Rural Off-grid Hybrid Wind/Hydro Renewable Power Generation for Rapid Development in Africa

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***Abstract*:** Many rural communities in Africa located far away from transmission corridors do not enjoy electricity supply and cannot hope to be connected to their national grids in the foreseeable future. However, many among such communities have small hydro potential and moderate wind resources. In this paper, an off-grid, hybrid, wind-hydro power generation model is proposed for such communities. Candidate sites for this model would possess small hydro capacity of up to 500 kW and annual mean wind speed of 7 – 10 m/s at 10 m hub height. The operation of an existing small, run-of-river hydro station in conjunction with a hypothetical, in-situ wind farm feeding loads typical of rural areas was simulated to demonstrate the feasibility of the scheme. Simulation results for the system operation were found to be satisfactory. Further, it was demonstrated that, in spite of being an off-grid scheme, the wind turbine generators, aided by the STATCOM are capable of Low Voltage Ride Through in the event of a severe three-phase fault on a major feeder in accordance with grid code requirements. It is anticipated that, with the provision of subsidy by government and/or development agencies, implementation of this model will translate into rapid economic and social transformation of numerous rural areas across Africa.

Keywords: Off-grid; hybrid; renewable power generation; rural development; STATCOM; sinusoidal pulse-width modulation; EMTP-ATP; low voltage ride through

Introduction

Electricity supply is an indispensable requirement for economic growth and development of all nations. Traditionally, electricity has been generated at large thermal and hydroelectric stations and transmitted on extra high voltage grids over very long distances before being distributed to consumers. The consumers are usually residents of big urban settlements and industrial centres.

Many rural communities have not benefitted from grid-based power supply because utilities have found it uneconomical to extend facilities to areas far removed from the transmission corridors. Meanwhile, great impetus has been given globally to power generation from renewable sources such as wind, solar, mini-hydro and biomass, with some countries targeting the attainment of up to 40 % of demand from renewables only (Renewable UK, 2012; Smith & Pasrsons, 2011; Ibrahim et al, 2010). Remarkably however, almost the entire power output from renewable sources are still being fed into the various national grids. That has led to the development of a number of national grid code requirements for wind turbines (The RSA Grid Code Secretariat; Research Institute for Danish Electric Utilities (DEFU), 1998; ELECTRA Transmission Planning, 2000). Where available, isolated renewable generating stations operate in single-modes only with the exception of a few, e.g. the wind power plant backed up by diesel generators described in (Carillo et al, 2004). Such single-mode, stand-alone power stations have been unable to meet local energy demands completely. On the other hand, for most of the studies on hybrid wind/hydro generation reported in the literature, pumped-storage hydro schemes are predominant (Taylor; Bakos, 2002; Papaefthimiou et al, 2009). One notable exception is (Jaramillo et al, 2004) in which the authors describe a theoretical framework in which two hypothetical facilities in Mexico - a wind farm located in the "LaVente" area and a hydro plant located in the "Presidente Benito Juarez" dam - would operate together to produce up to 20 MW of firm power in real time. That scheme was also intended for connection to the regional electricity distribution network. Thus, the needs of rural communities outside grid networks for reliable power supply still remain unmet.

The objective of this study is to look into the operation of off-grid *hybrid* renewable power generation with a view to establishing the means for a more reliable power supply for rural areas in Africa. In particular, the study will focus on the operation of an existing 150 kW, run-of-river hydro power plant (the Waya Dam Project in Nigeria) in conjunction with a hypothetical, in situ 150 kW wind farm in order to develop a model or template for the establishment of similar hybrid schemes at suitable sites around Africa. Data on the Waya Dam Project were obtained from (Mu'Azu) except for electrical data which were obtained from design of an equivalent generator. The electrical (machine) data are as shown below.

Section 1 contains the introduction and a statement of the problem. In section 2, the proposed system operation diagram is described and relevant equivalent circuits and the method of self-excitation derived. Also in section 2, gross estimates of energy capture are determined. Network simulation results are presented in section 3. Low voltage ride through capability of the wind turbine generators with the aid of the STATCOM is dealt with in Section 4 and section 5 contains the conclusions.

