Bulletin of Electrical Engineering and Informatics
Vol. 13, No. 1, February 2024, pp. 76~87
ISSN: 2302-9285, DOI: 10.11591/eei.v13i1.5873

Improving frequency regulation for future low inertia power grids: a review

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Article Info

Article history:

Received Jan 27, 2023
Revised May 24, 2023
Accepted Aug 2, 2023

Keywords:

Deloaded mode
Fast frequency response
Low inertia
Synchronous generator
Variable generation
Virtual inertia

ABSTRACT

The modern power system is witnessing an unprecedented increase in the penetration of renewable variable generation (VG) sources. Increased uptake of converter interfaced VG like solar PV and wind power while replacing conventional synchronous generators (SGs) introduces new challenges to grid operators in terms of dynamically handling frequency stability and regulation. Reducing the number of SGs while increasing non-synchronous, inertia-less converter interfaced VG reduces grid natural inertia, which is critical for maintaining frequency stability. To cure inertia deficiency, researchers, broadly, have proposed implementing supplemental control strategies to VG sources or energy storage systems to emulate natural inertia (virtual inertia (VI)). Alternatively, VG sources can be operated below their maximum power point (deloaded mode), making available a reserve margin which can rapidly be deployed in case of a contingency with the help of power electronic devices, to provide fast frequency response. This paper reviews recent solutions proposed in literature to address the low inertia problem to improve frequency stability. Additionally, it highlights the formulation of an optimization problem for VI sizing and placement as well as techniques applied in solving the optimization problem. Finally, gaps in literature that require further research were identified.

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1. INTRODUCTION

Power grids across the globe have experienced unprecedented increased penetration of converter interfaced variable generation (VG) sources in the past three decades. This energy transition in power grids has been dominated by wind power and solar photovoltaics technologies. For the year 2020 alone, 127 GW of solar and 111 GW of wind power new installations were made. As of 2020, wind and solar accounted for 50% of installed renewable energy capacity globally [1]. With the need to adopt cleaner generation technologies gaining traction, it is expected that VG sources will make a significant contribution in future power grids [2].

VG sources are non-synchronously connected to the power grid through power electronic devices. The inertia-less status of VG sources reduces the effective grid inertia as VG sources replace the legacy synchronous generators (SGs) in the power grid [3]. Reduced grid inertia results in frequency stability challenges such as a faster rate of change of frequency (RoCoF) and lower instantaneous frequency (frequency nadir) in the event of a contingency [4]. Grid inertia allows the power system to resist changes in system frequency via the resistance provided by rotating masses. The amount of kinetic energy stored in rotating masses connected to the system determines grid inertia [5]. SGs store Kinetic energy in their large rotating masses, which can naturally be released or absorbed in case of a power imbalance to minimize RoCoF. Grid inertia supplies power to the grid in the very short time before the active power control action of SGs (governor control) increases active power output [6]–[8].

As power grids ramp up the installation capacity of VG, it is important that researchers explore the ability of VG to provide ancillary energy balance services in the very short term to improve frequency regulation in inertia deficient grids [9], [10]. In literature, several alternative sources of inertia have been proposed and evaluated including the use of various technologies of energy storage systems (ESS) and harnessing inertia directly from wind turbines to increase inertia levels [11]. Increasing inertia levels, however, is not the only way to ensure frequency stability.

VG sources can be operated in de-loaded mode (below maximum power point) or in conjunction with an ESS to provide fast frequency response (FFR) in case of a power imbalance. FFR refers to the rapid increase in active power by a VG source operated in de-loaded mode proportional to the RoCoF and frequency deviation measured by a phased-locked lookup [12], [13]. This therefore, reduces the need for inertia from SGs and complements the work of primary frequency response (PFR). This work reviews the existing literature focusing on approaches proposed to solving the low inertia problem with increased penetration of VG for improved frequency regulation.

The rest of this paper is organized as follows: section 2 highlights conventional frequency response characteristics of a power system. Section 3 summarizes solution approaches in literature addressing the low inertia problem. Section 4 describes the formulation of virtual inertia (VI) allocation and placement problem while section 5 discusses optimization techniques used in solving VI allocation and placement problem. Section 6 identifies research gaps while section 7 concludes the paper.

