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Modelling and Loading Limits for Kenya Coast Power Network Using Continuation Power Flow

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Abstract: Shore to ship power connection for docked ship has recently been applied as one way of limiting pollution in ports. This paper studies the effect that a shore to ship connection at the port of Mombasa would have on the voltage stability of the coast region power network. A model of the coast region network is developed and implemented in PSAT. A power flow of the model is used to identify the bus with the highest likelihood of experiencing voltage collapse. Using continuation power flow, the loading limits on this bus are determined. The limits are compared with a load model of the off-shore load to determine the capacity of the existing network to carry the additional load. The paper finds that the existing network has the capacity to carry the extra load. It also recommends contingency actions to mitigate against possible line outages.

Keywords: Power Flow, Continuation Power Flow, Loading Limit, Shore to Ship

1. Introduction

Control of environmental pollution has become a central part of business operations around the world. In seaport operations, connection of shore power to berthed ships has the potential to reduce emissions in the port area. Where the shore power is derived from renewable resources, the connection will also result in a reduction of carbon emissions.

Several schemes have been developed for shore to ship connection [1], [2]. Many ports in Europe, North America and Asia have already installed shore to ship connections [3]. The port of Mombasa is supplied from coast regional network of the Kenya grid. Renewable energy sources (geothermal and hydro) account for more than 60% of the effective generation capacity in the Kenya grid [4]. Supply of berthed ship by on-shore power would therefore result in local and global reduction in harmful emissions. Further, this would assist the port of Mombasa realize key port modernization with well-coordinated framework for environmentally friendly operations as an international best practice considering that there is no buffer zone between the local community and the port [2].

Shore to ship connection at the port of Mombasa would result in an addition of a large intermittent load to the coast power network. The main loads in berthed ships are induction motors whose requirement s for active and reactive power vary significantly and this may result in instability phenomena, both short term and long term [9, 10]. An analysis of the effect of such a connection will allow for prediction of negative effects and formulation of mitigation factors to be incorporated in the installation. In this paper, a PSAT/Matlab model of the coast power network is developed. The model is used to analyze long term voltage stability using continuation power flow. The results are used to predict the capacity to take up additional load.

The rest of the paper is arranged as follows. Section 2 reviews the theory and related work on load modelling and long term voltage stability. Section 3 presents the modelling of the Coast region network and offshore load. The results of power flow are presented in Section 4. Section 5 presents conclusions and recommendation for further work.

2. Background and Previous Work

2.1. Load Modelling

Electrical power systems have their load distributed over many points. A study of the system requires modelling of the load. There are different load models that are suitable for different studies [5], [6], [7]. These include static load models, dynamic and composite models. The static model provides the active and reactive power needed at any time based on simultaneously applied voltage and frequency. They can also represent static load components such as resistive and reactive elements or be used as a low frequency approximation of dynamic loads such as induction motors.

However the static load model is not able to represent the transient response of dynamic loads. Examples of static models are polynomial (ZIP) model, exponential recovery model, voltage dependent load and frequency dependent load. A dynamic load model is a differential equation that gives the active and reactive power at any time based on instantaneous and past applied voltage and frequency. Induction motor loads are normally represented by a dynamic model with variable torque, power and slip. To represent aggregate characteristics of various load components, a composite load models that take into account both static and dynamic behaviour is considered. For a system with many induction motors, the complexity of the model can be reduced by use of aggregation models [5], [6], [7]. Power flow studies usually use the PQ model with constant active and reactive power.

Previous studies on shore power have been done mainly on evaluating different frequency converter's connections and transient's analysis with fault current limitation [16]. However, none of these studies has studied the impact of connecting shore power to a power distribution network in terms of voltage stability. The effect of shore to ship connection on the long term stability of the on shore network will be the focus of this investigation.

Power flow studies usually use the static PQ model with constant active and reactive power. In this investigation, existing loads and network distribution stations are modelled as static PQ loads. The ship loads are modelled as a combination of static PQ loads and an aggregated motor load. The equivalent PQ model of the ship load, which will be applied for power flow has been obtained by initialisation of the power flow as proposed in [7].

