Effect of Distributed Solar Energy Generation on Uganda's Electricity Grid Stability

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Abstract- Solar energy technology provides power and is only used when there is availability of the resource. However, large amount of solar energy is difficult to integrate into the grid because its availability is constantly changing and uncertain. The assessment aimed at establishing the extent to which an alternative solar plant would be able to support other intermittent solar generation on the grid. Generation possibilities like synchronization and asynchronous variations with no battery storage were evaluated using MATLAB Simulink. The grid voltage, grid current, real power, grid frequency and reactive power were monitored for the generation scenarios. For the scenarios of asynchronous generation, the grid behaved in the same way as though the generation was lumped at one location. This was a consistent observation since the reactive power support was still coming from the base hydro-generation plant. For synchronized distributed generation (60 MW and 10 MW of solar), reactive power was still available on the grid. Synchronization was used to integrate solar plants into the grid without requiring any further grid support. However, in this option, a deliberate investment must be made in a control system to support site synchronization. Precise controllers were required to send a real-time generation to alternate locations so that the reserves could be ramped up to restore stability.

Keywords; Solar energy, distributed generation, grid, asynchronous, reactive power, stability

1. Introduction

As renewable energy resources have been considered the main resource for the future power generation [1], expansion of the grid by integrating distributed renewable energy systems has turned out to be an emerging global trend [2]. Electricity utilities are experiencing the impact of high penetration of photovoltaic (PV) into distribution grids worldwide [3]. As solar PV penetration levels increases, power output variation of the PV system due to weather changes affects the electricity grid. This creates utility stability issues whereby grid frequency and voltage are affected. Variation in PV system output due to cloud cover calls for proper planning, management and operation of the grid [4]. A high level of PV penetration into the existing electrical grid is greatly affected by PV irradiance variations. Solar energy technology provides power and is only used when there is the availability of the resource. However, a large amount of solar energy is difficult to integrate into the grid because its availability is constantly changing and uncertain. Integration of solar energy resources into the grid ensures reliability at a reduced cost of generation and distribution [5]. It is generally difficult to maintain balance on the grid with large penetration of solar photovoltaics. This is because solar PV output keeps fluctuating and normally falls rapidly during cloudy weather. Additional generating capacity such as hydro must be kept available to provide the spinning reserve especially if solar PV makes up a considerable fraction of the generation mix. Although small amounts of PV power can be added to the grid with few changes, it is important to explore the effect of distributed solar generation on grid stability. This will enable the grid to operate smoothly during the day without stability issues since solar power plants are located in different geographical locations but within reach of the grid.

Grid-connected solar energy in Uganda requires spinning reserves from other generating sources like hydropower to cater for its intermittent nature. However, variability of solar energy due to cloud shading occurs at very short time scales, in order of one second [6] implying that staggering the location of solar PV energy plants in different parts of the country can provide spinning reserves which help in complimenting each other. According to Nwaigwe [7], photovoltaic variability due to cloud cover can be mitigated by dispersing solar farms across a wide geographic region. Power consumers, system operators and utility companies can benefit from the integration of distributed generation into the distribution network. However, degradation of the network performance can happen if critical aspects such as connection points and the capacity of distributed generations are not aptly determined. This could also result in increased voltage fluctuation and power losses [8]. Distributed generation in general and inverter-coupled photovoltaic generators in particular offer different technical features, such as reactive and active power control. Applying these features properly can positively influence the grid voltage as well as the line loading and hence defer or even avoid the need for grid reinforcements [9].

The challenges faced in Uganda are grid management issues such as difficulties in managing frequency and determining reserve margin. These issues are deterrents to increasing the penetration of utility-scale solar generation. The sudden variation in solar generation owing to the passage of clouds could also present challenges to the control of reactive power in the system and the voltage profile. The sharp electricity generation which is increased by solar energy creates a necessity for different studies to analyse the impacts of integrating solar energy on the electricity grid.

The assessment aimed at establishing the extent to which an alternative solar plant would be able to support other intermittent solar generation on the grid. With rising renewable energy sources penetration, grid stability management becomes a priority. Integrating solar into the grid must therefore be approached with uttermost care to prevent grid collapse resulting from voltage or frequency instability. A systematic assessment of the grid conditions under various generation capacities and scenarios is critical to identify any deficiencies and scale the generation source.

2. Literature Review

2.1 Electrical Grid

An interconnected network for delivering electricity from producers to consumers is what is termed an electrical grid [10]. It entails generating stations that produce electrical power, high voltage transmission lines that carry power from distant sources to demand centres, and distribution lines that connect individuals. Electrical grids are designed to supply voltages at largely constant amplitudes [11]. An entire grid must also run at the same frequency. Interconnection to the neighbouring grid operating at a different frequency requires a frequency converter. Interconnection is a group of distribution areas all operating with alternating current frequencies synchronized. This allows transmission of AC power throughout the area connecting a large number of electricity generators and consumers and potentially enabling more efficient electricity markets and redundant generation.

A distributed system is considered large-scale when loading on the system is greater than 10 MW, and systems under this limit do not qualify for power integration and usually have many power quality challenges. However, large-scale systems also experience power quality problems. Solar PV generation does not have the luxury of producing power on demand and hence requires a spinning reserve to cater for the deficit. Power quality issues range from voltage and frequency to other areas such as harmonics. The harmonics problem comes mainly from power inverters used in converting renewably generated DC voltage into AC. Harmonics are created by certain loads that introduce frequencies that are multiples of 50 or 60Hz and can cause equipment to not operate as intended [11].

