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# On the Viability Analysis of HVDC Light for Electrification of Mafia Island by National Grid

Sospeter Gabriel[1], Bakari M. M. Mwinyiwiwa[2], Mighanda J. Manyahi[2]
[1(]*Department of Electrical Engineering, Mbeya University of Science and Technology, Tanzania)*
[2(]*Department of Electrical Engineering, College of Engineering and Technology, University of Dar es Salaam Tanzania)*

**Abstract:-** HVDC Light systems range from 3MW to about 1000MW transmission technology combining power converters and DC cables. The power converters are based on Voltage Source Converters (VSC) and Pulse Width Modulation (PWM) control. The use of series connection of power semiconductors such as IGBTs is fundamental to the development of the HVDC Light technology. HVDC Light is excellent for underground and under water power transmission. By use of HVDC Light power converters and cables, it is possible to overcome the technical difficulties to connect small loads and small scale generating units to the AC grid and to make the connection economical and environmentally friendly. This paper presents viability analysis of using HVDC Light technology for electrification of Mafia Ireland (Tanzania) from the national grid. In the paper the load demand forecast has been performed to estimate the load for the next 25 years at Mafia Island. HVDC Light model has been developed and simulated using MATLAB/Simulink software. The simulation results show that HVDC Light system performance is capable of delivering reliable and quality power when the Mafia Island is supplied by national grid using HVDC Light system. The benefits include more reliable power supply reduced environmental effects.

**Keywords:-** VSC HVDC, HVDC Light, Sinusoidal PWM, IGBTs, DC Cable, load forecasting.

## I. INTRODUCTION

Majority of the population in developing countries, such as Tanzania, are living in rural and sub-urban areas where there are no possibilities for grid extension. This does not mean that those population do not need electricity instead they are using different sources of energy such as wood and fossil fuel which are not suitable due environmental reasons and therefore electricity is preferable. Human beings need electricity for sustainable development and poverty reduction. Electricity affects practically all aspects of social and economical development, including livelihoods, water, agriculture, population, health, education, job creation and environment concerns.

Many Islands distanced from the mainland use expensive electrical power generation using small uneconomical fossil fuel driven power generation plants which are also environmentally unfriendly. High voltage direct current based on Voltage Source Converter (VSC) namely HVDC Light can replace polluting, inefficient and expensive local generation power stations with power from main grid networks.

This paper presents viability analysis for electrification of Mafia Island (Tanzania) by national grid using HVDC Light technology. The study involves a long forecasting of load demand and simulation of a developed HVDC model. The power rating of the simulated HVDC Light system model is 18MW, 20MVA. Pulse Width Modulation and d-q control technique has been employed for the VSC employing IGBTs as switching devices. The AC National Grid is very soon expected to reach the mainland onshore village of Nyamisati. The proposed HVDC Light link is from Nyamisati village (Rufiji district) to Kilindoni town which is the headquarter of Mafia Island district. The estimated length of the proposed HVDC Light link is about 45km for connection of the AC National Grid at Nyamisati Village in Rufiji District.

Mafia Island is rich in tourism sites and activities including a long stretch of corals, sport fishing and diving. Figure 1 shows location of Mafia island with respect to Tanzania minland. The Island is on the Indian Ocean covering 435km$^2$ with 49km long, 17km in width.

Currently electricity supply to the Mafia Island is obtained using diesel engine driven generators. The total available generation is far below the total load demand and therefore majority of the population and business centres in the Island do not yet have access to electricity through utility company, Tanzania Electric Supply Company (TANESCO) Limited. Connection of National Grid to Mafia Island through HVDC Light link is anticipated to enhance power supply reliability, expansion of the supply and environmentally friendly as compared to diesel driven generators.


