Impact of installing renewable energy sources on a small-scale power network in the Caribbean

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Abstract - Many small island states in the Caribbean like Antigua and Barbuda depend heavily on petroleum-based products for power generation. Given the fluctuating oil prices, there is now an urgent push for increased energy security. Antigua is one of the fastest-growing islands for grid-connected Renewable Energy Sources (RES). Whilst the increase in grid-connected RES improves the islands’ energy security, and it is equally important to understand the impact that RES have on the network’s reliability and security. Thus, a base case model of the power network was built, and the following areas were analysed: load flow, contingency analysis, and fault analysis. The Antigua Public Utilities Authority (APUA) 69kV power network is used as a case study for this project. PowerWorld and Homer Energy software have been used to simulate and model the grid. Results from the project show that RES changes the power flow and could help to improve the system voltage profile if placed correctly. Whilst increased penetration of Wind Turbine Generators (WTG) on the grid increases the system fault levels, they also play a key role in active and reactive power control. This means that the APUA network must be more flexible, and system operators must have network visibility to react to changes on the network. The aim of this paper is to investigate the impact that RES (in particular, wind and solar PV) has on the operational, security, or reliability of a small-scale power network.

Keywords – Contingency analysis, power flow, Renewable Energy Source, Fault analysis.

1. Introduction
Antigua and Barbuda, like many other small island states in the Caribbean, have been making strides to increase their energy security by tapping into an abundance of untapped Renewable Energy Resources (RES). The primary source of power generation in Antigua is from fossil fuels (diesel and Heavy Fuel Oil). The country is heavily dependent on petroleum-based products as its primary source of fuel for power generation. This results in high import fuel costs which get passed onto the customers. The fluctuating fuel prices are unsustainable and unattractive for future growth and development of the island. There is now an increased effort to reduce the country’s dependency on fossil fuel power generation by supplementing the primary energy source with RES [1].

Wind and solar energy are the two most abundant and untapped RES on the islands [2]. The 2015 Paris Climate Conference was an important milestone in the country’s quest for energy security [2]. In 2016, the installation of two grid-tie Solar Photovoltaic (PV) Farms (3MW and 4 MW) was connected to the network. Although solar PV helps to improve the system voltage profile, they do not contribute to reactive power flow which is necessary for the operation of electrical equipment like motors, pumps, and Air Handling Units (AHU). Therefore, the effects of increased penetration in RES must be fully understood to effectively manage the network. The current technology used in Type 3 and 4 WTG uses Doubly Fed Induction Generator (DFIG) or Doubly Fed Asynchronous Generator (DFAG) which play a key role in active and reactive power generation and control [3].
2. Literature survey

2.1 Power Quality
The increased penetration of RES has many advantages; however, the RES must be effectively placed on the network in order to have maximum effect. The largest energy sector on the island is the commercial sector, with 45% energy consumption [2,3]. This sector absorbs a significant amount of reactive power which may result in voltage dips and system losses. Majority of modern electrical equipment contains some form of power electronics. Solar PV systems use DC-DC converters which are a source of generating harmonics in the power system. As a result, harmonics can shorten the equipment life span, cause equipment to malfunction and increase power loss. The use of Pulse Width Modulation (PWM) techniques can help to reduce harmonics [3].

2.2 Power System Security
The implementation of RES changes the power system’s topology, which directly has an impact on system security. The location of a RES, a sudden loss of transmission line or transformer on the network could result in additional stress on been placed on other components. These changes will increase the security risk and cause system violations. These generally caused two types of violations: low and high voltage violations on buses and line or transformer violations. Many power system operators use contingency analysis as a primary tool to assess the security state of the network [3].

2.3 System Stability and Reliability
The power output and reliability of RES connecting on the grid depend on the rating and technology used. The interconnection of some RES can cause operation and control problems especially large Solar PV, which cannot control its power output. The increased penetration of wind turbines increases the power system fault levels and may give rise to system instability and reliability [4][5].

2.4 Power Flow and Loss
In modern or upgraded power systems, power flow is expected to be bidirectional. The existing APUA network was designed based on omnidirectional power flow. The connection of RES at different points on the network changes the nature of power flow from the substation to end-user. Therefore, the power flow on the network is continuously changing, which also affects the losses on the system.

3. Network Topology
Following the American National Standard Preferred Voltage Ratings for Electric Power Systems and Equipment, the APUA network is considered a medium voltage (0.6kV - 69kV) network operating at 69kV/11kV [4]. The bulk of power is generated via conventional generators at 11kV and stepped up to 69KV for transmission. Power generation and transmission on the island is three-phase (3-phase), 60 Hertz (Hz) at two voltage (V) levels 110 V, and 230 V [3][6]. System frequency range is ±6% on nominal frequency. Figure (1) shows the PowerWorld model of the APUA network.