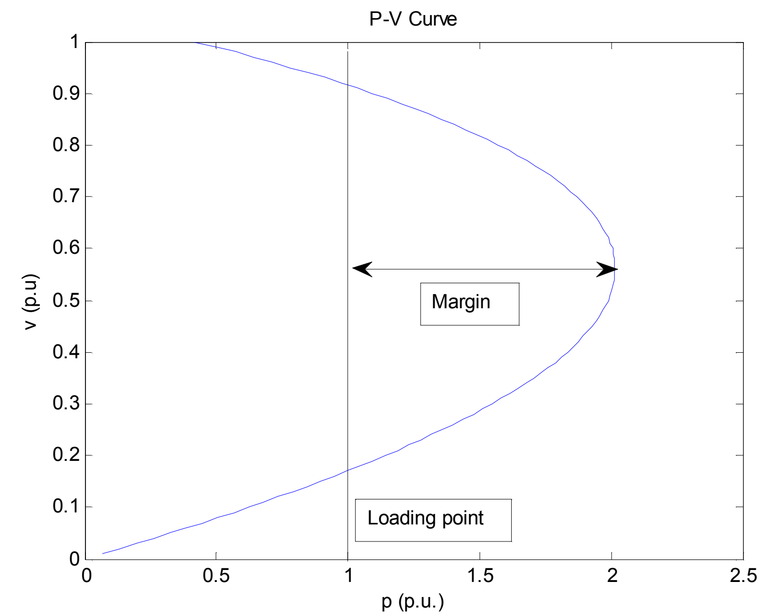

Figure 1. *Loading margin from P-V curve.*

2.2. Voltage Collapse Prediction

Voltage instability in a power system is the result of a mismatch between generation and the load [8] [9, 10]. It is divided into short term instability and long term instability. Short term instability is caused by short term disturbances such as increase in load, reduction in generation or a fault in the transmission system. Short term voltage instability is normally rectified by automatic regulating devices such as on load tap changers and over excitation limiters.

Long term voltage instability occurs when the resources required to match generation to load exceed the capacity of the power system. This arises when the active load exceeds the transmission capacity or the reactive load exceeds the generation capacity. The situation leads to voltage collapse.

For a heavily loaded power system, the possibility of voltage collapse can be predicted by measuring the distance between the current operating point and the point of collapse. The point of collapse for a given bus is indicated by the bifurcation point (the 'nose') in the P-V curve at the bus, as shown in figure 1. This point corresponds to the maximum transmission capacity for active power.

Plotting of the P-V curve in the neighbourhood of the bifurcation point is not possible because of the singularity at the point. The continuation power flow [11] is a tool that can be used to plot the complete P-V curve including the singularity. The continuation power flow is a modification of the standard power flow that is represented by eq (1).

$$p_h = p_G - p_L$$
$$q_h = q_G - q_L \tag{1}$$

Where p_h is active power injected at bus h,
p_G is active power generated at bus h
p_L is load power consumed at bus h
q_h, q_G and q_L represent reactive power injected, generated and consumed at bus h.

In the continuation power flow model, a loading factor, λ, is used to increment the load in fixed steps from a small value. In order to match power generation with the reduced load, all generator capacities are scaled by a participation factor k_g. The expressions for active power generated and load power (active and reactive) therefore become as shown in eq (2);

$$p_G = (\lambda I_N + k_g I_N) p_{GO}$$
$$p_L = \lambda p_{LO}$$
$$q_L = \lambda q_{LO} \tag{2}$$

Where, I_N is the identity matrix of size N,
N is the number of generators in the network and
p_{GO}, p_{LO} and q_{LO} are base values for generated power, active load power and reactive load power respectively.

A numerical solution of the continuation power flow is achieved through a series of prediction and correction step as demonstrated in Figure 2. This eventually results in a plot of the complete P-V curve, including the bifurcation point and the lower and upper solutions.