2.2 Recent Studies on Grid Integration

Recent studies on distributed generation show that the cost reduction of solar energy accessories has impacted significantly grid capacity expansion [12]. Distribution networks allow power to flow in one direction implying that connecting distribution generators into the grid could result in voltage fluctuation, reactive control problems and issues with the coordination of protective devices according to Chu et al. [13]. Power quality, voltage profiles and system stability are significantly affected due to the connection of distributed generation from solar to the grid [14]. Therefore, these distributed generations may perhaps be viewed as geographically localized voltage control points and their continuity must be ensured [15]. The impact on power quality will be determined by the capacity and number of connected distributed generations to the network. Enormous and uncontrolled injection of power from distributed generations could as well harm power quality [16]. Adil [17] evaluated the decentralized transition of energy systems in urban areas, mostly solar PV technology by conducting an inclusive evaluation of socio-technical co-evolution. The article provides an interdisciplinary review of social dynamics and technical co-evolving of decentralized energy systems focusing on distributed generation to ease their integration into urban planning policy. However, operational and actionable steps into practice for planning robust urban energy systems were not done. Celso [18] conducted research and observed that in networks with the presence of excess distributed photovoltaic generation, energy flow reverses at certain times of the day may cause changes in voltage profile. However, the negative effects resulting from the injection of distributed photovoltaic generation should not discourage the increasing adoption of solar energy. Jodan et al. [19] researched an optimal placement and sizing of renewable distributed generation using hybrid metaheuristic algorithm. He noted that integrating the power system with solar energy resources was a big task for balancing power demand. His article improved voltage stability through the introduction of a modified particle swarm optimization algorithm for optimal distributed generation positioning and sizing. Also, Vadi et al. [20] used particle swarm optimization algorithm to reduce distortion in dynamic response of the converter.

2.3 Inverters

The conversion of DC input voltage to asymmetric AC output voltage of desired magnitude and frequency is done by an inverter [21]. Inverters are classified into line-commutated and self-commutated inverters. The line-commutated inverter (LCI) depends on the grid parameters that dictate the commutation process. In addition, it requires some additional circuitry to turn off the switching devices. On the other hand, the self-commutated inverter (SCI) is a fully controlled device. Since the SCI is controllable, it can control both the current as well as voltage waveform at the output side of the inverter. Furthermore, it is well recommended for the grid-connected PV system as it is highly robust to grid disturbances, able to suppress current harmonics and therefore able to improve the grid power quality [22].

A study by Wenham [23] showed that energy created by solar array powers the loads directly resulting in net metering. Due to this interaction with the grid, inverters are required to have anti-islanding protection, meaning they must automatically stop power flow when the grid goes down. According to Hoke [24], there are advanced inverters devices that convert DC solar power into alternating current power for the grid and have features that could help control voltage and make the grid more stable.

2.4 Line Filter and Coupling Transfer

Line Filter and Coupling Transformer Power electronic circuits such as DC-DC converters or an inverter produce high-order harmonics that flow into the grid thus creating harmonic pollution that affects the power quality of the grid [25]. Passive and active harmonic power filters (APF) are used to reduce voltage distortion, and current harmonics and can act as a reactive power compensation in distributed generation systems [26]. A passive filter contains elements such as a resistor, capacitor, and inductor connected in several arrangements which respond to a frequency range of 100 Hz to 300 MHz.

2.5 Grid Synchronization

The grid-connected PV generation system has received extensive attention as more researchers focus on integrated and smart-grid distribution power systems. The implementation of these systems requires deep understanding, critical evaluation and detailed analysis in case of normal and abnormal operations. To synchronous single-phase or three-phase inverter systems to the grid distribution network, four vital conditions must be met as tabulated in Table 1.

Table 1. Grid synchronization parameters [27]

Parameters	Description
Phase sequence	The phase sequence or phase rotation of the three-phase inverter must be matching as phase sequence of the three phases of the grid
Voltage magnitude	The magnitude of the sinusoidal voltage of the grid must be equivalent to the magnitude of the sinusoidal voltage of the grid
Frequency	The frequency of the sinusoidal voltage produced by the inverter must be equal to the frequency of the sinusoidal voltage of the grid
Phase angle	The phase angle between the sinusoidal voltage produced by the inverter and the sinusoidal voltage generated by the grid must be zero.

The synchronization must occur in the first place before connecting the PV system to the grid. The main purpose of grid synchronization is to allow and automatically take the control action to prevent the abnormalities of parameters between the PV system, and the grid. Variables such as phase sequence, voltage magnitude, frequency, and phase angle should be continuously monitored within the permissible limits to guarantee a safe and effective synchronization operation of PV power converters connected to the grid [28]. A synchronization control algorithm must be able to cope with the disturbances of grid parameters such as voltage, frequency, and phase angle.

2.6 Islanding Detection Methods

Apart from the grid synchronization mechanism, a protection scheme against islanding is another crucial issue in the grid-connected PV generation system. The Electrical and Electronics Engineers (IEEE) standards defined islanding as the condition in which a portion of an area of the electric power system (EPS) is energized solely by one or more local EPS through the associated point of common coupling while that portion of the area EPS is electrically isolated from the rest of the area EPS. Generally, there are two types of islanding circumstances which are intentional and unintentional cases. The unintentional islands pose more tangible risks with high possibilities of damaging the electrical device due to the asynchronous re-closure, potential fire hazards to the personnel on-duty and safety issues [24].

