

REVIEW

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# An overview of inertia requirement in modern renewable energy sourced grid: challenges and way forward

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## Abstract

As the world strives toward meeting the Paris agreement target of zero carbon emission by 2050, more renewable energy generators are now being integrated into the grid, this in turn is responsible for frequency instability challenges experienced in the new grid. The challenges associated with the modern power grid are identified in this research. In addition, a review on virtual inertial control strategies, inertia estimation techniques in power system, modeling characteristics of energy storage systems used in providing inertia support to the grid, and modeling techniques in power system operational and expansion planning is given. Findings of this study reveal that adequate system inertia in the modern grid is essential to mitigate frequency instability, thus, considering the inertia requirement of the grid in operational and expansion planning model will be key in ensuring the grid's stability. Finally, a direction for future research has been identified from the study, while an inertial constant of between 4 and 10 s is recommended to ensure frequency stability in modern power grid.

**Keywords:** Inertia, Model, Optimization, Renewable energy, Virtual inertia

## Introduction

Conventional generators are becoming undesirable in the power sector due to the negative effect of fossil fuel emissions on the environment which has led to several climate-related challenges such as increased temperatures and rainfall variabilities [1–5]. Thus, many countries around the world are now replacing their existing conventional generators with renewable energy (RE) sourced generators, in line with the Paris agreement, and the European green deal goal of zero carbon emission by 2050 as well as other RE policies geared at reducing greenhouse gases emissions [6–9].

Subsequently, about 627 GW of photovoltaic (PV) systems and 743 GW of wind turbines have already been integrated into the grid globally, with an expected increase of 45% by 2040 [10]. Thus, developed countries such as China, United States, Spain, India, Ireland, and Uruguay have already achieved high penetration of RE generators integrated into the grid [10].

On the other hand, synchronous generators (SGs) benefit the grid in numerous ways such as providing voltage and reactive power support, as well as provision of

synchronous inertia, which is responsible for maintaining the grid's frequency, particularly during times of system contingencies such as sudden loss of load or generator [10–13].

On the contrary, PV systems and modern variable speed wind turbines provide zero inertia to the grid because they lack rotating mass (for PV) and are decoupled from the grid through converters, hence they inherently cannot provide primary frequency response to the grid [14–19]. Furthermore, the increasing dominance of these variable RE generators in the power grid has led to the reduced overall system inertia of the grid, which causes grid stability challenges such as severe frequency nadir, voltage instability, fast rate of change of frequency (RoCoF), and increased harmonics [19–21]. For example, countries such as New Zealand, United States, United Kingdom, Cyprus, and Ireland with high penetration of RE sources have already reported cases of power disturbances due to large frequency nadir (47.5 Hz) and fast rate of change of frequency (0.73 Hz/s) which led to power interruption to a large number of customers [22].

Several methods have been proposed in the literature to mitigate frequency instability by primarily emulating the inertia response of SGs and induction machines through the use of RE sources and energy storage sources (ESS) with a suitable converter control strategy, this concept is called virtual inertia control [19, 23–25]. Other methods adopted to provide frequency stability include RE curtailment or deloaded operation of RE generators [26–28], use of synchronous condensers to provide synchronous inertia [22, 29–31], and load curtailment using incentive-based demand response schemes such as direct load control, and time-of-use rates [32–34].

Furthermore, optimization models have been used to proffer solutions to challenges arising from the increasing growth of RE generators in the grid. The authors in [35] developed a generation expansion planning (GEP) model solved as a mixed-integer linear programming (MILP) optimization problem to minimize investment cost and air pollution. Authors in [36–39] proposed a generation and transmission expansion planning model (GTPEP) to minimize the investment and operational costs of new power plants. Authors in [40] and [41] developed a MILP model to minimize investment cost using the Tailored Benders decomposition algorithm in MATLAB and Nested Benders decomposition in Python. The studies, however, did not consider the frequency stability of the grid in planning. Furthermore, the authors in [42] carried out generation expansion planning for PV, thermal, and wind power plant to minimize the investment and operational costs. Fitiwi in [43] developed a linear AC optimal power flow model for generation expansion planning to minimize cost, voltage violations, and energy losses using the CPLEX solver in GAMS, this model was evaluated using the IEEE 23, 54, and 69 bus system. However, the study did not account for the inertia requirement of the grid for stability. Authors in [44] proposed a hybrid framework for GTPEP to minimize planning cost while considering the resilience of the power system components. Furthermore, Kim in [45] proposed a probabilistic model for grid expansion planning using the Weibull distribution, considering wind energy uncertainties, while the authors in [46] proposed a model for optimal placement of battery energy storage system (BESS) in transmission expansion planning (TEP) using the Benders' decomposition approach. More so, in [47], the authors proposed a generation, storage, and transmission expansion planning (GSTEP) model

to minimize cost while meeting the load demand. In [48], an integrated multi-period model of transmission, generation, and storage expansion planning (TGSEP) model was proposed considering uncertainties from renewable energy sources (RES) and load demand. However, this model is limited as only BESS was considered as the energy storage system. In [49], a TEP model was proposed to minimize power outages and cost using the Benders decomposition algorithm, while the authors in [50] carried out a multi-period generation expansion planning for wind power plants using a differential evolution algorithm. Furthermore, the authors in [51] developed a scenario-based stochastic model for integrated electricity and gas networks expansion planning (IEGNEP) model considering N-1 contingency criteria, and system uncertainties from PV generation and electrical loads. More so, the authors in [52] and [53] analyzed the economic effect of carbon tax on power system expansion planning model by developing a MILP model to minimize carbon emission in the power system for a period of 10 years. Authors in [54] developed a scenario-based multi-objective model to minimize CO<sub>2</sub> emission and cost of investment and operation in a distribution system expansion planning model (DSEP) considering system uncertainties. The authors in [55] also investigated the effect of climate changes on wind speed in GTEP for a 85 years planning period. Furthermore, the authors in [56] proposed a two-stage robust optimization approach to minimize investment cost in a distribution network, while considering N-1 generation contingency and demand response. The model was tested in a modified IEEE 123-bus test system.

The review of the literature reveals that no work has yet considered cost, emission, and the inertia requirement of the grid in joint generation and transmission expansion planning. This paper therefore aims to give foresight into inertia consideration in operational and joint generation and transmission expansion planning optimization model.

The specific objectives of this research are as follows:

- To provide a synoptic review of the impact of increasing RE sources on the dynamics of the power grid.
- To provide a review of virtual inertia topologies and strategies used in compensating system inertia in renewable energy sourced grid.
- To give a concise review of the modeling characteristics of energy storage systems essential for providing additional inertia to the grid.
- To provide a review on inertia estimation methods in power system.