2. PRELIMINARIES OF POWER SYSTEM FREQUENCY REGULATION

2.1. Conventional frequency regulation

The health of a power system is determined by how close the system frequency is to the nominal frequency. If the active power generation is higher than the load demand, the frequency increases above the nominal value and vice versa [14]–[16]. Increasing VG penetration in power grids while replacing conventional SGs increases the dynamic aspect of the power system due to decreased levels of system rotational inertia [17], [18]. In the event the generation side is lower than the net demand, the frequency evolves as shown in Figure 1. The RoCoF due to the imbalance is heavily dependent on the total system inertia. A system with low inertia means a higher RoCoF [19]. In the immediate time after a frequency event, the RoCoF is approximated by (1):

$$RoCoF = \frac{df}{dt} = \frac{f_o}{2} \times \frac{\Delta p}{H_{sys}} \tag{1}$$

where f_0 is the nominal frequency (in hertz), ΔP is magnitude of power mismatch (in p.u) and H_{sys} is the system inertia constant after a frequency event (in seconds).

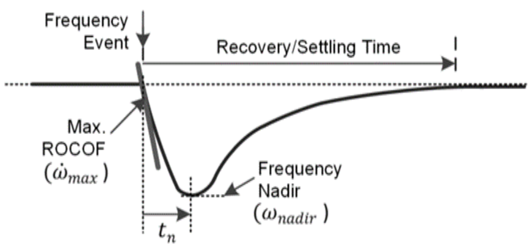


Figure 1. Power system frequency dynamics after a contingency [20]

Generally, frequency response in power systems can be divided in three phases going by the time instances of response after a generator tripping. The three main frequency response phases are: inertial response (IR), PFR, and secondary frequency response (SFR).

2.1.1. Inertial response

In case of a generator outage, there is an instantaneous decline in system frequency. Naturally, the kinetic energy stored in large rotating masses of SGs is dissipated in an attempt to bridge the active power gap to time t_n shown in Figure 1. This leads to reduction of the speed of the rotor. This is known as IR and is governed by the swing equation given in (2) [21]:

$$2H\frac{d\omega}{dt} = T_m - T_e\ p.u \tag{2}$$

where ω, H, T_m and T_e represent, rotational speed of the SG, inertia constant (in seconds), mechanical torque and electromagnetic torque respectively. From (2), it is evident that, any sudden changes in the active power balance between generation and the load are met by dissipation of the kinetic energy in the rotating masses of SGs. The value of system inertia is quantified in terms of inertia constant H. The lower the aggregate system inertia constant H_{sys}, the faster the system frequency will fall after a disturbance. The average system inertia constant is calculated by (3) [21], [22]:

$$H_{sys} = \frac{\sum_{i=1}^{n} H_i S_i}{\sum_{i=1}^{n} S_i} \tag{3}$$

Rotational inertia from SGs maintains the absolute RoCoF within permissible limits [23]. Replacing SGs with VGs compromises the ability of the power system to regulate frequency after a disturbance due to limited inertia [12].

2.1.2. Primary frequency response

After IR action, the turbine governor picks up the net power deficit and actuates the valves or gates to the runner blades to increase the mechanical torque to the turbine hence increasing the power output. This reduces the steady state frequency error as shown in Figure 1 [24]. PFR is slower than IR due to the electromechanical nature of the governor [21].

Power electronic based sources are characterized by incredibly faster active power control than SG governor controls but significantly slower than the SG IR [25]. This presents potential to deploy power electronic based sources in frequency regulation.

2.1.3. Secondary frequency response

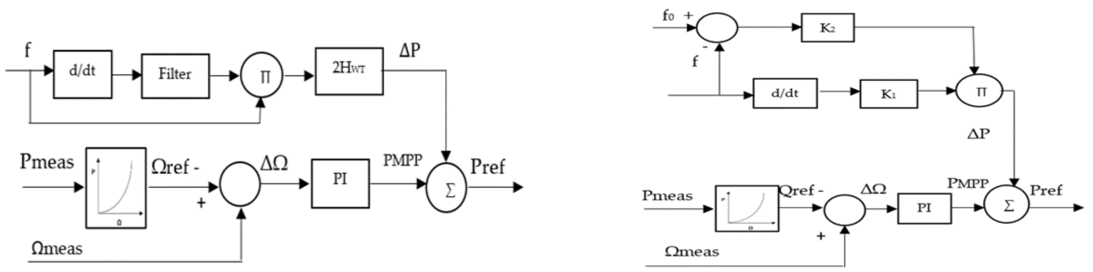
The third phase of frequency response is initiated by the automatic generation control (AGC). The AGC swings into action by the help of an integral controller. It modifies the operating set point of the governor, rapidly increasing the power output to remove the steady state error and restore the nominal frequency [7], [26]. SFR come into action from about 10 seconds and has a possibility to last for about 10 to 15 minutes. For purposes of ensuring economic dispatch, tertiary reserves from offline generators might be brought online to replace expensive secondary reserves deployed [17], [27], [28].

