Inertia monitoring and forecasting with deep penetration of photovoltaic source. A case study of the Republic of Mauritius power grid

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Inertia Monitoring and Forecasting With Deep Penetration of Photovoltaic Source. A case Study of the Republic of Mauritius Power Grid

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***Abstract*—This paper aims at monitoring and forecasting the system inertia for the Republic of Mauritius power grid based on a novel stochastic dynamic grid model under an extreme weather event. As the island has set the target of connecting 60% of photovoltaic source to the network by 2030 as a measure to reduce carbon emissions, it is expected that the grid inertia to reduce, leading to unstable conditions. Accordingly, we use the Auto Regressive Integrated Moving Average forecasting method to study the inertia behavior. We demonstrate this method by using an IEEE 9-bus for our study. The percentage of penetration of the photovoltaic source is set at 60% and we forecast the inertia for a period of 5 hours under a rainy period. Our findings establish a minimum power generation to maintain stability, below which operators are required to connect other generating sources in the mix to avoid peak shaving. With this research, utilities can anticipate future disturbances.**

***Index Terms*—Forecasting, Inertia, Probability, Weather change.**

TABLE I
NOMENCLATURE

RES	Renewable Energy Sources
H	Grid Inertia Constant
PV	Photovoltaic
ARIMA	Auto Regressive Integrated Moving Average
BESS	Battery Energy Storage System
MW	MegaWatt
ROCOF	Rate of Change of Frequency

I. INTRODUCTION

Maintaining a constant power supply distribution is very challenging, especially with the deep penetration of renewable energy sources (RES), as the latter is affected by weather changes. According to (1), extreme weather events have a significant impact on the power distribution infrastructure. To be able to maintain the reliability of such a type of utility network under weather changes, it is essential that the power grid has the required inertia (H) which will restore stability when subject to a disturbing event such as a frequency collapse. H refers to the energy stored in the rotating masses of synchronous generators, which are typically found in conventional power plants such as coal, gas, nuclear, and hydropower facilities. In contrast, RES such as a PV generator source has a flywheel as storage energy to emulate H (2). This stored kinetic energy provides an automatic and instantaneous response to fast frequency changes in the grid as explained in Figure 1.

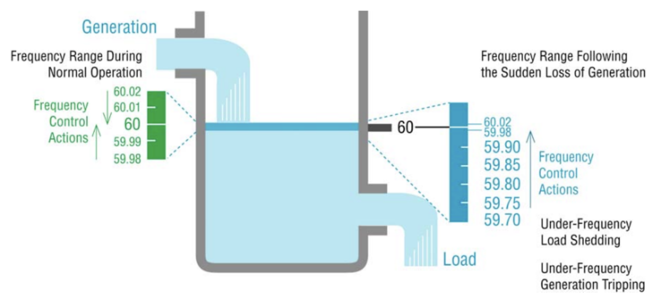

Fig. 1. Ranges of Power System Frequency During Normal Operations and Following the Sudden Loss of Generation,(3)

As many countries such as the United Kingdom & Greece are contemplating on the phasing out heavy oil generators due to environmental pollution and adopting an energy transition towards renewable energy sources (RES), significant reduction in H is expected as per (4). This observation is confirmed by (5), (6), (7) for the power grid of Denmark 60% & United Kingdom 67%. The aftermath of this significant reduction has led to a power outage in the United Kingdom in 2019 due to a frequency collapse. According to (8), such kind of power disruption affects the socio-economic activities of a country. The impact of this kind of power disruption can be worse for countries like the Republic of Mauritius with islanded grid condition.