**Fig. 1. The study area - Mafia Island on Indian Ocean – Tanzania**

## II. HVDC LIGHT TECHNOLOGY

HVDC Light is a new type of power transmission and distribution that is based on Voltage Source Converter (VSC) with Pulse Width Modulation (PWM). With HVDC Light, it is economically feasible to connect small-scale plants and renewable power generation plants to the main AC grid. Using the HVDC Light technology, remote locations such as Islands, mining districts and drilling platforms can be supplied with power from the main grid, thereby eliminating the need for inefficient, polluting local generation such as diesel units. HVDC Light technology is also suitable for power transmission using underwater cables which can replace overhead transmission lines at almost no cost penalty.

### 2.1 Voltage Source Converter

The basic Voltage Source Converter *(*VSC) HVDC topology is simply a power converter at each end and a pair of extruded DC transmission cables. VSC is a forced commutated converter that converts AC voltage into DC voltage or vice versa. The VSC has the ability to let bidirectional power flow and can change the power direction almost instantaneously. VSC one of the most important building block in high power applications including HVDC Light systems.

### 2.2 Pulse Width Modulation

Pulse Width Modulation (PWM) is the most widely VSC switching technique used to create a desired signal and in this case sinusoidal waveforms with determined amplitude and frequency. The method employs, in its basic waveforms to generate the driving signals of the converter valves. The first is the reference wave which has the fundamental frequency of the voltage to be generated, and the second is the carrier wave which has a higher frequency that is typically range between 1kHz and 2kHz as shown in figure 2.

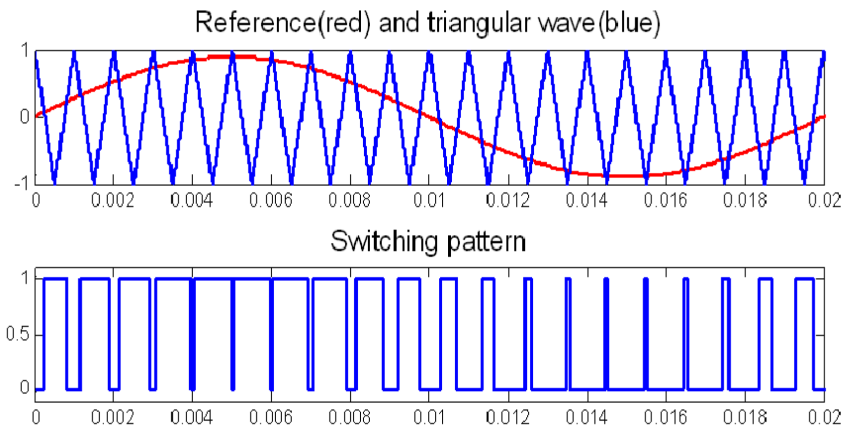


**Fig. 2 Reference and Carrier Waveforms Compared to form PWM Switching Pattern**

There are various modulation methods but they all have two objectives. The first objective is to calculate the on time for switches and the desired fundamental output voltage is obtained. The second objective is to arrange the switching process in order to minimize the harmonic distortion, switching losses and/or other specified criterion. The pulse pattern is generated by the pulse width modulation (PWM) where the reference signal is compared with the triangular carrier waveform signal. This fast control makes it possible to create any phase angle or amplitude which can be done almost instantaneously providing independent control of both active and reactive power.

The converters are using a set of six valves, two each phase equipped with high power transistors, IGBT (Insulated Gate Bipolar Transistor). The IGBTs switch can be switched on or off at will, therefore the output voltages and currents on the AC side can be controlled precisely. IGBTs are connected in series in order to be able to handle higher voltage than the rated voltage of one IGBT. All IGBTs must turn on and off at the same moment to achieve an evenly distributed voltage across the valve.

## 2.3 HVDC Light Cable

The cable used in HVDC Light applications are a new developed type, where the insulation is made of an extruded polymer material that is particularly resistant to DC voltage [1], [2] and they are very strong and robust. HVDC Light cables are buried underground or underwater so there is no visual impact from the power cables and contain no oil. They do not emit fluctuating electric and magnetic fields (EMFs) so there are no human health related issues. The cables are operated in bipolar mode, one cable with positive polarity and another with negative polarity. The cables are installed close in bipolar pairs with anti-parallel currents and thus eliminating the magnetic fields [2] as illustrated in figure 3. These cables are constructed both for submarine (copper) and land (aluminium) applications.

