# Dealing with Power System Stability Issues with Low Load and Low Inertia Systems

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**ABSTRACT**

*Rapid economic growth in Papua New Guinea in recent years has led to exponential growth in demand for electricity supply. This has caused strain on the power system infrastructure with the net impact being the need for improved system stability and efficiency within PNG Power Limited (PPL) operations.*

*System stability has been a key issue in PPL and is an area that has taken precedence in the Supply Side Management Section of PPL. It is a balancing act of a) running units below rated capacity to provide spinning reserve or, b) run less units to save cost yet risk grid collapsing in outage events. The issues pivoting PPL on this dilemma are; 1. Hydro Units run below rated capacity, 2. Total Inertia Contribution and 3. Frequency Control. Through the years PPL has worked on ways to address these issues and have put plans in place to correct future issues.*

*This paper will attempt to show the mitigation methods PPL has utilized to ensure we run units at optimal capacity, provide ample Frequency Regulation as well as ensure we stay within operational limitation from regulatory bodies.*

## Introduction

Papua New Guineas growth is quite rapid over the last decade. Annual population growth rate is at 3.1%, with 37.5% of the population living below poverty on US$ 1.25 (K3.70) a day. Of these population 19% currently have access to electricity and projections are for increase to 50% by the year 2022. Provision of electricity has predominantly been by the state owned utility company PNG Power Limited, who currently owns and operates the grid around the country. However, given the rapid growth in demand over the last decade, a policy shift was introduced with other Independent Power Producers been encouraged to enter the generation market. This means that the national system will consist of scattered independent power generating systems plugging into the PPL owned and managed national grid. This in turn will put added pressure on PPL to maintain stability in the total system, a task it has been able to manage despite its aging infrastructure.

The power industry in PNG is currently in transition phase of its development. It is undergoing many changes at a rapid rate. Energy forecasts in major cities such as Lae and Madang showed aggressive growth rates of 6%. The need for renewable technologies and advanced automation technologies associated with the increase in power generation, has put the state owned entity, PNG POWER Limited (PPL), in a difficult operational state in terms of System Stability.

Power System Stability is an area defined by C. Bayliss and B. Hardy (2017) as "the networks energy balance and the ability to generate sufficient restoring forces to counter system disturbances"[1].

As a response to dealing with disturbances to the system there is often mutual juggling of power between machines on the infinite bus or the power system. This process directly results in the maintaining of a single universal frequency.

Equilibrium is retained between the total kinetic rotational power/energy-input and the flowing electrical power/energy-output by natural adjustment of system parameters - voltage levels and frequency [2].

This paper explains that frequency stability at the synchronous machine level ensures counteracting response to steady state, transient, and dynamic disturbances. Likewise at the load end, frequency stability sets the behavior of the system equilibrium.

## Power System Stability

The following forms of stability are associated with power systems and although many have different names they are general understood as follows:

**(a) Steady state stability**

This is the capability of the system to stay in synchronism during minor disturbances or slowly developing system changes. Changes like steady increase in load to daily peak demand [4].

**(b) Transient stability**

Capability of the system to stay in synchronism following a sudden change in loading conditions. Such as fault events, the sudden loss of generation or a transmission line. Transient periods are defined in the order of a second. It is crucial in the design of power systems for behavior in this interval [5].

**(c) Dynamic stability**

Capability of the system to stay in synchronism between the transient state behavior and the steady state region. Dynamic stability studies involve the behavior of turbine governors, fuel flows, load shedding and the recuperation of loads as examples [6].

All three are vital for power system planning as each are interrelated to the other stability periods.

## Synchronous Machine Stability

Defining a power system as an infinite bus, all synchronous machines will be connected to this bus directly and indirectly affecting the characteristics of the system [7]. Taking the fundamental representation in figure 1, an important feature of synchronous machines is the relationship of its internal voltage (E) or internal excitation level and the outside represented terminal voltage ($V_t$). This relationship is denoted as the load angle (θ) of the synchronous machine and ultimately influencing its power factor (Ø). The internal reactance of the machine ($X_g$) also plays a vital role in the machine dynamics. The *Phasor diagram in figure1 can be modified to* show a low and high electrical output as well as a high and low excitation operation of synchronous machines. Ensuring a higher potential difference between E and $V_t$ dictates a lagging power factor and adversely a higher potential at $V_t$ dictates a leading power factor at the synchronous machine[8] [9].

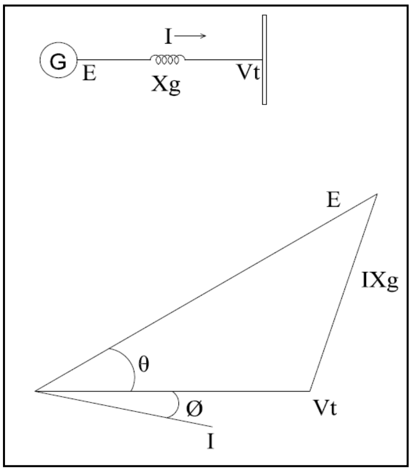


*Figure 1 Synchronous machine vector diagram*

This is important as it defines the stability of the sychronous machine as it responds to system requirements. the greater the electrical output, the greater the load angle and the more its power factor moves to unity. The higher the excitation the smaller the load angle and adversely the higher lagging the power factor. At all times in order for this machine stability to be met it must satisfy the following:

$$E\ sin\theta = IX_g cos\emptyset \qquad [10]$$

If the power representation is as;

$$P = V_t I cos\emptyset \qquad [11]$$

then the stability for power output of a synchronous machine on an infinite bus can be represented as:

$$P = \frac{V_t cos\emptyset \times E sin\theta}{X_g cos\emptyset} = \frac{V_t E \sin\theta}{X_g} \qquad [12]$$

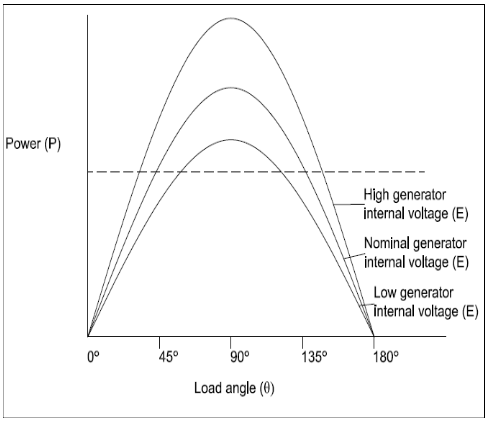


*Figure 2 Load Angle and Power Angle relationship*

Figure 2 shows the relationship of generated power to a sychronous machines load angle [13].

