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Optimal Placement of Renewable Energy Resources to Minimize the Rate of Change of Frequency and Improve Frequency Nadir

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Abstract
The integration of renewable energy resources (RESs), such as solar PV systems or wind turbines, in the grid is expected to enhance the system stability [1]. However, the location of these RESs needs to be carefully chosen to ensure the stability of the system is not negatively affected. Random placement of RESs may cause unwanted frequency deviations and voltage rise/fall, leading to instability. The optimal placement of RESs is proposed to minimize instability and improve the stability profile. This study presents a mathematical framework based on optimization for designing a resilient RESs that can maintain frequency stability of a system within a specified range through minimization of Rate of Change of Frequency (RoCoF) and improvement of frequency nadir even in the presence of system perturbations. The IEEE-14 bus system is analyzed with and without the placement of RESs using DIgSILENT Powerfactory software. The stability of the system is improved with the placement of RESs, and the best location for RESs is found using particle swarm optimization (PSO). After the optimal placement of RESs, the RoCoF of the system is observed to be minimized and also the frequency nadir is improved in a significant manner. The suggested strategy may lessen disturbances' impact, increasing the essential clearance time prior to frequency collapse and promoting safe power system operation.

Keywords
Renewable Energy Resources, Stability, Frequency deviations, Rate of Change of Frequency (RoCoF), System perturbations, Frequency nadir, optimal Placement

1. Introduction

Over the past few decades, the demand for electrical energy has been increasing due to the rise in the standard of living and economic expansion. However, traditional power systems face various financial, environmental, and technical challenges to keep up with the increased demand. Renewable energy sources (RES) are seen as a solution to these challenges and a turning point towards clean and affordable electrical energy generation. From an economic, technical, and environmental perspective, RES generally has advantages over conventional huge power plants [2]. Governments are setting ambitious goals to integrate RES on a broad scale in the near future [3]. The synchronous generator has been the "heart" of the power system since the first commercial electricity was produced . However, the pressure from restrictions on resource sustainability and climate change is forcing a significant transformation of the power sector [4]. Online synchronous generators become less common as inverter-based RES integration increases. Due to the fluctuating and intermittent character of the RES generating feed-in, the system inertia is not only decreasing but also becoming more time-varying. As a result, the notion that the power system has enough and consistent inertia loses some of its validity [5].

The integration of large-scale renewable energy generation will have implications for power system stability and reliability. RES units need to be strategically positioned and scaled, taking into account the technical requirements of the network, the objectives of the RES, and the network operator [6]. The ideal size and position of RES must be chosen to fully benefit from their deployment [2]. In most studies, the optimization problems for optimal sizing and positioning of RES focus on active and reactive power loss minimization and voltage profile improvement, which only consider static constraints [7]. However, inverter-based distributed generation (IBDG) units, such as solar and fuel cells, are becoming more prevalent. These units, with their quick reaction to network disturbances and little inertia, may cause signal stability to deteriorate with high sensitivity. As a result, as the penetration levels of IBDG units rise, the effects of these units on network small signal stability must be evaluated in RES deployment studies [1]. The objective of a specific study is to obtain the optimal placement of RES for improving frequency stability in an INPS section by minimizing the rate of change of frequency (RoCoF) and improving the frequency nadir. This highlights the importance of considering not only the static constraints but also the dynamic effects of RES integration on power system stability.

This paper proposes a particle swarm optimization (PSO) algorithm for minimizing the effect of system disturbances on frequency response by determining the optimal location and size of various RESs. The study incorporates an indicator for the security of power system as an objective function to obtain the site and size of RESs within a specified power system. In the analysis, it is considered that there is sudden power imbalance between generation and load leading to a deviation of the frequency. The evaluation of the results is done using indicators for dynamic analysis that quantify transient network disturbances like frequency, rate of change of frequency index (ROCOF) and frequency nadir. This paper is structured such that section 2 includes the literature review;

section 3 shows the methodology of the study; section 4 discusses the simulation and results; and section 5 includes the conclusion.

2. Literature Review

2.1 Frequency Stability

Frequency stability is a crucial aspect of power system operation, ensuring that the system maintains a steady frequency within specified limits. It is affected by various factors, including the balance between generated power and load, control and protection equipment coordination, generation reserves, and equipment responses [8].