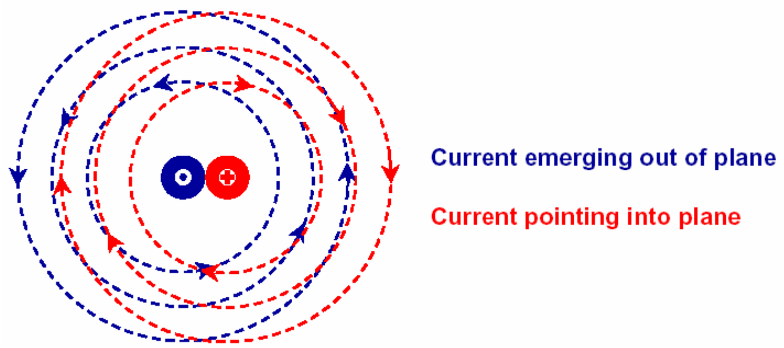


**Fig. 3. Diagram of a bipolar DC cable system**

## 2.4 Operating Principle of Voltage Source Converter

The converter can be brought as an equivalent of AC voltage source where amplitude, phase and frequency can be controlled independently. Thus the VSC Bridge can be regarded as fast controllable synchronous machine whose instantaneous phase voltage û is described by;

$$\hat{u} = \frac{1}{2} U_{dc} m Sin(\omega_e t + \delta) + harmonics \tag{1}$$

Where *m* is the modulation index which is defined as the ratio of peak value of the modulation signal and the peak value of the carrier signal, $\omega_e$ is the fundamental frequency and $\delta$ is the phase shift of the output voltage. Variables *m* and $\delta$ can be adjusted independently to obtain any combination of voltage amplitude and phase shift in relation to the fundamental frequency voltage of the AC system. The voltage drop $\Delta v$ across the phase reactor *X* can be varied to control active and reactive power flows. The active power flow between the converter and the AC system can be controlled by controlling the phase angle between the fundamental frequency voltage generated by the converter and the voltage across the AC-filter.

Taking the voltage at filter bus as a reference and assuming lossless reactor, the power transfer from the converter to the AC system will be

$$P = \frac{|v||U|}{X} Sin(\delta) \tag{2}$$

The reactive power flow is determined by the relative difference in magnitude between the converter and filter voltages. The reactive power flow is calculated as

$$Q = \frac{|v|(|v| - |U|)}{X} Sin(\delta) \tag{3}$$

Figure 4 shows the details of the HVDC Light system in a simplified way which indicates the arrangement of all the basic system components from AC side to DC and then to AC system again. Figure 5 elaborates some more details of the converter station as one of the major component in HVDC Light which is formed by the IGBT valves using StakPak module with a number of chips depending on the level of power.