From the equation above it is clear that machine power output (P) is directly proportional to E and $V_t$ but inversely proportional to $X_g$. When $X_g$ and $V_t$ are held constant, the power output curves in figure 2 are significant. There is a point at the load angle where electrical power output will decrease and as the mechanical input increases regardless of the increase in internal excitation.

$$\Delta E > \Delta\theta \qquad [14]$$

Past this point, the synchronous machine will lose synchronism with the other machines paralleled on the infinite bus [15].

In the event a generation point on the system is removed, the synchronous machine will increase P to ensure the load angle is within operable limits

taking on the load from the lost generation point to ensure synchronism is kept.
For the system, ensuring all machines on the system stays within these limits in interaction with each other is the key to stead state, transient and dynamic stability.

## Stability Issues in the Ramu System

The Ramu system is a challenging system to operate. As shown in figure 4 and 5, it is predominantly a radial network with no redundancy in transmission. Since the early 2000's there has been no redundancy in generation as well. Unlike the Port Moresby system which has a mesh network with double circuits to most substations, the Ramu

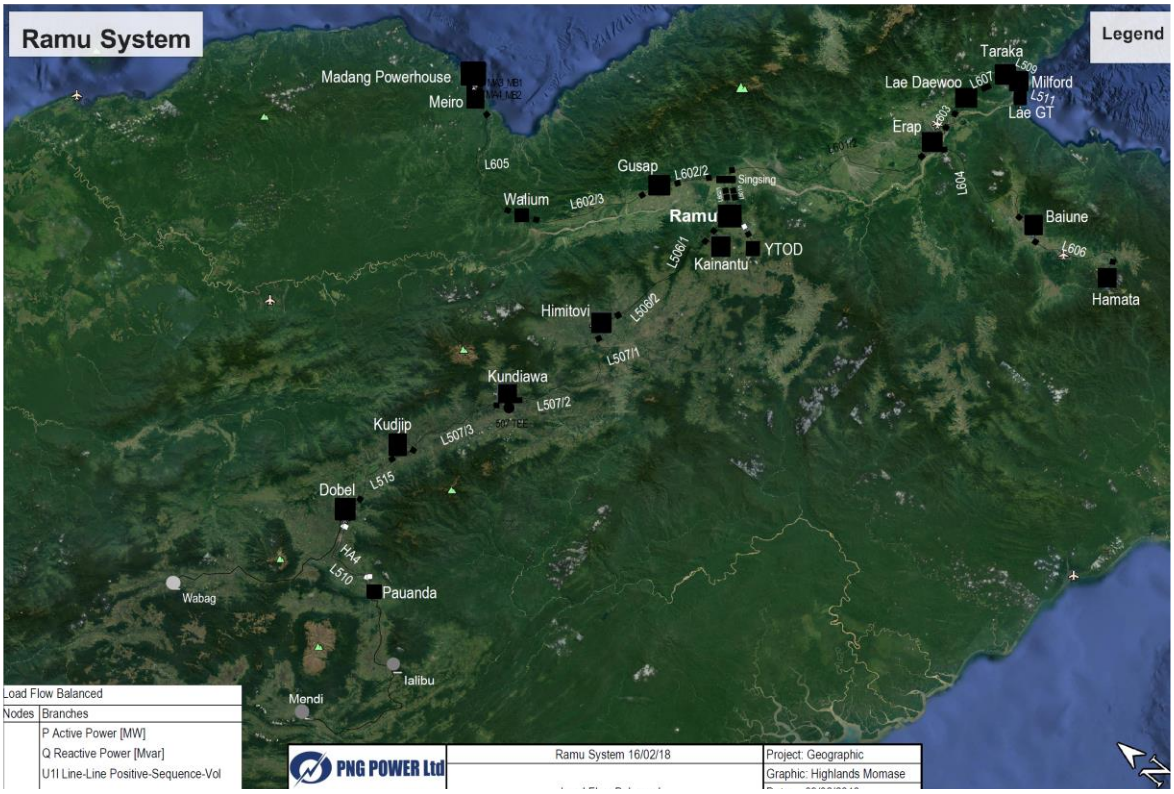


*Figure 4 Ramu System Load Flow*

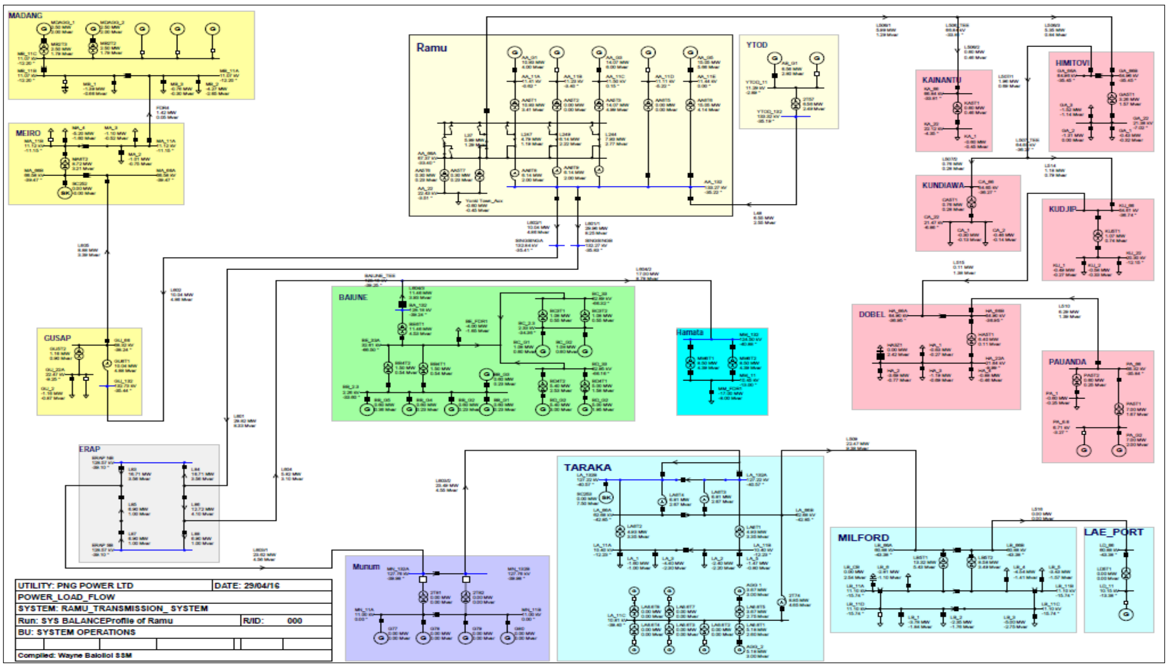


*Figure 4 Ramu Geographic Diagram*

System has the major issue of long single circuit lines supplying all of the Highlands centres, Madang and Lae. With generation shortfall due to lack of maintenance and up keep of aging generation infrastructure, the Ramu system hardly ran with a spinning reserve let alone a frequency regulating reserve.