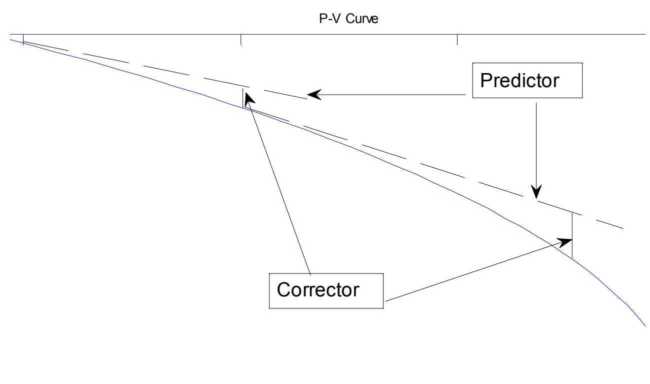

Figure 2. *Predictor and corrector in continuation power flow.*

In [12], the method has been applied to a system with induction motor load. In [7], a method is proposed which incorporates the limits for reactive power generation in the continuation power flow solution. This is achieved by implementing reactive power generation limits in the implementation algorithm.

In this investigation, limits for reactive power generation and transmission line capacity are applied in the algorithm in order to ensure that solutions obtained are within the capacity of the network.

3. Contribution

3.1. Network Description

The coast network is part of the Kenya national grid. It has two connections to the grid [4], [13], [14]. The first connection is a 132kV single circuit transmission lines from Juja Road Bulk Supply Station (BSP) in Nairobi to the Rabai BSP in Mazeras near Mombasa. The second connection is a 220kV single circuit transmission line from the Kiambere power station on the Tana River to the Rabai BSP.

The system supplies power to the counties of Taita Taveta, Kwale, Mombasa, Kilifi and Tana River through a network of 33kV distribution feeders. There are on-going plans to link the system to Lamu County, which is currently supplied by off-grid generation.

The coast network has four generating stations at Rabai, Kipevu I, Kipevu II (Tsavo Power) and Kipevu III. The capacity of the generating stations is summarised in Table 1.

Table 1. *Coast Region Generating Capacity.*

Generating Station	Installed Capacity, MW	Effective Capacity, MW
Rabai	90	90
Kipevu I	75	51
Kipevu III	120	115
Kipevu II	74	74

Table 2. *132kV Distribution.*

FROM	TO	km	kV	CIRCUITS	CONDUCTOR
Juja	Mtito	476	132	Single	132_LYNX
Mtito	Voi	91	132	Single	132_LYNX
Voi	Maungu	30	132	Single	132_LYNX
Maungu	Mariakani	90	132	Single	132_LYNX
Mariakani	Kokotoni	13	132	Single	132_LYNX
Kokotoni	Rabai	5	132	Single	132_LYNX
Rabai	Kiambere	416	220	Single	220_CANARY
Rabai	Galu	60	132	Single	132_LYNX
Rabai	Kipevu I & III	17	132	Double	132_WOLF
Rabai	Kipevu I & III	17	132	Single	132_LYNX
Rabai	Kipevu II	17	132	Single	132_LYNX
Kipevu	KPA	1.5	132	Single	400mm^2 Cu U/G
Rabai	New Bamburi	22	132	Single	132_WOLF
New Bamburi	Vipingo	13	132	Single	132_WOLF
Vipingo	Mombasa Cement	12.5	132	Single	132_WOLF
Msa Cement	Kilifi	17.5	132	Single	132_WOLF

In addition, the coast network is also connected to national the grid through a 132kV transmission line from Rabai to Juja Road BSP in Nairobi and a 220kV line from Rabai to the

Kiambere power station.

The connection to the national grid allows the coast network to supply excess power to the national grid when local generation exceeds consumption. It also allows the network to draw power from the national grid when local consumption exceeds generation. We can therefore model the connection to the national grid as a slack bus.

