Virtual Inertia Control Strategy in Microgrid Stability Control: A Conceptual Synthesis and Discussion

Debabrata Routray, Vijaya Kumar Dunna, Pravat Kumar Rout, and Binod Kumar Sahu

Abstract The integration of distributed generations in a smart microgrid distribution system as focused in recent times and considered as a solution towards the exponential rise of energy demands. However, the inverter-based energy sources lead to a weak power system in the sense of having low inertia. This, in turn, make the overall system more prone to instability. The related issues and challenges along with its remedial misuse in terms of control prospective need to be discussed thoroughly. On the above-related problems, this paper presents all possible virtual inertia topologies in the implementation stage. Apart from that, this paper explores potential research directions, major challenges, and technical analysis on the state-of-the-art of virtual inertia. Comparative analysis also discussed mentioning the merits and limitations of the topologies. To understand the concept, the related mathematical expressions and schematic diagrams of different topologies and control strategies are illustrated.

Keywords Virtual inertia · Frequency stability · Renewable energy sources · Distributer generators · Microgrid control

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1 Introduction

The operation of the power system needs to stabilize under any fluctuation or power discrepancy between the power generation and load demand. Synchronized operation with proper coordination and equilibrium is essential to maintain the desired frequency and voltage. For the above issues and challenges, the inertia of the power system and its components play a vital role, and its level indicates the system capability to handle the power deficiency and the subsequent effects.

The inertia of the rotating mass of synchronous generators (SGs) and turbines is a measure of their kinetic energy (KE) stored to regulate the power deviation and that in turn frequency fluctuations. This reserve K.E injects into the grid or absorbs from the grid to prevent any deviation in frequency. In other words, the frequency is a reflection of inequalities in the overall power balance, and a higher inertia system is more capable to stabilize fast due to the availability of K.E more in the rotating mass [1]. On the other hand, the higher the inertia, the higher is the damping and lesser fluctuation of grid frequency to sudden changes in load patterns as well as generation. The reverse dynamics play for the lower inertia systems. Figure 1 indicates the above dynamics related to inertia in microgrid system. This motivates to discuss further on inertia concept and its relevance in power systems.

In recent times to circumvent the deficit of power, distributed generators (DGs) are integrated at a smart distribution system. The microgrid system can operate in both grid-connected and islanded mode of operation. The dynamics, operational characteristics, and random intermittent power generation due to the environmental dependency of different types of DGs make the operation quite different in comparison to traditional centralized facilities. Due to the environmental dependency there is a chance of electrically decoupling of the DGs from the grid. So the DGs are unable to contribute inertia to the overall system. Moreover, the synchronous generator is providing inertia to the system that is very often missing

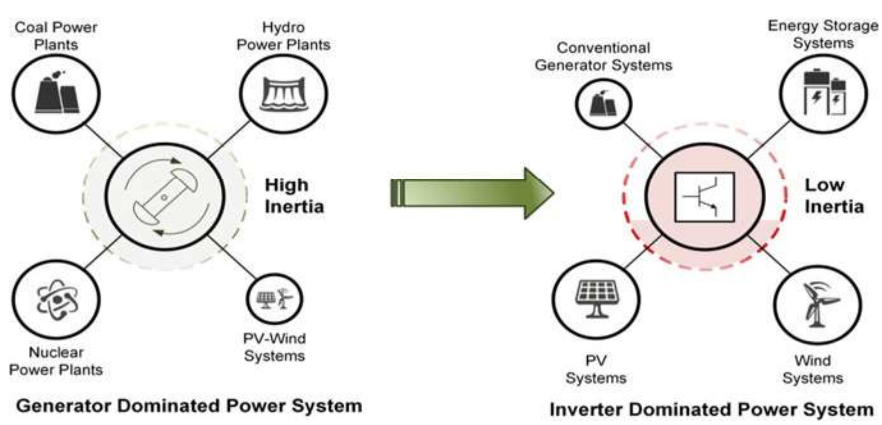

Fig. 1 Advancement towards an inverter-based power system

in these renewable generation units. So, the inertia of the modern smart power system decreases with the integration of a large number of converters connected generation units and loads. This in turn forced to behave a power system differently from before. This caused concerns for power engineers to stabilize the system. Therefore, a detailed study and revised analysis with possible futuristic methods to enhance the inertia through providing adequate control strategy is essential. In this paper, the relevance and possible inertia-based control strategy in power system sire discussed from a better operation, control, and stability of the smart microgrid system.