Prior to improvements to Ramu, System Stability would collapse when there was a:

**a) Lose of a major transmission line supplying a centre**

**b) Collapse of a Generation point**

## Addressing the Stability Issues

### I. Lose of a major transmission line supplying a centre

As the Ramu system is a radial network, the loss of a main transmission line means the loss of either a large predominant load or generation. Apart from system protection reviews to line protections and updating settings on PPL protection relays, N-1 scenarios were run for all transmission lines on the grid. It was imperative for us to isolate a line if it is under a genuine fault but that effect on the system as a whole and the isolated township that is supplied by the faulty line also needs to be considered. At almost all incidence surrounding a transmission line fault the system would collapse.

Mitigating the Issue

Our first concern in the issue is to return the system to an equilibrium. For Ramu, the step was to implement an Automated Under frequency load shedding scheme.

### Automatic Load Shedding (Case Study Ramu) and System Interia relationship

Automatic load shedding or Under Frequency Load Scheduling (UFLS) as used by PPL, is the automation of load shedding feeders at PPL substations. This is operational in the event of a serious frequency degradation through the loss of a large generation point. The shedding of these feeders are calculated through the feeder loading, the available generation, and the system sychronous kinetic energy constant of inertia [18]. Inertia is defined as,

$$H = \frac{W^0_{kin}}{P_r} \quad MW\ sec/MW \qquad [19]$$

Where $W^0_{kin}$ is the total rotational equipment of a system.

The relationship of the Power demanded ($P_D$) to Power generated ($P_G$) is,

$$\Delta P_G = \Delta P_D \qquad [20]$$

System sychronous kinetic energy are variable parameters of change in power generated and power demanded. As you have rotation mass constants in generation (coupling, crankshafts, flywheels, dampers rotors etc.) and motors on the power demand side (Inducive motors for conveyor system etc.). Frequency change and the derative of the rotational kinetic energy of the system can be represented together as:

$$\Delta P_G - \Delta P_D = D\,\Delta f + \frac{d}{dt}(W_{kin}) \qquad [21]$$

This is relevant for:

$$\Delta P_G - \Delta P_D = D\,\Delta f + \frac{2H}{f^0}\frac{d}{dt}(\Delta f) \qquad [22]$$

From this equation it can be said that stability can be reached from the change in kinetic energy and change in load from the change in frequency. As we lose inertia from the loss of generation, it must be counteracted by the change in frequency which is the load shedding action. The combination of both are able to adress system equilibrium [23].

**Ramu System UFLS**

Prior to settings changes on UFLS in Ramu, total system outages where inevitable as UFLS settings during that time had not been aggressive enough to counter frequency degradation. Figures 5 to 7 shows recurrent event of total system collapses.

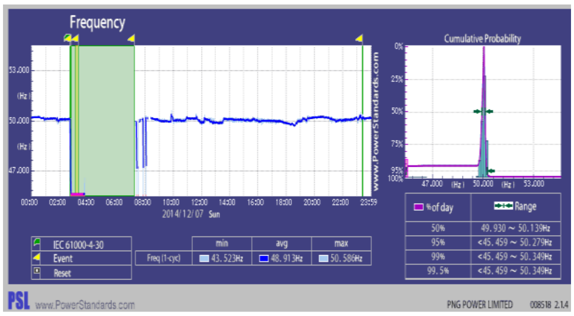


*Figure 5 Ramu System frequency degradation 07/12/2014*

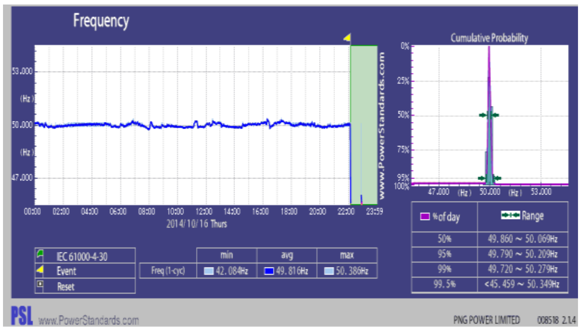


*Figure 6 Ramu System frequency degradation 16/10/2014*

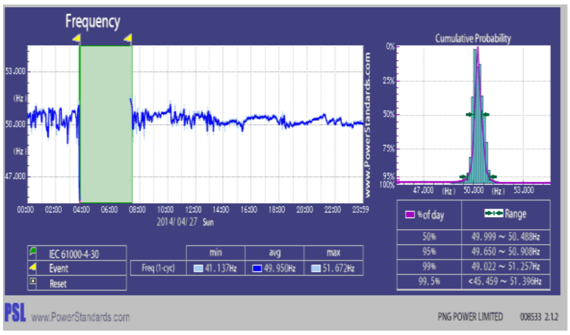


*Figure 7 Ramu System frequency degradation 27/04/2014*

Therefore for the Ramu System, the following UFLS settings in tables 1, 2 and 3 where established to counteract the loss of the largest generation source during peak and off peak operations.

### Implementation of UFLS Settings

In order to trip feeders at individual sub stations without personnel on site, frequency relays such as the one below in figure 8 were used. The following relays are utilized in this exercise:

1. Avera MiCOM P923
2. Schneider Electric_MiCom P142
3. Brown Boveri FCN-94-1

The frequency relays are used to sense frequency degradation and based on the settings in table 2 will send trip signals to the relevant feeders circuit breakers to operate.