All the generating stations supply power to the Rabai sub-station which acts as the bulk supply point for the coast network. Power is then distributed to the coast region through a 132kV network with interconnections as in Table 2.

From Rabai, power is distributed using a 132kV network to bulk supply points at Galu near Diani on the South Coast, Kipevu just outside Mombasa Island and Bamburi, Vipingo and Kilifi on the North Coast. In addition to the bulk supply points, there are two 132kV stations feeding individual consumers. These are Mombasa Cement on the North Coast and KPA on Mombasa Island. There is also reactive power compensation at the Rabai BSP. This is in the form of 2*15MVAr inductive compensation. Each of the bulk supply stations in the coast region supply power through 132kV/33kV distribution transformers. The total load connected to each station is presented in Table 3.

Table 3. *BSP load.*

BSP	Active Power, MW	Reactive Power, MVAr	Total MVA
Galu	14.25	6.9	15.83
Kilifi	13.38	6.48	14.87
Kipevu	99.86	48.37	110.95
New Bamburi	26.47	12.82	29.4
Rabai	7.63	3.7	8.47
MSA Cement	10.98	5.32	12.2
KPA	6.3	3.05	7
Kokotoni	3.27	7.5	7.5
Mariakani	5.36	12.3	12.3
Maungu	1.62	3.72	3.72
Mtito Andei	2.05	4.69	4.69
Voi	1.69	3.87	3.87

3.2. Network Model

The Power network described in section 3.1 is modelled on the PSAT/Matlab platform. A single line diagram of the model is shown in Figure 3. The model parameters are included in Table 4, Table 5 and Table 6.