The International Renewable Energy Agency (IREA) Renewables Readiness Assessment study [2] states that the peak electricity demand in 2016 was 51 megawatts (MW). Demand is expected to grow to about 55MW by 2025 [2]. The peak demand so far for 2019 is 54MW [5]. This sharp increase in load demand suggests that there is faster electrical growth than earlier predicted. Given the significant increase in major construction projects on the island, it is anticipated that peak demand will be greater than 55MW by 2025. Based on the current growth rate over the last three years (2016 – 2019), the new projected peak load is estimated to be in the region of 57 - 60MW by 2025 [3].

3.1 Network Load Characteristics
The loads connected on the network are grouped into three main categories: commercial (Com), industrial (Ind.) (represented by motor loads) and residential (Res) loads. Large-scale (LS) industrial and commercial loads are critical when performing transient and dynamic studies. Table 1 lists the load
models that are used in the simulation.

Complex load (CLOD) model is used to represent large and small induction motors found on rooftop Air Handling Units (AHU), Air-Condition Units (ACU), washing machines, and refrigerators. Models can also include discharge lighting and other PQ loads [3, 7]. Western Systems Coordinating Council (WSCC) load model assumes an 80% static and 20% dynamic loads. WSCC is designed to capture the effects of dynamic induction motor (IM) loads during summer peaks [3][8][9][10].

### Table 1. Simulation load models.

| Substation     | Supply to                      | Sub Loads                  | Load Model                  |
|----------------|--------------------------------|----------------------------|-----------------------------|
| Crabbs (CR)    | Generation substation          | RO Plant.                  | 3 phase Induction Motor (IM) |
| Cassada Garden (CG) | North, East & Central. | LS Com, Ind. & Res | WSCC, LDELEC, CLOD, CIM6 |
| Frias Hill (FH) | North & West central.         | LS Com, Ind. & Res         | WSCC, LDELEC, CLOD, CIM6 |
| Five Islands (FI) | West & South West. | LS Com, & Res             | WSCC, LDELEC, CLOD          |
| Belmont (BE)   | South West & central.         | Com & Res                  | WSCC, LDELEC                |
| Lavington (LA) | South East.                   | Com & Res                  | WSCC, LDELEC, CLOD          |
| Sweets (SW)    | South & Central               | Com & Res                  | WSCC, LDELEC                |

Electronic Load (LDELEC) model represents loads (e.g., TV sets, UPS) which may contain Switch-Mode-Power (SMP) supply or converter base loads [6]. CIM6 load model models a single or double cage induction motor typically use for pumps, large ACU and fans [8].

### 3.2 Network Challenges

The APUA network is currently undergoing significant changes, from its early days of transmitting power in a unidirectional manner to an omnidirectional flow of power due to the connection of various RES. This means the network must be more flexible, and system operators must have network visibility to ensure timely response to network changes. Some of the challenges identified are discussed next.

The increased number of power cuts and load shedding on the island indicates possible network protection grading issues or short line or transformer (Tx) capacity in some areas. A recent protection study indicates the early operation of downstream protective devices operating before the upstream devices [7]. It is a possibility that this may have occurred due to changes in the network’s topology, or protection device settings may have creeped out of range over time.

Approximately 92% of the island’s generation capacity is located on the Crabbs Peninsula (see Figure 1, area denoted as CR Sub). This increases the supply security risk of the network and possible power quality issues. The longest distance from generation to the substation is 9.5 miles. This is not significant: however, the distances from the substation to end-user is significantly increased via the 11 kV overhead lines (OHL).

The system MW losses are estimated to be 24% [11] which is approximately 12.96 MW of peak load (54MW). Simulation losses are showing approximately 2.6MW. Therefore, this suggests that over 10MW of losses are non-technical.
4. Analysis of Existing Network

This section of the project analyses the existing network with the aim of gaining a better understanding of the current state of the power system. Once the state of the systems has been established, the necessary improvements, and or upgrades can be identified.

