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Modelling and analysis of grid integration for high shares of solar PV in small isolated systems – A case of Kiribati

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ABSTRACT

Kiribati, a Pacific Island Country, is striving for high solar PV electricity into national grid in order to reduce its unsustainable dependence on imported fossil fuel. This, however, can pose technical challenges on the reliable operation of the small isolated system. In this work, a technical analysis was carried out to investigate the implications of the planned pipeline of grid connected PV systems on Kiribati's Tarawa power system. Variations in PV output and corresponding spinning reserve requirements to balance the short fall in the power output were analysed. The utility network was modelled using the *PowerFactory* software. Steady state and dynamic analyses were then carried out for the simulated scenarios. There were no major concerns identified at times of high load with high PV output. For low system demand with high PV output, dispatch constraints were identified. The current grid system will sustain maximum PV capacity above a load of 3250 kW but will require curtailment below this load. Dynamic simulations showed that fast negative ramps in the PV output can lead to frequency instability during a time of low demand and maximum PV output. The system is stable with PV curtailed at 900 kW if low loads and maximum PV output conditions exist.

1. Introduction

Renewable energy is now an essential part of the global agenda for sustainable development as nations are struggling with the impacts of climate change, depleting fossil fuel reserves and growing energy demand. Pacific Island Countries (PICs) are heavily dependent on imported fossil fuels for their energy needs. hence their economies are highly vulnerable to the impacts of fluctuating world oil price [1]. For an energy secure Pacific region, development and deployment of local renewable energy based solutions are vital. Solar energy has become a promising alternative source due to its advantages: abundance, pollution free and renewability [2]. However, as the number of installation of PV generators are increasing, the intermittent and stochastic electricity production pose technical and economic challenges. The deepening penetration of renewable energy sources exacerbates the challenge to maintain demand-supply equilibrium [3]. Active power curtailments and reactive power controls are being proposed to overcome voltage and frequency violations. Also, co-ordination strategies engaging independent power producers and system operators along with energy storage systems (ESS) in low voltage networks are being proposed and implemented to overcome voltage imbalances and to ensure reliability of the grid. Moreover, technical and economical assessment of various storage technologies for load shifting applications are being explored [4].

According to Eltawil et al. [5], identifying the technical requirements for grid interconnection and solving the interconnect problems are very important issues for widespread application of PV systems. Potential impacts of large amounts of intermittent PV electricity in small isolated networks include issues with system stability (especially frequency), changes in voltage profiles, reverse power flows, challenges with frequency regulation and changes in the fault currents and harmonics [6]. These effects have been analysed in many studies [7–11]. In any power system, the active power generation must constantly match the demand. Disturbances due to balance are compensated for by the kinetic energy of

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Nomenclature

ESS Energy storage system
GCPV Grid Connected PV System
IRENA International Renewable Energy Agency
JPEC Japanese Pacific Environment Community Fund
KIT Kiribati Institute of Technology
KGV King George V
Load P99 99^{th} percentile load
Load P1-No PV A scenario that represents 1st percentile load without any PV output
Load P1-PV Max A scenario that represents 1st percentile load at maximum PV output
Load P99-No PV A scenario that represents 99th percentile load without any PV output
Load P99-PV Max A scenario that represents 99th percentile load at maximum PV output
PIC Pacific Island Country
PUB Public Utilities Board
P1 1^{st} percentile is the value below which 1% of the set of values exist
P99 99^{th} percentile is the value below which 99% of the set of values exist; PV Max Maximum PV output
SCADA Supervisory control and data acquisition
SR Spinning reserves
SR - P1 Forecast 1^{st} percentile spinning reserves upon forecasting
SR - P5 Forecast 5^{th} percentile spinning reserves upon forecasting
SR - P50 Forecast 50^{th} percentile spinning reserves upon forecasting
SR - P95 Forecast 95^{th} percentile spinning reserves upon forecasting
SR - P99 Forecast 99^{th} percentile spinning reserves upon forecasting
SR-Variation Spinning reserves based on maximum variations
SR-Power output Spinning reserves based on maximum power output
TCH Tungaru Central Hospital
UAE United Arab Emirates
USP The University of the South Pacific

the rotating generators and motors connected to the network, resulting in a variation in the system frequency from its set point [12]. This has resulted in a need for the assessment of their impact on frequency control due to enhancing embedded generation in island networks.

Gomez et al. presented a procedure to plan secure operation of the grid on islands whilst maximizing the utilization of available and planned RE generation [10]. The procedure was applied to Samoa's Electric Power Corporation (EPC) planned integration of RE in the island of Upolu. It was found that there was a potential to increase contribution from PV plants from 2% to 18% of the total annual demand. In another study, for the same island, a network model of the island was implemented using the DIgSILENT *PowerFactory* software [13]. The effect of higher shares of renewable generation in Upolu's power system had a significant effect on the overall generation costs. The grid performance was assessed based on the following areas: Frequency stability Voltage stability and Transient stability.

In a pilot study by IRENA [7], an assessment was done for feasible PV penetration levels for a grid system in Palau. The network model was implemented in DigSILENT's *PowerFactory* software. According to this study, for up to 30% instantaneous penetration, no additional technologies such as enhanced automatic dispatch and/or storage facilities would be required. Lamberti et al. carried out a massive data analysis that showed the benefits of integration of energy storage systems with PV units in a real LV network in terms of voltage quality improvements. Delille et al. [12] investigated the use of fast-acting storage to tackle power fluctuations through wind and PV by providing a prompt, short-term support to frequency control. An ultra-capacitor was studied and dedicated supervision algorithms were developed to take full advantage of its very short response time.