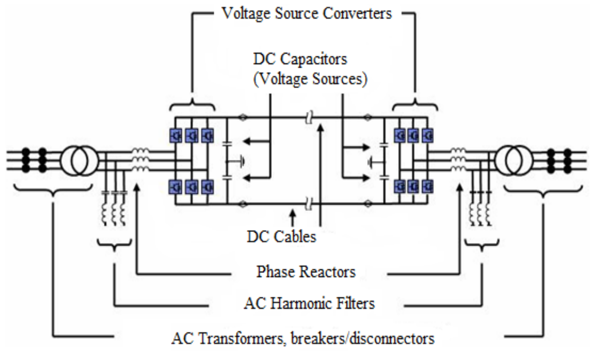


**Fig. 4. Simplified circuit diagram for 2-level VSC-HVDC showing the major components of the system [3]**

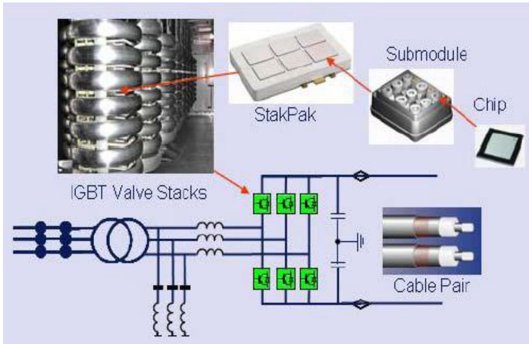


**Fig. 5. HVDC Light IGBT arrangements [4].**

## III. ELECTRIC LOAD FORECASTING

Forecasting means predicting what is going to happen in the future, next day, month, year, decade, etc. In general, the load forecasting is performed by studying the past events so as to be able to predict what the future electricity demand will be. Accurate forecasting requires high quality data, application of the appropriate forecasting technique and knowledge of data interpretation. According to [5], [6] the load forecasting is distinguished on the basis of forecasting periods as short term, medium term and long-term load forecasting.

**Short Term Load Forecasting (STLF):** Short term load forecasting (STLF) starts from few hours to weeks used for scheduling generating capacity and day to day operation and is commonly referred as to hourly load forecast.

**Medium Term Load Forecasting (MTLF):** Medium term load forecasting (MTLF) starts from few months to few years ahead and is used for the purpose of scheduling maintenance and fuel supply.

**Long Term Load Forecasting (LTLF):** Long term load forecasting (LTLF) starts from five (5) to twenty five (25) years is used for system capacity planning and is usually called annual load demand and energy forecast.

### 3.1 Load Forecasting Variables

Load forecasting variables represent the numerous factors that influence growth of electric load demand. In this case the load variables are electrical energy distributed by the supply authority, TANESCO Limited (Mafia Branch), to consumers in kWh, new customer connections trends which indicate the number of new customers connected to the power systems on monthly basis and the maximum apparent power demand in kVA for five years i.e. 2008-2012.

### 3.2 Load forecasting methods

Load forecasting methods are mainly classified into two categories, Statistical or Classical methods and Artificial Neural Network (ANN) based methods or Artificial Intelligence methods. In statistical methods a mathematical equation can be obtained showing the relationship between load and its relative factors after training the historical data, while ANN methods try to imitate human beings way of thinking and reasoning to get knowledge from the past experience and forecast the future load. In this research, statistical methods for load forecasting using historical load data collected is applied. The load forecasting using statistical method is mainly divided into three categories which are trend analysis, end use analysis and econometric analysis. In this paper the trend analysis model is applied using previous collected load data to forecast the future electricity demand for the next twenty five (25) years. The trend analysis focuses on past changes or movements in electricity demand and uses them to predict future changes in electricity demand.

## IV. ANALYSIS AND DISCUSSION OF TRENDS RESULTS

### 4.1 Customer Connection Trends for Mafia Island

The customer connection trends as shown in table 1 in appendices for five years from 2008 to 2012 as outsourced from TANESCO Mafia Island indicates the increase in number of costumers in different rates. In the year 2008 the new consumers connected by TANESCO was 20 costumers where 29 customers were connected in the year 2009, this was the growth increase of 45%. In the year 2010, the growth increase was 97% from that of 2009, while in the year 2011, growth increase was 19% from that of 2010. In the year 2012, growth increase was 103% from that of 2011. Generally this indicates that there has been an increase rate of new customer connection at the average of 66% in the years under this study.

This trend gives a good indicator to show that there is a high demand of electrical power at Mafia Island and this is regardless of insufficient and poor power distribution network system. It is the assumption of this research paper that if there were a reliable power source and good power distribution network at Mafia Island, then the number of new customer connection would have been more than these indicates here.

### 4.2 Power Distribution Trends for Mafia Island.

According to [7] report, the electric power distributed to consumers was approximated 1500MWh per year in 2005. Three year later in the year 2008 the electric power consumed was more than 2060MWh; this was an increase of 37%. In the year 2012 five years from 2008 the electric power consumed was 4039MWh; this was an increase of 96% for that period under study. The trend line analysis has been applied to indentify the existing trends for electric power supplied to consumer for five years as indicated in figure 6. The mathematical formula presented is used to derive an estimate of electric load for the next twenty five (25) years.