4.1 Load Flow

Successful operation and planning of any power system operating under normal steady-state balanced three-phase conditions are determined by the load flow (LF). Four main elements are identified from LF studies: real (P) and reactive (Q) power flowing through the system, voltage magnitudes (|V|) and angles (δ) at each bus (also referred to as nodes). This information forms the basis from which all other studies are carried out [9]. The information gained from the LF analysis allows the engineer to understand how the system will react in various hypothetical situations such as loss of a line or transformer. The connection of RES on the existing network will affect the overall power flow in the network. As a result, these changes will affect system losses and voltage profile. System losses are therefore dependent on the system topology and location of the RES source. Power flowing through the system is defined by equation 1.

\[ P = \frac{V_1 \times V_2 \sin \delta}{X} \]  

Table 2 shows the results of the power flow analysis performed in the base case. There are three buses that have been identified as been below the 0.94 p.u value.

| Name        | Nom kV | PU Volt | Volt (kV) | Load MW | Load Mvar |
|-------------|--------|---------|-----------|---------|-----------|
| FH Bus No. 01  | 69  | 0.974  | 67.21  |        |           |
| CG Bus No. 02  | 69  | 0.985  | 67.94  |        |           |
| CR Bus No. 03  | 69  | 1.000  | 69.03  |        |           |
| CR Bus No. 04  | 69  | 0.992  | 68.45  |        |           |
| FH Bus No. 22  | 11  | 0.936  | 10.30  | 8.38   | 4.19      |
| FH Bus No. 23  | 11  | 0.936  | 10.41  | 5.14   | 4.1       |
| FI Bus No. 21  | 11  | 0.928  | 10.21  | 7.5    | 4.64      |
| BE Bus No. 07  | 69  | 0.967  | 66.75  |        |           |
| SW Bus No. 06  | 69  | 0.972  | 67.10  |        |           |
| LA Bus No. 05  | 69  | 0.980  | 67.63  |        |           |

The power flow model shown in Appendix A Figure A-1 indicates that the Tx located at FI Sub has exceeded its monitored 80% MVA limit. The Tx capacity is currently at 92%. The limit monitoring
effects can be found in Appendix B, figure B-1 and B-2. The results from the simulator appear to be within acceptable limits as this Tx is currently being replaced [12].

4.2 Fault analysis.
A fault is generally any abnormal condition that may occur in a power system operating under normal steady-state balanced three-phase conditions. This may be due to a sudden external or internal disturbance. Initial fault analysis was conducted on the base case to get an overall understanding of the existing fault levels on the network. These faults will then be compared to the fault levels once the RES has been implemented.

Table 3 shows the fault magnitude for all 3-phase faults on the main 69kV buses. This will be compared to fault magnitude once the RES is added to the network.

| Bus Name       | Fault Type | Resistance (R) | Reactance (X) | Mag (A)   | Angle |
|----------------|------------|----------------|---------------|-----------|-------|
| FH Bus No. 01  | 3PB        | 0.069          | 0.052         | 5074.4    | -63.68|
| CG Bus No. 02  | 3PB        | 0.023          | 0.056         | 6881.19   | -64.89|
| CR Bus No. 03  | 3PB        | 0.064          | 0.048         | 7055.47   | -44.22|
| CR Bus No. 04  | 3PB        | 0.069          | 0.052         | 5675.61   | -45.95|
| LA Bus No. 05  | 3PB        | 0.03           | 0.077         | 4228.46   | -64.9 |
| SW Bus No. 06  | 3PB        | 0.03           | 0.073         | 3747.78   | -64.24|
| BE Bus No. 07  | 3PB        | 0.04           | 0.089         | 3451.1    | -63.43|
| FI Bus No. 08  | 3PB        | 0.02           | 0.055         | 3193.76   | -65.32|

4.3 Contingency analysis.
The number of load shedding and occasional power cuts across the island has raised concerns about the security of the network. In modern Energy Management Systems (EMS), power engineers perform Contingency Analysis (CA) to test the reliability and security of the power system [13]. By performing a CA, this also tests how well the system is interconnected and ensures it operates economically and efficiently to deliver power to the end-user. The initial CA identified a total of 66 violations. Majority of these violations stems from overloading of components (lines and Tx) in the event of an outage of a line or transformer. Figures B-3 and B-4 in Appendix B show the effects of an overload violation [3].

Most power systems in the world operate on the North American Electric Reliability Corporation (NERC) rule (n-1) [14]. The concept of the n-1 rule ensures continuous operation of the power system in the event of a component failure. The following equality and inequality constraints must be met when the system is operating under the normal steady-state condition:

\[
\sum_{i=1}^{NP} P_{Gi} = P_D + P_{Loss} \quad (2)
\]

\[
P_{min} \leq P_i \leq P_{max} \quad (3)
\]

\[
V_{min} \leq V_i \leq V_{max} \quad (4)
\]

Where NP is the number of power sources, \( P_{Gi} \) is the active power injected, \( P_D \) is the power demand, \( V_m \) voltage magnitude at the bus [3].