The present work is an analytical study for the Kiribati grid system and is focused on Tarawa atoll. Kiribati, a PIC, is one of the World's Least Developed Countries (LDC) according to the United Nations classification. Kiribati relies almost entirely on imported fuels for its power generation and transportation requirements. Fuel imports constitute approximately 25% of the cost of all imports. Kiribati is also vulnerable to the impacts of climate change. To address these challenges, the country is actively exploring renewable energy based solutions for its energy needs [14].

Electricity on Tarawa is provided primarily by the Public Utilities Board (PUB). There are two Power Stations: Betio Power Station has one generator with installed capacity of 1.25 MV A and Bikenibeu Power Station has three generators rated at 1.75 MV A with installed capacity of 5.25 MV A. The distribution voltage is 11 kV with no transmission network and the distribution lines are all underground. As with many Pacific Island utilities, there are two load peaks during a typical work day: a daytime peak mainly due to air conditioning loads for government offices and a smaller evening peak which relates to residential lighting and entertainment use. Weekend load patterns show only the evening peak. The noontime load on the weekend is around 2.3 MW, while during a work day it is around 1.5 times higher [14].

Currently, there are two large grid connected PV systems on Tarawa grid namely, the Japanese government (JPEC) funded 400 kWp system commissioned in 2014 and the United Arab Emirates (UAE) funded 500 kWp system commissioned in 2015. There are plans for further expansion through the World Bank projects with more than 500kW_p distributed on various rooftops within Tarawa. The present study investigates the impact of these projects on the operation of the system, considering the current grid infrastructure.

This study utilises real operational data for load and PV output for the year 2014–2015. The main components of this work are:

a) Analysis of solar variability to determine reserve requirements, necessary to balance power production and consumption;
b) Identification of critical scenarios for the operation based on statistical analysis of hourly demand data and possible PV generation profiles;
c) Steady state and dynamic simulation to check for security of operation under critical scenarios

The above mentioned assessments allow the identification of adverse impacts and possible mitigation measures.

2. Technical background

High penetration levels of intermittent resource based generation like solar PV can introduce technical, commercial and regulatory challenges in the systems when integrated. Some of the technical challenges include voltage rise effect, power quality issues, impact on protection schemes and stability of the network [15]. Distributed generation changes the power flows in the networks and breaks the traditional one way power flow from the high to the low voltage levels of the power system [16].

Solar PV like other variable renewables have the following characteristics that are different from conventional generation:

1) These systems are not necessarily located where the main power plants are and thus can be distributed.
2) They do not use synchronous machines, instead incorporate power electronics inverters.
3) The output fluctuates at different timescales, for example, it varies intra-hourly, seasonally and yearly.
4) It is not possible to predict output with 100% accuracy.

With high shares of PV generation, the characteristics described above can have impacts on the secure operation of the network. The location of the solar PV system in the network affects the power flows, therefore impacting the loading of the system elements and potentially the control of voltage. These impacts can be analysed through load flow studies. The absence of synchronous machine feature affects the dynamic response to events in the network like short circuit and imbalance between power production and consumption, thus having potential impacts on the stability of the system. This can be analysed through dynamic stability simulations. Furthermore, PV output fluctuations and limited predictability have an impact on the requirements for balancing power production and consumption. An assessment of fluctuations (ramps) become necessary to define spinning reserve requirements and also to see how quickly the reserves balance the system. Fluctuations in output along with inaccuracy in prediction affect the allocation of spinning reserves since there is a concern of uncertainty in the output.

3. Methodology

The study followed a framework proposed by IRENA to analyse the impacts of variable renewables on the operational security of electricity grids in Small Island Developing States. The methodology was adapted from the pilot study by Gomez et al. [10] and consists of the steps described in Fig. 1.

3.1. Data collection

Data was collected from Kiribati electricity utility, Public Utilities Board (PUB) through online correspondence and a site visit.

3.1.1. Demand data

The annual hourly total generation data for year 2014 of the grid in South Tarawa was made available by PUB.

3.1.2. Expansion plan for grid connected solar projects

The information about existing PV projects was collated and the expansion plan was included in the analysis to reflect the proposed total PV capacity. The total PV capacity to be modelled was 1459 kW_p as planned for the South Tarawa grid. This value comes from 7 projects, four of which are part of the expansion plan:

- 400 kW_p from Japanese PEC funded (JPEC) system in Bikenibeu (existing)
- 500 kW_p from UAE funded system in Bonriki (existing)
- 1 × 10 kW_p from USP system in Bairiki (existing)
- 118kW_p from the World Bank funded system at KGV School in Bikenibeu (projected)
- 176 kW_p from the World Bank funded system at TCH in Bikenibeu (projected)
- 118 kW_p from the World Bank funded system at KIT in Betio (projected)
- 137 kW_p from the World Bank funded system at Betio Sport in Betio (projected)

3.1.3. Solar PV system data

Three sets of solar PV production and resource availability data were collected. The first set of data was one month's solar radiation data which was collected at 1–10 min intervals for the JPEC funded 400kW_p grid connected PV system site. The second set of data was active power output from three months measurements taken between 1 and 10 min for the JPEC funded 400kW_p grid connected PV system. The third set of data was active power output data from three month's measurements taken at 10 min intervals for the UAE funded 500kW_p grid connected PV system.