*Figure 8 ABB FCN Frequency Relay Meiro Sub Station*

PAPUA NEW GUINEA POWER LIMITED

PROTECTION SETTING ADVICE

**To:** Manager, Test & Standards **Date:** 04th June, 2015

**From:** Protection Engineer **Sheet:** 1 of 1 sheet.

**PSA No.:** 7/P1/24 **Ammendment No.:** 0 **Supercede PSA Nos.:**

**SUBSTATION/POWER STATION:** Milford Substation

**CIRCUIT OR EQUIPMENT PROTECTED:** **11kV No.3 Feeder Under Frequency Protection**

| | |
|---|---|
| **Relay** | MiCOM P923 relay |
| **Model /Serial Number** | |
| **Protection CT Ratio and Class** | Ratio :<br>Class: |
| **VT Ratio and Class** | Ratio : 11,000/110 V<br>Class: |

| **Frequency Protection Settings- MiCOM P92xx** | |
|---|---|
| **Group 1,2,3 Frequency Protection Settings Status:** | Enabled |
| **Under Frequency Protection Settings** | Enabled |
| **Stage:** | - |
| **Frequency Setting:** | 48.0 Hz |
| **Time Delay:** | - |
| **Switch Position:** | Off |
| **dF/dt:** | Enabled (-0.6 Hz/s) |

**GENERAL COMMENTS:**

1. Over Frequency Protection (F>) is disabled.
2. dF/dt Frequency Protection of (-0.6 Hz/s) INSTANTANEOUS for all 3 stages will be applied on 11kV feeders 1,3,4,5,6 and will be set on MiCOM P923 Areva Relay.
3. Feeders 3 and 4 will be on the switch off position.
4. Other settings remain as existing and/or are set as factory or default settings.

**NOTE:**

1. Protection relay settings are prepared and issued by the Protection Engineer.
2. Relay settings shall be applied to relays only by the Test and Commissioning Engineer.
3. Relay setting shall not be changed without issue of an Amendment to previous Setting Advice or an authority of Protection Engineer.

| | | |
|---|---|---|
| **Calculated:** Wayne Baloiloi | **Checked:** Ivan.P/Melvin.A | **Settings Applied:** |
| **Des:** SSMS | **Des:** (SPE) | **Des:** |
| **Date:** 09/09/2014 | **Date:** 5/6/15 | **Date:** |

*Figure 9 PPL formal PSA*

These settings are calculated by System Operations Engineering and proposed settings sent to the Protection Engineering to review. Once reviewed, a formal protection settings advice (PSA) is given to the Field Test Team to test and apply the settings at the relevant substations. This exercise is reviewed annually.

Due to ICCC Grid Code Regulation [24], The System Operator shall maintain the system frequency within the limits of:

- **49.5 Hz to 50.5 Hz** during normal operation.
- **49Hz to 51Hz** During Single Outage Contingency and
- Between **47 Hz to 52 Hz** in the case of Multiple Outage Contingency or when the grid is in a state of emergency.

UFLS in the Ramu system therefore operates in the event the system frequency drops to 48Hz with 3 stages of time dependent load shedding to ensure a smooth dynamic frequency correction [25]. Synchronous machine response is utilized for normal operation and single outage contingency.

Table 1 gives this summary and shows the time dependent stages that operate in the event of the loss of generation. In addition to the UFLS Settings calculation for the loss of the largest generation unit in Ramu was done to ensure that stability was maintained in the N-1 criterion event. This is known as DFdt or ROCOF( Rate of Change of Frequency) which calculated response is shown in figure 11 and 12.

| SUMMARY STATS. | | |
|---|---|---|
| UFLS AT 48.00HZ | | |
| STAGE1 | TRIGGER | 48 Hz |
| | TIME DELAY | 0.00 sec |
| STAGE2 | TRIGGER | 48 Hz |
| | TIME DELAY | 0.50 sec |
| STAGE3 | TRIGGER | 48 Hz |
| | TIME DELAY | 5.00 sec |
| Rate of Change of Frequency | | |
| | TRIGGER | 48.5 Hz |
| | SETTING | -0.25 Hz/sec |
| | TIME DELAY | 0.00 sec |

*Table 1 UFLS and DFDT Ramu System Settings*

| Feeder | Max | Min | Applied Settings 05/06/15 | Proposed UFLS | Proposed Dfdt |
|---|---|---|---|---|---|
| Taraka | | | | | |
| LA1 ← | 1.3 | 0.7 | 3 | 3 | dfdt |
| LA2 | 2.5 | 1.6 | | | dfdt |
| LA3 | 1.4 | 0.8 | 3 | 3 | dfdt |
| LA4 | 3.5 | 1.5 | | | dfdt |
| LA5 | 4.1 | 2.4 | 3 | 2 | dfdt |
| Milford | | | | | |
| LB1 | 4.1 | 1.8 | 3 | 3 | dfdt |
| LB2 ← | 2.1 | 1.0 | 3 | 3 | 3 |
| LB3 | 5.2 | 1.4 | | | |
| LB4 | 4.6 | 2.1 | | | |
| LB5 | 3.5 | 1.8 | 3 | 3 | 3 |
| LB6 | 2.1 | 1.4 | 3 | 3 | 3 |
| Madang P/Station | | | | | |
| MA1 | 1.6 | 0.8 | NA | | |
| MA2 ← | 3.3 | 1.6 | NA | | |
| MA3 | 2.8 | 1.4 | NA | | |
| Meiro | | | | | |
| MB1 | | | | | |
| MB2 | 1.8 | 1.6 | 1 | 1 | dfdt |
| MB3 ← | 0.9 | 0.8 | 1 | 1 | dfdt |
| MB4 | 3.3 | 2.2 | NA | | |
| MMJV | | | | | |
| MMJV | 16.0 | 8.0 | NA | | |
| Mt Hagen Dobel | | | | | |
| HA1 | 0.8 | 0.4 | 1 | 1 | dfdt |
| HA2 ← | 3.8 | 1.9 | 3 | 3 | dfdt |
| HA3 | 1.1 | 0.5 | 3 | 1 | dfdt |
| HA4 | 1.4 | 0.7 | 2 | 3 | dfdt |
| Goroka Himitovi | | | | | |
| GA1 | 0.5 | 0.3 | 2 | 2 | dfdt |
| GA2 | 1.5 | 0.8 | 1 | 2 | dfdt |
| GA3 ← | 2.0 | 1.0 | 3 | 3 | dfdt |
| Ramu Sugar Gusap | | | | | |
| GU1 | 1.0 | 0.6 | NA | | |
| GU2 | 0.4 | 0.2 | NA | | |
| GU3 | | | NA | | |
| Kainantu | | | | | |
| KA1 | 1.5 | 0.7 | NA | | |
| Kudjip | | | | | |
| KD1 | 0.8 | 0.5 | 3 | 2 | 2 |
| KD2 | 0.6 | 0.4 | 3 | 2 | 2 |
| Kundiawa | | | | | |
| KU1 | 0.7 | 0.4 | 3 | 2 | 2 |
| KU2 | 0.3 | 0.2 | 3 | 2 | 2 |
| TOTAL (MW) | 80.67 | 41.52 | | | |