2.2. Emerging trends in frequency regulation for low inertia power grids

2.2.1. Inertia emulation

VG sources in their conventional operation lack the ability to participate in IR. Solar PV power plants for instance lack rotating masses in their generation technology. Unlike SGs which naturally provide IR devoid of any control action, wind power plants (WPPs) are incapable of automatically providing inertia from the rotating blades without additional control strategy. Through the use of power electronic converter with innovative supplementary control, kinetic energy can be harvested from their rotating blades for deployment in IR in the very short term (2-6 seconds). Hidden inertia emulation for wind turbines simulates the IR of a traditional SGs. In this case, the WPP is regarded as a virtual SGs with VI [29].

Hidden inertia emulation controls are available in two configurations: one loop and two loops. The one loop configuration uses RoCoF to dispense the archived kinetic energy in the rotating blades, whereas the alternative configuration uses RoCoF and frequency deviation [30]. As shown in Figure 2(a), the one loop inertia response is added to the speed control system to allow the wind turbine to respond to the RoCoF. The frequency is not restored to its nominal value as a result of this control strategy. An auxiliary loop proportional to the frequency deviation Δf is then added, as shown in Figure 2(b). This second loop will continue until the frequency returns to f_0.



(a) (b)

Figure 2. Inertia emulation controllers; (a) one loop and (b) two loop [3]

Figure 3 compares frequency responses with one or two loop controllers. This control loop is known as inertia emulation, and it precisely mimics the inertia response of conventional power plants, as illustrated in Figure 3 [3]. Consider Figure 2, where the reference rotor speed-Ω_{ref} is determined by the power from the wind turbine-Pmeas and the resultant signal-$\Delta\Omega$ is passed through a PI controller to provide maximum power-P_{MPP}. During normal operation, the reference power-Pref transferred to the converter equals the maximum power-P_{MPP} devoid of any contribution from the inertia control loop. Following a power deficit, the P_{MPP} will receive a certain amount of power ΔP based on the value of RoCoF and the VI constant K. As a result of the increased power, the generator will slow down, and the kinetic energy stored in the rotating wind turbine blades will be released. The extra power-ΔP is provided by the inertia response loop, which is dependent on RoCoF.

Because this strategy generates constant additional power form the inertial control loop, it introduces some challenges. The rotor speed is first rapidly reduced, resulting in significant aerodynamic power losses. Second, the controller recovers energy slowly during rotor speed recovery.

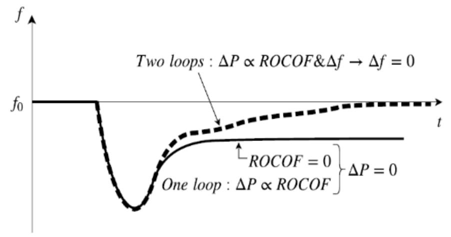


Figure 3. Frequency response of one loop and two loop controllers [3]

2.2.2. Deloading technique

VG sources are typically operated at maximum power point tracking (MPPT) to extract the maximum active power and are high up in the merit dispatch order by transmission system operators. However, VG sources can be operated below their MPP to provide some headroom for reserve active power capacity that can be quickly deployed in the event of a frequency contingency [31]. This is called deloading technique. Despite some cheap active power being curtailed, the goal is to address frequency stability concerns. In this case, the VG is considered a source of FFR.