3.1.4. Network data

The main parameters of the network for the implementation of the simulation model in *PowerFactory* were imported from an

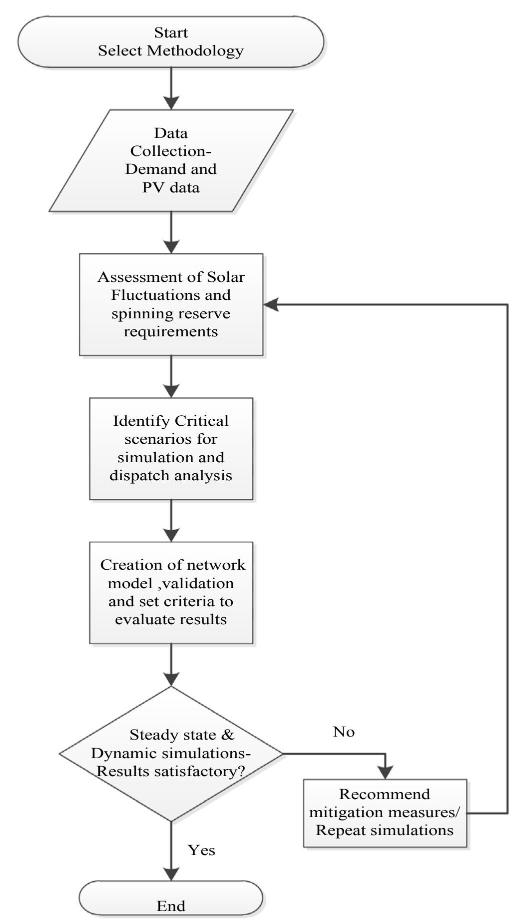

Fig. 1. Flow diagram of methodology utilised.

existing basic model of the Tarawa grid in the *EasyPower* software from a previous study [17]. The electrical parameters included were for the main network components such as: generators, transformers, cables and auxiliaries. Using the imported parameters, the network model was created with reference to the most recent single line network diagram.

3.1.5. Operational data

The operational data for the grid and real time measurements of the generator were obtained from PUB. The generator output and voltage measurements were collected for network validation in *PowerFactory* and the current operational practices were considered in the analysis. The steady state components were validated with real time measurements of active power, reactive power and voltage [18].

3.2. Assessment of solar fluctuations

The sets of data described in Section 3.1 were used to analyse the potentially fast solar fluctuations (ramps) in the production of PV output according to the planned expansion. For each set of data, the ramps were estimated as the change in active power from one period to another (at 10 min intervals). Using 99th percentile, the extreme but feasible ramps for power drops and rises for all 10 min intervals during production hours were calculated. A 99th percentile ramp is a ramp value below which 99% of the ramps exist or in simple terms it is amongst the highest ramps. The expected rise in power output are referred to as positive ramps and the potential drop in power are referred to as negative ramps. Three approaches for analyzing variability and determining reserves were investigated. In this, the individual results were scaled up to system level, considering the expected expansion of PV systems on the island.

A brief description of the three approaches to estimate significant values for the fluctuations are presented below:

- Worst case of 99th percentile active power ramps of the UAE $500kW_p$ and the JPEC $400kW_p$ systems.
- Smoothing of PV fluctuations by geographical dispersion of plants using the empirical formula, as in (1) [19]:

$$99^{th}(\Delta P_{\Delta t,N}) = 99^{th}(\Delta P_{600,1})\left(1 - e^{-0.24\Delta t}\right)S^{-c}N^{-a}; \quad a, c > 0 \tag{1}$$

where $99^{th}(\Delta P_{\Delta t,N})$ is the 99^{th} percentile of the largest fluctuation for N plants, Δt is sampling period, N is number of PV plants aggregated, S is PV plant surface area (Ha), and a and c are attenuation of power coefficients as a function of N and S respectively.

- Aggregate sum of the 99th percentile of active power fluctuations of 2 systems i.e. UAE and JPEC systems

The results from this analysis are used for spinning reserve calculations and are discussed in Section 4.

3.3. Allocation of spinning reserve requirements to compensate fluctuations

In the context of this work, spinning reserve is assumed as the unused capacity which can be activated on decision of the system operator and which is provided by devices which are synchronised to the network [20]. In Tarawa, as in many small isolated systems, the spinning reserves have not been used to cover loss of generators (contingency reserves), but only to balance unexpected load changes. Upon addition of PV systems, additional reserves will be required to follow fluctuations of PV output. If this is not done, then the balance between production and consumption cannot be maintained under normal conditions.

In a small isolated system with very high PV penetration levels, batteries can be used to provide spinning reserve to allow high instantaneous penetration levels. However, this was not considered in this study which aims to investigate the impacts on the current system and constraints to PV penetration with minimum investments in the infrastructure. The focus in this work was on positive spinning reserves. A constraint to the minimum generation of machines above actual minimum was assumed to ensure that enough headroom to reduce power output is available in case of sudden increase of power from PV.

Three simple methods for allocating spinning reserves to compensate ramps in the PV output were explored in this work. These methods aim for simplicity in order to facilitate their potential implementation in a simple system like Tarawa without major effort or sophistication.

Method 1. *Determining spinning reserves according to power output*

This method establishes fixed levels of spinning reserves for every half hour of the day between 6:00 a.m. and 6:00 p.m. It allocates enough spinning reserves to compensate the 99th percentile of the negative ramp (calculated using the methods from Section 3.2) for the maximum expected level of PV power output (called henceforth as PV Max) on each half an hour period of the day.