- RA -- Armature resistance, pu = 0.0252
- XL --Armature leakage reactance , pu = 0.0675
- XD -- d-axis synchronous reactance, pu = 0.853
- XQ -- q-axis synchronous reactance, pu = 0.512
- XD' -- d-axis transient reactance, pu = 0.3
- XD'' -- d-axis sub-transient reactance pu = 0.0677
- T_d' - d-axis short-circuit transient time constant, s = 1.5
- T_d'' -- d-axis short-circuit sub-transient time constant, s =0.03
- X_0 -- Zero-sequence reactance, pu = 0.15
- Z_n -- Neutral grounding impedance, pu = 0. .
- H -- Inertia constant, s = 4

Excitation Data

- VF , Rated Field Voltage, volts = 40
- IF, Rated Field Current, amps = 62
- RF, Field Winding Resistance, ohms = 0.6

2. System Operation Diagram

Fig 1 shows the system operation diagram (circuit breakers not shown for simplicity). It consists of (a) the two existing 75 kW hydro units which feed into a single 200 kVA, 0.4/33 kV transformer; a 33 kV transmission line, and a 33/0.4 kV distribution transformer, the secondary of which is connected to the main 400 V busbars; and (b) the two 75 kW wind turbine generator units. Each wind turbine unit comprises the wind turbine generator and its step-up 100 kVA, 0.4/11 kV transformer the HV side of which is connected to 11 kV Collector busbars. From the Collector busbars, an 11 kV transmission line conveys the power to a 200 kVA, 11/0.4 kV station transformer, the secondary of which is connected to the main 400 V busbars. At least one hydro unit would be expected to be in service to supply a small base load and be available to provide the required ramping up or down of real power output as dictated by the wind turbine performance, and also to provide start-up (magnetizing) power (as back-up to self-excitation) at cut-in times of the wind turbine. Also shown in the system diagram are 400 V outgoing feeders for typical rural loads: two 51 kVA village feeders for domestic lighting and power; a 9 kVA feeder for farm and irrigation pumps; a 24 kVA sawmill feeder and a 15 kVA quarry feeder.

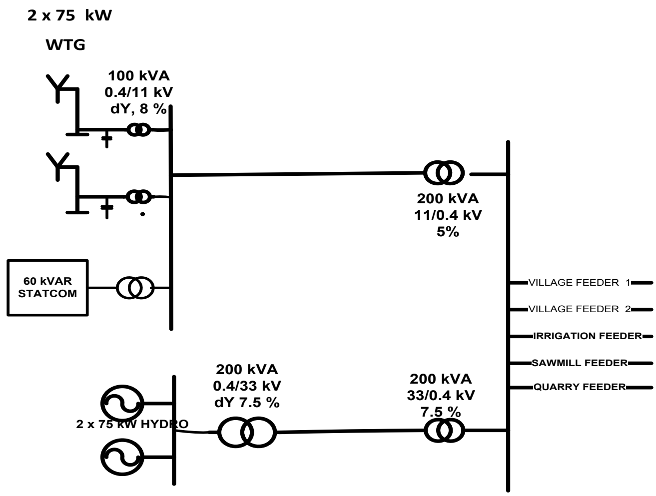

Figure 1 -- System Operation Diagram

A 60 kVAR Synchronous Staic Compensator (STATCOM) – which is a sinusoidal pulse-width modulated voltage source inverter - is connected to the collector busbars via a 100 kVA, 0.4/11 kV, 5 % power transformer for continuous wind turbines' terminal voltage regulation (by supplying reactive power to the induction generators when required) and to provide protection during system faults (low voltage ride-through) as demonstrated below in Section 4. In addition, by increasing the short circuit MVA, it enhances overall system stability (ABB Power Systems; Ronner et al, 2009; CIGRE, 2003; Singh et al, 2004; Mohan et al). The power transformer is also expected to act as a low pass filter for the output of the STATCOM, in addition to its normal role as the inductance between the STATCOM and the collector busbars. The Universal Machine Model was used to represent the wind turbine generator and all simulations of the power system were based on EMTP–ATP (Leuven EMTP Center, 1992).