To deload a PV system, the converter operates away from the maximum power point voltage-U_{mpp} as shown in Figure 4. For stability purposes, the converter is operated at a higher voltage $U_{mpp}+U_{deload}$. This provides some active power reserve or headroom $P_{deload} = P_{mpp} - P_{red}$. To rapidly utilize the power reserve in case of a power imbalance, a signal proportional to the frequency deviation is added to the DC output of the PV array which increases active power supplied. The new operating voltage U_{d_new} is given by $U_{d\_new} = U_{mpp}+U_{deload} - K_g x\Delta f$ as shown in Figure 5.

De-loading technique in WPPs can be implemented using two approaches: rotor blade over speed control and pitch angle control. Pitch angle control entails increasing the pitch angle from β_0 to β_1 for a specific speed while maintaining the rotor speed at Ω_{MPP} as shown in Figure 6. In this scenario, since the power extracted-P_{del} is below the maximum aerodynamic power available P_{MPP}, there is an active power reserve created given by $\Delta P = P_{MPP} - P_{del}$, which can be deployed the event of a frequency contingency.

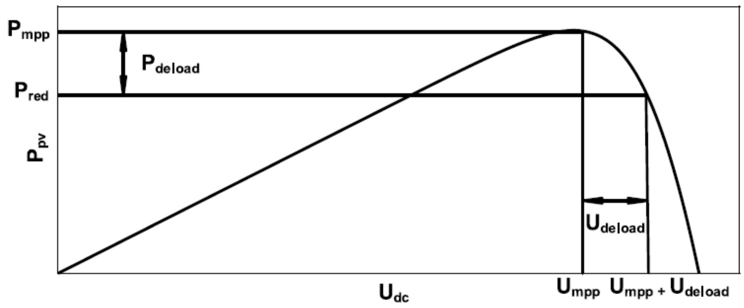


Figure 4. Deloaded PV system operation [31]

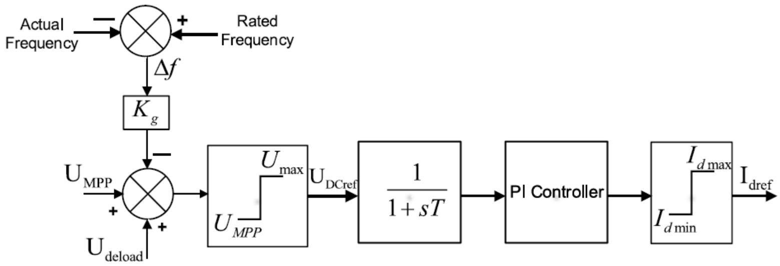


Figure 5. Active power controller for a deloaded PV plant

2.2.3. Droop control

Droop control mimics the behavior of a governor in a legacy SG while responding to changes in grid frequency. Under this mode of control, in case of a frequency event, the active power injected by the WPP varies correspondingly to the frequency deviation Δf as shown in Figure 7 where 1/R is the speed adjustment rate [15]. This controller significantly improves frequency stability indices such as frequency nadir as well as reducing the steady state error in frequency after disturbances. The relationship between active power injection and frequency deviation is linear and is given by (4):

$$\Delta P = PI - P_O = -\frac{fmeas - fnom}{R} \tag{4}$$

where R, fmeas, fnom, P_1 and P_o are droop constant, new frequency, initial/nominal frequency, new power output and initial power output respectively. Figure 7 depicts the linear relationship between frequency and wind turbine active power. To compensate for frequency deviations, when the frequency decreases from $fnom$ to $fmeas$, the wind turbine increases its power output from P_o to P_1. The droop controller for wind turbine is almost similar to the inertia emulation controller described in subsection 2.2.1. However, the additional power ΔP is dependent on the frequency deviation Δf and the defined droop constant R as shown in Figure 8.

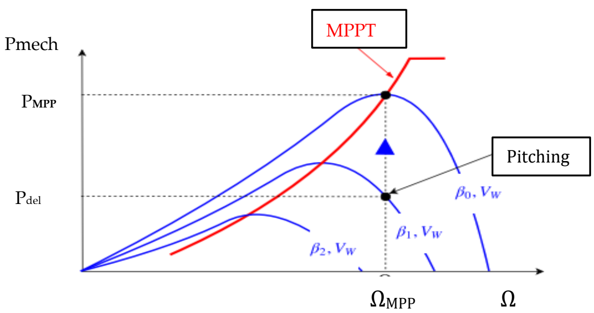


Figure 6. Deloading a WPP using pitch control [13]