The Republic of Mauritius is a small island located in the Indian Ocean. As per (9), its energy sector is highly dependent on fossil fuel as it contributes to 82% of the power demand, as indicated in Figure 2. Having established the objectives of connecting 60% PV to the generation mix by 2050 as part of its

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Source		July 2022 to June 2023 %
Renewable	Bagasse	8.91
	Hydro	2.66
	Solar PV	4.87
	Wind	0.34
	Cane Trash	0.22
	Waste to Energy	0.45
Total % Renewable Energy		**17.45**
Non-Renewable	Fuel Oil	53.24
	Coal	28.83
	JET A1	0.48
Total % Non-Renewable Energy		**82.55**

Fig. 2. Contribution of fossil fuel in the generation demand of Republic of Mauritius, (9)

long-term energy strategic planning, the Republic of Mauritius is bound to face major challenges in its energy sector by first ensuring stable power is delivered to customers. Second, the utility grid must cope with the uncertainties brought-in by the RES as its power distribution infrastructure is bound to face natural calamities such as cyclones (10), (11). Third, with the ageing of heavy oil generators and with no replacement project coming in the near future, it is essential to monitor H and ensure that it remains above the threshold limit, below which power outages occur. In this research paper, we develop a novel mathematical grid model for the power grid of the Republic of Mauritius where we consider the stochastic and uncertainty nature of RES to forecast and monitor H.

In literature, very few articles have sought of the impact of deep integration of PV generator source to the power grid of the Republic of Mauritius. In (12), the authors proposed to implement various PV farms at different locations to reduce the intermittency of the solar energy. However, this solution is very costly to implement. Furthermore, investigations carried out by (13) indicate that with increasing connection of PV, it may lead to a general black-out, if the heavy oil generators are not synchronized into the grid to compensate of the loss of power. However, this investigation is limited only to a deterministic analysis of the power grid of the island and does not consider any variability and uncertainties of parameters. With the limited research articles, we focus our investigations on previous works carried out in other countries. In (14), the importance of H is highlighted and describes the critical features of an inertia monitoring system. In (15) and (16), authors share similar view about H monitoring where they highlight that an estimation method is required prior for its monitoring. As no approved method of H exists, it becomes evident that a research gap exists in addressing H estimation, monitoring and forecasting so as to anticipate on future disturbing events. To the best of our knowledge, we are the first to propose a H monitoring and forecasting technique with deep penetration of RES for an islanded grid network such as the Republic of Mauritius. Therefore, with this research manuscript, we contribute in the following ways,

- **Development of a dynamic stochastic model of the Mauritian grid including variability and uncertainty of RES.**
  In this manuscript, we present a novel stochastic model to study the Republic of Mauritius electrical power network, which includes the variability and uncertainty of RES for an accurate analysis.
- **A novel approach for inertia estimation and forecasting**.
  We show a novel method of H estimation based on an on-line tracking of the rotor angle, δ and ARIMA.
- **Identification of minimum generation requirements for stable operation under extreme weather events.**
  With the objectives of connecting 60% of PV generating source to the grid, we identify a minimum generation load to ensure stable operation during extreme weather events.

A. Assumptions

- Our analysis considers the present state of the Republic of Mauritius power grid and assumes no increase in power demand, which would require additional synchronous generation.
- We neglect the contribution of bagasse since the harvesting area or yield amount can bring additional stochastic parameters in the grid and battery energy storage (BESS) to better understand the impact of variability and uncertainty brought in by the PV connected into the power grid.

We channel the rest of the paper as follows. Section II describes the methodology adopted, while in section III, we present the results and discussions. In section IV, we conclude on this research manuscript.

II. Methodology

The generation mix of the Republic of Mauritius mainly consists of heavy fuel oil synchronous generators, gas turbine and renewable energies, which is further divided into distributed generation. Accordingly, we represent in Figure 3 the various generating sources that contribute to the generating demand.