The hydro plant and water resources

The essential data of the Waya Dam relevant to this study are (Mu'Azu) :

- Storage Capacity : 30 million cubic meters
- Dead Storage : 8 million cubic meters
- Live Storage : 22 million cubic meters
- Ave Potential Head : 12 meters
- Design Discharge : 2.4 m^3 / s
- Potential Power : 200 kW

The wind plant and wind resources

The wind resource at the WAYA dam site (Bauchi) is very poor. The annual mean wind speed is less than 3 m/s.. Such is generally the case throughout Nigeria except for very few sites (Adekoya & Adewale, 1992) . However, in Africa, locations exist with bountiful wind resources , e. g. the Klein Karoo, near Worcester in the Western Cape; the Great Karoo, near the town of Graaf Reinet in the Eastern Cape (Blakeway); and the Wind Atlas of South Africa (WASA) sites in South Africa (see www.wasa.csir.co.za) (CSIR). Candidate sites for the hybrid power plants proposed in this study should have wind resources, at least intermediate between the above two for satisfactory results. A mean wind speed of 7 m/s at 10 m hub height is assumed for the candidate site. The horizontal-axis wind turbine (HAWT) – 30 m in diameter – is employed. It consists of three blades attached to the hub at one end of a horizontal shaft atop a 40 m mast. The configuration of the blades is upwind. At the other end of the shaft, a 75 kW, 400 V, 3-phase, 50 Hz, 4-pole, 1475 RPM squirrel-cage induction motor is installed via a 1:60 gearbox.

No-load, locked-rotor, and stator DC resistance tests of the 3-phase motor were conducted. The no-load characteristics are plotted in Fig. 2. The locked–rotor and stator DC resistance test results are shown in Tables 1 and 2 respectively. No-load self-excitation capacitance was estimated from the plot of no-load terminal voltage versus magnetizing susceptance (Fig 2A) , similar to the methods used in (Say, 2002;Burton et al, 2001; Bassett & Potter, 1935). A capacitance of C = 500 μF was found to be satisfactory (the exact figure from the plot was 573.25 μF). For the full-load case, a capacitance of 3000 μF was found to be adequate.

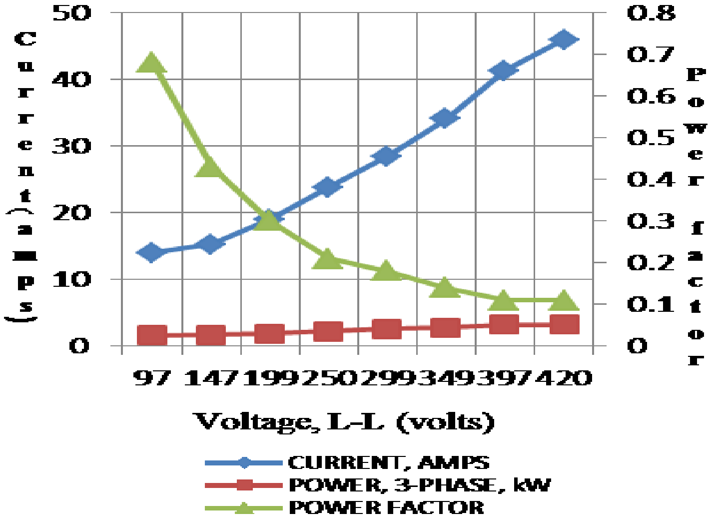

Figure 2 -- No-Load Characteristics of 75 KW Induction Motor

Gross estimates of energy capture

(a) Energy from the hydro plant

The total annual energy obtainable from the hydro plant was estimated by (Mu'Azu) as 1.08 GWh. This figure assumed 300 days of operation in a year.