The remaining part of this paper is organized as follows. “[Frequency stability in power system](#)” section highlights the transformation in grid composition and reviews the associated frequency instability challenges in the new grid. It further gives the modeling characteristics of energy storage systems suited for virtual inertia provision. “[The concept of inertia in power system](#)” section gives the description and mathematical formulation of system inertia. It further gives the various inertia estimation techniques in power system. “[Virtual inertia topology and strategy in modern power grid](#)” section gives the types of virtual inertia control topologies and strategies highlighting their merits and demerits. “[Operational and expansion planning](#)”

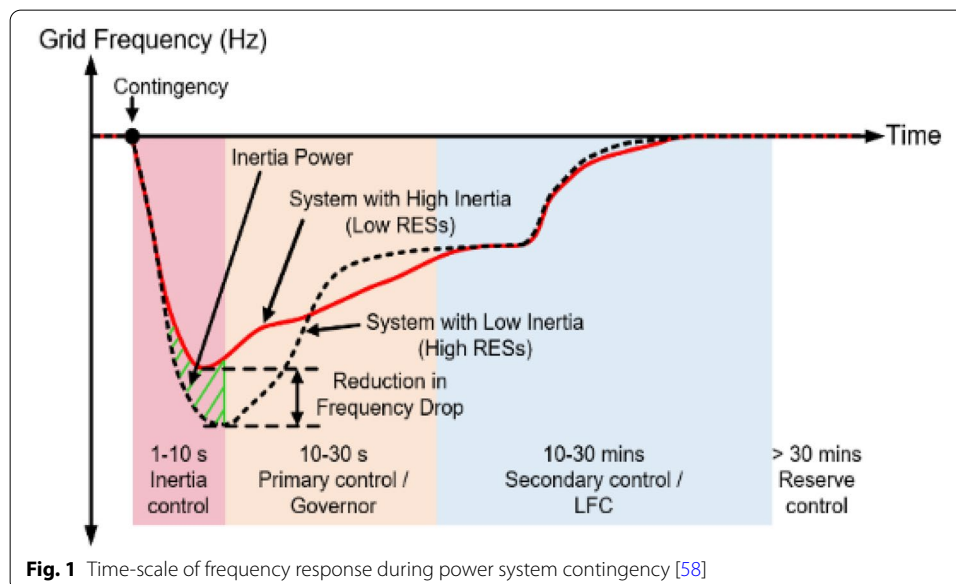
“[optimization in power system](#)” section gives an overview of various techniques used in operational and expansion planning optimization models, while “[Conclusion](#)” section gives the conclusion of the research.

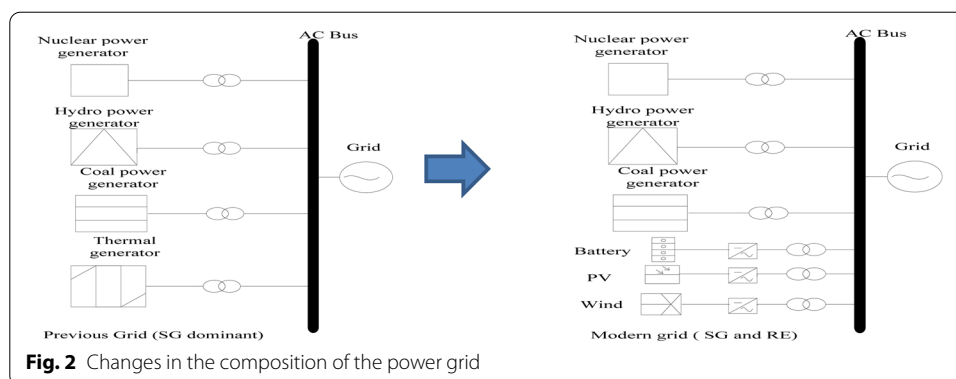
### Frequency stability in power system

Frequency control techniques are used to ensure frequency is maintained within a specified limit after system contingency [33, 57]. During times of system contingency, the inertia inherent in the grid reacts first by providing an instant frequency response within 1–10 s after the disturbance, just before the controllers are triggered [58–60]. Figure 1 shows the timeline of frequency responses in power system. It is seen that a system with low inertia will experience larger frequency nadir compared with a system with high inertia system. More so, it is observed that primary frequency controllers are set to operate immediately after the inertia response has been provided, while the secondary frequency control or automatic generator control action takes place between 10 and 30 min after the contingency as occurred [58, 61].

### Dynamics and composition of renewable energy-sourced Grid

The dynamics and structural composition of the power grid are changing due to the increased penetration of RE generators into the grid. This in turn is responsible for the declining overall inertia of the grid. More so, the inertia obtained from RE sources is time-varying due to the stochastic nature of RE generators thus making the overall system inertia time-varying inertia [62]. These changes have led to technical challenges such as high-frequency deviations (spike and nadir), unwanted frequency oscillations, and high rate of change of frequency [63]. These frequency instabilities are undesirable in power system as they may lead to cascaded system failures. Figure 2 shows the transformation in the composition of the grid over the years, from synchronous generators dominant to renewable energy generators dominant.





### Frequency mitigating strategies in Renewable energy sourced grid

Owing to the frequency-related challenges associated with renewable energy-sourced grid, countries such as Ireland and Australia have now pegged RE integration into the grid at a certain percentage (70%) to keep RoCoF below 0.5 Hz/s during contingencies, while others have revised their grid codes in line with the new dynamics of the grid [10]. The most commonly used method is by emulating the inertia of SGs and induction machines using RE sources, energy storage system with an appropriate converter control strategy [19, 24, 25]. Authors in [9, 13, 21, 64] also proposed the use of synchronous generators as spinning reserves, synchronous condensers, and rotating stabilizers to provide inertia to the grid during times of contingency, while RE generators remain the main source of power generation. Though this method provides the needed system inertia, it is however limited by its high cost of implementation and high carbon emission. Authors in [21, 22, 65] proposed the use of energy storage systems together with renewable energy sources in a hybrid combination such as PV-BESS, wind turbine-flywheel energy storage (FES), and PV-supercapacitor (SCES). Authors in [66] proposed a model comprising a hybrid combination of BESS and SCES to mitigate frequency fluctuation at the point of coupling of rooftop solar PV units.

### Characteristics of energy storage systems

Energy storage systems are often used to provide stability in the grid by supplying energy to the grid during times of deficiency or absorbing energy from the grid during times of excess [80]. Good knowledge of the characteristics of the various types of energy storage systems used for providing additional inertia to the grid is important for proper modeling of the dynamics of the new grid. The unique characteristics of commonly used energy storage systems suited for inertia provision are discussed here.

#### **Battery energy storage system**

Battery energy storage system is one of the commonly used storage systems in modern power system. BESS can be modeled based on its characteristics such as the number of charge–discharge cycles, state of charge (SoC), depth of discharge (DoD), and charging and discharging rate [81–84] as seen in Table 1.

The charging and discharging equation of a battery can be given as in Eqs. (1) and (2), respectively.