Method 2. *Determining spinning reserves according to the maximum variations*

This method also establishes fixed levels of spinning reserves for every half hour of the day. In this method, the spinning reserves were determined based on the maximum variations in power output observed in every half an hour period of the day. Thereafter, the spinning reserves were taken as values to cover up the corresponding drop in output or the power lacked by the system to meet the demand during that period.

Method 3. *Determining spinning reserves upon simple persistence forecasting*

This method intends to establish variable spinning reserve at every half an hour interval based on forecasted PV output. Here, persistence forecasting approach was adopted to predict the power output for the next half an hour. The persistence forecasting formula adopted for the research is given below.

$$P(t+1) = P(t)\frac{P\max(t+1)}{P\max(t)} \tag{2}$$

where:

P(t + 1) is power output forecast for the next time interval, *P(t)* is power output for the current time interval, *Pmax (t + 1)* is maximum power output for the next time interval and *Pmax (t)* is maximum power output for the current time interval.

Upon forecasting the power output for the next half hour interval, spinning reserves were calculated using Method 1.

3.4. Identification of critical operational scenarios for steady state and dynamic simulations

The demand profile and the solar PV resource data were analysed, using percentiles to identify extreme but feasible conditions that may be challenging for the secure operation of the grid. Low demand days (weekends) with high PV production could be challenging since during this time the generators were identified to work below their minimum loading capacities. Also, having fewer machines dispatched during this time, the system may have less inertia and thus, voltage control may be difficult since the reactive power is provided only by the synchronous machines in Tarawa. It can be assumed that if the system is able to survive these challenging conditions, it should be able to survive less severe situations. These conditions combined with the reserve considerations determine the dispatch of the machines and hence the critical operational scenarios for the simulations. Taking the above points into consideration, the following scenarios were selected:

- Low load without PV (Load P1-No PV)
- Low load with maximum PV output (Load P1-PV Max)
- High load without PV (Load P99-No PV)
- High load with maximum PV output (Load P99-PV Max)

The generator dispatches for all the above listed scenarios were formulated for the time of 12:00 p.m. It was also ensured that generators do not work below the minimum and above the maximum capacity. The minimum and maximum capacity of the generators were taken as 600 kW and 1200 kW respectively.

3.5. Steady state and dynamic power system simulations to check for secure operation

A model was implemented in *PowerFactory* [18] and steady state and dynamic simulations were carried out. Through simulations, the operational security of the system under feasible but most challenging operational scenarios were proved.

For the evaluation of results of the load flow simulation, a predefined set of criteria was used. The allowable loading was set at ± 4.5% of full load. For voltage, it was ensured that the voltage at the buses were within the adopted criteria (i.e. between 0.9 p.u to 1.1 p.u). The load flow calculations were conducted for all listed scenarios in Section 3.4. The Steady State model was verified with the measurements available for the generators from the SCADA system at Bikenibeu Power Station. Betio Power House has manually logged data and the rest of the grid is not covered with SCADA, thus restricting measurements and validation.

Dynamic modelling was used to analyse frequency stability for the critical scenarios in Section 3.4. The adopted criteria to evaluate the results in the particular case of Kiribati was that the frequency should be maintained between 48 and 52 Hz (the assumed range for diesel generators) following feasible imbalances of active power. This would guarantee that disconnection of diesel machines and the consequent collapse of the system would occur under these selected criteria. The Under Frequency Load Shedding Schemes (UFLS) were not considered, as there is no UFLS currently implemented in Tarawa. The Bikenibeu power plant has 3 generators with automatic primary and secondary control. The secondary controller was modelled according to standard behavior as data was not available.

The PV systems were represented in the dynamic simulations through simplified models of active power sources working at user defined set points and unity power factor, where the frequency and the voltage were within the utilised operational ranges. It was assumed that PV systems have the same frequency range as the diesel generators (48–52 Hz), with disconnection occurring immediately if the limits were reached. PV generation also disconnects immediately when the voltage is outside ± 10% of the nominal value. Ramps in the PV power output were represented by changes in the set-point of the active power sources. Dynamic simulations were performed for constant PV output (PV Max), 80% decrease in PV output (from PV Max to 20% PV) in 1 min and continuous fluctuations in 10 min.

The following events were considered in the dynamic simulations: trip of a generator, trip of largest PV system and trip of the largest load. The plots obtained are discussed in Section 4.

4. Results and discussion

4.1. Expected net load

The load profile and solar output data in Tarawa were analysed using the methodology presented in Section 3 to identify extreme but feasible operational conditions.

Fig. 2 presents the different expected load levels for each hour of the day and the maximum possible PV generation.