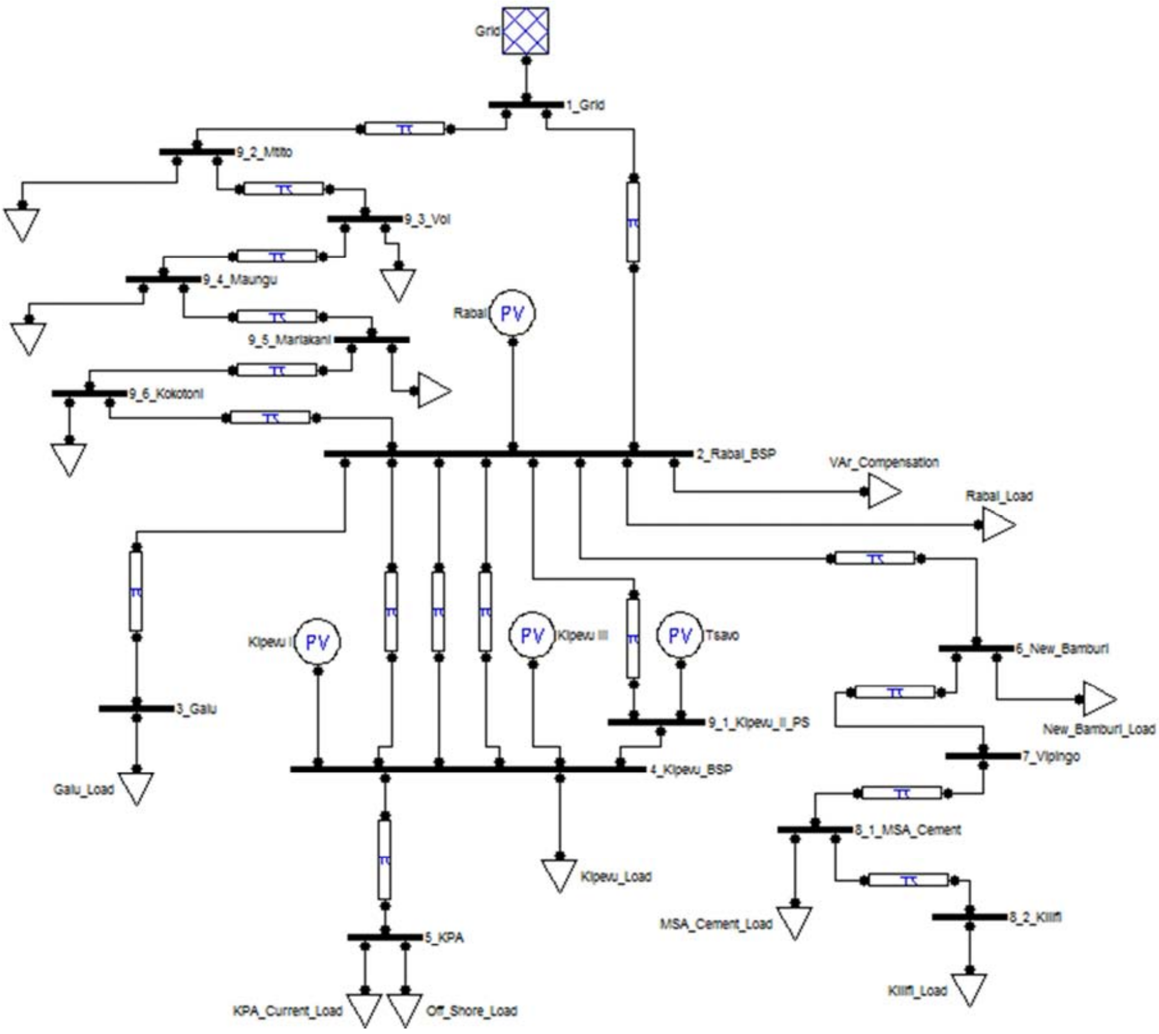

Figure 3. *Matlab / PSAT Model of Coast Network.*

Table 4. *Generation.*

Generating Station	Bus	Power Generated, P (p.u.)
Rabai	Rabai BSP	0.3000
Kipevu I	Kipevu BSP	0.1700
Kipevu III	Kipevu BSP	0.3833
Tsavo (Kipevu II)	Kipevu II	0.2467

Table 5. *Line data*

FROM	TO	r (p.u.)	x (p.u.)	b (p.u.)
Rabai BSP	Galu	0.1962	0.4449	2.7789E-06
Rabai BSP	Kipevu BSP	0.0644	0.1274	7.7858E-07
Rabai BSP	Kipevu BSP	0.0644	0.1274	7.7858E-07
Rabai BSP	Kipevu BSP	0.0556	0.1261	7.8736E-07
Rabai BSP	Kipevu II	0.0556	0.1261	7.8736E-07
Kipevu BSP	KPA	0.0012	0.0058	4.1322E-09
Rabai BSP	N. Bamburi	0.0834	0.1649	1.0076E-06
N. Bamburi	Vipingo	0.0493	0.0974	5.9539E-07
Vipingo	M. Cement	0.0474	0.0937	5.7249E-07
M. Cement	Kilifi	0.0663	0.1312	8.0148E-07
Grid	Rabai BSP	0.5479	3.1515	1.8837E-05
Grid	Mtito	0.8078	1.8315	1.1440E-05
Mtito	Voi	0.2976	0.6748	4.2147E-06
Voi	Maungu	0.0981	0.2224	1.3895E-06
Maungu	Mariakani	0.2943	0.6673	4.1684E-06

Table 6. *Bus data – Connected loads.*

BUS NO.	BUS NAME	LOAD		STATIC VAR (p.u)	BUS TYPE
		P (p.u.)	Q (p.u.)		
1	Grid	-	-	-	Slack
2	Rabai BSP	0.0254	0.0123	0.1000	PQ
3	Galu	0.0475	0.0230	-	PQ
4	Kipevu BSP	0.3329	0.1612	-	PQ
5	KPA	0.0210	0.0102	-	PQ
6	N. Bamburi	0.0882	0.0427	-	PQ
7	Vipingo	-	-	-	PQ
8	M. Cement	0.0366	0.0177	-	PQ
9	Kilifi	0.0446	0.0216	-	PQ
10	Kipevu II	0	0	0	PV
11	Mtito	0.0141	0.0068	-	PQ
12	Voi	0.0116	0.0056	-	PQ
13	Maungu	0.0112	0.0054	-	PQ
14	Mariakani	0.0369	0.0179	-	PQ
15	Kokotoni	0.0225	0.0109	-	PQ