2.1.1 Rate of Change of Frequency (RoCoF)

ROCOF is an indicator for the frequency stability in the power system. It is a measure of how quickly the power system frequency is changing over time. It qualifies as a critical index for frequency stability of low-inertia power system [9]. It is calculated based on the deviation of frequency during a disturbance. It is particularly relevant in the context of renewable energy integration, as the integration of large size RESs can impact frequency stability. The rate of change of power output from renewable sources can lead to high ROCOF values, which can cause frequency instability [10]. The closer the RoCoF value to zero, the better the control response. This metric measures the rate of frequency response shortly after an electrical power imbalance (such as the disconnection of a generator or a load trip) but before any control is applied [1]. RoCoF can be mathematically represented in terms of the power imbalance Δ $P_{imbalance}$, power demanded P_{load}, frequency before the disturbance f_0, and the inertia constant H, as shown in the following equation.

$$ROCOF = \left.\frac{df}{dt}\right|_{(T=\tau)} = \frac{\Delta P_{\text{imbalance}}}{P_{\text{load}}} \frac{f_0}{2H} \tag{1}$$

2.1.2 Frequency Nadir

Frequency nadir is a term used in power systems to indicate the lowest frequency that the system reaches during a disturbance. It is an crucial indicator of the frequency security of the system, as it can indicate the impact of a sudden generation loss or a large load increase [11]. The frequency nadir can be estimated using predictive system controls,dynamic analysis and power system operators use it to evaluate the frequency security of the system [12].

2.2 Optimal Placement

An optimization problem can be developed that addresses the best location for RESs. Because studying the power system's frequency control response is the primary objective, minimizing the RoCoF is the objective function [1]. Mathematically, the objective function can be described as,

$$\text{Minimize F} = \min(RoCoF) \tag{2}$$

3. Methodology

3.1 Dynamic Analysis and Optimization

The methodology can be divided into two sections: dynamic analysis and optimization. Dynamic analysis refers to the study of the behavior of a power system during transient conditions, such as faults, switching operations, and sudden changes in load or generation. The objective of dynamic analysis is to ensure that the system remains stable and secure during these conditions. Through the optimization, the placement of the RESs is done in the selected power system such that the dynamic stability of the system is not affected during any disturbances.

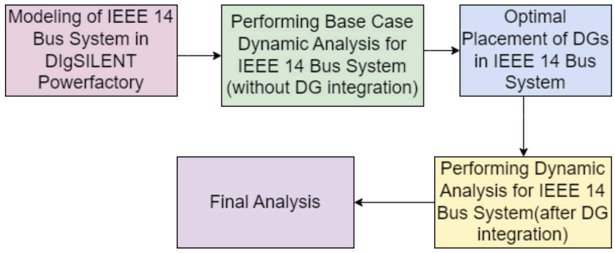

Figure 1: Block Diagram of the Methodology

The block diagram of the methodology is shown in figure 1. The IEEE 14-bus system is selected and modelled in DIgSILENT Powerfactory as part of the methodological approach. The system's base case dynamic analysis is performed without RES integration. An optimisation is done in MATLAB using an algorithm to find the best location for RESs. Following the integration of RESs, the dynamic analysis of the IEEE 14-bus system is completed. Figure 2 shows the overall methodology where the interfacing of MATLAB and Digsilent powerfactory. During the interfacing, the two software shares results of ROCOF and Optimal size and location of DG for the analysis.

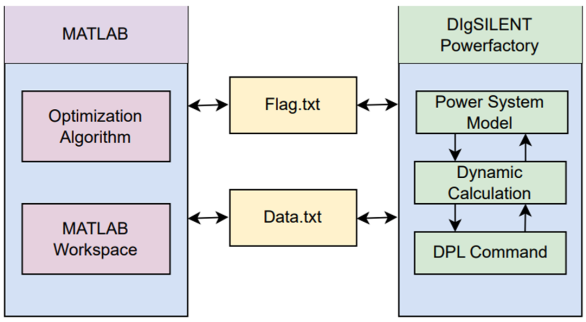

Figure 2: Overall Methodology

3.2 Particle Swarm Optimization

Particle Swarm Optimization (PSO) is used as the optimization tool for the study. It is a population-based algorithm that draws inspiration from animal natural motions like bird or fish behaviour. It is regarded as one of the most effective techniques for solving continuous and discrete optimisation issues [23]. In PSO, the various population members, sometimes referred to as the particles of swarm, migrate towards the target, or the global best, by altering their position and speed [24]. The following equations can be used to calculate the ith particle's velocity and position.

$$v_i(t+1) = W.v_i(t)+c_1.r_1.(pbest_i - x_i(t))+c_2.r_2.(gbest - x_i(t)) \tag{3}$$

where, $v_i(t+1)$ is the ith particle's velocity at the next iteration; w is the inertia weight; c_1 and c_2 are accelation coefficients, r_1 and r_2 are random numbers between 0 and 1; $pbest_i$ is the personal best position; gbest is the global best position and x_i is the current position of i at iteration t.

$$x_i(t+1) = x_i(t) + v_i(t+1) \tag{4}$$

where, $x_i(t+1)$ is the ith particle position at the next iteration.