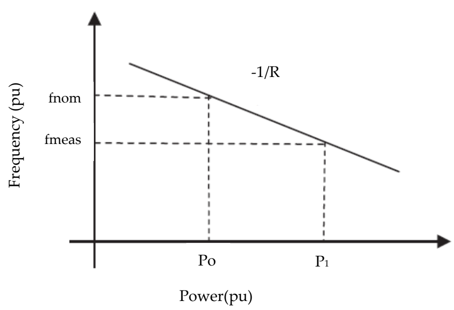


Figure 7. Wind turbine droop characteristics

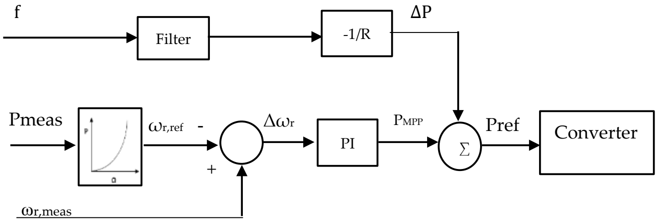


Figure 8. Frequency droop controller for wind turbine [13]

3. SOLUTION APPROACHES TO ADDRESSING THE LOW INERTIA PROBLEM

Several researchers in literature have addressed the problem of reduced inertia with increased uptake of VG by proposing alternative sources of additional inertia christened as VI. Also, viability of deployment of FFR from ESS and VG sources to improve frequency regulation with decreased inertia has been explored. Approaches to address the low inertia problem including main objective, findings and weaknesses are summarized in Table 1.

Table 1. Summary of recent approaches to addressing the low inertia problem

Ref	Approach	Main objective	Findings	Weaknesses
[6]	Grid forming vs grid following inverter	Analyzing the impact of inverter type on frequency regulation	Grid forming inverters damped frequency swings while grid forming inverters aggravated the swings in case of a contingency	No effort in sizing reserve capacity of VG used
[22]	Virtual synchronous generator (VSG) based on superconducting magnetic energy storage (SMES)	Modeling a VSG based on dynamic behavior of SG	SMES-based VSG guaranteed frequency stability under low and high penetration of VG compared to BESS-based VSG which resulted in enormous frequency excursion and high penetration	No efforts made to optimally place VSG on the network
[32]	Battery energy storage (BESS) based	Large scale utility BESS versus small distributed BESS for droop based frequency support	Centralized utility scale BESS was more effective for frequency support than distributed BESS under high penetration of VG	Capacity and placement of BESS was arbitrarily done
[33]	VG and BESS based FFR provision	Techno-economic analysis of FFR provision from VG versus BESS	For highly VG penetrated systems, using BESS for frequency response is more efficient though costly than operating VG in de-loaded mode for the same service	Lacks dynamic system simulation to validate strategy adopted for frequency regulation
[29]	WPP with super-capacitor for rotational inertia provision	Harvesting inertia from wind turbines	Inertial control from wind turbine was effective in frequency regulation	Complexity of the control system deployed to harvest inertia
[34]	BESS based VI provision	Viability of BESS for IR for large PV	BESS was effective in provision of IR with increased penetration of VG	Optimal sizing and placement of BESS was not considered
[35]	Hybrid energy storage system (HESS) based FFR provision	Optimal sizing of HESS (BESS and ultra capacitors) for fast frequency support	Larger ultra-capacitors should be used to increase HESS power capability and frequency support	Optimal placement was not considered
[36]	BESS based FFR provision	Optimal BESS sizing for dynamic frequency control	Optimal sizing of BESS using Grey Wolf Optimization improved frequency regulation with minimal BESS size	Optimal placement not considered
[37]	BESS as a VI source	Optimal sizing and tuning of BESS controller	Incorporating frequency metrics in sizing BESS ensures there’s sufficient capacity for worst contingency	Optimal placement of VI not considered
[38]	FFR vs VI from VG	Performance distinction between FFR and VI	VI only reduces RoCoF while FFR reduces absolute RoCoF and improves frequency quality	Aggregate models of SGs and VGs were used reducing accuracy of the model
[30]	WPP as a VI source	Techno-economic performance of WPP as a VI source	Deploying VG as a VI is only beneficial in power grids with frequency relaxed limits	Increased system operation cost for grids with tight RoCoF limits
[21], [31], [39], [40]	Solar PV power plant as an FFR source	Operating solar PV in de-loaded mode to participate in frequency control	De-loaded margin of 2-5% was ideal for frequency control. De-loading margins of above 5% did not significantly improve frequency regulation for chilean grid. De-loading margin for PV plants decreased with increase in PV penetration	Optimal placement not considered