*Table 2 Feeder Load Shedding Settings*

Here, feeders will be automatically load shed not at the trigger of 48Hz but the detection of -0.25Hz/sec which is the deceleration of frequency due to the loss of the Lae TM2500 GT at 23MW. Due to the lack of regulating and spinning reserve the UFLS and Dfdt settings are quite aggressive to ensure system equilibrium is maintained in major disturbances.

| | Loading Shedding (MW) | | | | | Correction Rates (Hz/sec) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Dfdt | Stage1 | Stage2 | Stage3 | Total load shed | Dfdt | Stage1 | Stage2 | Stage3 |
| Peak | 0 | 4.6 | 8.6 | 21.6 | 34.9 | 0.0 | -0.2 | -0.1 | 0.1 |
| Peak Dfdt | 30.8 | 4.9 | 11.1 | 11.8 | 58.7 | 0.07 | 0.12 | 0.25 | 0.38 |
| Offpeak | 0 | 3.3 | 4.9 | 10.1 | 18.36 | 0 | -0.20 | -0.11 | 0.07 |
| Offpeak Dfdt | 16.9 | 13.0 | 26.0 | 6.0 | 61.9 | 0.05 | 0.28 | 0.75 | 0.86 |

*Table 3 Rate of change of Frequency Calculated for Ramu*

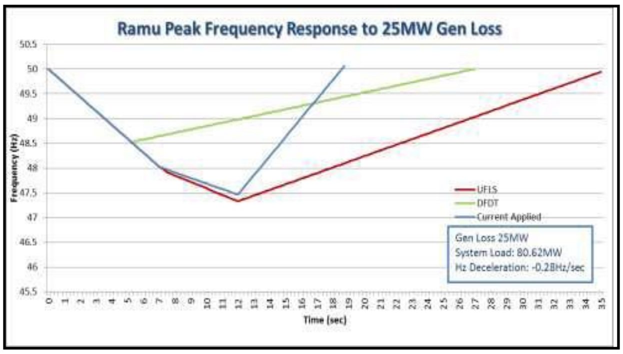


*Figure 10 ROCOF for peak load, Loss of Lae TM2500GT*

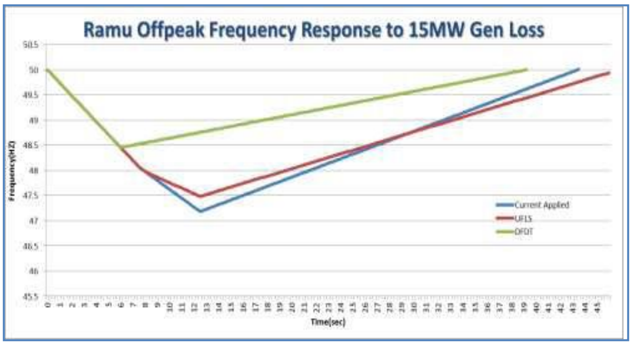


*Figure 11 ROCOF for off peak load, Loss of Ramu1 Unit 5*

This change in frequency due to the shedding of load ensures system stability in steady state and dynamic disturbances. In events where the loss of generation has caused frequency degradation, UFLS has operated 82% of the time to ensure stability and preventing total Ramu system outage. The nominal total restoration time for a total system outage is 4 hours whereas the restoration time for UFLS is a minimum of 15 minutes depending on generation availability.

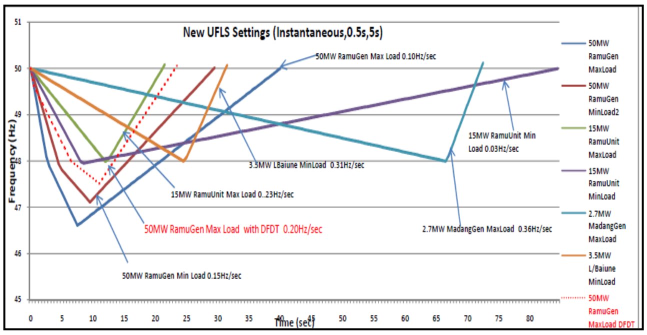


*Figure 12 Frequency response of Ramu system with respect to loss of generation*

In the event mentioned earlier for the loss of the Lae GT on the 11/02/17, the machines kinetic response reacted to the loss of generation but it was too much for the Ramu1 Unit 3 and 5 to handle allowing the frequency to degrade to 48Hz and triggering UFLS to operate. UFLS operation allowed the Ramu System to regain frequency stability as shown in figure 13 below.


*Figure 13 Assistance of UFLS in frequency stability in the loss of the Lae GT 11/02/17*


*Figure 14 Assistance of UFLS in frequency stability in the loss of the L601 21/02/17*

Above in figure 14 is another example of UFLS operating in conjunction with Ramu1 AGC to counter the tripping of L601 on the 21/02/17 at 0555Hrs. feeders in our Dobel substation and Meiro sub stations operated well to stabilize the system.

From similar examples shown above, it is estimated that 75% of system disturbances can result in total system collapses are avoid with the use of demand control in conjunction with machine stability response.

### Effectiveness of Demand Control

The grading of UFLS is done in line with frequency regulating reserve at the Ramu1 hydro power plant which will be discussed later. It is important that there is demarcation between the machine response and the load response so the system does not fight itself to regain stability. In order for UFLS to be most effective the following is compulsory:

1. <u>Adequate spinning reserve in the system</u>
2. <u>Frequency regulating units online with headroom capacity</u>
3. <u>Machine governor response is operational</u>
4. <u>Most large inertia carrying units online.</u>
5. <u>All transmission lines must be intact post disturbance and pre disturbance</u>

Without these areas, UFLS cannot operate at its most efficient and most times failing to hold system equilibrium [26].

The Ramu system has difficulties addressing these issues and most times the above conditions are not met. PPL management has endeavored to ensure that the issues mentioned above, with regards to system stability, are closely monitored and corrective actions put in place to address them.