2.7 Grid Stability

Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact. The three main categories of power system stability are rotor angle, voltage and frequency stabilities. Voltage stability is the ability of the power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance [29]. Rotor angle stability is defined as the ability of a synchronous machine of an interconnected power system to remain in synchronism after being subjected to a disturbance. It depends on the ability to equilibrium between electromagnetic torque and mechanical torque of each synchronous machine in the system.

a) Voltage Stability assessment: Voltage stability refers to the ability of an electrical grid to maintain synchronism under steady-state conditions and after being subjected to a contingency. Voltage stability problems appear mainly when energy demand is higher than the capacity of the network. Voltage instability is manifested by a slight voltage decrease or increase in different buses until the critical point is almost reached when the voltage drops fast. Some of the problems that have to be considered in the context of intermittent energy integration into the electricity grids are the precariousness of both solar and wind energy and the behaviour of wind and solar farms in case of a fault in the electricity grids and their influence on voltage stability. The P-V curves are a very important tool in determining voltage stability because with their help we can find out the stability limit.

b) Frequency stability assessment: Frequency stability refers to the ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load. It can be deduced from the frequency that settling time and the maximum overshoot are proportional to the values of the inertia constant. The higher the values of the inertia constant, the higher the settling time and of course the maximum overshoot of the frequency.

2.8 Solar Distribution in Uganda

Among the renewable energy sources, solar photovoltaic is the viable option due to its potential and availability in most parts of the country (see Fig. 1). It's because of this abundance that the government of Uganda expanded rapidly the application scale and scope of the PV power generation system [30].

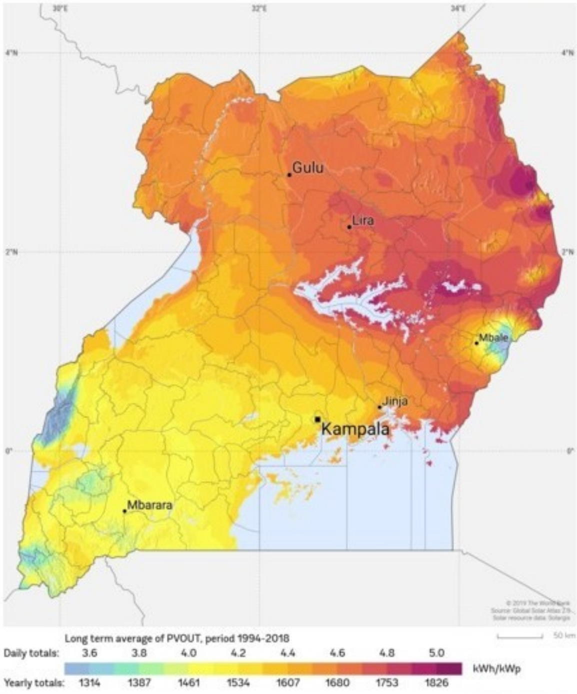

Fig. 1. Solar irradiance distribution in Uganda

3. Methodology

A first step requires a careful component design to support intermittent daily interruption resulting from both weather and cloud cover whilst the second step involves sizing the generation plant to fit within current grid limitations. The next step discusses the selection of appropriate generation sites for a solar plant. The sizing of solar components then follows to allow for the generation of high-quality power suitable for grid integration. A final discussion details how the current grid was modelled to accommodate distributed solar generation via different scenarios using Simulink.

3.1 Solar Component Design

A typical workflow recommended by the Institute of Electrical and Electronics Engineers (IEEE 1547) and the International Electro-technical Commission (IEC 61,727) was followed for component selection and design of the solar facility [31]. Components were sized for a minimum generation solar farm of 10MW directly in line with the grid integration standards defined in the grid code. Based on the base generation requirement of 10MW, different components were selected and power quality simulated. As required by the IEC (61, 727) the following design procedures were considered for the 10MW solar plant.

The module used in the design consisted of polycrystalline cells connected in series. The advantage of using Polycrystalline cell modules is that they have better efficiency with less variation amidst hotter temperatures like those in Uganda. A highly transparent glass sheet was used on the front side of the PV module. This transparent glass was characterised by a significant resistance against mechanical shocks. The structural support of the module was formed by a frame of anodized aluminium (covered by a layer of protective oxide). Each module contained a by-pass diode which eliminates the hot-spot phenomena that can damage PV cells [32]. The diodes are flexible, especially during cloudy periods and this prevents undesired heating. Modules of PV cell data are available from manufacturers like Sharp, Mitsubishi, Suntech, Sanyo, LDK, and BP Solar. In this study, SunPower SPR-315E-WHT-D modules, with 315W maximum power were selected because they matched those already installed in Uganda. The technical specifications for one module are given in Table 2. To determine the number of series connected modules per string and parallel strings, DC-DC boost converter input voltage value and inverter power were required. The rated Dc input voltage for the boost converter was determined by halving the output voltage, i.e., the Dc link voltage. The number of PV modules connected in series was estimated considering the output voltage of the strings of series connected PV modules which is the sum of component modules, and the minimum Dc link voltage for the inverter. The solar irradiation data is very important in the design of the solar PV system; therefore, the weather data was downloaded from the National Solar Radiation Database (NSRDB).

Table 2. Specification for solar module

Solar panel parameters	Value
Maximum power (W)	315
Voc (v)	64.6
Maximum voltage VMP	54.7
Maximum current IMP	5.76

After setting the number of series connected modules, the number of parallel strings was computed based on the rated power of the inverter. To match the corresponding solar generation, a 1200KW inverter was selected and the characteristics of the inverter are presented in Table 3. A simulation of PV cells using the design parameters of the PV park was done using MATLAB Simulink. SimPowerSystem library was used in Simulink modelling.