**Table 1** Modeling features of BESS

Modeling parameters	Range of values	Refs.
Average state of charge(SOC) of BESS	0.05–0.95	[86]
Annual battery degradation capacity	0–2.59	[87]
Depth of Discharge (%)	45–90	[88]
Energy to Power Ratio (MWh/MW)	0.25–10	[47, 89]
Average Investment Cost (US\$/MWh)	536,000	[47, 90]
Ramp rate (%)	100	[89]
Operation and Maintenance costs (\$/kW)	10–28	[91]
Power density (Wh/kg)	16–250	[92]

$$E_b^t = E_b^{t-1} + P_{b,c}^t \cdot \eta_b^c \quad (1)$$

$$E_b^t = E_b^{t-1} + P_{b,d}^t / \eta_b^d \quad (2)$$

where  $E_b^t$  and  $E_b^{t-1}$  are the stored energy in the battery after and before charge, respectively.  $P_{b,c}^t$  is the charging power of battery,  $P_{b,d}^t$  is the discharging power of the battery,  $\eta_b^c$  and  $\eta_b^d$  are the charging and discharging efficiency of the battery, respectively.

The state of charge of a battery can then be estimated as in Eq. (3) [85].

$$SoC_{b,t} = SoC_{b,t-1} + [P_{b,c}^t \cdot \eta_b^c - P_{b,d}^t / \eta_b^d] \quad (3)$$

where  $SoC_{b,t}$  and  $SoC_{b,t-1}$  defines the present and previous state of charge of the battery, respectively.

The DoD of a battery indicates the battery's discharge percentage relative to the total capacity of the battery. The DoD can be expressed in terms of the battery's SoC as in Eq. (4).

$$DoD = 1 - SoC \quad (4)$$

### **Pumped hydro storage system**

Pumped hydro energy storage (PHES) is an energy storage system that is often used in hybridized forms such as PV-PHES, WIND-PHES, WIND-PV-PHES, and HYDRO-PHES, which can provide synchronous inertia to the grid. Pumped hydro storage system comprises the pump, hydro-turbine, penstock, upper and lower reservoirs [93, 94]. PHES operates in generating mode during times of energy deficiencies and in the pumping mode during times of energy surplus. In the generating mode the water from the upper reservoir drives the hydro turbine to generate electricity, while in the pumping mode, water is transported from the lower to the upper reservoir for storage [95, 96].

PHES can be modeled based on its characteristics such as the size of its reservoirs, water flow rate, volume of water stored, type of pumps and turbines as seen in Table 2 and expressed in Eqs. (5, 6, 7, 8).

During pumping mode, the electrical power used by the pump is expressed as in (5).

**Table 2** Modeling characteristics of PHES

Modeling parameters	Range of values	Refs.
Average construction Time [Months]	36–42	[47]
Energy to Power Ratio (MWh/MW)	10:1	[94]
Investment Cost (US\$/MWh)	175,000	[91]
Start-up time charging/discharging (min)	15/5	[89]
Shut-down time charging/discharging (min)	5/10	[89]
Ramp rate (%Pnom/min)	20	[89]
Power capacity	100–1000 MW	[91]
Operation & maintenance costs (\$/kW)	3	[91]

$$P_{out} = P_{input} \eta_m \quad (5)$$

where  $P_{input}$  defines the motor's input power, and  $\eta_m$  the motor's efficiency.

The flow rate  $Q_p$  of water in ( $m^3/s$ ) is expressed in Eq. (6):

$$Q_p = \frac{P_{input} \eta_p}{Hg \rho} \quad (6)$$

where  $\rho$  is the water density in ( $kg/m^3$ ),  $g$  is gravitational acceleration in ( $m/s^2$ ),  $H$  is the height difference between the two reservoirs in (m), and  $\eta_p$  is the pump efficiency.

During times of energy deficiency, the hydro turbine converts the potential energy  $P_{HT}$  of water in the upper reservoir to electrical power  $E_{HT}$  as expressed in Eqs. (7) and (8).

$$P_{HT} = Hg \rho Q_p \eta_{ht} \quad (7)$$

$$E_{HT} = Hg \rho V \eta_{ht} \quad (8)$$

where  $\eta_{ht}$  is the efficiency of the hydro turbine, and  $V$  is the volume of the upper reservoir in ( $m^3$ ).

### **Flywheel energy storage**

Flywheel energy storage is an electro-mechanical storage system that offers numerous advantages such as environmental friendliness and reduced maintenance cost while providing synchronous inertia to the grid [97]. It is usually used in hybridized forms such as BESS-FES, and DIESEL-FES and can be modeled based on its mass and rotational speed [98–101].

Equations (9) and (10) give the expression of the kinetic energy stored and the moment of inertia in FES.

$$E = \frac{1}{2} J \omega^2 = \frac{1}{2} k \pi \rho h (\omega^2) (r^4) \quad (9)$$

$$J = \frac{1}{2} m r^2 \quad (10)$$



where  $E$  defines the kinetic energy of the flywheel in Joules,  $J$  defines the moment of inertia of the flywheel in ( $\text{kg}\cdot\text{m}^2$ ),  $k$  defines the shape factor,  $\rho$  defines the density of rotor material in ( $\text{Kg}/\text{m}^3$ ),  $h$  defines the height of the rotor(m),  $\omega$  defines the angular velocity of the rotor in ( $\text{rad}/\text{s}$ ),  $m$  defines the mass in kg of the cylindrical rotor, and  $r$  defines the radius of the cylindrical rotor in (m).

### Supercapacitor storage system

Supercapacitor storage system is an efficient energy storage system often used in power systems and desired for providing virtual inertia in the grid through a control strategy. It can also be used in hybridized forms such as PV-SCES and WIND-SCES [102, 103].

SCES are desired in power system because of their winsome characteristics such as high efficiency and long life cycle. The energy stored in SCES is given as in Eq. (11). Equations (12–13) define the SoC and DoD of the SCES, respectively.

$$E = \frac{1}{2}CV^2 \quad (11)$$

where  $C$  is the capacitance and  $V$  is the capacitor's voltage.

$$SoC = \frac{E_{inst}}{E_{rated}} = \frac{\frac{1}{2}CV_{inst}^2}{\frac{1}{2}CV_{rated}^2} \quad (12)$$

where  $E_{inst}$  is the instantaneous energy capacity of the SCES, and  $E_{rated}$  is the rated energy capacity of the SCES.

**Table 3** Generic characteristics of energy storage systems [104–109]

ESS Type	Efficiency (%)	Response time	No of Cycles	Lifetime (years)	Specific energy (Wh/kg)	Energy cost (\$/kWh)	Self-discharge (%/day)	Application
BESS	75–90	Milli-seconds(ms)	500–4000	5–10	90–200	150–2500	1–20	Frequency control and regulation
PHES	60–95	Minutes	10,000–30,000	30–60	0.5–1.5	600–2000	~0	Used as spinning reserves, provides voltage stability support
FES	70–95	< 10 ms	3000–5000	20–30	5–200	1000–5000	20–100	Used to maintain power quality, and for frequency regulation
SCES	85–98	< 10 ms	$10^5$ – $2 \times 10^7$	10–15	0.1–15	300–200	2–40	Mitigate voltage instability, and provides frequency control



$$DoD = \frac{E_{discharge}}{E_{rated}} = \frac{P_{load} \cdot T}{\frac{1}{2} C V_{rated}^2} \quad (13)$$

where  $E_{discharge}$  is the energy consumed by the load which is a function of the load power  $P_{load}$  and discharge duration  $T$  in seconds. Table 3 gives the summarized characteristics of various storage systems used in power system.