3.3. Off-Shore Load

The port of Mombasa has 22 deep water berths [15]. Of these, 9 are container berths, 9 are for general cargo, 2 are for oil tankers and 2 are for roll-on roll-off vehicle carriers. Port traffic is estimated as 38% container ship, 20% general cargo, 14% bulk carrier, 14% Ro-Ro and car carriers and 13% oil tankers. The power demand for each category of ship has been estimated by the following process:

a. Data on electrical loads on a ship is collected.
b. The load is modelled as a composite load comprising aggregated induction motor load and constant impedance loads.
c. The steady state PQ load for use in power flow is determined by an initialisation process.

The load aggregation and initialisation method is presented in [16]. A comparison is also done with global data from [1], [2], which includes data on the actual percentage of total load that is utilised when ships are at berth.

From this analysis, an estimate of the total demand of ships in berth at the port of Mombasa is presented in Table 7. A shore to ship connection for the port of Mombasa will therefore be expected to carry a load of approximately 22MW.

Table 7. *Off-shore power demand for Mombasa port.*

Type of Berth	No.	Peak Load (kW)	In Port Demand	Berth Load (kW)
Container	9	4,000	20%	7,200
General Cargo	9	2,800	40%	10,080
Ro-Ro	2	1,800	30%	1,080
Oil Tanker	2	2,500	65%	3,250
Total	22			21,610

4. Results and Discussions

4.1. Base Case Power Flow

The results of power flow on the model in Figure 3 are presented in Table 8. It can be observed that the buses 11 and 12 (Mtito and Voi) have the lowest voltage levels at 0.93 per unit. We However, it can be observed that these are loads tapped from the transmission line from the grid. Their main supply is therefore from the grid and not from the coast network. Of the buses that are a core part of the coast grid, the lowest voltage is experienced ad Kilifi and Mombasa cement. The next investigation will therefore carry out continuation power flow at those buses.

Table 8. *Power flow results.*

BUS	V (p.u.)	phase (rad)	P gen (p.u.)	Q gen (p.u)	P load (p.u.)	Q load (p.u.)
Grid	1.05	-	(0.31)	0.28	-	-
Rabai BSP	1.00	0.73	0.30	0.49	0.03	0.11
Galu	0.98	0.71	-	-	0.05	0.02
Kipevu BSP	1.00	0.74	0.55	0.08	0.33	0.16
KPA	1.00	0.74	-	-	0.02	0.01
New Bamburi	0.97	0.71	-	-	0.09	0.04
Vipingo	0.96	0.70	-	-	-	-
MSA Cement	0.95	0.69	-	-	0.04	0.02
Kilifi	0.95	0.69	-	-	0.04	0.02
Kipevu II	1.00	0.76	0.25	(0.10)	-	-
Mtito	0.93	0.34	-	-	0.01	0.01
Voi	0.93	0.49	-	-	0.01	0.01
Maungu	0.94	0.54	-	-	0.01	0.01
Mariakani	0.98	0.69	-	-	0.04	0.02
Kokotoni	0.99	0.72	-	-	0.02	0.01

4.2. Continuation Power Flow

A continuation power flow has been carried out with an additional 22MW load connected on bus 5 (KPA) to simulate the shore to ship connection. The resulting P-V curves are presented in Figure 4. It is observed that the point of instability occurs at a loading of more than 5 per unit. This implies that even with the additional load, the network has a large margin of safety against voltage collapse.

It is however noted that the voltage level falls below 0.9p.u when the load factor is 1.77p.u. Voltages below this level may lead to motor stalling. This loading value provides a limit for the possible load on the network. The Kilifi bus, which is farthest from the generation point experiences the lower voltage.