4. VIRTUAL INERTIA ALLOCATION AND PLACEMENT OPTIMIZATION PROBLEM

The inertia allocation problem formulation is anchored on finding the right balance between minimization of cost associated with provision of additional emulated inertia and ensuring frequency stability while considering other system constraints. In this paper we consider the approach adopted in formulating VI placement from ESS as a techno-economic problem [41].

4.1. Cost of energy storage system

A general methodology that is applicable for a wide variety of ESS is considered. The cost of ESS can be evaluated using either total capital cost (TCC) or life cycle cost (LCC) [42]. When using TCC strategy, (5) is used to quantify the cost:

$$C_{cap} = C_{PCS} + C_{BOP} + C_{stor} \times t_{ch} \ (\$/kW) \tag{5}$$

where C_{cap}, C_{PCS}, C_{stor}, t_{ch} and C_{BOP} represent the TCC, power conversion system cost, cost of ESS, charging/discharging time and cost of balance of ESS respectively [23]. LCC is a more commonly used metric for assessing and evaluating various ESS technologies. The annualized LCC is calculated as shown in (6):

$$C_{LCC,a} = C_{cap,a} + C_{O\&M,a} + C_{R,a} \ (\$/kW - yr) \tag{6}$$

where $C_{LCC,a}$, $C_{O\&M,a}$ and $C_{R,a}$ represent the annualized LCC, operation and maintenance cost, and restoration cost respectively. Additionally,

$$C_{cap,a} = TCC \times CRF \ (\$/kW - yr) \tag{7}$$

$$CRF = \frac{i(1+i)^T}{(1+i)^T - 1} \tag{8}$$

$$C_{O\&M,a} = C_{FOM,a} + C_{VOM,a} \times n_{cycle} \times t_{ch} \ (\$/kW - yr)$$

$$C_{R,a} = CRF \times \sum_{K=1}^{r} (1+i)^{-kt} \times \left(\frac{C_R \times t_{ch}}{\eta_{sys}}\right) \ (\$/kW - yr) \tag{9}$$

where i, T, r, t, CRF and η_{sys} are interest rate, life time, number of substitutions in a lifetime, capital recovery cost and overall system efficiency respectively; $C_{FOM,a}$ and $C_{VOM,a}$ represent the fixed and variable $O\&M$ costs.

4.2. Objective function and operational constraints

The objective is to minimize the post contingency energy expended (VI) in returning a low inertia power system back to steady state operation while considering system constraints. To formulate the objective function for VI placement, in (6) is rewritten in terms of VI [41]. The synchronous inertia constant-H is given by (10):

$$H = \frac{0.5 J_{VI} \omega^2}{S_{base}} \tag{10}$$

where J_{VI}, S_{base} and ω are moment of inertia, rated apparent power and angular velocity respectively. Assuming a unity power factor for the ESS, in (11) can be rewritten in joules as:

$$KW_{ESS} = KVA_{ESS} = \frac{h_{ESS} \times S_{base}}{3600} \tag{11}$$

$$h_{ESS} = \frac{3600 \times KVA_{ESS}}{S_{base}} \tag{12}$$

In (12) represents the average hourly power absorbed from the grid or dissipated to the grid by the ESS [43]. Replacing (12) into (6), the objective function can be stated as [41]:

$$min\,i\,mize \ \mathrm{F}(h_i) = \sum_{i=1}^{n_{ESS}} \left(C_{LCC,a\,\mathrm{i}} \times \frac{h_i S_{base}}{3600} \right) \tag{13a}$$

$$st \ \mathrm{RoCoF}_i \le RoCoF_{max} \tag{13b}$$

$$\Delta f_{nadir\,\mathrm{i}} \leq \Delta f_{nadir\,\max} \tag{13c}$$

$$SOCi_{max_{min}} \tag{13d}$$

where SOC is the state of charge of the ESS and n_{ESS} is the number of ESSs. The SOC is determined by:

$$SOC(\Delta t) = SOC(0) - \frac{\int_0^{\Delta t} \zeta p dt}{E_{ESS,rated}} \tag{14}$$

where $p(t)$ is the ESS power, its negative while ESS charges and positive while the ESS discharges. $E_{ESS,rated}$ and ζ represent nominal energy capacity, charge/discharge time and charging/discharging efficiencies respectively.