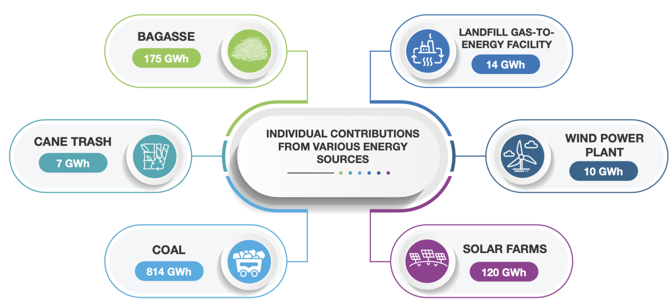

Fig. 3. Contribution of various generating sources to the power grid, (9)

As per (9), the peak demand for the Republic of Mauritius during the year 2023 was 479.90MW. Based on this data and with 60% of PV connected into the grid, we thus represent the Republic of Mauritius grid model on a modified IEEE 9-bus, shown in Figure 4 with the specifications as laid in Table II for stability analysis. This approach is inline with (17).

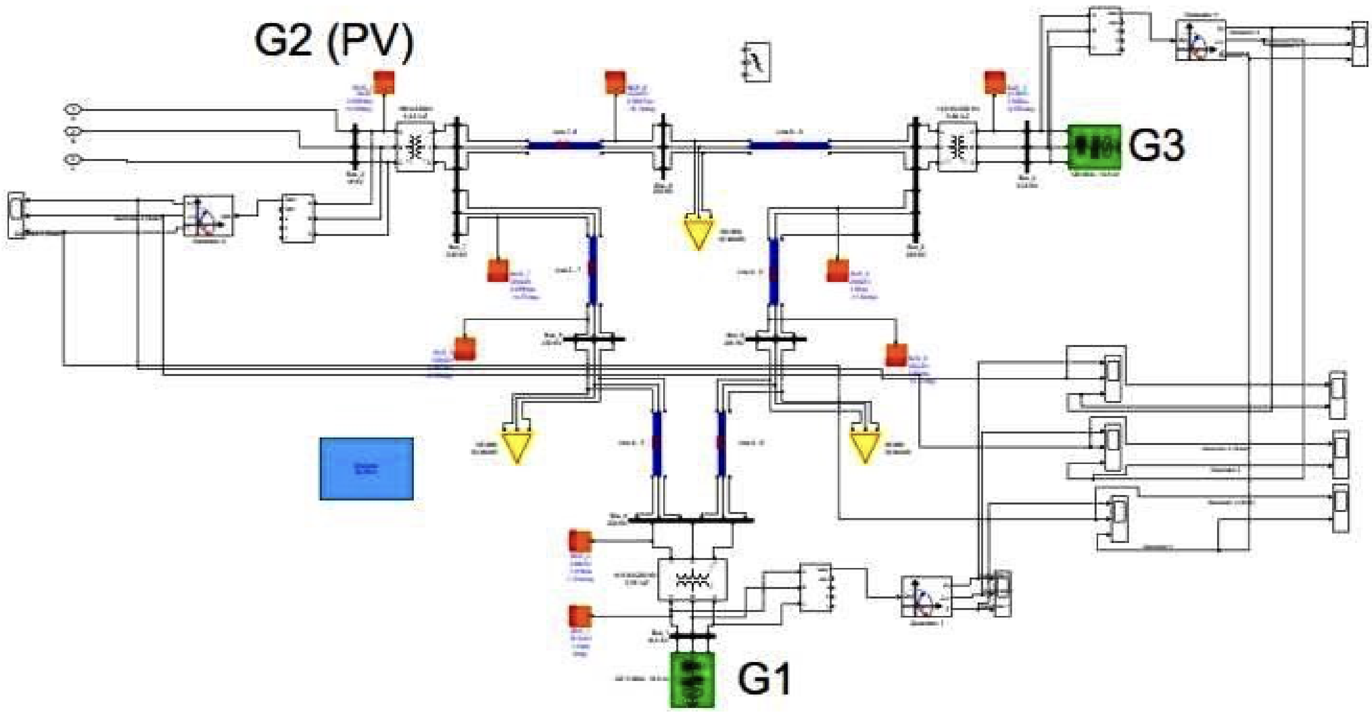

Fig. 4. Republic of Mauritius power grid represented by a modified IEEE 9-bus

TABLE II
PLANT CAPACITIES OF VARIOUS GENERATING SOURCE

Generating source	Capacity (MW)	Generator label
Thermal Power	360	3
PV	287.9	2
Gas Turbine	78	1