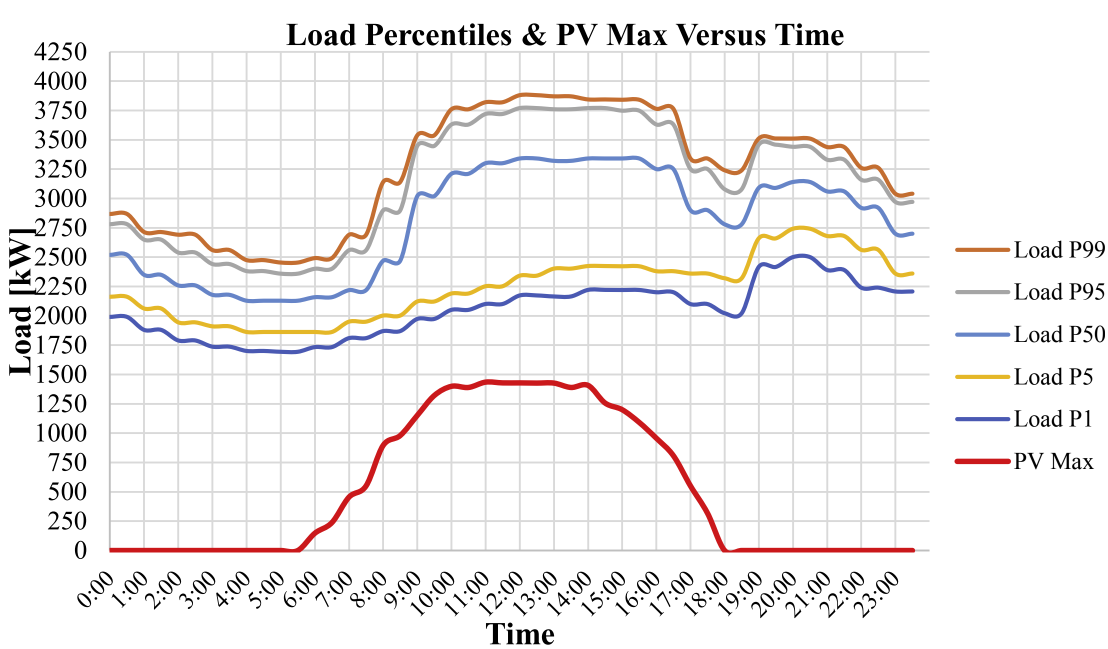

Fig. 2. Plot of different load percentiles & PV Max against time.

Load P99 represents an exceptionally high load on a week day having a mid-day peak and an evening peak. Load P1 represents the minimum load typical on a weekend or a holiday.

Fig. 3 presents expected net load values for different load levels, assuming maximum possible PV generation.

When PV systems are coupled to the grid, during times of low loads.i.e. Load P1 and P5, there would be limited diesel generation capacity online. The diesel generators provide inertial response with accompanied governor response during fast net load and generation fluctuations.

From this assessment, low loading levels with high PV output are identified as challenging conditions as shown in Fig. 3. This will be further analysed in dynamic simulations. The net loads during this time coincide with the PV generation.

Moreover, at Load P99-PV Max, the instantaneous penetration is estimated around 38%. This scenario will also be considered in the simulations since at peak load, there is major stress in the network because of loading and also changes in voltages are expected due to the location of the PV systems and changes in power flows.

4.2. Solar PV output fluctuations

Following the procedures explained in Section 3, the P99 ramps were obtained. Fig. 4 shows the 99th percentile negative changes (P99 negative ramp) that were obtained using the three approaches. It can be noticed that the P99 negative ramp of the worst case of single system has the largest P99 negative ramps. As for Tarawa, there is no single plant with 1459 kW_p PV output thus it cannot be related to the P99 negative ramps of a single system.

For this study, the method plotted in the middle in Fig. 4 was adopted.i.e. aggregate sum of two systems for estimating reserves. This will ensure a practical approach.

The adopted plot shows a P99 negative ramping of around 80% of the power output. In other words, for a PV output of 1000 kW, 800 kW of maximum drop in power output could be experienced.

Fig. 5 shows the plots for 99th percentile positive changes (P99 positive ramps) obtained using the same three approaches utilised for P99 negative ramps.

It is observed that the P99 positive ramps is highest for low outputs for a single system. As expected, it is lowest for smoothed PV fluctuations due to geographical dispersion approach.

The approach depicted in the middle plot on aggregate sum of two systems would also be adopted for analysis on P99 positive ramps.

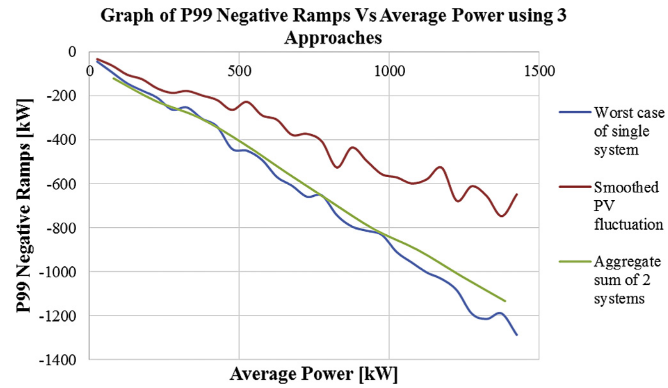

Fig. 4. Graph showing P99 negative ramps using 3 approaches.

4.3. Spinning reserve requirements

Fig. 6 shows the spinning reserve allocation against time using the three methods described in Section 3.3. The results from Section 4.2 were used for P99 negative ramps which were linearised as 80% of the power output for Methods 1 and 3 to determine spinning reserves. The top curve namely “SR – Power output” indicates fixed spinning reserve allocation in the system according to the maximum power output observed every half an hour in a day (Method 1). “SR – Variation”, represents the spinning reserves based on maximum negative variation observed every half an hour in a day (Method 2). “SR - P99 Forecast”, “SR - P95 Forecast”, “SR - P50 Forecast”, “SR - P5 Forecast” and “SR - P1 Forecast”, represent the percentiles of spinning reserves upon forecasting (Method 3).

It is precisely clear in Fig. 6 that maintaining fixed spinning reserves according to the maximum PV output would mean high reserves in the system, however this is not always required.

There are times with less variations in the PV output thus requiring smaller reserves. The spinning reserves “SR - P5 Forecast” and “SR - P1 Forecast” denote that at some point in time the spinning reserves fall even below 20% due to small variations. Thus, this method would be much more efficient to manage reserves, avoiding unnecessary commitment of generators just to provide reserves and ultimately avoid curtailment. Persistence forecasting is very simple to implement and could bring benefits. For simulating dispatch of the units and setting the operational conditions for steady state and dynamic simulations, the selected method is Method 1 which is similar to “SR-P99 Forecast” and is therefore good for the security check.