Specific to small and smart DGs integrated microgrid system, inertia study is very crucial due to the major factors like:

I The inertia of these types of systems is comparatively very low to large power systems or grid-connected power systems. This concept is illustrated in Fig. 2.

II Secondly, the ratio of the magnitude of a possible generation outage to the total spinning capacity is relatively large for these systems.

III The DGs are generally inverter based rather than rotational based like PV and wind turbines. The inverter-based generation does not give any mechanical inertial response, so that we compromised with frequency stability.

IV Frequency stability in recent times becomes a serious concern and needs a better control strategy due to a lack of inertia.

V There is a necessity to integrate DGs in the microgrid system with a larger percentage irrespective of the limitation. Inertial control brings stability to the system in a very short time interval (less than 10 s) automatically as illustrated in Fig. 3; so adequate inertia control is necessary to open up the high penetration level of the DGs [2].

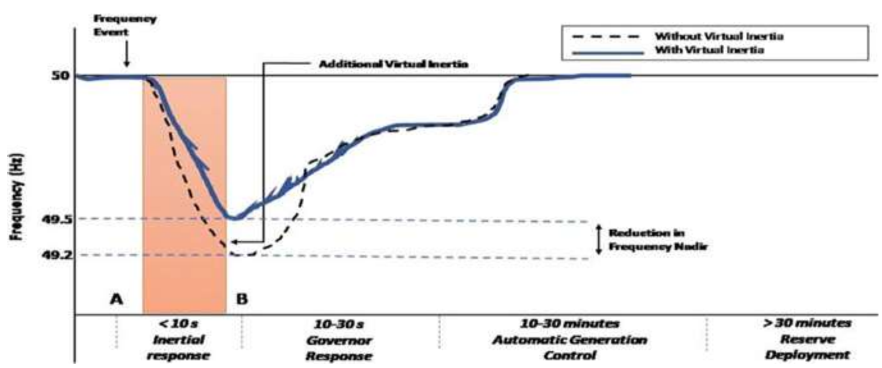

Fig. 2 Multiple time-frame frequency responses following a frequency event in a power system

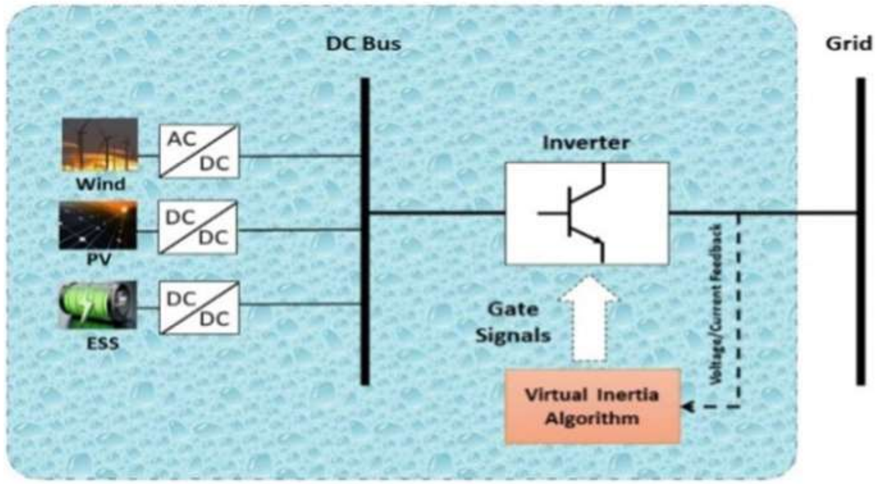

Fig. 3 Virtual inertia concept

2 Microgrid Instability with High Penetration of RES

This section presents inertia of the traditional power system (PS), frequency response of conventional power system, and the impact of DGs on inertia of the power system.