Based on Table II, we observe that with the deep connection of PV generating source at 60%, there will be approximately 50% of spinning reserve on the grid but with a reduced inertia H and we apply an extreme weather event such as a rainy period of 5 hours for our investigation, which represent a local condition of torrential rain as set by the Mauritius Meteorological Station. Based on observations made by (18), the bulk grid is now not sufficient to accommodate the large portion of RES for different reasons. First, the connection of RES into the grid brings an algorithm bottleneck due to added nonlinearity and increasing in dynamic. Second, the bulk grid now contains uncertainties and predicted errors. Third, the existing droop control of the grid cannot accomodate large portions of RES due to the asynchronous nature of RES. Therefore, to overcome the above limitations, we focus on a novel approach based on a similar varying inertia, $\frac{dH}{dt}$ with the PV generator source working as a virtual synchronous generator (VSG). A similar approach was observed in (19).

Accordingly, based on (20), we use the equation given by

$$\frac{1}{H}\frac{dH}{dt} = \frac{(1-P_{\max})\,(\omega(t)-\omega_s)\cos(\delta(t))}{1+2P_{\max}\sin(\delta(t))-P_m}. \tag{1}$$

and using equation (9) from (19), we derive the expression given by

$$\frac{1}{H}\frac{dH}{dt} = \frac{f\sin\delta}{P_e} \times \frac{V_{dc}\times dV_{dc}}{df} \times \frac{1}{V} \times \frac{1}{\omega_s}\frac{d\omega}{dt} \tag{2}$$

Due to space restriction on the research paper, we did not provide the derivation of Equation 2. However, the same can be made available upon request. The total inertia of the power grid will be the summation of the inertia contribution of the various generating units connected to the grid, and is expressed by Equation 3, (16)

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

Since, this research is focus on a synchronised inertia between a synchronous generator and PV generating source, the total inertia for the grid is given by Equation 4

$$\begin{aligned}\frac{d}{dt}(H_{sys}) &= N \times \frac{d}{dt}(H_{syn.gen}) + M \times \frac{d}{dt}(H_{RES.solar})\\ &= \frac{S_{sys.gen}}{S_{sys}}\sum_{i=1}^{N}\frac{d}{dt}(H_{gen}) + \\ &\quad \frac{S_{RES.solar}}{S_{sys}}\sum_{j=1}^{M}\frac{d}{dt}(H_{RES.solar})\end{aligned} \tag{4}$$

We define below the various terms in the model expressed by Equation 4

H_{sys} = system inertia (s) of the utility grid under investigation.
N = Number of synchronous generating source.

M = Number of PV generating source
S_{sys} = System MVA.
$S_{sys.gen}$ = rated power of synchronous generator (MVA).
S_{solar} = rated power of solar PV source (MVA).
$H_{sys.gen}$ = Inertia for synchronous generator (s).
$H_{RES.solar}$ = Inertia for solar PV source (s).
P_m = Mechanical Power (pu).
P_e = Electrical Power (pu).
P_{max} = Maximum Power of generator (pu).
ω = angular velocity (rad/s).
f = Frequency (Hz).
V = Voltage (V).
V_{dc} = Voltage across the DC Link capacitor,(V).
dV_{dc} = Change in voltage across the DC link capacitor, (V).
df = Change in frequency,(Hz).

By using this approach, we add an increasing non-linearity in the grid model for the Republic of Mauritius and also develop stochastic differential equation (SDE). According to (21), the only way to solve a stochastic differential equation is by using numerical methods and as per (22), Runge Kutta 4th order method provides a better approximation of the stochastic differential equations,(SDE).