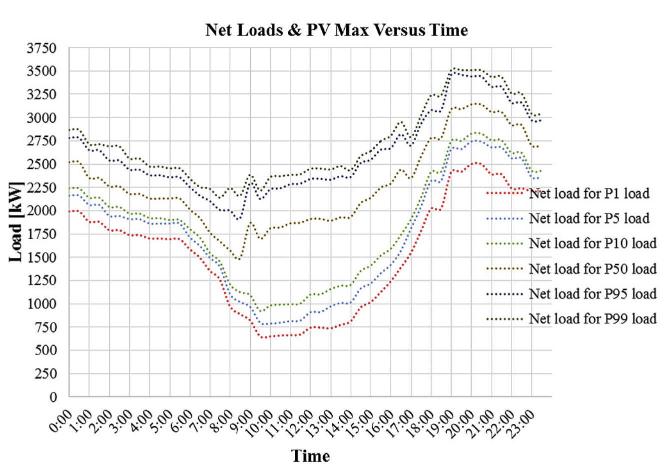

Fig. 3. Plot of Expected Net loads for different load percentiles Vs time.

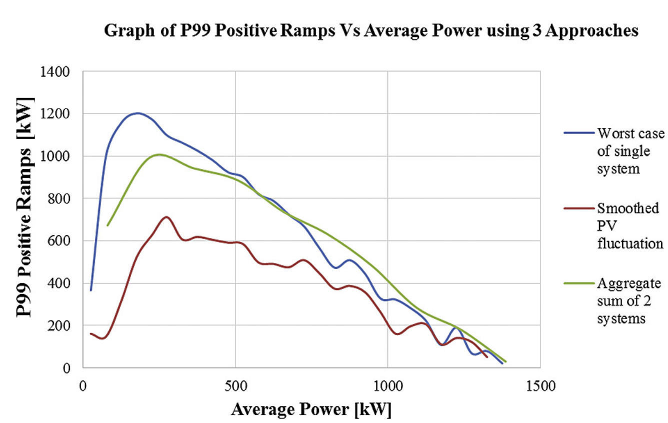

Fig. 5. Graph showing the P99 positive ramps using 3 approaches.

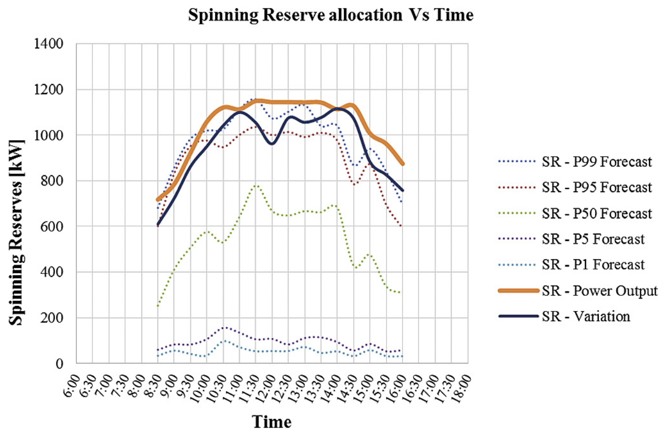

Fig. 6. Graph comparing Minimum Reserve allocation against time using 3 methods.

4.4. Expected generation dispatch for critical scenarios

With reference to the methodology in Fig. 1, the next step was to work out dispatch for critical scenarios identified in Section 3.4. The feasibility of dispatch of generators according to demand profile and spinning reserve requirements was verified, considering maximum and minimum capacity of generators for the identified most challenging feasible conditions.

It is observed in Fig. 7 that between 10 a.m. and 2 p.m. at **Load P1-PV Max**, the generators will have to be operated below their minimum capacity if PV curtailment is not applied. The minimum active power capacity assumed was 50% of rated capacity i.e. 600 kW. During this time, the two generators in Bikenibeu will have to be dispatched around 370 kW. This is owing to the high spinning reserves required during this time that adds to the online generation requiring two machines instead of one. This situation could be unhealthy for the diesel generators and should therefore be avoided. On the other hand, spinning reserves in the system could be reduced but this may put a threat on grid stability if suddenly PV output drops and the reserve allocation is not sufficient to compensate. Thus, during this time, curtailment of PV output could be adopted in order to ensure secure grid operation. Through dispatch analysis, it was found that the system would need curtailment below a load of 3250 kW experiencing maximum PV generation otherwise spinning reserves could not be provided and that would be a risk on system reliability. The system will sustain solar capacity of 1459 kW at this load. Further simulations would lead to conclusions on whether reducing the reserves or curtailment of PV proves to be feasible for the security of the system.