Table 3. Inverter specification

Inverter parameter	Value
IGBT Bridge	3 -Level IGBT
Control	Pulse Width Modulation
Efficiency	98%
Output voltage(v)	350
Output power (W)	1250000
Input Voltage (OC)	1000

3.2 Grid Data

Uganda's national grid is broadly divided into two segments: a transmission grid maintained and operated by Uganda Electricity Transmission Limited (UETCL) and a distribution grid concessional to Umeme limited [33]. The transmission grid consists of high voltage lines above 66KV. The high voltage lines are largely used for evacuating power from generation facilities. medium and low voltage lines are operated by Umeme limited. The grid network for this study was obtained from UETCL [34] and Load data from Umeme [35] while associated generation sources were obtained from the Ministry of Energy and Mineral Development (MEMD) web portal [36].

3.3 Network

The Network considered for this study was the Eastern grid network shown in Fig. 2. The Network starts from the 250 MW Bujagali hydropower station through to the export substation in Tororo with a T-off in Iganga. From Tororo, the Network runs directly to Lira through the Opuyo substation. At Opuyo the line extends to Mbale to the recently commissioned mobile substation. The Eastern Ugandan grid was considered because it's critical that the solar generation facility be located in a region with a lower reactive load demand as solar can only generate a limited amount of reactive power. It can be observed that the current locations of the current solar generation plants are in the eastern part of Bujagali. The Eastern part of the Bujagali grid satisfies the load characteristics when compared with the industrialised central region. For these reasons, the solar generation for this study was located in the Eastern part of the national grid between Opuyo and Lira and at Mbale (see Fig. 3). The locations received required reactive power support from the Bujagali hydropower station.

3.4 Generation sources

Details of the Generation sources along the Grid were obtained from MEMD portal [36]. A summary of the generation source on the grid together with their associated plant factors are presented in Table 4. Generations of plants were each modelled using Simulink to match the required output.

Table 4. Current generation on the selected grid segment

Plant	Type	Rated capacity (MW)	Plant factor
Bujagali	Hydro	250	0.90
Mayuge	Solar	10	0.71
Tororo	Solar	10	0.70
Soroti	Solar	10	0.71

3.5 Load Data

Data regarding the current loads and predicted loads were obtained from the current Umeme Network diagram. The load was further counter-checked with data from the Uganda Investment Authority regarding the planned industrial park loads. The projected industrial loads for the grid segment include a planned industrial park in Lira, Soroti and Mbale (see their location on the eastern part of the grid in Fig. 2). The grid was designed to support power demand for the industrial loads in addition to the domestic loads.

3.6 Grid Calibration

The grid was calibrated via two pathways, first, a normal power flow analysis for alternating current of the grid without internment generation was performed using powersim studio 10 tools. The power flow analysis results were compared to existing generation data from the different plants. Existing solar plant data were then gradually added while ensuring the grid sustains all the generation and load while staying within the grid stability limits (balance in production and consumption within the electrical grid and able to respond to volatility in voltage and frequency limit of 50±0.05 Hz). A stable grid was then used to formulate scenarios for additional distributed solar generation.

3.7 Distributed Generation

Distributed generation was assessed to establish to what extent it would improve the integration capacity of the grid. The assessment aimed at establishing the extents to which an alternative solar plant would be able to support other intermittent generation on the grid. Under distributed grid, other generation possibilities like synchronization and asynchronous variations with no battery storage and one plant having a constant 10 MW while the second plant capacity varied were evaluated. A summary of scenarios is presented in Table 5.

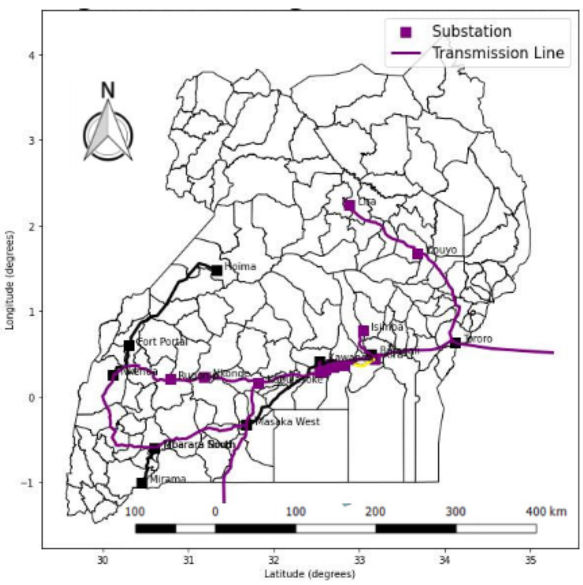

Fig. 2. Current Uganda transmission grid

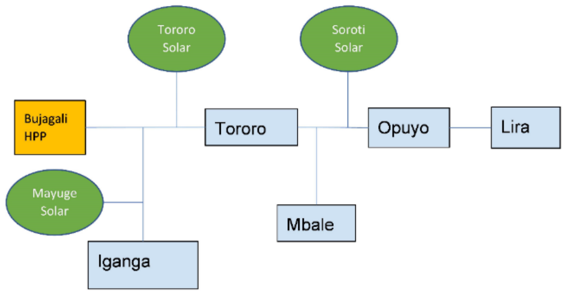

Fig. 3. Grid Layout with current generation sources

Table 5. Distribute grid scenario Matrix

Scenario name	Plant 1 (MW)	Plant 2 (MW)
A	10	10
B	10	20
C	10	60
d (Synchronized)	10	60

3.8 Grid Monitored Parameters

Across all the scenarios, the main grid performance parameters were checked for consistency at selected buses. In all cases, the grid voltage, grid current, real power, grid frequency and reactive power were monitored for the generation scenarios.

