the PM requirement (\( \text{PM}_{\text{req}} \geq 30^\circ \)). To establish the design, bode diagram of the PFL and QVL for the various values of \( M_p \) and \( N_q \) are plotted in Fig. 8. From Fig. 8a, it is clear that with the increase of \( M_p \) the PM decreases but attenuation of the double frequency components in the power terms gets better. Although high PM is always desirable from stability point of view it increases the settling time and overshoot and oscillation in the response. Therefore, a trade-off is needed to decide the \( M_p \) so that satisfactory attenuation can be achieved with a good PM. In this work \( M_p \) is decided at 20 where PM is at around 46° and the attenuation at double line frequency is \(-7\) dB. In case of the PFL, the maximum value of \( M_p \) is decided from the PM criteria but for QVL PM is always \( >30^\circ \) and it is 108° irrespective of the value of \( N_q \). Therefore, to select the value of \( N_q \), the magnitude plot in Fig. 8b is considered to check the attenuation of the double frequency terms. The value of the \( N_q \) is considered is 15 at which attenuation at double frequency is around \(-8\) dB.

Due to the use of the RC, the steady-state part of the VIE characteristics of the VSG is improved. In order to investigate the effect of the RC on the dynamic behaviour of the VSG, the transfer function of the inertia emulation is derived from Fig. 7 and it is given by

\[ T_{PFL}(s) = \frac{\Delta \omega_{e}(s)}{\Delta P_{set}(s)} = \frac{s}{M_p s^2 + (D_p + k_p) s + (K_p + k_p)} \]
\[ T_{QVL}(s) = \frac{\Delta V_{q}(s)}{\Delta Q_{set}(s)} = \frac{s}{N_q s^2 + (D_q + K_q + k_q) s + k_q} \]

The function of the RC is to eliminate the steady-state error of the voltage magnitude and frequency. As RC is the outer loop control, thus the response of the controller should be slower as compared with the inner part of the VIE controller to avoid the interference between the control loops. RC is basically integral (or I type) controller is used to eliminate the steady-state error in a slower time frame. Now to check the behaviour and the inertia emulation performance of the PFL, and QVL including RC, the family of root locus of the complete VIE loops with RC (Fig. 7) for different values of the \( k_p \) and \( k_q \) have been established and given in Fig. 9.

In the root locus plots, the value of the \( M_p \) is varied between 0 to 40 and \( N_q \) is varied between 0 to 50, respectively. However, for a
Fig. 9 Family of root locus of the VIE loops with RC
(a) Root locus of the PFL with RC while \( M_p \) is varying from 0 to 40 and \( k_i \) is set at the values of 0, 1500 and 3000, (b) Root locus of the QVL with RC while \( N_q \) is varying from 0 to 500 and \( k_i \) is set at the values of 0, 1500 and 3000

Table 1 Parametric values of the VSG

| Parameters          | Value   | Parameters          | Value   |
|---------------------|---------|---------------------|---------|
| rated active Power, \( P_c \) | 7.5 kW   | rated reactive power, \( Q_a \) | 2 kWAr    |
| voltage, \( V_a \)  | 230 V   | DC link voltage, \( v_{dc} \) | 750 V     |
| frequency, \( f_a \) | 50 Hz   | DC link capacitance, \( C_{dc} \) | 5 mF      |
| filter inductance, \( L_f \) | 4 mH    | filter resistance, \( r_f \) | 0.1 Ω    |
| line inductance, \( L_e \) | 3.8 mH  | filter capacitance, \( C_f \) | 100 μF   |

In the first two cases (Cases 1 and 2), the RC is deactivated to study its impact on the output voltage and frequency of the VSG. Therefore, the active and reactive power set points \( (P_{set} \neq 0 \text{ and } Q_{set} = 0) \) and vice versa. During the load change, shown controller in the system-wide performance, the following cases are considered:

- **Case 1**: VSG operation without VIE \( (M_p = 0) \), VEE \( (N_q = 0) \) and RC \( (P_{set} = 0 \text{ and } Q_{set} = 0) \).
- **Case 2**: VSG operation with VIE \( (M_p \neq 0) \) and VEE \( (N_q \neq 0) \) but without RC \( (P_{set} = 0 \text{ and } Q_{set} = 0) \).
- **Case 3**: VSG operation without VIE \( (M_p = 0) \) and VEE \( (N_q = 0) \) but with RC \( (P_{set} \neq 0 \text{ and } Q_{set} = 0) \).
- **Case 4**: VSG operation with VIE \( (M_p \neq 0) \), VEE \( (N_q \neq 0) \) and RC \( (P_{set} \neq 0 \text{ and } Q_{set} \neq 0) \).

5.1 Without restoration control (cases 1 and 2)

In all four cases, the pattern of load variation and change in renewable energy generations are kept the same for the comparison. The pattern of the power output of the individual microgrid forming components along with the power supply to the load is given in Fig. 10.