### 4.3 Fuel Consumption Trends at Mafia Island TANESCO Power Plant

Electric power generation at Mafia Island is performed using two diesel generators rated at 525kVA each. Fuel consumption has been increasing from one year to another regardless of the difficulties in its transportation to Mafia Island which leads for sometimes shutdown of the power plant. In the year 2008, fuel consumption was 680,992 litres and in five year later in 2012, the fuel consumption was 1,255,132 litres, which is 84.3% increase.

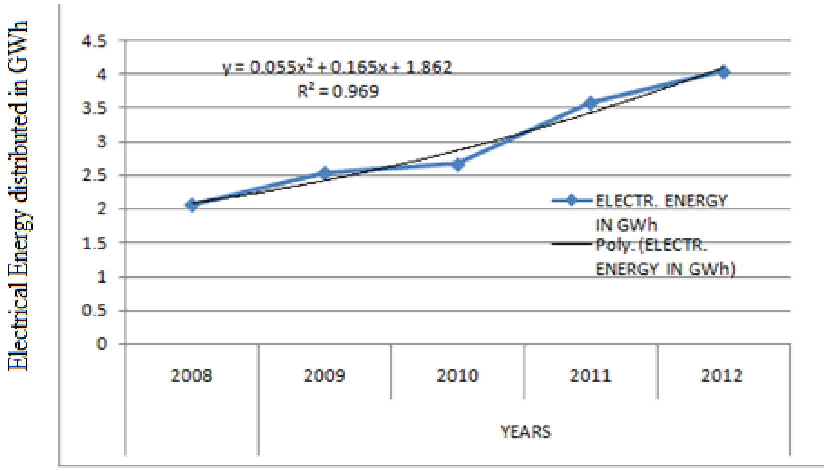


**Fig.6 Trend Analysis for the Electric Energy Distributed to Consumers.**

### 4.4 Lubricants Consumption Trends at Mafia Island TANESCO Power Plant

Lubricants are one among the major components which contributes to the electricity generation cost. They are used to maintain smooth running of the mechanical parts of the electric generator systems. In the year 2008 the lubricants consumption was 9,050 litres while in 2012 the lubricant consumption was 11,080 litres, this was an increase of 22.4% for the years under study.

### 4.5 Maximum Demand Trends at Mafia Island

The maximum demand is the greatest demand of load on the power station during a given period. Maximum demand is generally less than the connected load because all consumers do not switch on their connected load to the system simultaneously. In the year 2008 the average maximum demand was 518.33kVA, while in 2012 the average maximum demand was 839.17kVA, this was an increase of about 62%. The trend line analysis has been applied to indentify the existing trends for maximum power demand for five years as indicated in figure 7. The mathematical formula presented is used to derive an estimate of electric load for the next twenty five (25) years.

### 4.6 Load Forecasting at Mafia Island

The full extended demand forecast is presented in figure 8 for electric energy to be supplied to consumers and figure 9 for maximum demand forecast as extended from equations indicated in figure 6 and 7 respectively. The load forecasting distributed and their respective percentage increase for both maximum power demand and electric power to be twenty five (25) years is as shown in table 2 in the appendices.