### The concept of inertia in power system

In this section, a detailed mathematical representation of system inertia is given. Furthermore, a concise review of inertia estimation techniques is provided.

#### Analytical representation of inertia in power system

Inertia can be defined as the amount of kinetic energy stored in the rotor of synchronous generators which tends to resist changes in grid frequency, particularly during times of contingency. The inertia inherent in synchronous machines is called synchronous inertia, hence the moment of inertia of a synchronous generator can be defined as in Eq. (14).

$$E = \frac{1}{2} J \omega^2 = S.H \quad (14)$$

where  $E$  defines the kinetic energy of the SGs in (MWs),  $J$  defines the moment of inertia in ( $\text{Kg/m}^2$ ),  $\omega$  defines the angular frequency in (rad/s),  $S$  defines the base apparent power in VA, and  $H$  is the inertia constant in seconds.

Also, from Eq. (14),  $H$  can be expressed as in Eq. (15):

$$H = \frac{E}{S} = \frac{J \omega^2}{2S} \quad (15)$$

Furthermore, the power imbalance can be represented using the swing equation as in Eq. (16):

$$P_m - P_e = P_a = \frac{dE}{dt} = J \omega \frac{d\omega}{dt} \quad (16)$$

Equation (16) can then be expressed in terms of torque as in Eq. (17):

$$\tau_m - \tau_e = \tau_a = J \frac{d\omega}{dt} = J \frac{d^2\theta}{dt^2} \quad (17)$$

where  $P_m$  defines the mechanical power developed in p.u,  $\tau_m$  defines the mechanical torque developed,  $\tau_e$  defines the electrical torque,  $P_e$  defines the electrical power output in p.u, and  $P_a$  defines the acceleration power in p.u,  $\theta$  defines the angular displacement of the rotor in rad,  $t$  is the time in seconds,  $f$  defines the supply frequency in (Hz), and  $df/dt$  is the RoCoF of the system.

From Eq. (16) and (17), we can obtain Eq. (18):

$$\frac{2H}{\omega} = \frac{J\omega}{S} = \frac{dt}{d\omega} \frac{[P_m - P_e]}{1} \tag{18}$$

Rearranging Eq. (18) gives Eq. (19):

$$\frac{2H}{\omega} \frac{d\omega}{dt} = \frac{[P_m - P_e]}{S} \tag{19}$$

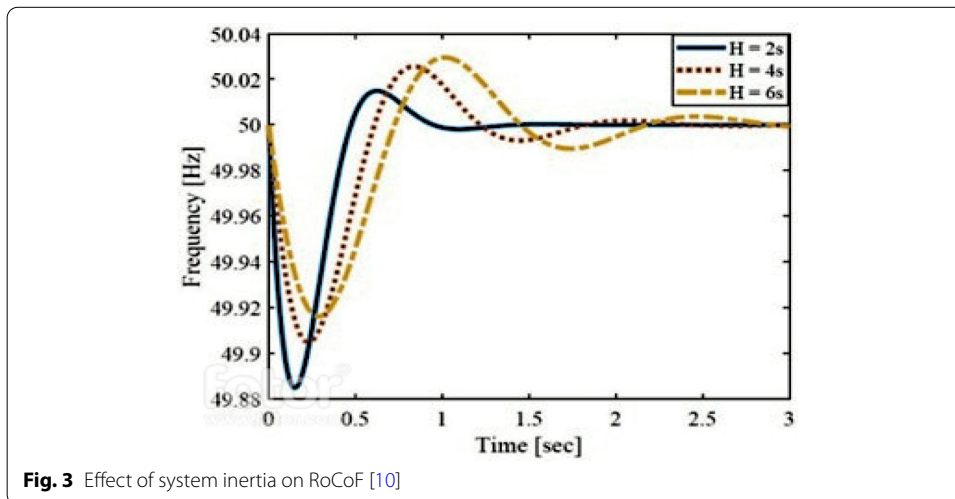
Replacing the angular frequency with the supply frequency and making RoCoF and inertia constant  $H$  the subject, we have Eq. (20) and (21):

$$\frac{df}{dt} = \frac{P_a}{S} \frac{f}{2H} = RoCoF_{p.u} = \frac{Pa_{p.u}}{2H} \tag{20}$$

Equation (20) can be modified to give Eqs. (21) which is used for designing virtual inertia controllers [67].

$$Pa_{p.u} = 2H_{VI} \frac{df_{p.u}}{dt} = K_i \frac{df_{p.u}}{dt} \tag{21}$$

where  $H_{VI}$  is the virtual inertia constant,  $Pa_{p.u}$  is the per unit change in power,  $K_i$  is the virtual inertia gain, and  $\frac{df_{p.u}}{dt}$  is the per unit rate of change of frequency. Equation (20) show the dependence of RoCoF ( $df/dt$ ) on the power change  $P_a$ , and the inertia constant ( $H$ ). It further reveals that the inertia constant is inversely proportional to RoCoF, and so the higher the inertia constant the smaller the RoCoF and vice versa. Also, RoCoF is directly proportional to the acceleration power  $P_a$ , so the greater the power imbalance the greater the RoCoF. Therefore, a reliable and resilient power system can be achieved by having high system inertia values [68, 69]. Furthermore, Fig. 3 shows the variations of frequency nadir with increasing values of system inertia, and it is seen that the higher the system inertia, the lower the frequency nadir. In light of this, frequency instability in the modern power grid can primarily be mitigated by providing adequate inertia in the grid.



**Fig. 3** Effect of system inertia on RoCoF [10]

### Inertia in renewable energy-sourced power system

The effective inertia constant in the power system can be represented as the sum of the individual inertia of all connected SGs to the grid, aggregated as a single generator model. It can be expressed as in Eq. (29) [14, 40].

$$H_{eq} = \frac{\sum_{i=1}^N H_i S_{B,i}}{S_B} \quad (22)$$

where  $H_{eq}$  is the aggregated synchronous inertia in the grid,  $S_B$  is the base apparent power,  $S_{B,i}$  is the individual generator apparent power,  $N$  is the total number of connected generators, and  $H_i$  is the inertia constant of each generator.

Similarly, since the modern power system comprises a hybrid combination of synchronous generators, ESS and RE generators, hence, the total inertia in the system will comprise of the synchronous inertia provided by the synchronous generators and the virtual inertia obtained from RE generators and energy storage systems. Therefore, the effective inertia  $H_{eq}$  in a modern power grid can be expressed as in Eq. (23), [78, 111, 115].

$$H_{eq} = \frac{\sum_{i=1}^N H_i S_{B,i} + \sum_{j=1}^V H_{V,j} S_{B,j}}{S_B} \quad (23)$$

where  $H_{V,j}$  and  $S_{B,j}$  are the virtual inertia constant in seconds and the rated apparent power in VA of the  $j$ th virtual machine, respectively.  $V$  and  $N$  define the number of the RE generators, and synchronous generators connected in the network, respectively. If  $H_{V,j}$  is very small, then the effective inertia  $H_{eq}$  in the grid will be substantially reduced, this explains why RE dominant power grid is associated with low inertia. Table 4 gives the average inertia values of different types of power generators. It is seen from Table 4 that the inertia constant from SGs ranges between 4 and 10 s, while the virtual inertia constant from ESS is between 2 and 4 s [74]. Therefore, it can be inferred from Eq. (23), that the aggregate inertia constant of modern power system should be between 4 and 10 s to ensure stability of the modern power grid.