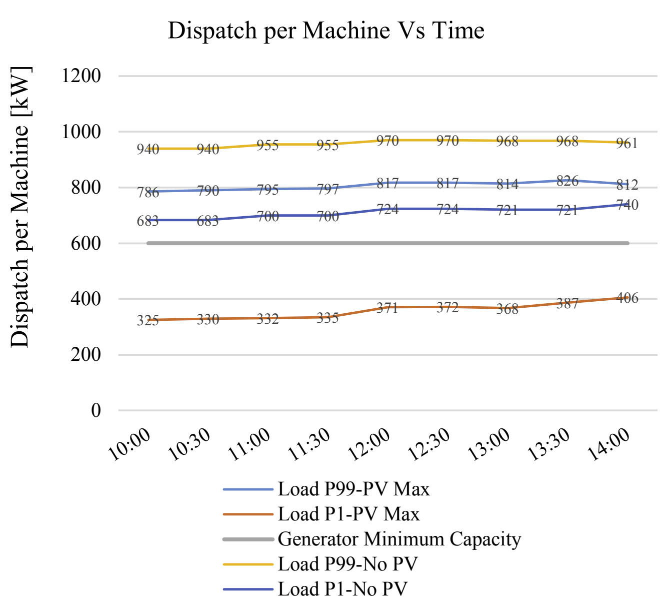

Fig. 7. Graph of Dispatch of generators against time with No PV and Maximum PV (kW).

Fig. 7 also presents the generator dispatch with no PV. It is evident that when there is no PV, there are no major dispatch issues.

4.5. Steady state simulations

The extreme critical scenarios in Section 3.4 were tested for secure operation of the grid. The load flow simulations were conducted to determine that the voltages at bus bars were within criteria and line loadings were acceptable with and without high PV penetration levels. It was noted that the voltages were within the set or adopted voltage criteria utilised.i.e. between 0.9 p.u and 1.1 p.u. Under normal conditions, there was no major concern of extreme voltage drop or over-voltage for all the tested scenarios. The results stated that there was no overloading of lines for the tested scenarios. The maximum loading was determined as 58% for Load P99-PV Max. This indicated that the cables utilised for the Tarawa grid have the capacity to cater for more load according to the expansion plan. This conclusion is based on capacity and is irrespective of the current state of cables.

4.6. Dynamic simulations

The dynamic simulations were done to evaluate if the grid would be stable under new conditions imposed by PV generation with a rise in capacity. The following operational scenarios were considered.

4.6.1. Scenario 1: low load without PV (load P1-No PV)

The network model was used to simulate the behavior of the system. Upon tripping a generator, the frequency went below 48 Hz for more than a second and therefore the system would collapse (see Fig. 8). This result was expected as there is no under frequency load disconnection scheme in place and spinning reserves are not allocated for occurrence of a generator trip. Irrespective of the PV capacity, the current operation of the system is not designed to

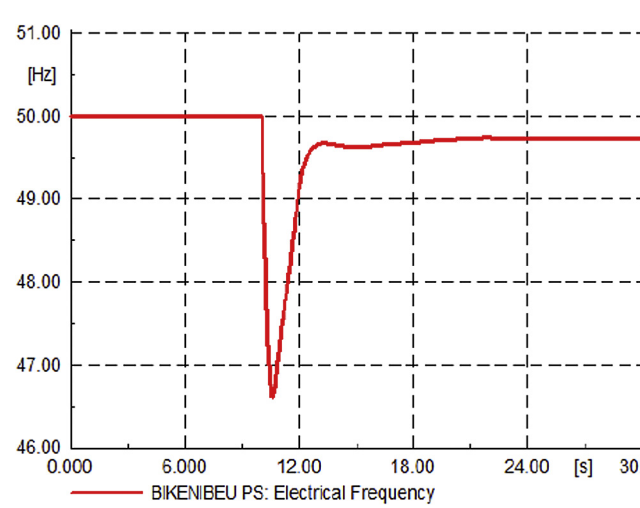

Fig. 8. Frequency plot obtained in *PowerFactory* at Bikenibeu PS.

withstand the loss of a generator.

4.6.2. *Scenario 2: low load with maximum PV output (load P1-PV Max)*

a) Constant maximum PV output

The spinning reserve allocation was reduced from 1149 kW (80% of maximum PV output) to 450 kW to overcome dispatch constraints as discussed in Section 3.4, almost by 60% to allow dispatch of a single machine with loads above its minimum capacity during this time. This resulted in one generator dispatched at 740 kW due to the net load being 737 kW during this time. There being only one machine running in the system during this scenario, the secure operation was not ensured.

It was observed that tripping of PV UAE 500kW$_p$ system led to a blackout. This is indicative of the fact that tripping of a large PV system during low loads could lead to a grid collapse. The model was also simulated for tripping of the largest load at Load P1-PV Max and the grid survived. This shows that tripping of large loads do not have much impact on the grid operation.

b) Load P1-PV Max - 80% decrease in PV output in 1 min (i.e. from PV Max to 20% PV)

The PV output values were then simulated representing 80% decrease in PV output in 1 min. As discussed earlier, during this time, there is only one machine dispatched assuming limited reserves. Under normal conditions (without any event), the grid collapsed and all PV systems tripped. This represented a critical situation at Load P1-PV Max upon continuous negative ramping. Since it is clear that the system would not survive without adequate reserves, curtailment of PV could be resorted.

4.6.2.1. With PV curtailment at 900 kW PV production. It was evaluated that above PV production of 900 kW, the system will experience dispatch constraints at low loads as generators will have to be dispatched below their technical minimum loading. Upon curtailing the PV output at 900 kW, the security criteria is met. This curtailment will not be required always but for certain periods when load is low and PV output is maximum (around 1400 kW).

There were not any dispatch issues identified below this output of 900 kW. Under normal conditions, the system survives 80% decrease in PV output in 1 min as shown in Fig. 9. Thus, this confirmed that curtailment of PV could be adopted to ensure secure operation.

c) Continuous increase and decrease in PV output in 10 min

PV output was simulated to represent continuous fluctuations in the PV output of different PV systems in the network. Under normal conditions (without any events activated), the grid collapsed. This also represented a critical situation at Load P1-PV Max. The system would not survive fast fluctuations due to less inertia in the system or operation of a single machine during this time.