2.1 Inertia of the Conventional Power System

The frequency response of a PS on a frequency event/disturbance is regulated according to the swing equation.

$$P_{\mathrm{g}} - P_{\mathrm{l}} = \frac{\mathrm{d}}{\mathrm{d}t}(E_{\mathrm{K.E}}) = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{1}{2}J\omega_{\mathrm{g}}^2\right) \tag{1}$$

$$P_{\mathrm{g}} - P_{\mathrm{l}} = \frac{J\omega_g \mathrm{d}\omega_g}{\mathrm{d}t} \tag{2}$$

where P_{g}, P_{l}, J, and ω_g are denoted for generated power, power demand (losses are included), total system inertia, and angular system, respectively. The normalized inertia constant of the PS 'H' can be defined in terms of apparent power S_{g} of the integrated generators in the system.

$$H = \frac{1}{2}\frac{J\omega_g^2}{S_g} \tag{3}$$

Substituting (3) in Eq. (2)

$$P_g - P_l = \left(\frac{2S_g H}{\omega_g^2}\right)\omega_g \frac{d}{dt}(\omega_g) \tag{4}$$

Simplifying

$$\frac{2H}{\omega_g}\frac{d\omega_g}{dt} = \frac{P_g - P_l}{S_g} \tag{5}$$

Expressing Eq. (5) in terms of frequency (f) and substituting

$$\omega = 2\pi f \text{ rad/sec}$$

$$\frac{2H}{f}\frac{df}{dt} = \frac{P_g - P_l}{S_g} \tag{6}$$

where $\frac{df}{dt}$ is the rate of change of frequency (ROCOF) of the system.

The following conclusions can be drawn from Eq. (6).

(a) $\frac{df}{dt}$ is higher with less H. So, to integrate more DGs, there is a necessity to increase H.
(b) The value of H is very low in case of inverter-based DGs as shown in Fig. 1, as these sources are decoupled from the grid and not participate for inertia compensation.
(c) The K.E of generator is due to rotating mass that K.E contributes to the grid or absorbs from the grid under frequency variation. In other words, from any discrepancy between the demand and supply, frequency of the system will fluctuate proportional to the system inertia.
(d) The study interprets 'inertia' in conventional PS, as the opposition/resistance offered by the SG, to change in the rotational speed. In another aspect, any energy backup/support for an extremely short period of time during load fluctuations can be interpreted as inertia [3].

2.2 Frequency Response and Effect of Inertia on Frequency

In normal operation, under any abnormal event occurrence, the system frequency starts to decline due to generation-demand unbalance. However, the level of decline and rate of frequency both depend on total system inertia as illustrated in Fig. 2 and Eq. (6). Before any controller activate, due to the inbuilt inertia factor, the synchronous generator releases the K.E stored in its rotating mass lasting within 10 s duration from the time of inception as illustrated in Fig. 2. Despite of this, if the frequency declines beyond some threshold value, the primary frequency controllers are activated within 30 s. After that, if the frequency deviation will occur in the system (10–30 min), then the secondary control will take care of that and make the system frequency to a normal value. Finally, the tertiary control takes care of remaining power variation and subsequently frequency stabilization (>30 min). Reserve power availability plays a vital role of controlling in this stage [4].

The same thing can be analysed in case of inverter dominated power system; energy storage system (ESS) plays a prominent role for achieving normal frequency by providing 'inertia' to the microgrid.