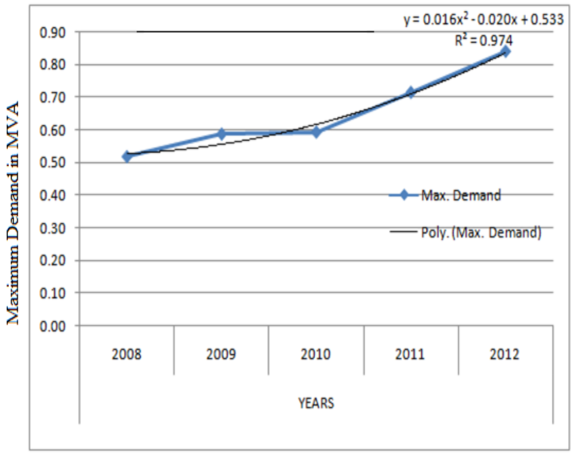


**Fig. 7. Trend Analysis for the Average Annual Electric Power Demand.**

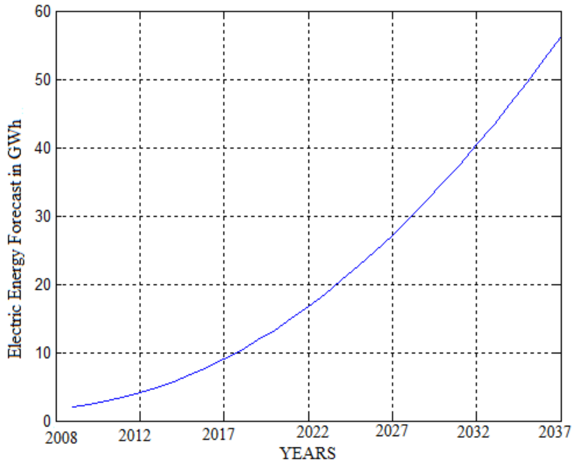


**Fig. 8. Electric Energy forecast to be distributed to consumers in GWh at Mafia Island for the next 25 years.**

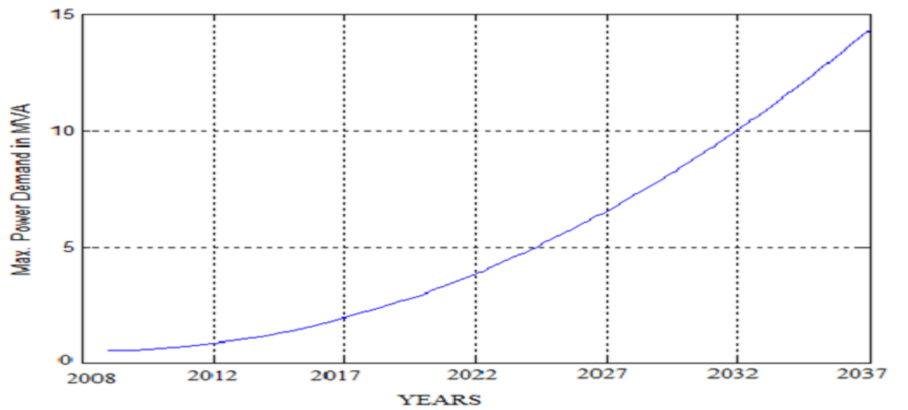


**Fig. 9.Load Forecast for Maximum Power Demand in MVA at Mafia Island for the next 25 years.**

The load demand forecasting shown in figure 9 does not include those customers which get their electric power independent of TANESCO. As it was pointed out in MIRREA report of 2005 [7] that, there was an installed capacity of electric power of about 2.5MW independent of TANESCO, this means that for proper load demand forecasting this power need also to be incorporated because on the availability of reliable and cheap electric power source from the Utility Company (TANESCO) all these consumers will need to be connected. From that reality, the electric power independent from TANESCO was assumed to increase at 8% i.e. 0.2MW, i.e. from 2.5MW to 2.7MW.

Since the Maximum Power demand are always less than the installed capacity of the power plant for a proper operation, the maximum demand of about 60% was assumed in this research i.e. 1.62MW and also a load factor of 40% was assumed to be used.

Units generated from this independent power source is calculated using (4). Energy generated per annum is given by

$$E_{an} = (P_{\max})(LF)(H) \quad (4)$$

Where $P_{max}$ is maximum power demand, LF is Load Factor and H is number of hours per annum. Therefore energy units generated per annum is given by

$E_{an}$= 1.62*0.4*8760=5676.48MWh ≈ 5.68GWh. This implies that the total energy to be transmitted to Mafia Island is 56.312GWh + 5.68GWh, which is equal to 61.992GWh ≈ 62 GWh in year 2037. For the case of maximum power demand in MVA, the power factor (pf) of 0.9 was assumed in this research. Therefore the maximum apparent power demand, $S_{max}$, is calculated as given in (5).

$$S_{max} = \frac{P_{max}}{pf} = \frac{1.62}{0.9} = 1.8\,MVA \tag{5}$$

Where $P_{max}$ is maximum power demand in MW and pf is power factor.