Operating constraints (13b) and (13c) enforce RoCoF and Frequency nadir limits. These are dynamic indices that increase the sophistication of solving the optimization problem. To simplify the optimization problem and increase tractability, the lower/upper bounds can be rewritten in terms of emulated inertia through Taylor series expansion about specific variables [41].

5. OPTIMIZATION TECHNIQUES APPLIED IN SOLVING THE VIRTUAL INERTIA ALLOCATION PROBLEM

Integration of VG and distributed generation to the power system has made it more dynamic than ever before. In this regard, power system analysis problems have also evolved. Power system problems are formulated as nonlinear, multi-objective, nonconvex and multi-constraint optimization problems which cannot be satisfactorily solved using calculus based methods. These methods have a tendency to stagnate in local search hence compromising the ability to achieve global optima [44].

Metaheuristic approaches have widely been adopted in literature in solving current complex power system analysis problems due to their flexibility, robustness and devoid of gradient computations. Additionally, metaheuristic approaches conduct a wider search and strive to achieve the global optima [45]. They include evolutionary algorithms such as genetic algorithm (GA) and swarm intelligence optimization algorithms [46]. The VI allocation problem in literature has largely been formulated as a nonconvex, nonlinear and multi-constraint optimization problem. From the sampled literature, few studies have been conducted to determine the best position and capacity of VI and FFR sources.

Borsche *et al.* [47] investigate where it is most advantageous to add VI sources and how inertia distribution affects the dynamic behavior of power systems. After linearization of the optimization problem parameters, an iterative optimization approach was used to determine the day ahead optimal levels of inertia to be maintained in order to ensure benign transient behavior after a frequency event. Golpira *et al.* [41], authors develop a techno-economic optimization problem from the perspective of frequency stability to optimally size energy storage as well as locate VI sources. The main goal was to improve frequency stability while using as little ESS capacity as possible in low inertia power systems. GA was used in the study to calculate the amount of VI in each PV bus.

The works in Poolla *et al.* [48] formulate the inertia allocation problem as a performance metric using network coherency. The results show that, contrary to popular belief, the location of the disturbance as well as the placement of the VI sources, rather than total system inertia, are key determinants of the resilience of low inertia power systems. Based on a linearized networked swing equation model, the inertia placement problem was solved using a gradient-based optimization approach. An optimization problem for allocating synthetic inertia and damping was developed in [49] and sequential linear programming based method applied to solve after linearization of the problem. Eigen values of the linearized system were calculated after every iteration sequence increasing the computational complexity of this approach.

Grid forming and grid following VI devices were modeled in MATLAB [50]. An optimization problem was developed to optimize the parameters and location of these devices while taking frequency metrics into account. To tune the parameters and determine the location of VI devices, H_2 norm-based optimization was used, which is inherently complex. The findings revealed a strong relationship between system resilience and the distribution of VI devices.

Table 2 shows a summary of recent work in literature on optimal sizing and placement of VI devices and sources. Both analytical and metaheuristic methods have been applied in literature. Different test systems have been deployed to validate different optimization techniques by authors which makes comparison challenging in certain aspects of computation time and accuracy of results. However, majority of the studies focused on minimizing the required energy storage capacity to provide VI or FFR while meeting frequency stability indices.

Table 2. Summary of research works on optimal allocation of VI and FFR sources

Ref.	Intervention	Design variable	Objective function	Method	Test system
[35]	FFR from HESS	Sizing	Minimize HESS cost to provide FFR	MVMO algorithm	9-bus IEEE
[36]	FFR from BESS	Sizing and tuning controller parameters	Minimize BESS size	Grey wolf optimization	Flinders Island micro grid
[41]	Provision of VI	Size and distribution	Minimize the size of ESS used to provide VI	GA	68-bus
[37]	VI&FFR from ESS	Sizing and tuning controller parameters	Minimize BESS installation cost to provide VI&FFR	Gradient-based	9-bus IEEE
[50]	Provision of VI	Distribution	Minimize active power injection from VI devices	H_2 norm-based optimization	59-bus South-East Australian system
[47]	Provision of VI	Size and distribution	Maximize worst case damping ratio	Sensitivity analysis based on damping ratio	12-bus
[48]	Provision of VI	Distribution	Minimize network coherency index through allocation of VI	Gradient-based	12-bus
[49]	Provision of VI	Distribution	Minimize damping ratio, overshoot and RoCoF	Sequential linear programming	59-bus South-East Australian system