A. Runge Kutta method

According to (23), Runge-Kutta method can predict the system behaviour at a time step Δt ahead. For instance, the position of the rotor angle δ can be predicted at time step $n+1$ as

$$\delta_{n+1} = \delta_n + \frac{1}{6}(K_1 + 2K_2 + 2K_3 + K_4) \tag{5}$$

where

$$K_1 = f(\delta_n, t_n)\,\Delta t \tag{6}$$

$$K_2 = f(\delta_n + \frac{K_1}{2} t_n + \frac{\Delta t}{2}) \tag{7}$$

$$K_3 = f(\delta_n + \frac{K_2}{2} t_n + \frac{\Delta t}{2})\Delta t \tag{8}$$

$$K_4 = f(X_n + k_3, t_n + \Delta t)\Delta t. \tag{9}$$

K_1 is the slope at the beginning of the time step Δt. K_2 is the first approximation to slope at midstep Δt. K_3 is the second approximation to slope at midstep Δt. K_4 is the slope at the end of the time step Δt.

B. Forecasting

In the analysis of the uncertainty in power system, it is essential to forecast the behaviour of H so as to ensure proper operational planning of the dispatchable generators. As per (24), there exists several forecasting methods such as

- Autoregressive Indicated Moving Average(ARIMA).
- Autoregressive Integrative Moving average with explanatory variable,(ARIMAX).
- Seasonal Autoregressive Indicated Moving Average,(SARIMA).
- Seasonal Autoregressive Indicated Moving Average with exogeneous variables,(SARIMAX).

As per the study carried out by (25), the ARIMA model provides a better accuracy than the ARIMAX model. Hence, the ARIMA model will be selected in our forecasting analysis.

1) ARIMA Model: As per (26), an Arima model consists of 3 important terms namely

- autoregressive terms denoted by p.
- number of differences,d
- number of moving averages,q.

where the autoregressive process is a linear function of the preceding parameters and is given by

$$Y_t = \alpha_1 Y_{t-1} + \epsilon_t \tag{10}$$

, the number of differences between two successive values of Y is given by

$$Y_t = Y_{t-1} + \epsilon_t \tag{11}$$

where ϵ_t is a white noise, and number of moving average is the linear combination of current disturbance with one or more previous disturbances. The moving average can be explained by

$$Y_t = \epsilon_t - \theta_1 \epsilon_{t-1} \tag{12}$$

As per (27),the ARIMA model was first introduced by Box and Jenkins and according to (25), the model analyzes a univariate stochastic time series for forecasting.

III. Results and Discussions

To recall, the aim of this research paper was to monitor and forecast H for the Republic of Mauritius power grid under an extreme weather event such as a rainy period with a view of ensuring grid reliability with the energy transition in-place. First, we use an inertia constant (H) to be 6s according to recommendation of (28) to enable deeper penetration of RES. Second, with the technique described in the section II, we provide a scattered sampling approach for the most probable outcome of H in Figure 5 and Figure 6, for both the heavy oil generators and the PV generator source with the time duration of investigation.

Based on results obtained in Figure 5, the most probable contribution of the inertia (H) would be 4s from the synchronous generator, while in Figure 6, the contribution of grid inertia (H) from the PV generating source would be 3s. As such, both generators would still be connected to the grid but with a significant reduction in the power delivered by the PV generating source as indicated by Figure 7. We valid our observations by forecasting H for the period of 5 hours as depicted in Figure 8 We observe based on Figure 8 that with the 95% confidence interval of H over the 5 hours duration, we are able to maintain the PV load with a maximum RoCOF of 0.25Hz. Consequently, we observe that with the present configuration of the generation mix, it is most likely that the power system operators will require to use the gas turbine generators and the battery energy storage system (BESS) to avoid any peak shaving, thus ensuring stable power.