4. Results and Discussions

4.1 Output from the Solar Modules

The solar modules were sized and the output components summarized in Table 6. The solar grid layout is shown in Fig. 4. AC power quality was checked for integration into the grid. The output current and voltage to the grid are shown in Fig. 5. Since voltage and current have both phase and magnitude, a plot of the phase and voltage shows an overall smooth sine wave and meant that a unity power factor was obtained. Also, the MPPT used directly tracks the maximum power point as can be seen in the duty cycle (see Fig. 6).

Table 6. Summary of Computed Parameters for 10MW solar Plant

Parameters	Ratings
Power Requirement (MW)	10
Output Voltage (V)	350
Number of Inverters	8
Grid Frequency (Hz)	50
Grid voltage (V)	132,000
Panel Type	SunPower SPR-315E-WHT-D
Number of series Components	10
Number of Parallel Components	392

Boost type	Skiip 3614GB17E4-6DUW v2, Air cooled
Boost Capacitor	4.00 exp-04
Boost Inductor	5.46 exp-05
IGBT	Skiip 3614GB17E4-6DUW v2
Inverter Type	Skiip 3614GB17E4-6DUW v2, Air cooled
Switching Frequency (Hz)	15000
PWM coil Inductance	4.31 exp-05

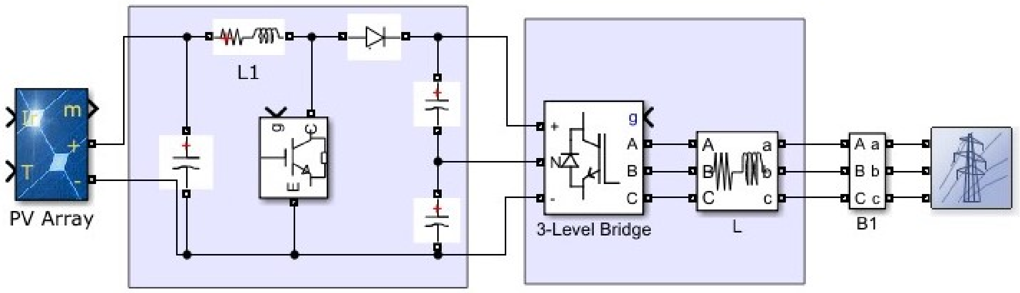

Fig. 4. Solar-Grid system Layout in Simulink

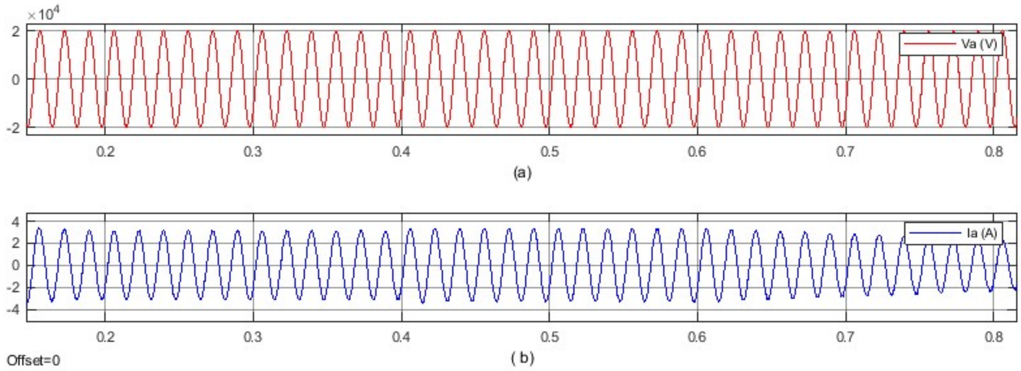

Fig. 5. Voltage (a) and Current (b) output from the designed Module to the Grid

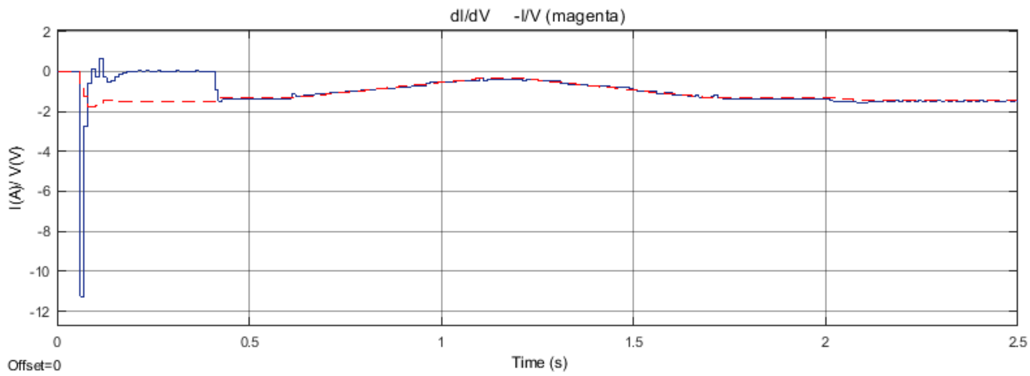

Fig. 6. MPPT control output for the solar module

The energy output of a solar PV plant is defined by Maximum Power Point Tracking (MPPT) which is an essential characteristic. Temperature and radiation intensity at which the module operates are the parameters that affect the power characteristic curve of a PV module [8]. These parameters also affect the voltage and current output of the PV modules. To generate maximum power from the module in presence of these variations, converters with algorithms for tracking the maximum power point were used [37].

4.2 Discussion of Distributed Generation Scenarios

Distributed generation was evaluated for grid integration and the results are presented in Fig. 8 to Fig. 11. Figure. 7 shows a schematic of the grid layout for distributed generation. One solar plant had a constant 10MW supply to the grid while the second solar power was varied. Other generation possibilities like synchronization and asynchronous variations with no battery storage were evaluated. In the asynchronous casen (scenarios a, b & c), the solar generation sites were operated independently while in the synchronous case (scenario d) a regulator was used to detect generation at the different buses and counter the generation deficiencies.