6. DISCUSSION AND RECOMMENDATIONS FOR FUTURE STUDIES

The problem of low inertia power grid is still a fairly new challenge for power system operators. Commendable efforts have been made by various researchers in proposing solutions to deal with the low inertia problem. Based on the reviewed literature, the following recommendations for future advancements in the research field are provided:

- In general, most of the research is centered on the control side of VI devices with minimal effort on the power system side. Some studies did not consider exploring the impact of VI sources on different aspects of the power system such as frequency and transient stability.
- Researchers have focused mostly on increasing the level of inertia using different alternative means to secure frequency stability. There is little effort in the literature reviewed to investigate the deployment of VG sources for FFR. Majority of the literature has concentrated on the use of energy storage technologies, such as battery or HESS, to provide synthetic or VI for low inertia power grids. Since VG sources are expected to play a more dominant role in future power grids, it’s important to explore their ability to efficiently provide ancillary services such as participating in frequency regulation.
- Most of the recent research works did not consider assessing and comparing the effectiveness of VI and FFR in improving frequency regulation. These solutions to low inertia problem have been mostly studied independently.
- Optimal allocation of VI devices has been done for a balanced power system network. Studying the dynamics for optimal allocation of VI for an unbalanced power transmission network can be considered for future research. Also, small and medium network test systems have largely been used, there is little consideration for large network test systems.
- Most reviewed literature on optimal allocation of VI devices did not validate performance of optimization technique applied with other metaheuristic or analytical methods in terms of result accuracy, convergence characteristics and computation time. Among the evaluated and reviewed publications, only a few have attempted to use metaheuristic algorithms to solve non-linear, non-convex, and multi-constraint VI allocation problem.
- There has also been little effort made to optimize the fast frequency reserve capacity of VG sources operating in de-loaded mode, which provides FFR for frequency regulation. Also, in the few publications where optimal deloading level has been explored, variability of VG output with respect to time and whether was not considered. A summary of optimal deloading level results of PV power plants integrated in the IEEE-39 bus New England system are shown in Table 3. Optimization techniques (gradient search and GA) posted better results in terms of deloading level compared to statistical approach (multiple linear regression model (MLRM)). The optimal deloading level decreases with increased PV penetration which implies that PV power plants can operate with little headroom/reserve capacity hence allowing transmission system operators to sufficiently utilize the cheap power while addressing frequency stability concerns.

Table 3. Optimal deloading level for recent research studies

Optimization/statistical approach	Contingency event	PV penetration (%)	Optimal deloading level (%)
Gradient descent optimization	Generator outage:	30	6.96
	508 MW	40	5.9631
		50	4.968
GA	Generator outage:	30	7.03
	508 MW	40	5.98
		50	5.24
MLRM	Generator outage:	30	7.283
	508 MW	40	6.536
		50	6.335

7. CONCLUSION

This paper presents a distillate from recent literature on the approaches proposed in addressing the low inertia problem in power systems with increased penetration of VG for improved dynamic frequency stability and regulation. The achievements as well as limitations of previous works in improving frequency regulation and stability have been highlighted. The design, control and sizing of VI devices has dominated in literature in addressing the low inertia problem. Significant progress has been made solving the optimization problem of sizing and placement of VI devices as captured in this paper. The literature has largely formulated the VI allocation problem as a nonconvex, nonlinear, multi-constraint optimization problem can be solved using analytical or metaheuristic optimization techniques with each having their pros and cons highlighted. With a clear distinction between VI and FFR contributions in providing frequency support for low inertia grids, a number of recommendations were made to be considered for future research.

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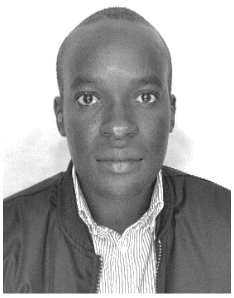

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