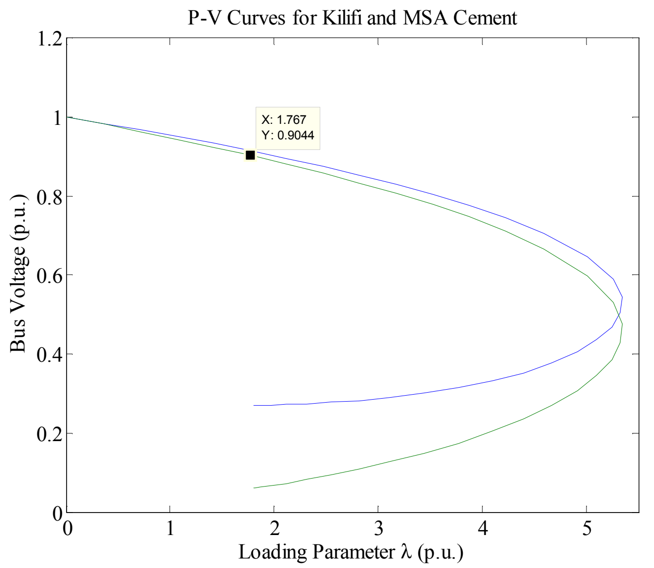

Figure 4. *PV Curves for MSA Cement and Kilifi buses.*

A similar study for buses 3 (Galu) and 5 (KPA) is shown in Figure 5. It can be noted that the loading limit will not be reached even when the applied load is more than 5 times the planned load. The Galu bus will however experience voltages below 0.9p.u. When the loading is above 4.7 time the rated load.

4.3. Effect of Line Outages

In order to investigate the effect of a line outage a load flow study was conducted under the following conditions:

a. An outage on one of the Rabai – Kipevu transmission lines.
b. An outage on the Juja – Rabai transmission line (at Kokotoni.
c. An outage of the Kiambere – Rabai transmission line.

It was observed that in case (a), the power flow could be successfully concluded and the bus voltages were similar to those in section 4.1. In the case of (b) and (c), the power follow could not converge after 21 iterations. Outage of any of the connections to the grid results in insufficient capacity for in the system.

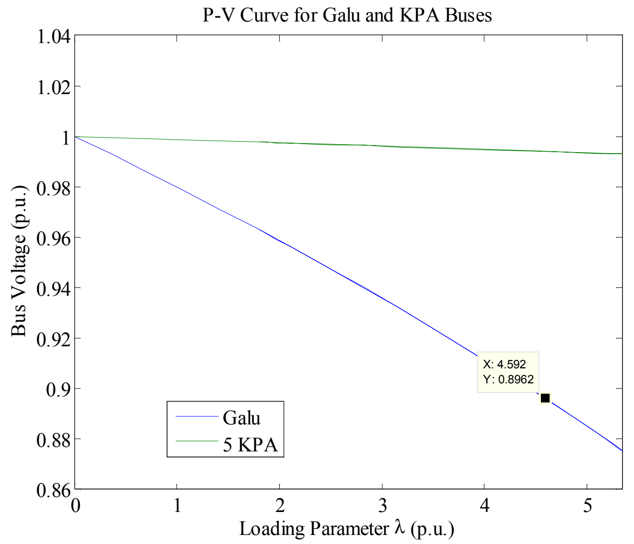

Figure 5. *PV Curves for Galu and KPA Buses.*

5. Conclusions and Further Work

This work has demonstrated the application of power flow and continuation power flow in determining the impact of a shore to ship connection on a regional power network

A model of off-shore load at the port of Mombasa has been developed. The Coast Region power network has also been modelled. A power flow study has been applied to identify the buses with highest likelihood of voltage collapse. Continuation power flow has further been applied to identify the loading limit on the selected buses.

The study finds that there is sufficient capacity in the coast network to handle the additional load that would result from a shore to ship connection at the Mombasa port. The study also finds that the system would collapse if there was an outage in any of the two transmission lines connecting the coast network to the national grid. Long term stability of the system therefore requires reinforcement of the connection to the grid.

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