For the scenarios of asynchronous generation, the grid behaved in the same way as though the generation was lumped at one location. This was largely because grid support in terms of reactive power still came from the base hydro-power generation. Fig. 8 (a) shows that the ratio of power generation to loading on the grid decrease with increased generation of solar plants. However, the reactive power available (Fig. 8 (b)) for grid power reduces to 15 MVARs from the base hydropower plant. The overall grid voltage (Fig. 8 (c)) stays stable with no raise above 5% of the nominal grid value. Current injection (Fig. 8 (d)) into the grid also showed variation based on the grid power demand and voltage. The grid frequency shown in Fig. 9 was more turbulent with higher fluctuations during solar generation peak hours even though no frequency violation at the monitored buses was observed. From the results observed, the grid is stable and can sufficiently accommodate a solar generation of a combined 20MW at sites between Opuyo and Lira. According to Johnson et al. [38], overall grid stability can be affected by high penetrations of non-synchronous solar energy generation. This is because national inertia is not provided in the same way as traditional synchronously connected generators. Solar generation was increased to 20MW at plant 2 while maintaining plant 1 at 10MW for scenario b and observations were made for Real power, reactive power, grid Voltage and grid current. The generation was directly matched to the load for real power. It was observed that the reactive power reduced to 11Mvars representing a 4Mvars reduction from the previous reactive generation. The reduction was due to the added intermittent generation requiring more reactive power for grid support. The grid voltage is stable with no increase greater than 5% at any one of the buses. The grid frequency (Fig. 10) showed few shocks resulting from the variations in a generation. The changes in the frequency were small to cause any significant instability in grid generation. For scenario c, the status of the grid in terms of real power, reactive power, grid voltage, grid current and grid frequency did not deviate from the normal. As in previous scenarios, a drop in reactive power was observed. The grid frequency was also more turbulent with higher fluctuations during solar generation peak hours even though no frequency violation at the monitored buses.

A special case evaluated was the synchronous generation (scenario d) with two sites communicating the deficiencies and supporting each other. Fig. 10 showed that the reactive power would still be available to support the grid even for the 60 MW of solar at one of the sites. According to Benjamin [39], voltage increase along the power lines is caused by the provision of active power. To counteract the voltage increase, additional provision of reactive power is required to raise the hosting capacity of the respective grid areas. There exists the possibility of integrating solar generation into the grid without losing grid stability. The grid was stable even for the generation of solar energy above 60 MW at one of the plants. It appears as though each generation source acted as a reserve to the other and so behaved like battery generation. The grid frequency (Fig. 11 (b)) was more turbulent with higher fluctuations during solar generation peak hours even though no frequency violation at the monitored buses was observed. It is important to characterize the short-term variability of generated solar power for grid integration, as frequency can help in quantifying insights on temporal averaging effects on the highest observed peaks and ramp rates, which closely relate to grid stability [40]. The most optimum design, in this case, would include battery storage at one solar plant 1 to serve as a base reserve to support all the other distributed generations.

5. Conclusion

Two main sub-scenarios were evaluated. A sub scenario that looked at asynchronous grid generation and a sub scenario that looked at synchronous generation. For an asynchronous distributed generation, the grid behaved in the same way as though the generation was lumped up in one location. The reactive power support was still coming from the base hydro-generation plant. For synchronized distributed generation (60 MW and 10 MW of solar), reactive power was still available on the grid. Synchronization was used to integrate solar plants into the grid without requiring any further grid support. However, precise measurement, communication and actuation are required to achieve the support.

In the case of synchronous generation, more than one site 60MW plus 10MW at a secondary reserve site can be added. However, in this option, a deliberate investment must be made in a control system to support site synchronization. Using a base solar generation plant with battery storage would further enhance the performance of the generation plant. Precise controllers are needed to send a real-time generation to alternate locations so that the reserves could be ramped up to restore stability.