2.3 DGs Impact on the Inertia of the PS

In the modern smart microgrid structure, the loads and renewable energy sources (RESs) are integrated with the grid by means of power electronics-based interfacing devices as shown in Fig. 3. As the inertia of the overall system reduces with RESs integration, the ROCOF and frequency variations would increase under any contingency events occurrence, and frequency instability that is why very likely to occur due to the low inertia, nonlinear dynamics, and damping influence of the grid [3]. The ROCOF is an indicator to the way how rapidly the frequency changes after a sudden imbalance between generator and load. The ROCOF can be defined as:

From Eq. (6),

$$\mathrm{ROCOF} = \frac{1}{2}\frac{f * \Delta P}{S_{\mathrm{g}} H} \tag{7}$$

Due to DGs integration, there is a deviation in frequency (high ROCOF). Essential measures like emulated inertia controls for converts are required. Inertia can be increased by applying various topologies in the PS [5]. The application of various topologies in PS is another option for handling the issue which arises due to offering of less inertia from loads and sources.

3 Basic Concepts on Virtual Inertial Application Strategy

3.1 Synchronverters-Based Virtual Inertia Control Topology

Synchronverters are operated to behave exactly like the SG and try to reduce the issue of lack of inertia in DG operation in a microgrid. The dynamic equations for both are the same. The mechanical power exchanged with the prime mover (with the mechanical load in another case) is replaced by the power exchange with the inverter along with filter inductors and capacitors. As a result, the voltage and frequency in microgridare regulated by DG providing inertia and damping to the grid as like conventional SG performs [6]. The basic operating principle of synchronverter topology is illustrated by an overall schematic diagram in Fig. 4 showing operating principles. Even though the synchronverters successfully able to mimic the dynamics of SG, till the complexity of the differential equations applied can lead to numerical instability. Apart from that, the topology based on voltage source converter may fetch to protection problems.

3.2 Virtual Synchronous Generator (A Swing Equation-Based Topology)

The virtual inertia can be realized for any DGs by adding a short term and fast acting energy storage system (ESS) along with a optimal control strategy for the power electronics converter. In this way, the DG dynamics can act like a virtual synchronous generator (VSG). By using a ESS with DG, VSG can be realized having virtual inertia which acts equivalently to rotor's inertia of SGs [4]. A simple

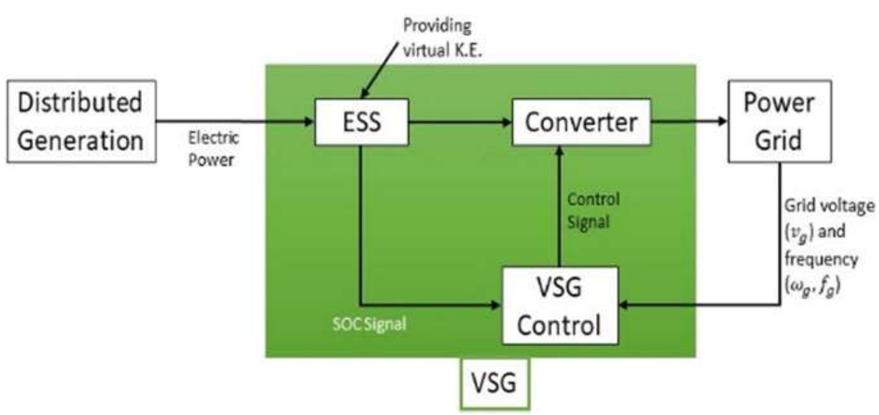

Fig. 4 Schematic diagram of synchronverter control

VSG model is illustrated in Fig. 5. A proper control signal is generated by VSG control unit based on the grid voltage/frequency and state of change (SOC) of ESS to the inverter to inject or absorb the requisite amount of power. This way the grid stability is maintained by using the virtual inertia of the VSG in the same way like the rotor inertia of SGs by using storages and keeping synchronization with other generators in microgrid [7, 8].

The K.E of rotor can be expressed as:

$$\text{K.E} = \frac{1}{2} J\omega_m^2 \tag{8}$$

where J and ω are the inertia coefficient and rotor speed (a virtual angular frequency), respectively.