**Table 4** Summary of inertia values of different power generators

Type of generator	Types of inertia	Rated power range (MW)	Inertia constant H(s)	References
Thermal	Synchronous inertia	10–1500	2.0–10.0	[30, 111, 112]
Hydroelectric	Synchronous inertia	10–200	2.0–4.75	[111, 113]
AC Wind turbine	synchronous inertia	0.016–750	0.5–6.8	[11]
Nuclear	Synchronous inertia	1000–1200	4.0–4.8	[111]
Biogas fired	Synchronous inertia	200–300	2.0–4.1	[111]
Synchronous condensers	Synchronous inertia	50–250	2.0–3.0	[10]
Compressed air energy storage(CAES)	Synchronous inertia	15–600	3.0–4.0	[14]
Pumped Hydro Energy Storage	Synchronous inertia	1–300	2.0–4.0	[10, 21]
Open cycle gas turbines	Synchronous inertia	50–150	6.0–6.5	[114]

### **Inertia estimation techniques in power system**

Inertia estimation in power system is important to help power operators predict futuristic frequency deviation and make appropriate control decisions [40]. This sub-section gives a review of the various inertia estimation techniques in power system while highlighting their merits and demerits.

Inertia estimation techniques discussed here are classified based on the timing of estimation. Using this criterion three main approaches will be discussed; offline or post-mortem approach, online real-time approach, and forecast or predictive approach. The offline and online techniques are the most commonly used, while the predictive approach is still being advanced.

#### ***Offline or Post-mortem inertia estimation method***

This is a post-mortem disturbance-based inertia estimation method driven by historical data of large disturbance events obtained using the phasor measurement units (PMUs). PMU is a measuring system installed at generator buses to monitor power system operating conditions such as voltage phasor, current phasor, active power, frequency deviation, harmonics, and power imbalance. The data obtained from the PMU is then used to estimate the system's inertia at discrete time instances using an appropriate algorithm. The accuracy of this method depends on the precision of the measuring system and the algorithm used for inertia estimation. This approach is however limited by inaccurate frequency measurements due to oscillatory components, as well as distortions and noises in the system, subsequently, its accuracy can be improved by eliminating noise and other distortions in the system [40, 110].

#### ***Online inertia estimation approach***

Unlike the offline method, the online estimation approach is a dynamic technique that uses real-time measurements from PMUs to give continuous and discrete inertia values of the power system. Examples of online inertia estimation techniques and models are dynamic regressor extension technique, autoregressive data-centered models, sliding discrete Fourier transform, and electro-mechanical oscillation modal extraction method [10].

Challenges of this estimation approach include (1) inaccurate estimation of the total system inertia (2) extended inertia estimation time (3) large computational burdens due to large dataset.

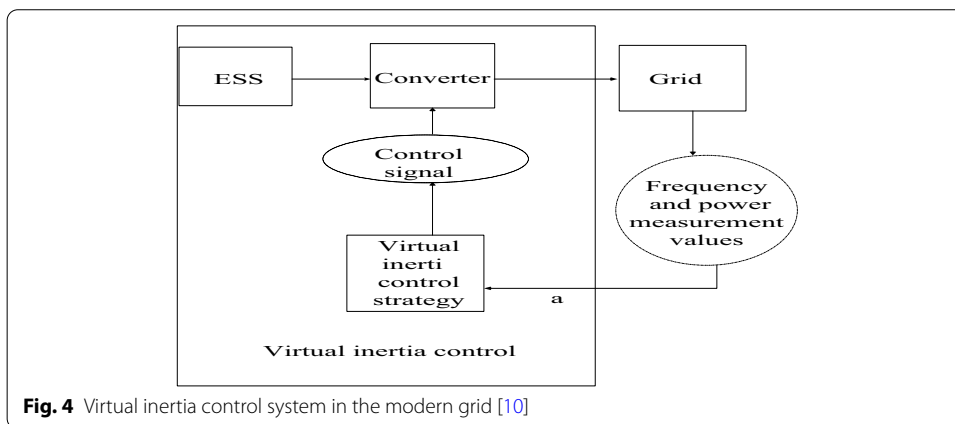
#### ***Inertia forecasting or prediction approach***

Forecasting techniques are now being used for inertia estimation due to the time-varying nature of inertia from renewable energy generators. Several forecasting models are being developed for inertia estimation such as artificial neural network (ANN) based models, linear regression models, time series models, and probabilistic inertia forecasting models [13, 111]. However, this approach is still being advanced for inertia estimation due to the changing dynamics of the modern power system.

Other unclassified approaches used for inertia estimation are the system identification approach, and the zonal inertia estimation technique. The zonal inertia estimation approach sums up the inertia from each contributing zone to give the total system

**Table 5** Inertia estimation techniques and their characteristics

Inertia estimation approach	Advantages	Disadvantage	Ref
Online	It is a real-time inertia estimation approach Gives higher accuracy as real-time data are used Gives continuous as well as discrete inertia estimation Well suited for RE dominant power system	Requires large measurement data Takes a long time for computation Associated with large computation burden	[40]
Offline	Requires lesser computation time Involves lesser data Has a lesser computation burden	Only discrete inertia estimation can be provided Not suited for RE dominant power system Can only estimate inertia after a large disturbance has occurred Inaccuracy of inertia estimation exist due to the presence of noise and distortion in the system It is not real-time-based	[13],
Predictive	Can be used to predict futuristic frequency response Can be used to predict futuristic system inertia so as to take precautionary control measures if needed	Accuracy is still low because of the stochastic nature of the RE sources Technology is still being advanced Prediction is limited to short-term prediction	[10]

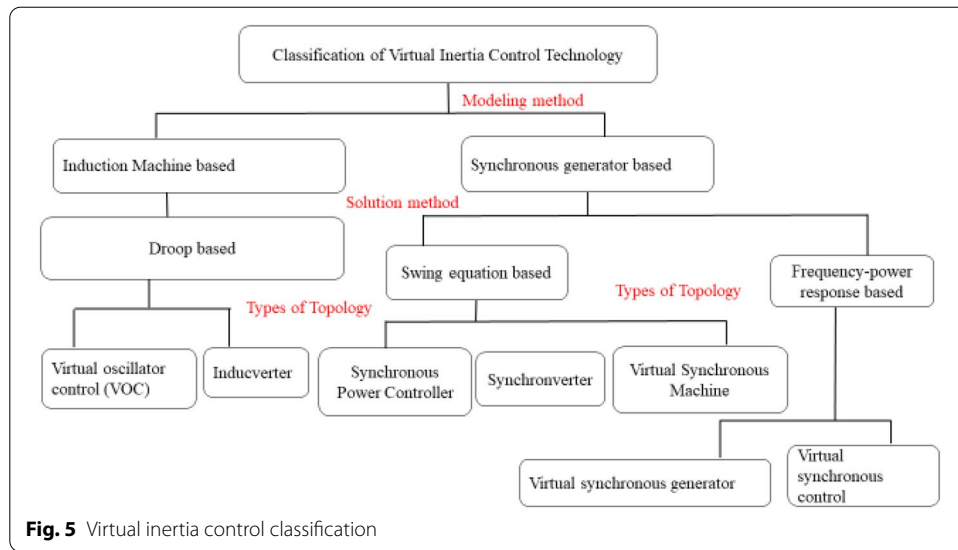


**Fig. 4** Virtual inertia control system in the modern grid [10]

inertia [13]. The summarized characteristics of different inertia estimation schemes highlighting their merits and demerit are presented in Table 5.