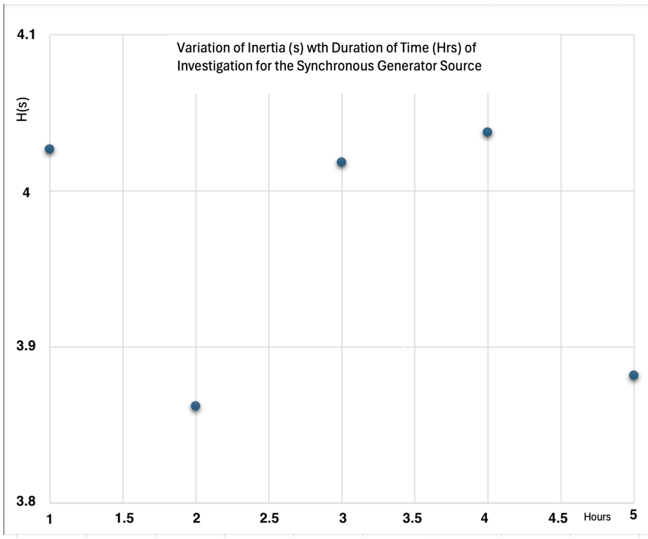

Fig. 5. Variation of inertia of the synchronous generator with time of investigation- Scatter Plot

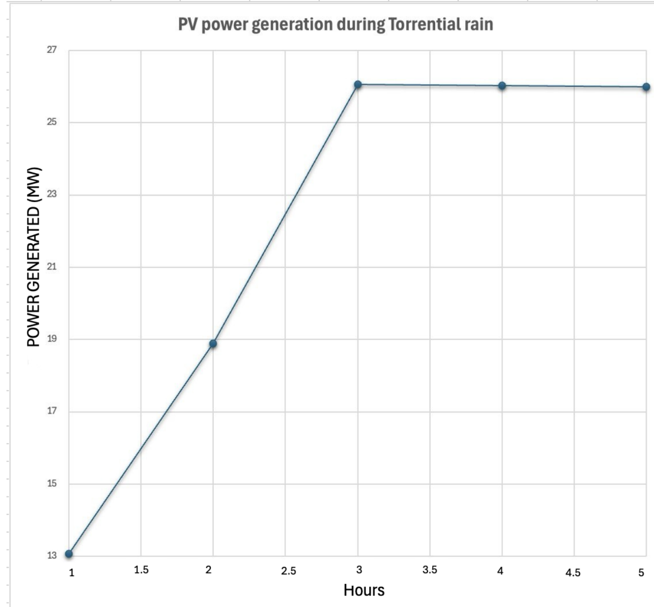

Fig. 7. Expected Power produced by PV generating source under extreme weather event

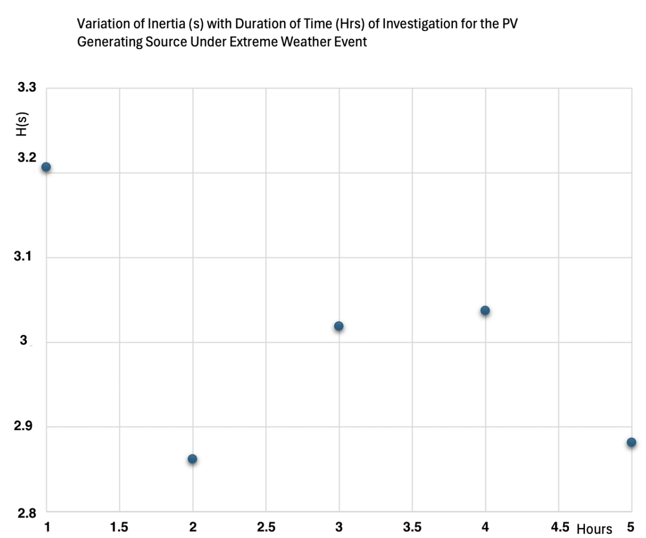

Fig. 6. Variation of inertia of the PV Generator source with time of investigation - Scatter Plot