(b) Energy from the wind -- The wind resource at a candidate site may be modeled by the Weibull probability density function (Burton et al, 2001; Hogg & Tanis, 2010);

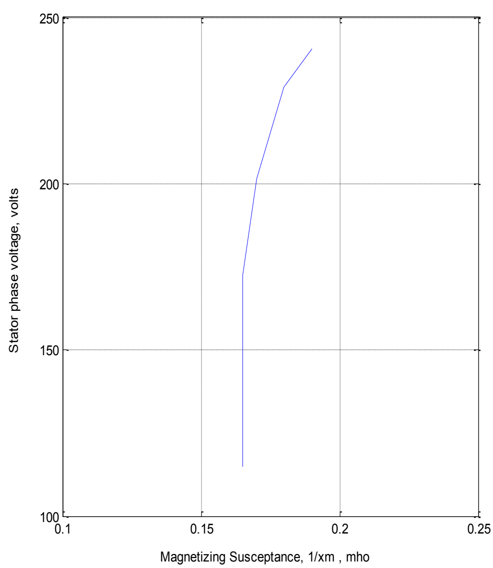

Fig 2a -- Phase Voltage versus Magnetizing Susceptance

$g(u) = \frac{\alpha u^{\alpha-1}}{\beta^{\alpha}} \exp\left(-\left(\frac{u}{\beta}\right)^{\alpha}\right)$, u > 0

where u = the wind speed. The mean wind speed is given by:

$$\mu = \beta\,\Gamma\left(1 + \frac{1}{\alpha}\right)$$

where Γ is the Gamma function. At typical sites, α = 2 is adequate. That corresponds to the Rayleigh distribution. For a mean wind speed of 7 m/s at 10 m hub height, the equivalent at 40 m hub height is (Heier, 1998):

$$u_{40} = u_{10}\left(\frac{h}{h_{10}}\right)^{a},$$

Where: u_h = wind speed at height , h m

a = Hellman Exponent = 0.14 – 0.17

Let a = 0.15, then

$$u_{40} = 7\left(\frac{40}{10}\right)^{0.15} = 8.62 \text{ m/s}$$

Thus 8.62 = β Γ(1.5)

β = 8.62 / 0.88623 = 9.73

thus: g (u) = 0.021 u exp (- 0.01 u^2) , u ≥ 0 (1)

$$P_{aero}(u) = C_p \cdot \frac{1}{2}\rho A u^3 \quad (2)$$

Where $\rho = 1.225\ kg/m^3$ = density of air , and C_p is the power coefficient. The dimensionless $C_p - \lambda$ curve is approximated by two piecewise linear curves (see p. 174 of (Burton et al)) :

$$C_p = 0.18\lambda - 0.45 \ , \ 0 \le \lambda \le 7$$

$$C_p = -0.04375\lambda + 0.74375 \ , \ \lambda > 7$$

Now, $\lambda = \frac{\Omega R}{u}$

For a gearbox ratio of 1:60 and given a slip of -1.7 % , generator constant rotor speed of 1500 x 1.017 = 1525.5 RPM,

Wind Turbine shaft speed = $\frac{1525.5}{60}$ = 25.425 RPM

Therefore, $\Omega = 25.425 \times \frac{2\pi}{60}$ = 2.66 rad/s

The assumed rotor diameter = 30 m. Then R = 15 m implies that tip-speed ratio ,

$\lambda = \frac{2.66 \times 15}{u} = \frac{39.9}{u}$

Thus λ = 7 implies u = 5.7 .

$C_p = \frac{7.182}{u} - 0.45\ ,\ \infty \ge u \ge 5.7$ (3a)

$C_p = -\frac{1.746}{u} + 0.74375\ ,\ u < 5.7$ (3b)

The expected power generation, E (P_{aero}) is:

$$E(P_{aero}) = \int_{u_0}^{u_\infty} P_{aero}(u)g(u)du \quad (4)$$

Therefore, from eqs. (1) to (4), assuming a cut-in wind speed of 3 m/s at 10 m hub-height = 3.69 m at 40 m, and a cut-out wind speed of 15 m/s at 10 m hub height = 18.47 m/s at 40 m , energy captured over one year, T = 8760 hours will be:

$$E = 8760 \int_{3.69}^{18.47} C_p \frac{1.225x\,\pi\,x15^2}{2x1000} u^3 g(u)du$$ kW

$$E = 3793.08 \int_{3.69}^{18.47} C_p u^3 g(u)du \text{ kWh}$$

Applying (3a) and (3b),

$E = E_1 + E_2$ kWh

$$E_1 = 79.655 \int_{5.7}^{18.49} (7.182\,u^3 - 0.45\,u^4)\exp(-0.01u^2)\,du$$

$$E_2 = 79.655 \int_{3.69}^{5.7} (-1.746\,u^3 + 0.74375\,u^4)\exp(-0.01\,u^2)\,du$$