**Virtual inertia topology and strategy in modern power grid**

Virtual inertia control strategies help to provide artificial inertia to the grid through the use of RE sources, energy storage systems, and converters with appropriate control strategies [70]. The control strategies try to mimic the characteristics of SGs and induction machines to provide inertia virtually to the grid [71]. Figure 4 shows the virtual inertia control process in the modern grid, while Fig. 5 gives a broad classification of virtual inertia control topologies based on its modeling technique and solution method. Furthermore, Table 6 gives detailed characteristics, merits,



and demerits of the different virtual inertia control topologies and strategies, while Table 7 compares key parameters among the control strategies.

**Control equations of virtual inertia topology**

The various types of inertia emulation topologies and strategies arise from the different mathematical models used to mimic the dynamics of SGs and induction machines. In this subsection, the mathematical equation which defines the different types of virtual inertia topology is given.

**Swing equation-based topology**

The swing equation-based topology is governed mathematically by Eq. (24) obtained by considering the damping coefficient in the conventional swing equation [40, 73].

$$P_m - P_e = J\omega\left(\frac{d\omega}{dt}\right) + D_m(\omega - \omega_{ref}) = 2H_{VI}\frac{d\omega_{p.u}}{dt} + D_m(\omega - \omega_{ref}) \tag{24}$$

where  $P_m$  is the input power,  $P_e$  is the output power,  $J$  is the moment of inertia,  $\omega$  is the angular frequency,  $\omega_{ref}$  is the reference angular frequency, and  $D_m$  is the damping factor. The control model of the swing equation-based synchronous power controller is given in Fig. 6 with gain  $K$  and time constant  $T_d$ .

**Frequency-power response topology**

The control equation of the frequency-power response based topologies can be described by Eq. (25) [61, 73]:

$$P_{out} = K_D\Delta\omega + K_i\frac{d\Delta\omega}{dt} \tag{25}$$

**Table 6** Overview of the characteristics of virtual inertia control strategy

Classification based on solution method	Types of control strategy/Topology	Characteristics	Merits	Demerit	Refs.
Frequency-power response based topology:	Virtual synchronous generator (VSG) and virtual synchronous control (VSYNC)	Utilizes a 1st-order model of a synchronous machine. It is a simplified approach to emulate system inertia. Inertia emulation method is based on the frequency response of synchronous generators Current controlled source method: A control signal is generated to inject the required amount of power from the storage units commensurate to the frequency deviation	Can provide fast frequency response in steady-state It has inherent overcurrent protection Simplified strategy for reducing frequency nadir in the modern power grid. Achieves better stability in weak power grid compared to the droop control method.	Frequency response is not as fast as SG Inaccurate frequency derivative data from phase-locked loop (PLL) Can be used only in grid-connected mode Prone to instability as a result of noise	[10, 19, 72, 75] [22, 74, 76]:
Swing equation-based Topology	Synchronverter and Virtual Synchronous Machine (VISMA)	Inertia emulation is based on the exact dynamics of synchronous generators Frequency droop loop is used to regulate output power from converter Operation based on power angle control Operates on de-loaded RES Utilizes a 2nd, 5th, and 7th-order model of a synchronous machine It is a current-controlled voltage source method	Has small damping ratio with lower distortions. It can operate in both off-grid and on-grid mode Provides frequency and voltage regulation Phase-locked loop is not required.	Complex algorithms used may result in numerical instability. No inherent overcurrent protection hence external protection devices are required during transient conditions Difficult to implement in real life Lacks fault ride-through capability Presence of high-frequency noise due to converter switching	[22, 58, 74, 77]
	Synchronous Power Controller (SPC)	Gives an approximate emulation of the dynamic frequency response of the SG based on the conventional swing equation Utilizes a lower order model of a synchronous machine	It is simple to implement Can operate in island as well as grid-connected mode. Has inherent overcurrent protection	Prone to numerical instabilities Difficulty in obtaining accurate control parameters may lead to unwanted oscillation	[10, 22, 74, 78, 79],
Droop control	Virtual oscillator control (VOC) and Inducverter	Inducverter is based on emulating the exact dynamics of inductor machines. Regulates active power based on frequency deviation using the virtual rotor inertia of the inverter	Phase-locked loop is not required Less prone to grid faults	Respond slowly to transients. Can operate in grid-connected mode only Prone to instability in weak grid Associated with high-frequency noise and vibrations	[10, 22, 24, 59, 78]



where  $\frac{d\Delta\omega}{dt}$  is the rate of change of frequency,  $\Delta\omega$  is the change in angular frequency,  $K_I$  is the inertia constant, and  $K_D$  is the damping constant. Figure 7 gives the control model of frequency-power response-based virtual synchronous generator.

### **Droop control topology**

The droop control based topology can be represented using Eq. (26) [73, 74].

$$P_m - P_e = \frac{1}{D_p}(\omega_{ref} - \omega) + \frac{T_f}{D_p} \cdot s \cdot \omega \quad (26)$$

where  $\omega_{ref}$  is the reference angular frequency,  $\omega$  is grid frequency,  $D_p$  is the active power droop,  $P_m$  is the reference active input power,  $P_e$  is the active output power, and  $T_f$  is the time constant of the low pass filter. Figure 8 shows the transfer functions block diagram of the droop control based topology.

## **Operational and expansion planning optimization in power system**

### **An overview of power system optimization methods and techniques**

The increasing complexity, changing dynamics, and the need to ensure grid stability have necessitated power system researchers to focus on advanced optimization techniques that have capabilities of handling the new grid peculiarities [14, 65, 116].

Power system optimization problems can be solved using several methods. These methods can be majorly classified as exact and approximate approaches. Exact approaches are also called mathematical or classical method while approximate method uses heuristics or meta-heuristics algorithms [38, 117]. These modeling approaches are the most suited to capture the dynamics and address specific challenges of the power grid with clearly defined objective functions, decision variables, and constraints.