### Adverse Effects of UFLS

In the Ramu System, there are adverse effects to heavy load shedding. These are:

#### a) High voltage events on L601 and L603 connecting Ramu1 Hydro Plant to Lae

In the event of heavy load shedding in Laes Taraka and Milford Substations, the system experiences events of high line charging often times tripping of the Ramu switchyard Breakers on over voltage. In this event switching becomes more difficult as synchronizing at high voltage difference prolong restoration times leading the 1.5 to 2 hours of Laes isolation from the rest of the Ramu System.

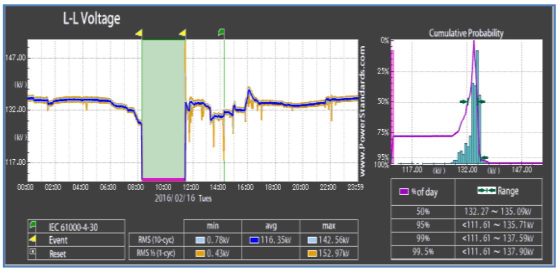


*Figure 15 Voltage profile of L601 after an outage event 16/02/16*

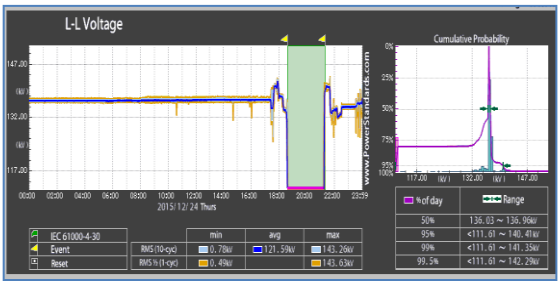


*Figure 16Voltage profile of L601 after an outage event 24/12/15*

Above in figure 14 and 15 show voltage levels reaching 152.97kV and 143.63kV 1/2 cycle rms during outage events on L601. Voltage instability at these levels are hindrances to quick system restorations of Lae to the rest of the Ramu system.

### b) Isolation without frequency Regulation

Ramu1 Units 5 and Unit 3 currently take care of AGC (Automatic Generation Control) of the Ramu System. In the event we have a trip on L601 or L603 the Lae system if partial intact does not have a frequency control unit which means frequency is manually controlled by the largest unit on the isolated system.

### c) Reduction in Reliability Index

This effect of UFLS is where the dilemma of reliability as opposed to stability comes in. UFLS is inevitably the system operator switching of power to customers to ensure that the system does not collapse. The more disturbance on the system with regards to the loss of generation whether it be a generating unit tripping, generating transformer tripping, bus bar protection tripping, or transmission line supplying from a generation source tripping will all set of frequency degradation resulting in load shedding of some sort.

## II. Collapse of Generation

This stability issue in the Ramu System could be derived from serval factors:

I. Fault on the transmission line supplying the generation
II. Machine malfunction trips or
III. System parameters causing the machine to trip

## Synchronous Generation Mix in the Ramu System

Understanding the generation mix and the roles each power station and individual machine plays is vital in addressing the collapse of generation and adversely the loss of load. For PPL as well as other utilities, we define our generation as either:

### a) Base Generation

This plant or unit will have a nominated generation level for a full 24 hour period. This is the lowest production cost of energy. In PPL these are our Hydro machines.

### b) Intermittent Generation

This plant will increase and decrease levels based on the system controller dispatch requirements and often times runs for 24 hours.

This is often times Independent power producers and the mid-range production cost of generation.

### c) Peak Generation

These machines and plants are the easiest to start up and often times are the most expensive generation.

### d) Frequency Regulation

These machines are the units on the system that we use to regulate frequency and are the first response to stability events.

Below is an example of the generation mix in the Ramu system of PNG:

**PNG POWER Ltd**

**RAMU SYSTEM DAILY STATUS**

**Day:** Monday 2/07/2018 **Time:** 8:00 **Hrs**

**Generation Status:**

| Unit | Rated (MW) | Available (MW) | Present (MW) |
|---|---|---|---|
| **Ramu - Hydro** | | | |
| Unit 1 | 15.0 | 0.0 | 0.0 |
| Unit 2 | 15.0 | 11.0 | 10.0 |
| Unit 3 | 15.0 | 11.0 | 7.0 |
| Unit 4 | 16.2 | 10.0 | 14.0 |
| Unit 5 | 16.2 | 0.0 | FO |
| YTOD U1 | 9.0 | 0.0 | FO |
| YTOD U2 | 9.0 | 0.0 | FO |
| Total | 95.4 | 32.0 | 31.0 |
| **Pauanda - Hydro** | | | |
| Unit 1 | 6.0 | 0.0 | FO |
| Unit 2 | 6.0 | 5.0 | 5.0 |
| Total | 12.0 | 5.0 | 5.0 |
| **Baiune - Hydro** | | | |
| | 12.0 | 12.0 | 7.6 |
| Total | 12.0 | 12.0 | 7.6 |
| Total Hydro | 119.4 | 49.0 | 43.6 |
| % Hydro Availability | = | | 41.04% |
| **Milford (Thermal)** | | | |
| Diesel 1 | 0.00 | 0.00 | BOS |
| Diesel 2 | 0.00 | 0.00 | BOS |
| Diesel 3 | 0.00 | 0.00 | BOS |
| Diesel 4 | 2.00 | 0.00 | FO |
| Diesel 5 | 0.00 | 1.20 | FO |
| Diesel 6 | 1.80 | 1.50 | SB |
| Diesel 12 | 0.50 | 0.50 | aux |
| Total | 4.30 | 3.20 | 0.00 |
| **Taraka (Thermal)** | | | |
| Diesel 1 | 1.44 | 0.00 | FO |
| Diesel 2 | 1.44 | 0.00 | FO |
| Diesel 3 | 1.44 | 0.80 | SB |
| Diesel 4 | 1.44 | 0.80 | SB |
| Diesel 5 | 1.44 | 0.00 | FO |
| Diesel 6 | 1.44 | 0.00 | US |
| Diesel 7 | 1.44 | 0.80 | SB |
| Diesel 8 | 1.44 | 0.80 | SB |
| Total | 11.52 | 3.20 | 0.00 |
| **Dobel (Thermal)** | | | |
| Diesel 7 | 0.85 | 0.85 | SB |
| Diesel 8 | 0.85 | 0.85 | SB |
| Diesel 9 | 0.85 | 0.85 | SB |
| Diesel 10 | 0.85 | 0.85 | SB |
| Diesel 11 | 0.85 | 0.85 | SB |
| Diesel 12 | 0.85 | 0.00 | SB |
| Total | 5.10 | 4.25 | 0.00 |