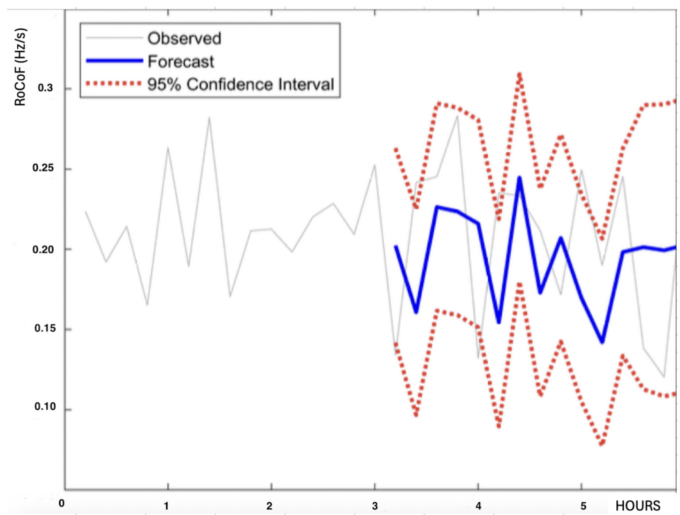

Fig. 8. Inertia Forecasting for a period of 5 hours during extreme weather events

IV. Conclusions

In this paper, we present a novel stochastic dynamic grid model for the Republic of Mauritius to monitor and forecast the grid inertia constant, H, under extreme weather event. The analyses were mainly focus on the most probable sampling output of H for both synchronous generator and PV generator source. Our key finding shows that with the proposed method discussed in this paper, we produce a maximum ROCOF of 0.25Hz/s, which is within the acceptable limit. The use of storage energy becomes primordial to restore this small frequency deviation as quickly as possible. The implication of this finding is profound. It underlines the urgent need for policymakers to adopt novel approaches for H monitoring and forecasting of the power grid. In conclusion, the energy industry of the Republic of Mauritius will still be dependent on heavy fuel oil generators to maintain grid stability unless novel approaches and solutions for modernization of the power grid are adopted. A possible future avenue is to validate our historical frequency data and integration of additional RES types such as offshore wind and hybrid BESS solutions.

References

[1] S. Poudel and A. Dubey, "Critical load restoration using distributed energy resources for resilient power distribution system," *IEEE Transactions on Power Systems*, vol. 34, no. 1, pp. 52–63, 2018.

[2] A. Soomro, K. R. Pullen, and M. E. Amiryar, "Hybrid pv system with high speed flywheel energy storage for remote residential loads," *Clean Technologies*, vol. 3, no. 2, pp. 351–376, 2021.

[3] J. H. Eto, "Use of frequency response metrics to assess the planning and operating requirements for reliable integration of variable renewable generation," 2011.

[4] J. Jaeger, "These 10 countries are phasing out coal the fastest," Nov 2023. [Online]. Available: https://www.wri.org/insights/countries-phasing-out-coal-power-fastest

[5] F. Milano, F. Dörfler, G. Hug, D. J. Hill, and G. Verbič, "Foundations and challenges of low-inertia systems," in *2018 power systems computation conference (PSCC)*. IEEE, 2018, pp. 1–25.

[6] M. Nedd, J. Browell, K. Bell, and C. Booth, "Containing a credible loss to within frequency stability limits in a low-inertia gb power system," *IEEE Transactions on Industry Applications*, vol. 56, no. 2, pp. 1031–1039, 2019.

[7] J. Shair, H. Li, J. Hu, and X. Xie, "Power system stability issues, classifications and research prospects in the context of high-penetration of renewables and power electronics," *Renewable and Sustainable Energy Reviews*, vol. 145, p. 111111, 2021.

[8] J. Jasiūnas, P. D. Lund, J. Mikkola, and L. Koskela, "Linking socio-economic aspects to power system disruption models," *Energy*, vol. 222, p. 119928, 2021.

[9] D. Paligadu, "Powering a greener future," CEB, Tech. Rep., 2023.

[10] C. Palanichamy, N. S. Babu, and C. Nadarajan, "Renewable energy investment opportunities in mauritius—an investor's perspective," *Renewable energy*, vol. 29, no. 5, pp. 703–716, 2004.