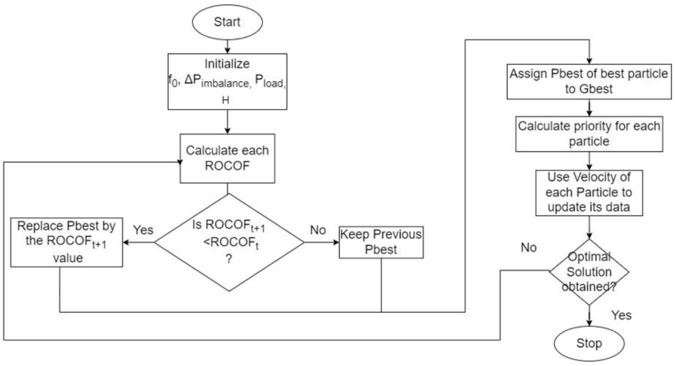

Figure 3: Flowchart of PSO

Figure 3 shows the flowchart of PSO where f, P_{load},Δ $P_{\text{imbalance}}$ and H are initialized and the ROCOF for each is calculated. Pbest is calculated for each iteration from the minimum value of ROCOF and the gbest is finally assigned to the pbest of the best particle.

3.3 System Modeling

The IEEE 14 bus system is modelled as shown in figure 4, and the required dynamic analysis is carried out. The AVR and Governor used in the generator frames in DIgSILENT Powerfactory for the IEEE-14 bus system. The system consists of 5 generators namely G1, G2, G3, G4 and G5 with their individual AVR and governor system, where G1 is the largest generator.

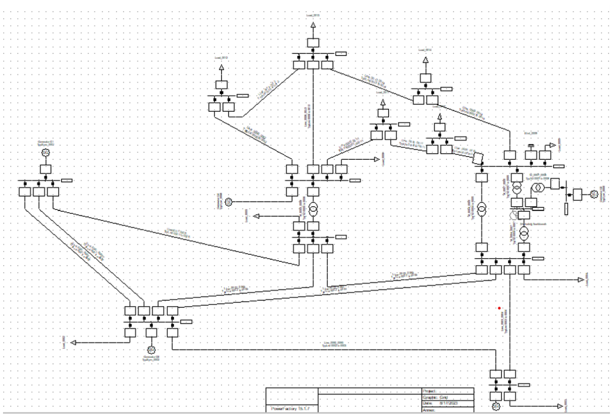

Figure 4: Model of IEEE 14-bus system in DIgSILENT Powerfactory

4. Results and Discussion

The analysis of the system is done for four cases: case (1) is normal operating condition, case (2) is operation during largest generator outage, case (3) is operation with random RESs placement and case (4) optimal RESs placement during largest generator outage. The RESs used in this system is Solar Photovoltaic (PV) System.

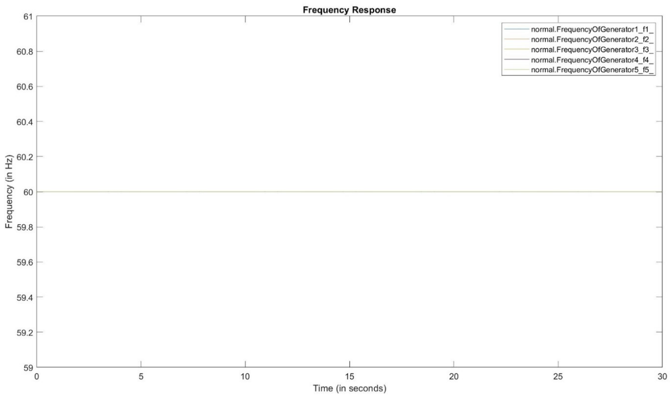

Figure 5: Case (1): System Frequency during Normal Operating Condition

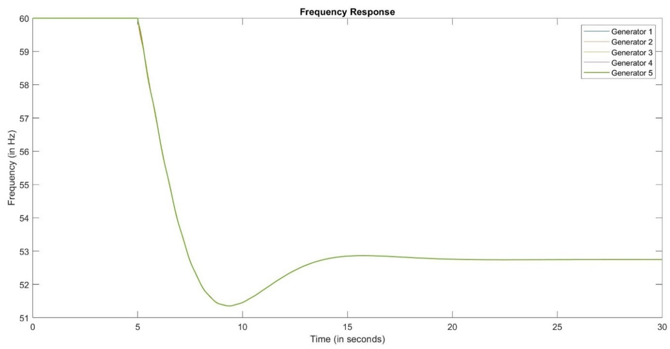

Figure 6: Case (2): System Frequency during G1 outage

For the placement of random RESs, the PV systems of sizes 39.16 MW, 48.23 MW, 42.76 MW and 48.12 MW at buses 1, 2, 3 and 8 respectively.