The swing equation model for the VSG can be expressed as:

$$P_{\text{ref}} - P_{\text{act}} = J\omega_m \frac{\mathrm{d}\omega_m}{\mathrm{d}t} + D.\Delta\omega_m \tag{9}$$

where D and $\Delta\omega_m$ are the damping factor and $(\omega_m - \omega_g)$, respectively. Here, ω_g denotes the rotating speed of the grid voltage. Equation (9) is applied to drive the power converter. Due to that, the inverter performs like a SG. The grid frequency and power are measured to calculate $\Delta\omega_m$. Then the virtual rotor speed ω_m is computed by the VSG control block according to Eq. (9). Generally, Runge-Kutta method is used to obtain the ω_m from the differential Eq. (9). The virtual mechanical phase θ_m is computed from ω_m. This is used as the input (control signal) to the converter as a phase control command from controlling the converter output to regulate voltage and frequency as shown in Fig. 6.

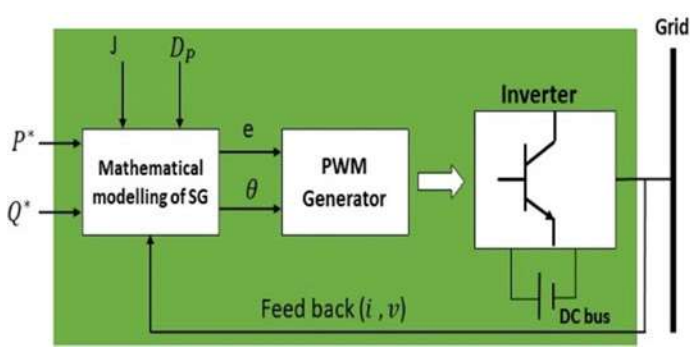

Fig. 5 VSG schematic diagram

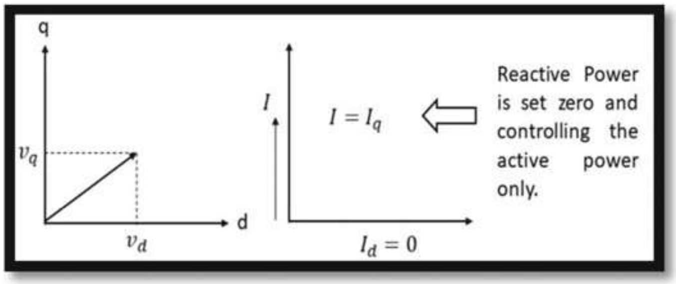

Fig. 6 *d-q* based approach

3.3 A Power-Frequency-Based Topology

The basic principle of VSG based on frequency-power response characteristics of an SG in a DG system is to emulate the inertia response characteristics with respect to frequency change; according to the frequency change response, the DG unit is operated such that it supplies or absorbed K.E exactly like the SG [5]. Under this condition, the DG acts as a dispatchable source and capable to contribute dynamic frequency control rather than only frequency regulation like conventional DG system. The basic strategy followed for this dynamic frequency control is to release inertial power by contribution of K.E or absorption of K.E same as the SG during power imbalance according to the derivative of the frequency measurement [9, 10]. The controlling output of VSG can be expressed as:

$$P_{\mathrm{VSG}} = K_{\mathrm{D}}\Delta\omega = \frac{K_{\mathrm{I}}\mathrm{d}\Delta\omega}{\mathrm{d}t} \tag{10}$$