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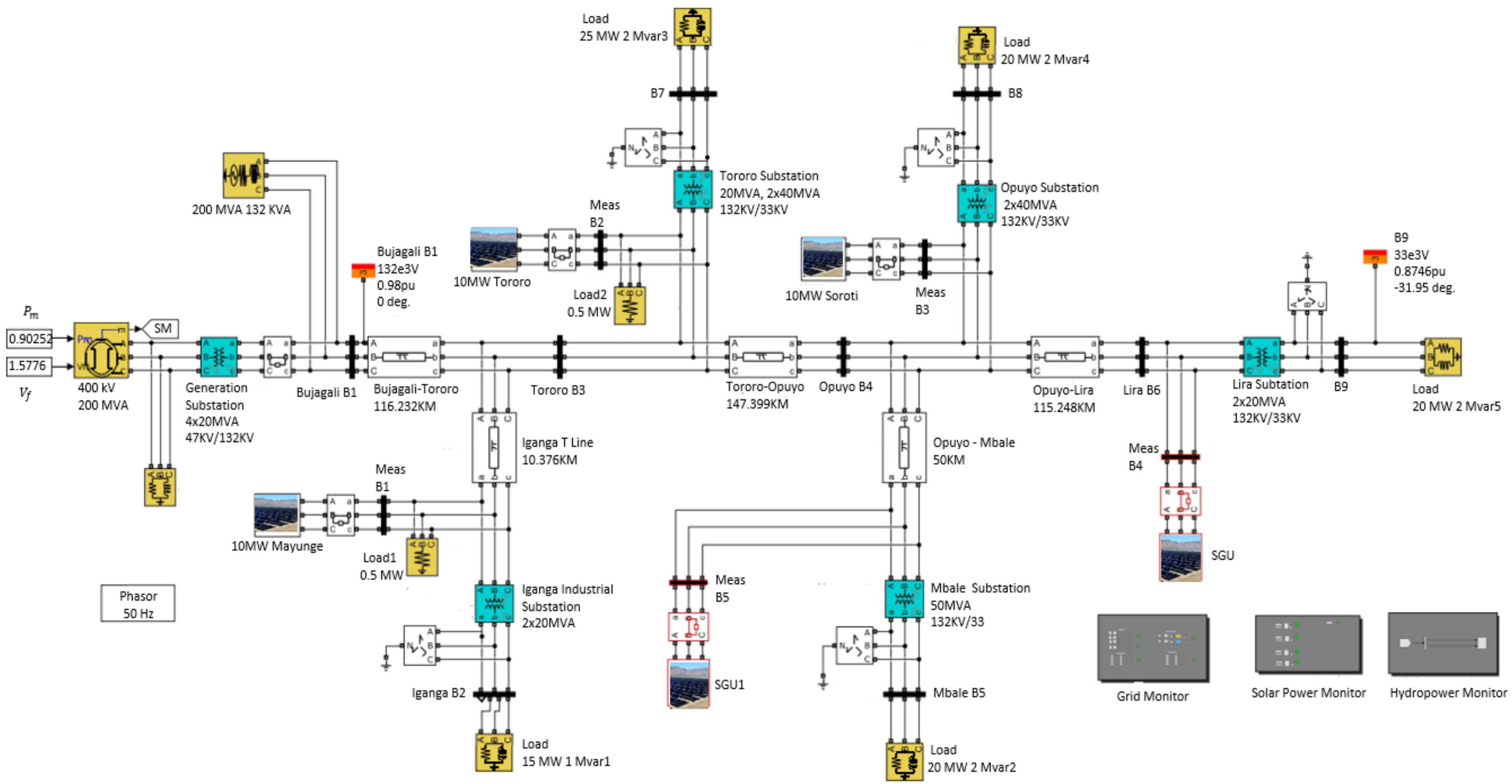

Fig. 7. Grid integrated with solar via a distributed network

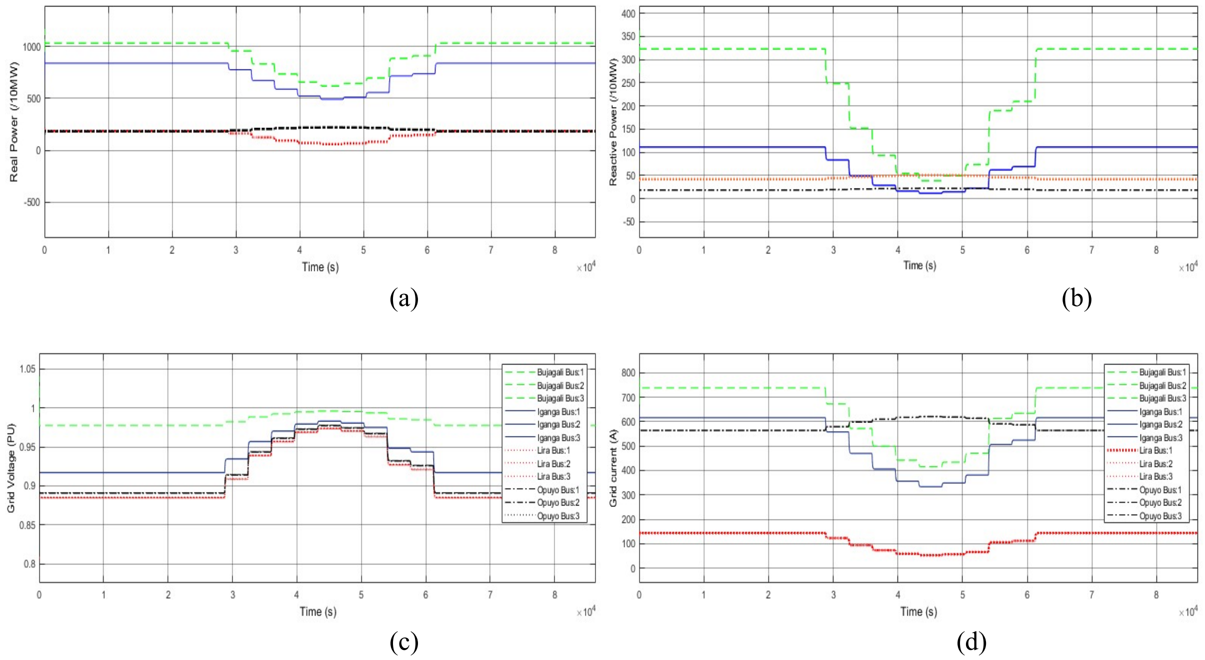

Fig. 8. Solar plants with 10MW, 10MW; (a) Real power, (b) Reactive power (c) Grid voltages (d) Grid current