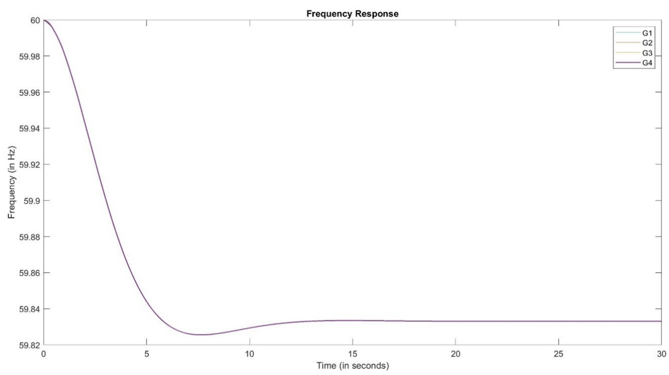

Figure 7: Case (3): System Frequency during G1 outage with Random PV Placement

For the optimal placement of RESs, one PV system of size 187.97 MW is placed at bus 2 and the frequency response from the system is shown in figure 8.

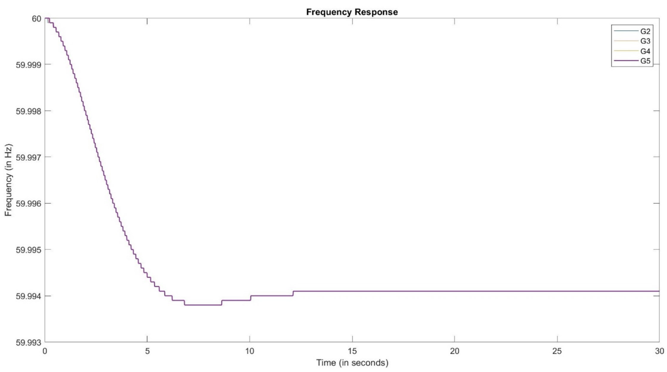

Figure 8: Case (4): System Frequency during G1 outage with optimal PV placement

During the normal operation in IEEE-14 bus system, the frequency of the system is maintained at 60Hz which showed that the system is stable during normal operating condition as shown in figure 5. However, when the largest generator is cut off, the IEEE 14-bus system becomes unstable with constant frequency at around 53Hz as shown in figure 6. This shows that the system becomes unstable with continuous large disturbances and thus, the integration of RESs in the system could hopefully help in improving the system stability. With the optimal placement of PV system, the system frequency during the disturbances stabilizes at the value within the allowable limit as shown in figure 7.

Let us consider generator G2 bus as a reference for the comparison between the results for different cases and the ROCOF and frequency nadir for G2 are tabulated in Table 1.

Table 1: RoCoF and Frequency Nadir during different cases for Generator 2

Cases	ROCOF (Hz/s)	Frequency Nadir (Hz)
G1 Outage	0.09854	51.6276
G1 Outage with Random PV Placement	0.02325	59.8258
G1 Outage with Optimal PV Placement	0.00069	59.9938

The results from table 1 show that the RoCoF is minimized after the optimal placement of the PV in the system and the value of Frequency nadir also improved. Thus, if PV systems are optimally placed in the power system, it can help to improve the system stability.

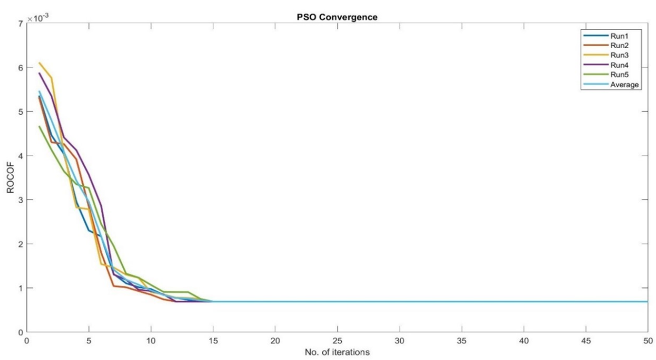

Figure 9: Convergence of PSO

Figure 9 shows the convergence of the PSO algorithm. Five independent runs for the model is carried out where the total population, N_{pop}= 50. The value of ROCOF for run 1 to run 5 is plotted along with the average ROCOF value obtained from the average of the five independent runs. The plot shows the relationship between the ROCOF for 5 different runs as well as the average with the number of iterations.