Here, $\Delta\omega$ denote the change in angular frequency, $\frac{\mathrm{d}}{\mathrm{d}_t}\Delta\omega$ is the corresponding rate of change, K_{D} denotes the dropping constant, and K_{I} represents the inertial constant. The value of K_{D} factor regulates the frequency to decrease the frequency nadir and also achieve the steady-state value. The K_{I} seizes the ROCOF by providing a faster dynamic frequency response based on the derivative of frequency. On this approach, a detail control strategy to implement virtual inertia is illustrated in Fig. 6, based on *d-q* composition with deriving current reference as:

$$I_d^* = \frac{2}{3}\left(\frac{V_d P_{\mathrm{VSG}} - V_q Q}{V_d^2 + V_q^2}\right) \tag{11}$$

where V_d and V_q denote the *d*-axis and *q*-axis components of the grid voltage ‘V’. As shown in Fig. 6, the inverter acts as a current controlled voltage source inverter, and its gate signal is generated by the current controller based on the grid current feedback [11]. Use of phase lock loop (PLL) from synchronization and high sensitiveness due to use of derivative term are two major limitations Fig. 7.

3.4 Droop-Based Virtual Inertia Control Concept

The frequency droop equation can be represented as:

$$\omega^* - \omega_g = m_p(P_{act} - P_{ref}) \tag{12}$$

where ω^*, ω_g, P_{ref}, and P_{act} denote the reference frequency, the local grid frequency, reference set active power, and active power output (measured) from the DG unit, respectively. m_P denotes the active power droop. Similarly, the voltage droop equation can be written as:

$$v^* - v_g = m_q(Q_{act} - Q_{ref}) \tag{13}$$

where v^*, v_g, Q_{ref}, and Q_{act} denote reference voltage, local grid voltage, reference set reactive power, and measured reactive power out from the DG unit [12]. The m_q represents the reactive power droop coefficient. Both frequency and voltage droop curves as expressed in Eqs. (12) and (13) are illustrated in Fig. 8.

The schematic diagram of implementation of droop-based virtual inertia control is illustrated in Fig. 9.