There are generally four security states which determine the state of the power system and the necessary remedial actions. Normal state means the system is secure in the N and N-1 situations [14]. Alert State means the system is secured in N-situation but not in the N-1 situation [14]. Emergency State means the system is not secured in N or N-1 situation, and remedial actions may be required. Automatic Actions State means the system is not secured in N nor N-1 situation and no remedial actions possible [3, 14].
5. Implementation of RES
There is a number of proposals from the local authorities for the connection of WTGs on the Crabbs Peninsula, Sir Vivian Richards’s cricket stadium, and a Solar PV farm near the Mount St John’s Hospital. However, these additional RES help in reducing the CO₂ footprint, the reinforcing of the network security must be considered.

5.1 New Load Flow
The addition of RES has increased the loading of the 11kV line by 20-22% connecting CG Bus No. 24 to CG Bus No. 34. The MVA loading on the transformer connecting CG Bus No. 34 to CG Bus No. 02 also increases by 20%. This increase is due to the high reactive power flow [3]. Therefore, there is a requirement for reactive power compensation on the network.

The connection of the solar PV on the FH Bus has improved the voltage profile of the network. The blue highlighted cells in Table 4 shows the p.u improvement on FH Bus No. 22 and 23 when compared to Table 2. A sensitivity analysis must be carried out in order to identify the most suitable location for the placement of compensation schemes or placement of RES [3].

Table 4. Addition of RES on FH Bus.

| Name          | Nom kV | PU Volt | Volt (kV) | Load MW | Load Mvar |
|---------------|--------|---------|-----------|---------|-----------|
| FH Bus No. 01 | 69     | 0.987   | 68.11     |         |           |
| CG No. 02     | 69     | 0.997   | 68.79     |         |           |
| CR Bus No. 03 | 69     | 1.006   | 69.40     |         |           |
| CR Bus No. 04 | 69     | 1.004   | 69.25     |         |           |
| FH Bus No. 22 | 11     | 0.958   | 10.54     | 8.38    | 5.19      |
| FH Bus No. 23 | 11     | 0.961   | 10.57     | 5.14    | 4.1       |
| FL Bus No. 21 | 11     | 0.931   | 10.36     | 7.5     | 4.64      |
| BE Bus No. 07 | 69     | 0.980   | 67.63     |         |           |
| SW Bus No. 06 | 69     | 0.985   | 67.95     |         |           |
| LA Bus No. 05 | 69     | 0.992   | 68.46     |         |           |

5.2 Sensitivity analysis
The application of sensitivity analysis (SA) in power systems can be used for system improvements, fault location, or reliability evaluation of the network [15]. As system load increases, this causes a reduction in efficiency and a drop in voltage. Therefore, some form of compensation is required to improve the system power factor. However, the best efficiency is gained when the compensation scheme is placed at an optimal point in the system. This has the effect of reducing system losses, reducing generation cost, and improving the power factor. SA largely depends on the Optimal Power Flow (OPF). The OPF model can be written as:

\[
\min \sum_{i=1}^{NG} C_i (PG_i) = \alpha + (\beta_i P G_i) + (Y_i P_i G_i)
\]

Where: \(C_i (PG_i)\) is the cost of generation at generator Bus i [3, 15].

OPF is carried out in order to minimise the total operating cost and losses, which may be subject to constraints such as equality of generation and demand. Therefore, fuel cost and operational and maintenance (O&M) cost must be first established. Fuel cost is estimated at $0.30 per kWh and O&M cost of $0.20 per kWh [3, 16]. The fuel cost is then converted in $/MBTU and $/MWh, respectively (see Appendix B, Table B-8). The P and Q sensitivity values highlighted in Table 4 show the main buses, which have the highest injection of reactive power with respect to the voltage at the bus. An injection value that is \(\geq 0.0005\) p.u is used as a benchmark and indicates that a compensation scheme is required at the right bus to yield the most considerable system improvement. After placing a 20 MVAR shunt capacitor on CG Bus No. 2 and FH Bus No. 1, Table 5 shows the reduction in reactive power p.u across

\[\]
the whole system. This shows a significant reduction in Q value, which indicates convergence [3].