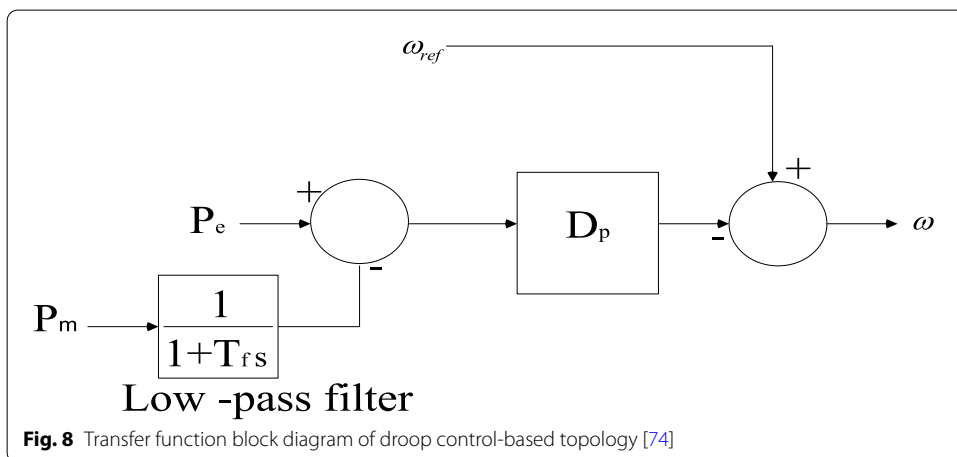
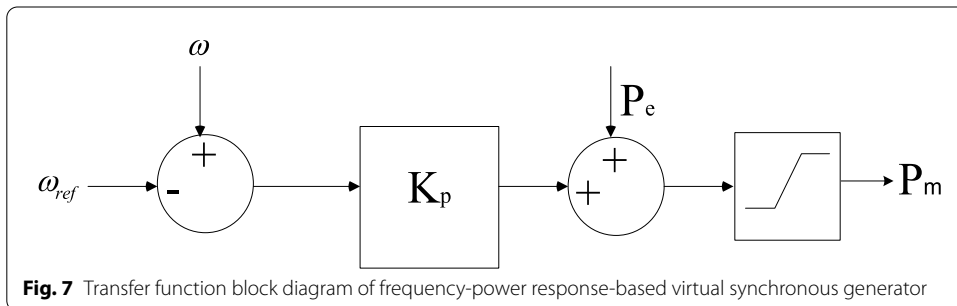
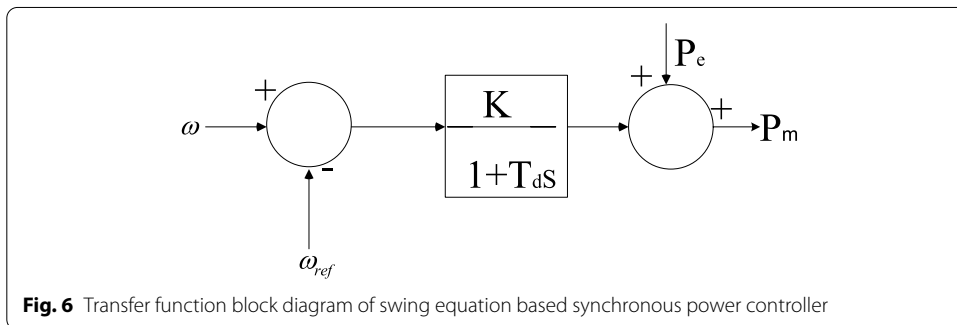
Mathematical optimization models can be defined by the nature of the constraints which could be linear or nonlinear. Linear optimization problems are solved using linear programming (LP) and MILP techniques, while nonlinear programming (NLP), mixed-integer nonlinear programming (MINLP), and mixed-integer quadratic programming (MIQP) are used to solve nonlinear mathematical models [118, 119].

Furthermore, complex mathematical optimization models are now being solved using algebraic modeling languages such as General Algebraic Modeling System (GAMS), Advanced Interactive Multidimensional Modeling System (AIMMS), Grid Reliability and Adequacy Risk Evaluator (GRARE) software package, Python, PLEXOS, and Multi-Area Reliability Simulation (MARS) [125, 126].

On the other hand, heuristic and meta-heuristics optimization techniques are formulated based on the social behaviors of living organisms [108]. They have shorter processing times and achieve faster convergence, however, they do not guarantee optimal solutions, unlike mathematical techniques. Examples are genetic algorithm (GA), Benders decomposition, simulated annealing, Tabu search algorithm, differential evolution, binary fireworks algorithm, particle swarm optimization (PSO), nodal ant colony optimization, evolutionary programming (EP), etc. [120–124]. These algorithms can also be used in hybridized forms such as GA-PSO [127].

**Table 7** Comparative analysis of virtual inertia control parameters

Types of Topology	Protection scheme	Grid-connectivity	Off-grid connectivity	Stability level	Model order	Model complexity
VSG	Internal		X	High	1st	Simplified
VSYNC	Internal		X	High	1st	Simplified
Synchronverter	External			Medium	2nd	Complex
VISMA	External			Medium	5th,7th	Complex
SPC	Internal			Medium	Low-order	Simplified
Inducverter	External		X	Low	High-order	Complex



**Table 8** Review of operational optimization models in power system

Objective function	Model description	Software and solvers	System specification	Refs.
Minimize hydropower curtailment and water spillage	Robust, MINLP Optimization	BARON solver in GAMS 24.7.1	Not Given (NG)	[118]
Maximize the energy production	MILP	Xpress solver in Python	Intel Core i5 Processor, 8 GB of RAM	[121]
Minimize cost and peak load regulation	Robust unit commitment model	NG	NG	[132]
Minimize load changes	MILP	NG	3.3 GHz processor and 8 GB RAM	[122]
Minimize operational cost and maximize the utilization of ESS	Scenario-based stochastic model	BARONS solver and SCENRED2 tool in GAMS	Intel 2.4 GHz computer	[80]
Minimize total operating cost	Robust optimization and MILP model	Gurobi solver in MATLAB	NG	[133]
Minimize cost of market-clearing operation	MILP model	ILOG CPLEX 12.6.0.0 solver in GAMS	NG	[134]
Minimize the operating cost of power system	Mixed-integer second-order cone programming model	CVX toolbox and GUROBI 7.52 solver in Python	2.6 GHz CPU Intel Core (TM) 2 Duo, and 4 GB RAM	[135]

Several optimization models and expansion planning models have also been proposed to address the peculiarities of the modern renewable energy dominant grid as seen in Tables 8 and 9. Furthermore, to account for uncertainties arising from RE sources as well as variations in load demand, robust optimization models was developed in [38, 116, 120], while stochastic optimization models and risk assessment method were adopted in [116, 128–131]. Table 8 gives an overview of operational optimization models, and techniques used to address related power system problems.

#### Expansion planning optimization model in power system

Expansion planning optimization models are gaining prominence in modern power system analysis due to the expected dominance of RE sources in the power grid and increasing energy demand. Expansion planning models are formulated as optimization problems with well-defined objectives and constraints [136–139]. Power system expansion planning models are mainly of three types; generation expansion planning (GEP), transmission expansion planning (TEP), and distribution expansion planning (DEP) [140, 146–149].