4.6.2.2. With PV curtailment at 900 kW PV production. According to simulations, the grid would survive continuous fluctuations at 900 kW PV production. Fig. 10 shows that the voltage and frequency values stayed within the defined criteria. This suggested that curtailing the PV output at 900 kW would ensure secure operation at low loads and maximum PV output.

4.6.3. *Scenario 3: high load without PV (load P99-No PV)*

In this scenario, it was necessary to investigate how the grid behaves upon events at high loads when there is no PV. Tripping of any one of the 4 generators led to a blackout during peak load. The system is not robust upon tripping of any generator with or without PV as explained before.

4.6.4. *Scenario 4: high load with maximum PV output (load P99-PV Max)*

a) Constant maximum PV output

The event, tripping of the generator was activated after 10 s which resulted in the grid collapsing. This indicated the dependence on the diesel generators even after PV projects have been incorporated.

The grid behavior upon tripping of the largest PV system at PUB was also investigated and it was found that at high loads, tripping of a large PV system did not result in the system collapsing. Voltage and frequency response upon tripping of the largest load were also studied in this work where the grid survived. This shows that fluctuations from large loads do not affect secure operation during this condition.

b) 80% decrease in PV output in 1 min

Under normal conditions, the frequency fluctuated proportional to the change in output, however the grid survived suggesting that at high loads, fast negative ramping in PV output do not cause the system to collapse. This situation did not affect secure operation.

c) Continuous increase and decrease in PV output in 10 min

Under normal conditions, there were fluctuations in voltage and frequency without any major concern of results violating the voltage and frequency criteria. Thus, the grid survived fluctuations at high loads unlike low loads. This situation did not affect secure operation.

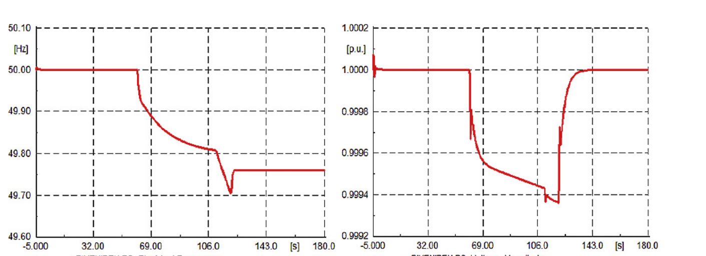

Fig. 9. Frequency and voltage plots in *PowerFactory* at Bikenibeu PS.

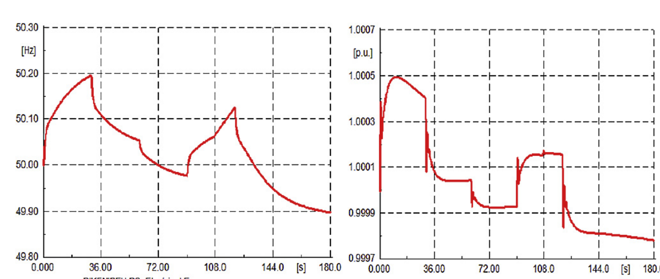

Fig. 10. Frequency and voltage plot in *PowerFactory* at Bikenibeu PS.

5. Conclusions

In this paper, the impact of grid connected PV systems on utility grid performance in Tarawa, Kiribati for the secure operation was studied. A methodology proposed by IRENA for small island networks was adopted for this study. The four upcoming grid connected PV systems (to be funded by World Bank) were included in the analysis taking the PV capacity to 1459kW$_{p.}$ Analysis of solar PV output fluctuations indicated a 99th percentile negative ramp of around 80% of PV power output for the PV systems. Simple persistence forecasting method denoted that there is a possibility of allocating lesser reserves at times, however, this needs to be further explored. Moreover, it was found that the scenario of low load with maximum PV output (Load P1-PV Max**)** will experience dispatch issues upon expansion. For this scenario, the generator's loading were below their minimum active power capacity. This indicated the need for curtailment of PV output during times of low load since reducing the reserves in the system during this time affected secure operation. In addition, to overcome dispatch constraints, PUB should consider bringing in suitably rated generators. Moreover, it was evaluated that the system will sustain maximum PV capacity above a load of 3250 kW and will require curtailment below this load to cater for dispatch constraints in certain conditions. The load flow simulations showed that there was no major concern of overvoltage or under voltage for the simulated scenarios, also the cable loadings were below 58% for Load P99-PV Max. Upon dynamic simulations, for scenario, Load P1-NO PV, it was noted that the grid collapsed upon opening one of the generators showing the vulnerability of the PUB grid. It was also concluded that 80% decrease in PV output in 1 min (negative ramp) causes a potential grid collapse at Load P1-PV Max whilst it did not collapse at Load P99-PV Max. Also, upon continuous increase and decrease in PV output in 10 min, the grid collapsed for scenario Load P1-PV Max whilst it survived for Load P99-PV Max. The current instantaneous PV penetration at PUB is estimated around 43% at Load P1 and 23% at Load P99. However, for the proposed PV expansion at PUB, the instantaneous penetration could increase to around 55% at Load P1 (with curtailment) and 38% at Load P99. The system is stable with PV curtailed at 900 kW for low loads with maximum PV output condition. However, analysis on other economical options are such as demand side management, best dispatch strategy, storage systems, automated control of PV systems at peak output and load shifting are necessary. This study provides useful recommendations to PUB for secure implementation of planned PV systems into the Tarawa grid and the analysis can be applied to similar systems elsewhere.

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