The impact of the virtual inertia and excitation emulation with RC in the VSG operation for different cases are analysed in the following subsections.
in Figs. 11a and b, the voltage magnitude in Fig. 11d and frequency in Fig. 11c, both vary smoothly under Case-2 as compared with Case-1. This happens because of the presence of non-zero inertia and excitation coefficients (i.e. $M_p = 20$, $N_q = 15$) in Case-2. Therefore, sharp nature (Case 1) of the variations in the magnitude and frequency of the output voltage gets smoothed out when proposed inertia and excitation emulation is applied (Case 2). Corresponding percentage deviations in frequency and the voltage magnitude, respectively, are shown in Figs. 11e and f, and a steady-state error is observed. Therefore, VSG operation with RC is essential to improve the output voltage quality of the VSG. This is discussed in Case-3 and 4 in the following subsection.
5.2 With restoration control (Cases 3 and 4)

The problems discussed in the previous subsection are eliminated by considering RC. In Case 3 and 4, RC is considered to generate \( P_{\text{set}} \) and \( Q_{\text{set}} \) from the steady-state errors in frequency \( \omega_o \) and voltage magnitude \( V_o \). The frequency and voltage magnitude of the VSG output and their deviations along with the active and reactive power output under Case 3 (red) and Case 4 (blue) are given Fig. 12. From the figure, it is clear that with the change in load active and reactive power, as shown in Figs. 12a and b, the magnitude (Fig. 12d) and the frequency (Fig. 12e) of the output voltage varies smoothly with less transient peak under Case4 (blue) as compared with Case3 (red). The smoothness is mainly occurred due to the inertia and excitation emulation, i.e. non-zero inertia and excitation coefficients (i.e. \( M_p = 20, N_q = 15 \)). However, due to the RC, the output voltage and frequency gradually reache to their nominal value once transient dies out. This is due to the reason that the active and reactive power setpoints \( (P_{\text{set}}, Q_{\text{set}}) \) are re-adjusted to the new value based on the load change. The corresponding percentage deviations in the frequency and voltage magnitude are shown in Figs. 12e and f, respectively, and are reduced to almost zero at steady state. Therefore, the implementation of the proposed inertia and excitation emulation along with the RC (Case 4) improves the transient as well as steady-state performance in both the voltage and frequency response of the VSG including frequency nadir of the microgrid.

Moreover, in Fig. 10, it is observed that there is a difference in the power delivered to the load under different cases. This is mainly occurred due to the presence of the RC in the VSG operation. When VSG is operated without RC, the voltage and frequency are less than the rated value. Due to the constant impedance type load, it is not able to consume its rated power when RC is absent. However, in presence of RC, power consumption by the load is at its rated value. Therefore, it can be concluded that the RC is essential for the VSG operation in the microgrid.

6 Advantages/disadvantages of proposed VSG technique over direct voltage and frequency control

In comparison with direct voltage and frequency control technique, the proposed VSG control technique is more complex in nature due to the presence of an extra layer of control in VSG. However, the cost of complexity due to the extra control layer pays off in terms of the following advantages for the VSG.

- Incorporation of inertia and damping feature in the control structure.
- Stability enhancement under large load variation by reducing the overshoot and undershoot.
- Easy future expansion through parallel operation without changing control structure.

7 Usefulness of the proposed control in real time

Generally, the presence of inertia and excitation systems plays an important role in improving the transient stability of the system.
However, the PEC dominated microgrid poses vary low inertia. Hence, the presence of proposed emulations can add inertia and excitation characteristics in the converters through VSG control. In real-time practice, when more and more PEC interfaced renewable generators would be integrated into the main grid, the total inertia of the power system will be reduced. In that case, small boost of inertia by VIC in individual microgrid level may help to improve overall inertia in a large integrated power system and improve its transient stability in terms of frequency. Similarly, the emulation of excitation would help to provide well regulated voltage in the system under high penetration of microgrids. Therefore, it is expected that the proposed control in individual microgrid level will play a significant role in real-time practice also.

8 Conclusions
An emulation based controller consists of VIE and VEE techniques for a VSG of a standalone microgrid has been presented in the paper. The proposed VEE, implemented by mimicking excitation behaviour of an SG, produces comparatively smooth AC voltage magnitude during transients. The frequency and voltage restoration controllers are augmented with the inertia and excitation emulation for the improvement of steady-state responses and achieving isochronous control. The performance analysis and the parameters design of the proposed controller are also presented. The results show that the proposed controller is able to improve the profile of the voltage magnitude and frequency variation during both transients and steady state. Finally it is observed that the RC is very essential for the standalone operation of a microgrid. Otherwise the power delivered to the constant impedance load is reduced due to steady-state error.

9 References
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