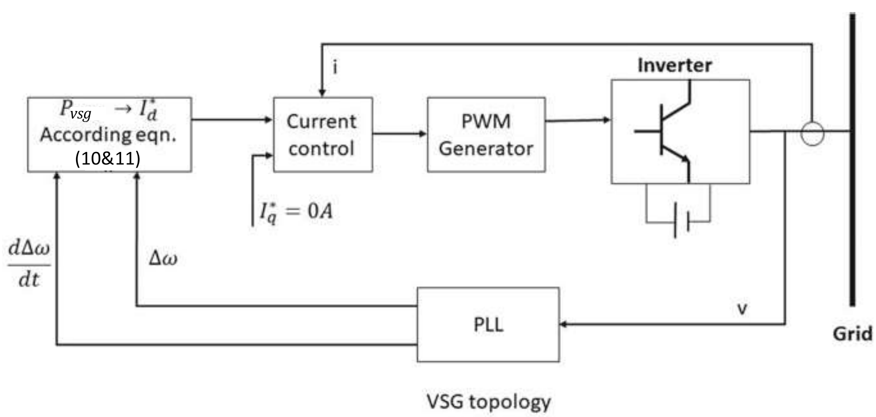

Fig. 7 Power-frequency-based topology

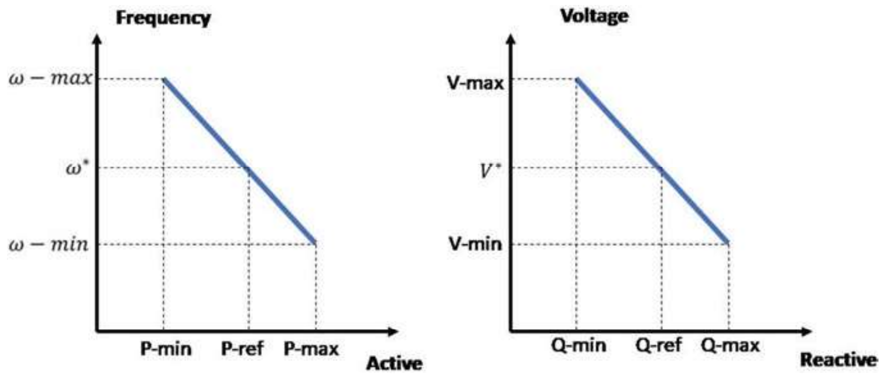

Fig. 8 Frequency and voltage droop curves

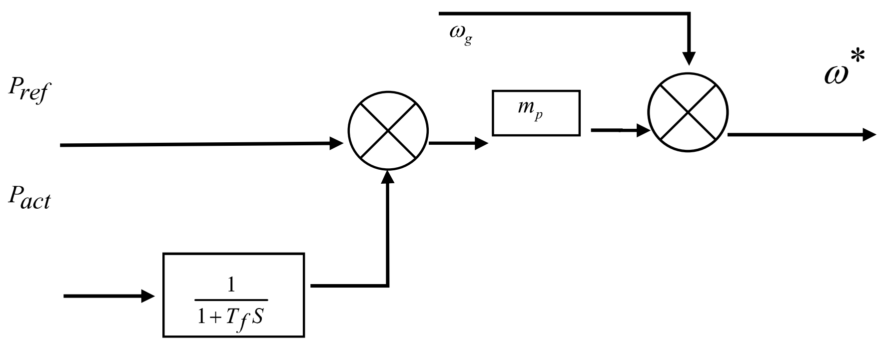

Fig. 9 Schematic diagram for frequency droop control

From Fig. 9,

$$P_{\mathrm{act}} = \left(1 + T_f S\right)\left\{\frac{1}{M_P}\left(\omega_{\mathrm{g}} - \omega^*\right) + P_{\mathrm{ref}}\right\} \tag{14}$$

Rearranging

$$P_{\mathrm{ref}} - P_{\mathrm{act}} = \frac{1}{M_P}\left(\omega^* - \omega_{\mathrm{g}}\right) + T_f \frac{1}{M_P} S\omega^* \tag{15}$$

Can be represented as:

$$P_{\mathrm{ref}} - P_{\mathrm{act}} = K_{\mathrm{D}}\left(\omega^* - \omega_{\mathrm{g}}\right) + K_{\mathrm{I}} S\omega^* \tag{16}$$

where $K_{\mathrm{I}} = T_f \cdot \frac{1}{M_P}$ and $K_{\mathrm{D}} = \frac{1}{M_P}$

Equation (16) is similar to the virtual synchronous generator (VSG) as presented in Eq. (9). The insertion of filter mimics the dynamics of SG as represented in Eq. (16). The key factors for the filter integration are:

(a) The virtual inertia system is identical with the droop-based control approach dynamics and this is done by the filter.
(b) The filter put a delay in the measurement of power and mathematically, and it is equivalent to virtual inertia. The droop gain here is similar to damping. However, slow transient response and cannot perform satisfactorily beyond inductive grid systems are two major limitations [6, 13].

4 Discussions and Findings

Synchronous generator (SG) model-based virtual inertia control strategy based on the accurate replication of SG dynamics; in this approach, phase-locked loop (PLL) is essential for synchronization, and frequency derivation is not necessary for control; however, improvisation of this technique needs to be focused on over-current protection, numerical instability concerns, and voltage source implementation. The method based on swing equation is a very simple model in comparison to SG based model. However, the control strategy is the limitations like power and frequency oscillations. Later, to overcome the limitations of the over two methods, a novel approach based on frequency-power response has emerged and gain attraction due to straight forward implantation and inherent over current protection, However, it is found that instability due to PLL in week grid, the requirement of frequency derivative and system susceptibility to noise is the measure associated limitations; lastly as discussed, droop-based approach is communication less and having a similar concept to conventional droop control in SGs till so transient response and improper transient response active power sharing are the two associated measure limitations.

5 Conclusions

The major contribution of this paper can be summarized as follows:

i. An extensive literature review on virtual inertia systems and control in the smart distribution system with DGs is presented.
ii. Different topologies and principle of operation of various virtual inertia control are discussed and analysed.
iii. The major advantages and limitations of each approach are maintained to help the reader for further improvement.

iv. The basic concept and the relevance of inertia in power system for frequency stability are emphasized.

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