Generation expansion planning (GEP) problem determines the type of generators to be installed, optimal capacity of generators, location of generators, construction time of prospective generating units, and cost implications of new generators' installations. Similarly, transmission expansion planning (TEP) problem determines the best choice for the installation of new transmission lines which aids power transfer within a planning horizon [36, 141].

The planning period for expansion could be static or dynamic (multi-period). In static expansion planning models, the decisions are made within a given target year, while dynamic expansion planning involves making decisions at different phases of the planning horizon, thus making use of a yearly representation of the investment decisions [43,

**Table 9** Overview of expansion planning models in power system

Objectives	Constraints	Types of uncertainties	Model framework	Expansion planning model	Solver/software/system configuration	Inertia Consideration	Refs.
Minimize cost comprising operating, investment, and environmental costs	Unit commitment and DC-Optimal power flow (OPF) constraints	Not Considered (NC)	Deterministic MILP	GTEP	CPLEX 12.9.0.0 solver; 2.67 GHz processor and 64 GB RAM	No	[36]
Minimize emission, and maximize profit	Operational constraints	Varying capacity of wind turbine	LP	GTEP	CPLEX solver in GAMS. Core i5, 3 GHz processor and 16 GB of RAM	No	[140]
Minimize cost, energy losses, and voltage violation	DC-OPF	NC	MILP	GEP	CPLEX solver in GAMS. Intel Core i7-4770 processor	No	[143]
Minimize investment costs	DC-OPF	NC	MILP	GTEP	LINPROG function in MATLAB and CPLEX Solver in GAMS. 2.5 GHz CPU, Core i5 and 4-GB memory	No	[44]
Minimize cost, and energy not supplied (ENS)	DC-OPF, N-1 constraints	NC	MILP	TEP	CPLEX Solver in GAMS. Core-i7, 2.81-GHz processor and 16-GB RAM	No	[46]
Minimizing cost	DC-OPF	Load demand	Stochastic two-stage MILP optimization model	GSSTEP	NG	No	[47]
Minimize investment, maintenance, and CO <sub>2</sub> emission cost	AC-OPF and renewable energy policy constraints	Load demand and RES variations	MINLP	TGSEP	Accelerated Benders Dual Decomposition algorithm	No	[48]
Minimize cost and energy not served (ENS)	Security and resilience constraints	NC	MILP	TEP	Benders Decomposition algorithm	No	[49]
Minimize cost and emission	N-1 contingency constraints	PV generation and load variations	Scenario-based stochastic MILP	IEGNEP	CPLEX's solver in GAMS 25.1.2 1.60 GHz CPU; core i7 and 4-GB memory	No	[51]
Minimize cost and carbon emission	Generation and transmission limits, ramp constraints	load demand variations	Deterministic MILP	GTEP	Branch and bound method and weighted sum bisection method (WSBM)	No	[52]

**Table 9** (continued)

Objectives	Constraints	Types of uncertainties	Model framework	Expansion planning model	Solver/software/system configuration	Inertia Consideration	Refs.
Minimize cost	Reliability constraints	NC	Multi-level game theory model	GEP	Game theory and bi-level modeling in MATLAB. 8 GB RAM computer	No	[124, 144]
Minimize cost and CO <sub>2</sub> emission	AC-OPF	Load demand and generation variations	MINLP	DSEP	CPLEX solver using the branch-and-bound algorithm	No	[54]
Minimize investment, operation, and transmission service cost	DC-OPF	Nil	MILP	GTEP	BONMIN solver in GAMS	No	[37]
Minimize the investment costs while considering system uncertainties	DC-OPF	NC	MILP	DSEP	Gurobi solver in Python. 8 cores and 32 GB of RAM	No	[56]
Minimize investment and operational cost	Ramping, DC-DC-OPF constraints	Water flow variations	LP	GEP	Progressive Hedging Algorithm (PHA) and Gurobi 7.0 solver in Python 24-core computer and 32 GB RAM	No	[145]

142]. Table 9 gives a summarized overview of various optimization techniques, methods, and solvers used in expansion planning models. It can be observed from Tables 7 and 8 that most optimization techniques and models only consider economic objective such as operational cost of generators, and technical objectives such as power flow, ramping limits, and voltage limits. Most models did not consider the inertia requirement of the grid which is important to ensure grid stability in renewable energy sourced power system.

#### **Future research work**

The review of the literature reveals that no study has yet considered cost, emission, and the inertia requirements of the grid in joint generation and transmission expansion planning. Therefore, in future, a new deterministic optimization model for generation and transmission expansion planning model will be developed to minimize cost and CO<sub>2</sub> emission while maximizing the overall system inertia. Furthermore, the resilience of this new model during transient conditions will also be investigated.

#### **Conclusion**

This paper highlights the challenges associated with the modern power grid and further explains the role of inertia in ensuring frequency stability in the power grid. The following are the areas of discussion of this research: (1) A concise review of the modeling characterizes of different energy storage system used to provide inertia support to the grid. (2) Mathematical formulation of system inertia in power system. (3) overview of inertia estimation methods in power system. (4) Review of different virtual inertia control topologies and strategies highlighting their merit and demerit. (5) Review of optimization planning methods, techniques, and tools.

Findings of this study reveal the following: (1) adequate system inertia in the grid is important to mitigate frequency instability in the modern grid. (2) Disregarding inertia in power system operational and expansion planning optimization models could lead to sub-optimal optimization model. (3) Online inertia estimation technique is the most suited approach for inertia estimation in modern renewable energy-sourced grid due to the stochastic behavior of renewable energy sources. (4) Frequency-power response based topology such as VSG and VSYNC are preferred control strategies in renewable energy grid because they give better frequency stability.

In future, a new deterministic optimization model will be developed that will consider cost, CO<sub>2</sub> emission, and the inertia requirement of the grid in planning. This model will help to increase the frequency stability of the modern power grid as well as reduce emission level.

#### **Abbreviations**

RE: Renewable energy; ESS: Energy storage system; SCES: Super capacitor energy storage system; BESS: Battery energy storage system; SGs: Synchronous generators; VI: Virtual inertia; PV: Photovoltaic; VSG: Virtual synchronous generator; PHES: Pumped hydro energy storage; VOC: Virtual oscillator controller; RoCoF: Rate of change of frequency; VISMA: Virtual synchronous machine; GEP: Generation expansion planning; SPC: Synchronous power controller; GTEP: Generation transmission expansion planning; TEP: Transmission expansion planning; MILP: Mixed integer linear programming; FES: Flywheel energy storage; GSTEP: Generation, storage and transmission expansion planning; SOC: State of charge; DoD: Depth of discharge; PMUs: Phasor measurement units.

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**Author contributions**

AJO was involved in conceptualization, and prepared initial paper draft. PM helped in editing and KK helped in proof reading. We hereby declare that all the authors contributed to this research, and the manuscript has also been read and approved by all authors.

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**Declarations****Competing interests**

The authors declare that they have no competing interest.

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