This gives $E_1 = 5.31 \times 10^5$ kWh and $E_2 = 2.56 \times 10^4$ kWh. The total energy per wind turbine is thus $E_1 + E_2$ = 5.57 x 10^5 kWh. The two wind turbines could generate up to 2 x 5.57 x 10^5 kWh = 1.114 GWh.

Table 1-- Locked - Rotor Test

VOLTAGE, L - L, VOLTS	CURRENT, AMPS	POWER, 3 - PHASE, kW	POWER FACTOR
60	109	3.3	0.3

Table 2 - DC Resistance Test (Stator Winding)

WINDING	RESISTANCE (mΩ)
A1 - A2	69.9
B1 - B2	70.1
C1 - C2	69.8
AVERAGE	**69.93**

3. Network Simulation

Figures 3 – 8 below show results of the simulation of the network. As can be observed, the results were very satisfactory except for the minimal distortion of the waveforms due to incomplete filtration by the STATCOM transformer.

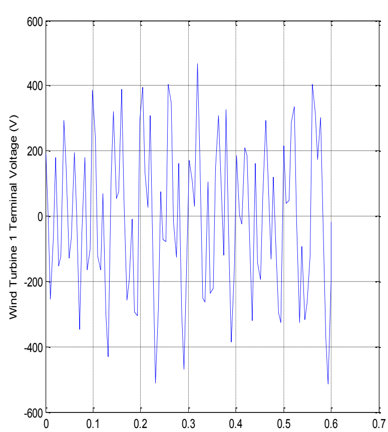

Fig 3 -- Wind Turbine Generator 1 Terminal -- A-phase Voltage, V

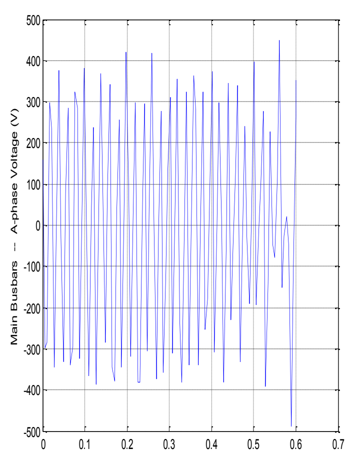

Fig 4 -- Main Busbars - A-phase Voltage, V

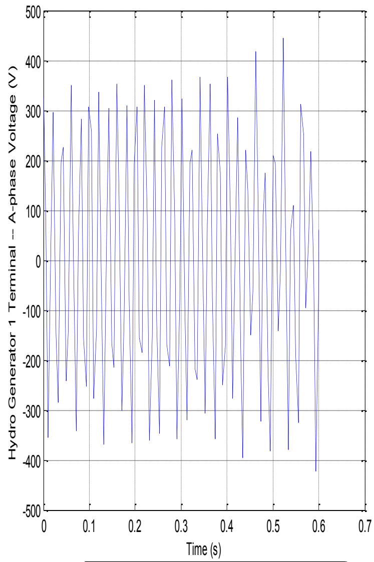

Fig 5 – Hydro Generator 1 Terminal – A-phase Voltage, V

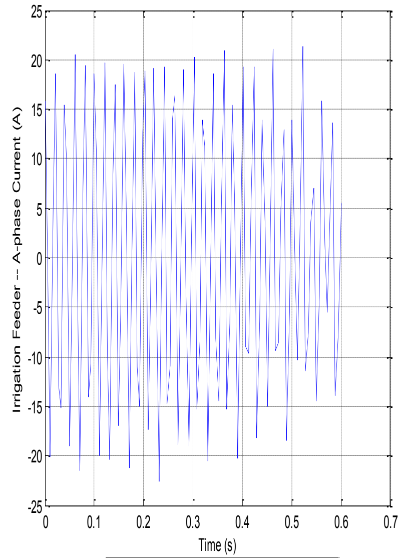

Fig 6 – Irrigation Feeder - A-phase Current, A

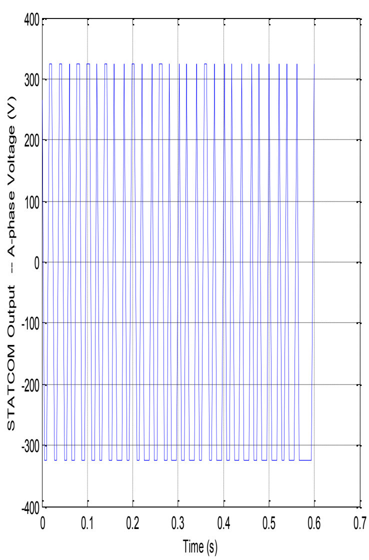

Fig 7 – STATCOM Output – A-phase Voltage, V

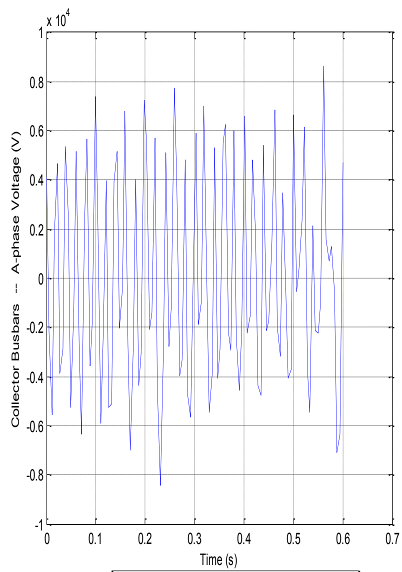

Fig 8 – Collector Busbars – A-phase Voltage, V

4. Low Voltage Ride Through

Even though the system in this study was off-grid, it was considered desirable to determine if the wind turbine generators were capable of low voltage ride through (LVRT) in the event of faults. The South African and the German Grid Codes, (The RSA Grid Code Secretariat; Pannell et al, 2010; Vidal et al, 2013; Pannell et al, 2013) require that wind turbine generators remain connected to the grid for 150 ms following all types of fault resulting in voltage dips down to zero volts. That is to aid system recovery following the clearance of the fault and to provide voltage support (reactive power). As pointed out earlier, the STATCOM enabled the wind turbine generators to successfully ride through the voltage dips in compliance with grid code requirements. Figs 9 to 16 below show simulation results for a three-phase fault – the severest – on one of the village feeders. The fault was applied at t = 1 sec and cleared at t = 1.15 secs. It is clear from the figures that the wind turbine generators remained connected to the network during the fault in compliance with grid-code requirements. However, shaft over speed occurred during the fault but normal speed was restored soon after the fault was cleared.