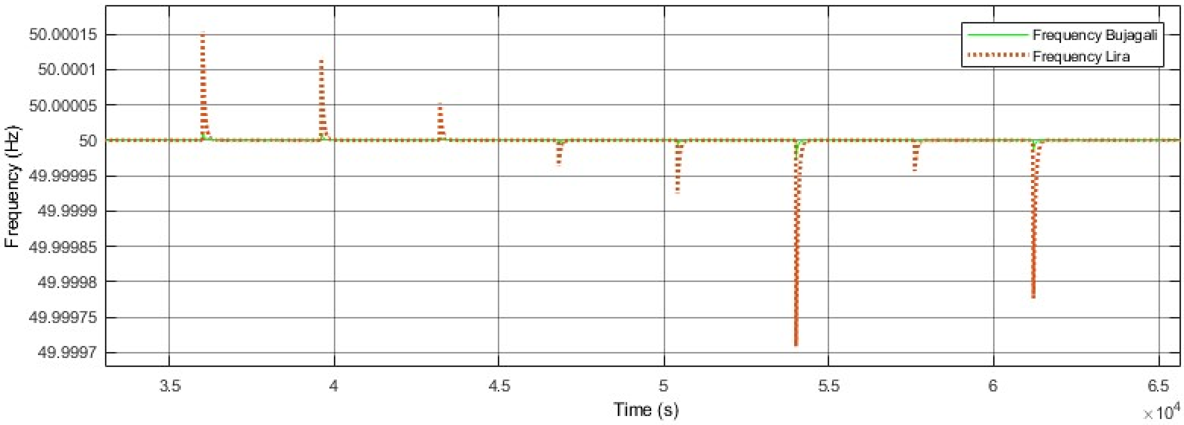

Fig. 9. Distributed generation with (10MW, 10MW of solar); Grid Frequency

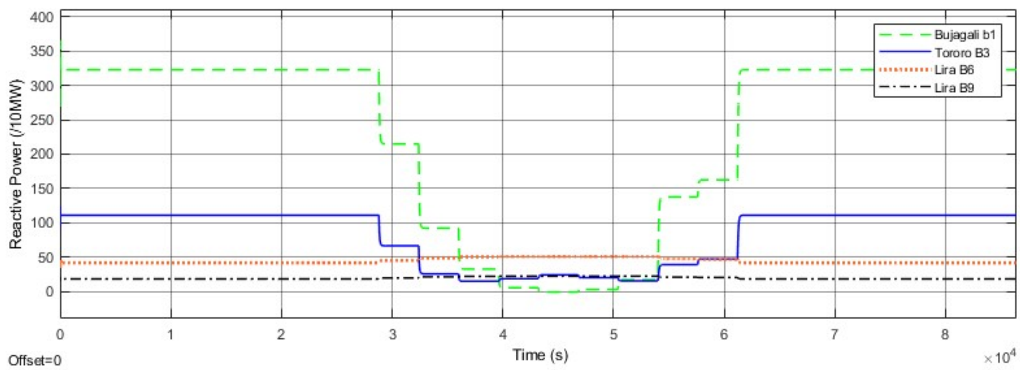

Fig. 10. Reactive power for synchronized distributed generation with 10MW, 60MW of solar

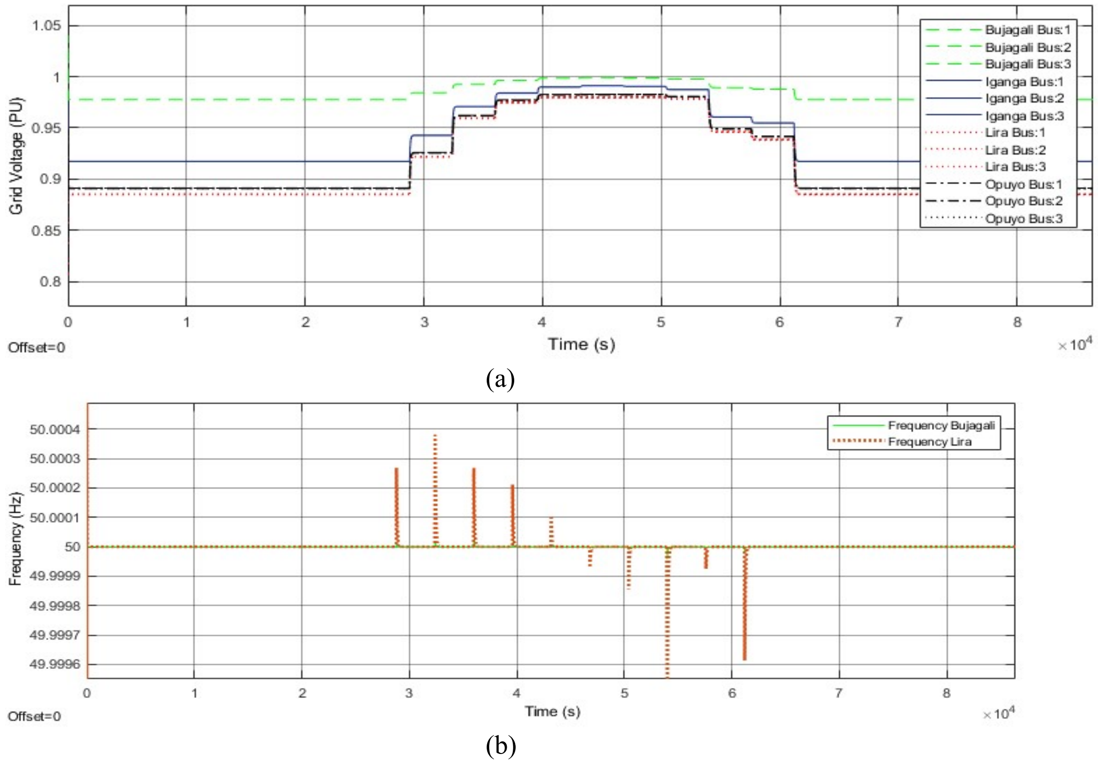

Fig 11. Distributed generation with 10MW, 60MW with Synchronization; (a) Grid voltages, (b) Grid frequency

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