[11] E. U. EU Commission, 2020. [Online]. Available: http://tinyurl.com/yc35h5h9

[12] T. Hookoom, K. Bangarigadu, and Y. K. Ramgolam, "Optimisation of geographically deployed pv parks for reduction of intermittency to enhance grid stability," *Renewable Energy*, vol. 187, pp. 1020–1036, 2022.

[13] D. Rughoo, B. S. Bhujun, K. Ragoopathee, and R. K. Dreepaul, "Analysis of the power system stability upon integration of pv system into the national grid of the island of mauritius," in *2022 International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME)*. IEEE, 2022, pp. 1–5.

[14] L. Lavanya and K. Swarup, "Inertia monitoring in power systems: Critical features, challenges, and framework," *Renewable and Sustainable Energy Reviews*, vol. 190, p. 114076, 2024.

[15] K. Prabhakar, S. K. Jain, and P. K. Padhy, "Inertia estimation in modern power system: A comprehensive review," *Electric Power Systems Research*, vol. 211, p. 108222, 2022.

[16] F. Zeng, J. Zhang, G. Chen, Z. Wu, S. Huang, and Y. Liang, "Online estimation of power system inertia constant under normal operating conditions," *IEEE access*, vol. 8, pp. 101 426–101 436, 2020.

[17] S. Peyghami, P. Davari, M. Fotuhi-Firuzabad, and F. Blaabjerg, "Standard test systems for modern power system analysis: An overview," *IEEE industrial electronics magazine*, vol. 13, no. 4, pp. 86–105, 2019.

[18] A. Dubey, "Distribution grid optimization at-the-edge-interfacing," Washington State University, Tech. Rep., 2024.

[19] R. Ghosh, N. R. Tummuru, B. S. Rajpurohit, and A. Monti, "Virtual inertia from renewable energy sources: Mathematical representation and control strategy," in *2020 IEEE International Conference on Power Electronics, Smart Grid and Renewable Energy (PESGRE2020)*. IEEE, 2020, pp. 1–6.

[20] A. A. Jhumka, Y. B. Ruhomally, C. Ramasawmy, R. T. A. King, and M. Z. Dauhoo, "Swing equation in power systems: approximate analytical solution for the dynamics of the system inertia," in *IET Conference Proceedings CP822*, vol. 2022, no. 27. IET, 2022, pp. 36–41.

[21] F. Milano and R. Zárate-Miñano, "A systematic method to model power systems as stochastic differential algebraic equations," *IEEE Transactions on Power Systems*, vol. 28, no. 4, pp. 4537–4544, 2013.

[22] E. O. Oduselu-Hassan and I. N. Njoseh, "A review of numerical methods for stochastic differential equations," *Nigerian Journal of Science and Environment. Vol*, vol. 17, p. 1, 2019.

[23] K. Uçak, "A runge–kutta neural network-based control method for nonlinear mimo systems," *Soft Computing*, vol. 23, no. 17, pp. 7769–7803, 2019.

[24] S. Haben, M. Voss, and W. Holderbaum, *Core concepts and methods in load forecasting: With applications in distribution networks*. Springer Nature, 2023.

[25] Ď. Peter and P. Silvia, "Arima vs. arimax–which approach is better to analyze and forecast macroeconomic time series," in *Proceedings of 30th international conference mathematical methods in economics*, vol. 2, 2012, pp. 136–140.

[26] J. Fattah, L. Ezzine, Z. Aman, H. El Moussami, and A. Lachhab, "Forecasting of demand using arima model," *International Journal of Engineering Business Management*, vol. 10, p. 1847979018808673, 2018.

[27] G. E. Box, G. M. Jenkins, G. C. Reinsel, and G. M. Ljung, *Time series analysis: forecasting and control*. John Wiley & Sons, 2015.

[28] M. Ghandhari, "Stability of power systems, an introduction," 2011.