| Unit | Rated (MW) | Available (MW) | Present (MW) |
|---|---|---|---|
| **Madang -Thermal** | 26.9 | | |
| Diesel 5 | 3.20 | 0.00 | FO |
| Diesel 6 | 0.00 | 0.00 | BOS |
| Diesel 7 | 1.00 | 0.00 | FO |
| Diesel 8 | 1.12 | 0.00 | FO |
| Diesel 9 | 1.12 | 0.50 | SB |
| Diesel 10 | 1.80 | 0.00 | FO |
| Diesel 11 | 0.00 | 0.00 | FO |
| Diesel 12 | 1.80 | 1.20 | SB |
| Diesel 13 | 2.50 | 2.50 | SB |
| Diesel 14 | 2.50 | 2.50 | SB |
| Total | 15.04 | 6.70 | 0.00 |
| **Mendi- Thermal** | | | |
| Diesel 4 | 1.50 | 0.90 | SB |
| Total | 1.50 | 0.90 | 0.00 |
| **Wabag - Thermal** | | | |
| Diesel 1 | 0.30 | 0.00 | FO |
| Diesel 2 | 0.23 | 0.18 | SB |
| Diesel 3 | 0.62 | 0.00 | FO |
| Diesel 4 | 1.40 | 1.00 | SB |
| Total | 2.55 | 1.18 | 0.00 |
| **Kundiawa - Thermal** | | | |
| Diesel 1 | 1.44 | 0.00 | FO |
| Total | 1.44 | 0.00 | 0.00 |
| **Goroka - Thermal** | | | |
| Diesel 1 | 1.44 | 1.20 | SB |
| Diesel 2 | 1.44 | 1.20 | SB |
| Total | 2.88 | 2.40 | 0.00 |
| **Lae - Gas Turbine** | | | |
| GT1 | 25.00 | 10.00 | SB |
| Total | 25.00 | 10.00 | 0.00 |
| **Lae Daewoo IPP (Thermal)** | | | |
| IPP | | | |
| Diesel 1 | 8.40 | 7.50 | 8.00 |
| Diesel 2 | 8.40 | 7.50 | 8.00 |
| Diesel 3 | 8.40 | 7.50 | 8.00 |
| Diesel 4 | 8.40 | 7.50 | 8.00 |
| Total | 33.60 | 30.00 | 32.00 |
| Total Thermal | 101.49 | 61.83 | 32.00 |
| % Thermal Availability | = | | 60.92% |

| Ramu System Load Forecast - Today | |
|---|---|
| Total System MW (Hydro+thermal): | 110.83 |
| Estimated Max Demand (MW): | 78.9 |
| Estimated Load to be Shed (MW): | 0 |

US - Unserviceable SB - Stand By FO - Forced Outage BOS- Decomissioned

*Figure 17 Ramu Daily Stats*

From the daily stats in figure 18, Base Generation comes from Pauanda Hydro, Lae Daewoo IPP and Ramu Units 4 which we discuss the station philosophy in detail in the next section. Our Intermittent generation comes from Baiune Hydro and Ramu Units 2 and 3. Several generation across points across the system are peak generation stations from figure—with the final voltage regulation being from the Ramu station as a whole

## Generation Philosophy

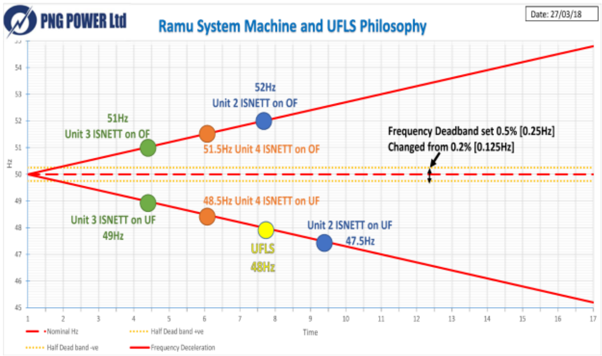


*Figure 18 Ramu System Machine Philosophy*

Figure 17 above was designed to give a pictorial view of the Ramu Hydro stations dynamic response philosophy. The Ramu Hydro governor control has a feature defined as Isonett enabling. This basically means that the units can switch in and out of 1. Power Mode- a setpoint function control where the operator dials in a MW setpoint and the machines stay at the level and 2. Speed Mode- feedback loop control function which in nature is a traditional droop control.

The modes are programmed to change over when a certain frequency setpoint is detected. Figure 17 above shows that Unit 3 changes from power mode to speed mode at 49Hz and 51Hz respectively. This means that in a generation loss event degrading system frequency below 49Hz, only Unit 3 will respond to the event. If the degradation reduces the system frequency below 48.5Hz then Unit 4 is signaled to change from Power mode to frequency mode. This is also graded with the under frequency load shedding.

Industry standards and larger grids do have either AGC or a dedicated unit regulating frequency for a grid. Although this is ideal, as this unit is responding dynamically to system events, its mechanical wear and tear also increases. PPL cannot afford this.

As a unit runs in a dedicated frequency regulation, Speed control or frequency mode, its output is based on the systems requirement so if the requirement is lower than the cavitation limit of the Hydro unit for example, it will run at that level as the system requires it to. Below are examples were Units were run in Frequency Control below operational limits. Severe turbulence exists at part load of the rated hydro turbines load and although the material properties of the turbine blades having the ability withstand short intervals at these loadings, at an extended steady state conditions it starts pitting the blades eventually causing a failure in the turbine.

*Figure 19 Ramu Unit 1 Cavitation Pitting 2012*

*Figure 20 Unit 5 Runner Blade failure due to running of the unit outside operational limits 2012*

It is for this reason that the cascaded generation philosophy was developed to reduce the wear and tear on the hydro units yet allow for regulation within ICCC grid code requirements.