5. Conclusions

This research paper proposes a methodology for determining the capacity of RESs that can be penetrated into a power system where the objective function is set for minimizing a security indicator; specifically, RoCoF is minimized during a large and continuous disturbance in the power system. The optimization process includes the constraints ensuring the active and reactive power balance, capacity of line and the bus voltages. PSO is implemented in MATLAB for oprimization and then finally executed in DIgSILENT Powerfactory to obtain the optimal site and size of the RESs which reduces the effect of the disturbances in the power system. The random placement of PV systems of sizes 39.16 MW, 48.23 MW and 42.76 MW at bus 5, 10 and 13 respectively shows that the integration of RESs in the IEEE 14-bus system could help in improving the frequency stability in a power system as The improvement of ROCOF from 0.09854 Hz/s to 0.02345 Hz/s and frequency nadir from 58.6276 to 59.8258 is observed. Moreover, the optimal placement of the PV system ensures the maximum frequency stability in the system as the ROCOF is further decreased to 0.00069 Hz/s and frequency nadir is improved to 59.9938. Thus, it is observed that when the RESs are optimally located,adverse effects of the disturbances on the transient frequency response is reduced.

References

[1] Manuel S Alvarez-Alvarado, Johnny Rengifo, Rommel M Gallegos-Núñez, José G Rivera-Mora, Holguer H Noriega, Washington Velasquez, Daniel L Donaldson, and Carlos D Rodríguez-Gallegos. Particle swarm optimization for optimal frequency response with high penetration of photovoltaic and wind generation. *Energies*, 15(22):8565, 2022.

[2] Warren J Farmer and Arnold J Rix. Optimising power system frequency stability using virtual inertia from inverter-based renewable energy generation. *IET Renewable Power Generation*, 14(15):2820–2829, 2020.

[3] Pieter Tielens and Dirk Van Hertem. Grid inertia and frequency control in power systems with high penetration of renewables. In *Young Researchers Symposium in Electrical Power Engineering, Date: 2012/04/16-2012/04/17, Location: Delft, The Netherlands*, 2012.

[4] P Kundur. „power system stability and control" mcgraw, 1994.

[5] Andreas Ulbig, Theodor S Borsche, and Göran Andersson. Impact of low rotational inertia on power system stability and operation. *IFAC Proceedings Volumes*, 47(3):7290–7297, 2014.

[6] Carlos D Rodríguez-Gallegos, Oktoviano Gandhi, Dazhi Yang, Manuel S Alvarez-Alvarado, Wenjie Zhang, Thomas Reindl, and Sanjib Kumar Panda. A siting and sizing

optimization approach for pv–battery–diesel hybrid systems. *IEEE Transactions on Industry Applications*, 54(3):2637–2645, 2017.

[7] Angel A Recalde and Manuel S Alvarez-Alvarado. Design optimization for reliability improvement in microgrids with wind–tidal–photovoltaic generation. *Electric Power Systems Research*, 188:106540, 2020.

[8] Nima Amjady and Farzad Fallahi. Determination of frequency stability border of power system to set the thresholds of under frequency load shedding relays. *Energy Conversion and Management*, 51(10):1864–1872, 2010.

[9] Francisco Gonzalez-Longatt, Juan Manuel Roldan-Fernandez, Harold R Chamorro, Santiago Arnaltes, and Jose Luis Rodriguez-Amenedo. Investigation of inertia response and rate of change of frequency in low rotational inertial scenario of synchronous dominated system. *Electronics*, 10(18):2288, 2021.

[10] Jiahao Liu, Cheng Wang, Junbo Zhao, and Tianshu Bi. Rocof constrained unit commitment considering spatial difference in frequency dynamics. *IEEE Transactions on Power Systems*, 2023.

[11] Harold R Chamorro, Alvaro D Orjuela-Cañón, David Ganger, Mattias Persson, Francisco Gonzalez-Longatt, Vijay K Sood, and Wilmar Martinez. Nadir frequency estimation in low-inertia power systems. In *2020 IEEE 29th International Symposium on Industrial Electronics (ISIE)*, pages 918–922. IEEE, 2020.

[12] Diego Ortiz-Villalba, Jacqueline Llanos, Yanira Muñoz-Jadan, Rodrigo Moreno, Claudia Rahmann, and Bikash C Pal. Optimizing system operation with nadir considerations via simulations of detailed system dynamic responses. *Electric Power Systems Research*, 212:108533, 2022.