| Name           | Area No. | P Sen   | Q Sen   |
|----------------|----------|---------|---------|
| FH Bus No. 01  | 1        | 0.00063 | 0.000937|
| CG - Bus No. 02| 1        | 0.00044 | 0.000551|
| CR Bus No. 03  | 3        | 0.00027 | 0.000184|
| CR Bus No. 04  | 3        | 0.00036 | 0.000337|
| FI Bus No. 08  | 2        | 0.00068 | 0.000787|
| BE Bus No. 07  | 1        | 0.00057 | 0.000784|
| SW Bus No. 06  | 2        | 0.00049 | 0.000539|
| LA Bus No. 05  | 3        | 0.00042 | 0.000493|
| FH Bus No. 22  | 1        | 0.0007  | 0.000991|
| FH Bus No. 23  | 1        | 0.0007  | 0.000991|

Table 4. Sensitivity Analysis of base case.

| Name           | Area No. | P Sen   | Q Sen   |
|----------------|----------|---------|---------|
| FH Bus No. 01  | 1        | 0.000272| 0.00041 |
| CG Bus No. 02  | 1        | 0.000202| 0.000263|
| CR Bus No. 03  | 3        | 0.000153| 0.000137|
| CR Bus No. 04  | 3        | 9.61E-05| 4.74E-05|
| FI Bus No. 08  | 2        | 0.000212| 0.000147|
| BE Bus No. 07  | 1        | 0.00021 | 0.000267|
| SW Bus No. 06  | 2        | 0.000142| 0.000147|
| LA Bus No. 05  | 3        | 8.99E-05| 2.52E-05|
| FH Bus No. 22  | 1        | 0.000238| 0.000389|
| FH Bus No. 23  | 1        | -0.00017| 1.92E-05|

Table 5. Reduction in reactive power.

6. Network Improvements and Cost

Power system performance generally depends on three interconnected factors: reliability is the probability of the long term satisfactory operation of the system [17], security is the percentage or degree of risk in which the system is likely to survive any imminent disturbances [3][17], and stability is the continued operation of the system after a disturbance.

6.1 Network improvements

In order to ensure better system security and reliability, the network must be secured to the n-1 level as per the CA. Further network improvements can be achieved through network area sectioning (see Figure 1), better distribution of energy sources, and the addition of a new 69 kV substation in the in Ffyres or Bolands (FB sub) area (see Figure 1) which improves voltage profile and system reliability [3].

6.2 Energy analysis

HOMER Energy software was used to carry out a cost-benefit analysis and energy management of the improved system. The model uses the load Following dispatch strategy whereby, whenever a generator is dispatched, it only produces enough generation to meet the demand. Figure (2) shows the network load and generation profile. In the first graph at the top, the dark blue line shows the energy demand met, and the light blue line shows the total AC load demand. The other three lines (red, light blue and purple) show the response of the generators to the changing load. The second graph at the bottom shows the wind (blue line) and solar (red and yellow line) energy output. As a result of installing additional RES, this has reduced the response demand from the conventional generators [3]. Therefore, this reduces the total CO2 from 224,558 Mg/yr to 216,792 Mg/yr, a reduction of 776.7 kg/yr (4.5%).
7. Future Research

This paper investigated issues relating to the connection of RES to a small island network. The project has confirmed some issues identified in the literature review [3]. However, further investigations are needed in other areas. The impact of Electric Vehicle (EV) charging is one area that requires further investigation. There is a steady increase in EV on the island, and it is essential to understand the impact on the grid. Since all Solar PV on the network are grid-tied, investigations should be conducted to assess the benefits of a Battery Storage system.

8. Conclusion

This paper investigated the impact of RES on a small-scale power network. A model of the APUA network in Antigua was used as the base case. An initial analysis of the system was performed looking at power flow, system security (CA) and fault analysis [3].

The addition of RES on the grid can improve the voltage profile if effectively placed on the network. However, penetration levels of WTG on the network will increase system fault levels. Therefore, the increase in fault levels will affect the network protection scheme. By using Type 3 or 4 WTG, they have the capability to participate in active, and reactive power control, thereby, ensuring grid stability when required.

The increased penetration levels of WTG connecting to the grid will also have an effect on the stability of the power system during and post disturbances. The response to disturbances of WTG is
significantly slower than conventional generators. This slow response of the WTG in settling back down to steady-state stability leaves the system more vulnerable to instability with increased penetration levels [3]. Therefore, fault ride-through applications should be considered.

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Figure A-1 gives a better understanding of how the line overload is caused as a result of no shunt capacitor on the FH Bus No. 01. As this section of the island is one of the fastest growing areas for large scale commercial business. Therefore, the increase in reactive load requirements increases the line MVA limit.
Figure B-1. Line & Transformer limit monitoring.

Figure B-2. Bus limit monitoring.

Figure B-3. Removal of substation component.

Figure B-4. Removal of substation component.