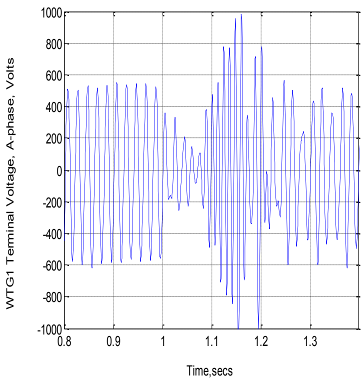

Fig 9 -- LVRT: Wind Turbine Generator 1 Terminal Voltage, Volts

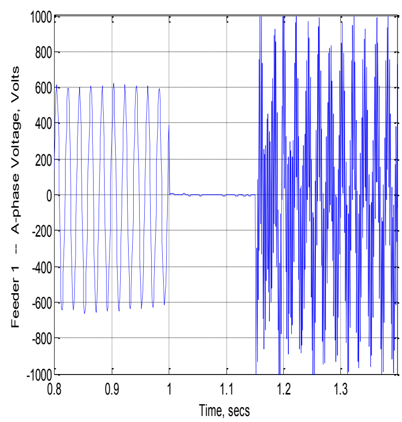

Fig 10 -- LVRT: Village Feeder 1 A-phase Voltage, Volts

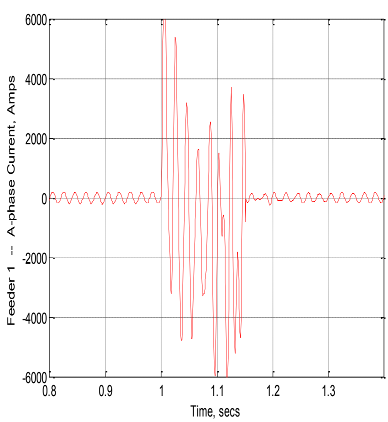

Fig 11 -- LVRT: Village Feeder 1 A-phase Current

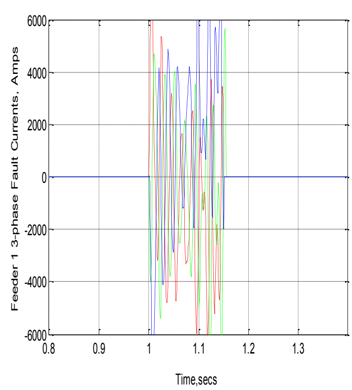

Fig 12 -- LVRT: Village Feeder 1 3-phase Fault Currents

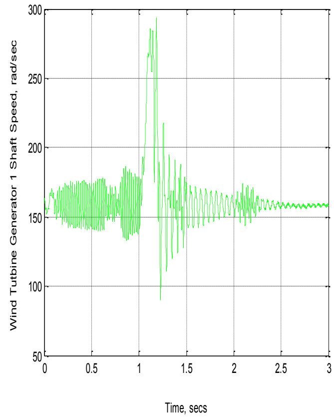

Fig 13 – LVRT: Wind Turbine Generator 1 Shaft Speed

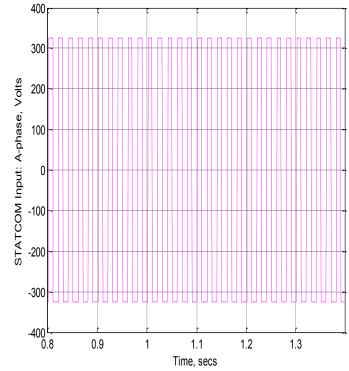

Fig 14 – LVRT: STATCOM Input - A-phase

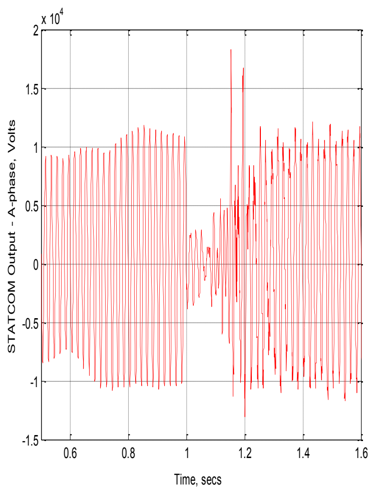

Fig 15 – LVRT: STATCOM Output Voltage - A-phase

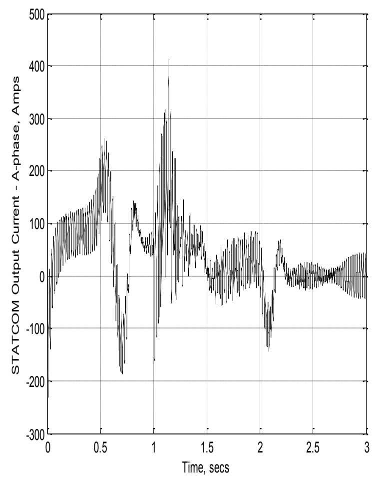

Fig 16 – LVRT: STATCOM Output Current - A-phase

5. Conclusion

Results from this study demonstrate that rural communities in Africa that possess modest wind and hydro resources can benefit immensely from the off-grid hybrid electricity schemes long before they get connected to their national grids. In particular, in spite of the very moderate wind speeds considered, the potential energy production capability at the WAYA dam site can be seen to have doubled and thus more villages could be connected to the supply than hitherto. Furthermore, the wind turbine generators were capable of low voltage ride through as required by grid codes.

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