## Steady state Frequency Stability

As per the generation philosophy in normal operational conditions, all units run in the Power mode governor control limited by a deadband at ±0.25Hz. Prior to these settings changes the deadband on the response to frequency excursions was set quite narrow forcing the ramu Hydro units to react sporadically below in figure 19 and figure 20 are the differences to the flat lining of system frequency:

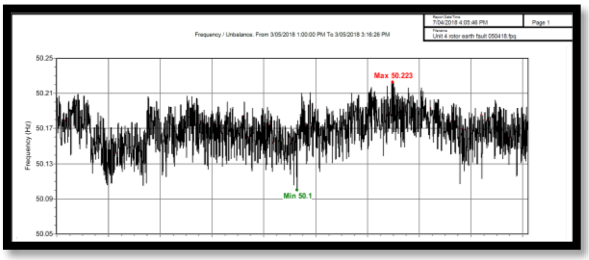


*Figure 21 Frequency Trend before settings change deviation 0.123Hz*

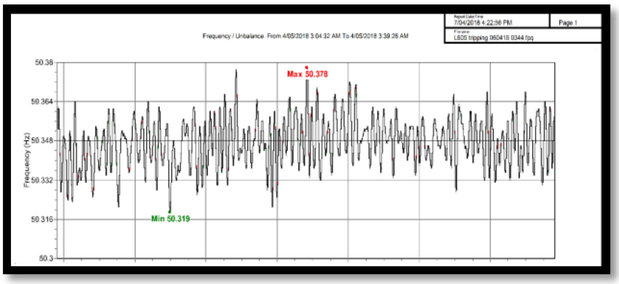


*Figure 22 Frequency Trend after settings change deviation 0.059Hz*

Prior to changes in the deadband, the frequency deviations in steady state conditions were found at 0.123Hz. After the settings changes the deviations reduced to 0.059Hz. This proved widening the deadband settings on the units allowed the system frequency to float without the interaction of the machine governors also ensuring the Hydro units don't respond mechanically to the fluctuations.

All Synchronous machines connected to the Ramu system have their governor and droop settings reviewed prior to interconnection to the grid to ensure all units respond in direct relation to how the system controller requires them to. These settings are done with reference to the Ramu Hydro Station as the reference regulation station.

## Examples of Generation loss and the Ramu Systems response

### Example 1

Figures 21 and 22 shows an example of machine response to the loss of the Lae Port TM2500 GE Gas Turbine. The blue trend being the system frequency and the red being the MW from the unit. On 11/02/17 18:40hrs the GT tripped at 12MW when the system demand was at 42.13MW. The GT was contributing 28.4% of the system generation. Unit 5 and Unit 3 stabilized system frequency within 24.570secs with the assistance from load shedding which was mentioned earlier in this paper.

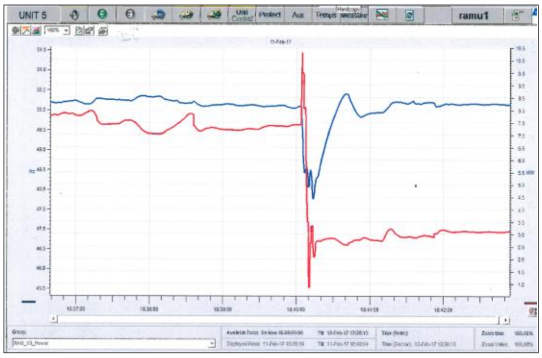


*Figure 23 Response of Ramu1 Unit 5 to the Lae GT Tripping 11/02/17*

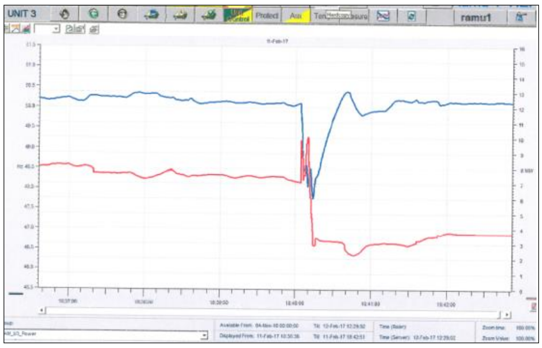


*Figure 24 Response of Ramu1 Unit 3 to the Lae GT Tripping 11/02/17*

Without the response from Unit 5 and Unit 3, a total system blackout was inevitable with the loss of 28.4% of system generation.

### Example 2

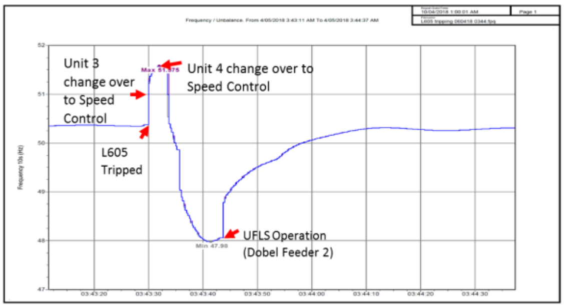


*Figure 25 System Frequency during L510 fault*

Figure 23 above is another example of an event where we lost a major transmission line L510 supplying our Madang township load. The system frequency trend shows the Unit 3 and Unit 4 changing over to speed control as the frequency increases due to the loss of load then an under shoot which eventually reached nominal range after 19.87seconds.

Prior to the grading of the machines and UFLS feeders, the disturbances the example should have caused a total system outages. With the changes, the system worked together to ensure stability was met.

## Conclusion

PNG will continue to face rapid growth in demand over the next decade. The growth is being addressed by entry of independent power generation providers who will be filing the loss of load expectancy into the national grid. This linkage will put added pressure on PPL to manage the stability of the total national grid. The lessons learnt from this experience has been very valuable for PPL going forward. The UFLS demand control and its integration with the machine philosophy that has assisted with stability in major centers in PNG is a testament to PPLs ability to provide reliable electricity service despite its the limited facilities. The principal lesson learnt from this experience is that a lot can still be achieved if the basic fundamentals of engineering is understood and utilized effectively to achieve system stability. The challenge for PPL is that greater work needs to be done in all facets, not only in the Ramu System but the other systems as well as the isolated centers in the country, to achieve stability and operational efficiency, and reliability of the total system going forward into the growing power demand.

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## Biography

Wayne Baloiloi is the Supply Side Management Specialist in the System Operations Business Unit PPL. Exposure to Academia and the Power Industry has allowed him to translate fundamental Engineering knowledge to Regulatory, System analysis and Technical Policy Development. He has assisted the Department of Petroleum and Energy for Stanley Gas Development Forum as an Energy Analyst in 2014 and was part of the Technical Advisory Workshop to Department of State Owned Enterprise on the Development of the PNG Bio Fuel Industry Structure in 2015. He was the System Operations Engineer in the Installation and Commissioning of GE TM2500 23MW at Lae and also for the Exxon Mobil Export to the Port Moresby Grid 25MW and Lead Commissioning Engineer for the Daewoo 34MW Lae Power Plant.