This implies that the load forecast maximum demand power up to 2037 is expected to be 14.333MVA + 1.8MVA, which is equal to 16.133MVA.

Normally a power station is so designed that it has some reserve capacity for meeting the increased load demand in the future. Therefore, the installed capacity of the plant is always somewhat greater than the maximum demand on the plant. From that concept the installed power plant capacity in this research is assumed to be at least 25% more than the load forecast maximum demand power which gives the proposed installed power plant capacity of approximately 20MVA, i.e. 16.133*1.25=20.16625MVA, where for the power factor of 0.9, this is equivalent to 18MW. This implies that the installed capacity for Mafia Island for the next 25 years will be expected to be about 18MW.

## V. SIMULATION RESULTS AND DISCUSSIONS

The simulations were performed in three different criteria which are under steady state condition, when the system is under single phase to earth fault and finally when the system is under three phase fault condition.

**(i) steady state condition:** Figure 10 shows three phase voltage and current waveforms of the proposed HVDC Light system under steady state operating conditions.

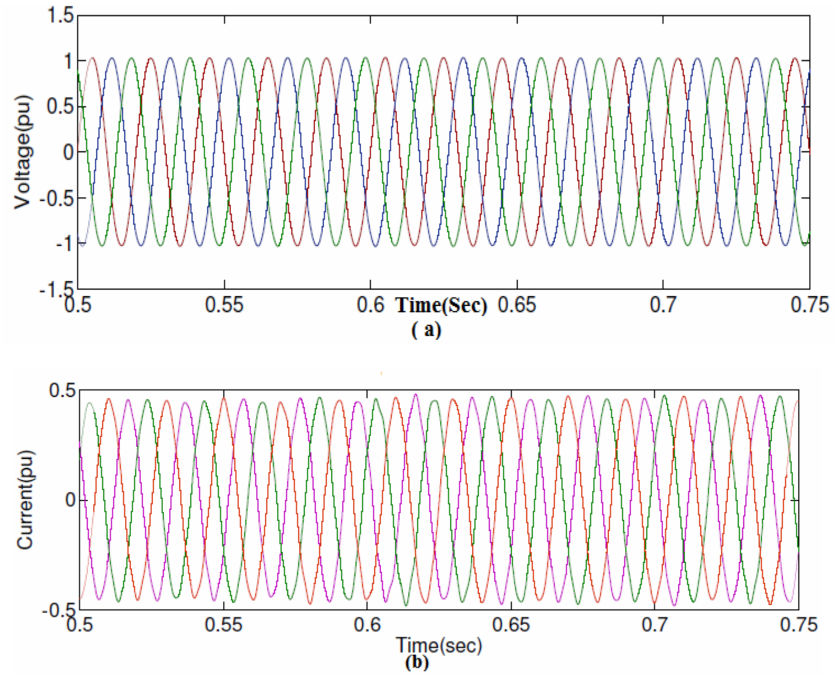


**Fig. 10 Simulation results of the voltage and current when the HVDC Light system is under steady state operation condition.**

**(ii) Single Line to Ground Fault *(SLGF):*** In this case, the behavior of the HVDC-Light system during unbalanced faults due to single phase to ground faults was investigated. Figure 11 shows simulation results on both converters which are resulted from a single phase to ground at inverter side (VSC 2) of the HVDC Light system. Active power, Reactive power, Voltage and Current signal of both converter sides are shown where the fault takes place at t=1.0s with a duration of five (5) cycles i.e. 100ms. From the simulation results, it can be noted that before the fault the active power flow of 0.4pu was transmitted from station 1 to station 2, and slightly during the fault the active power reduced to about 0.3pu. Voltage and Current at both stations contain small oscillations during the fault on the HVDC Light system.

**(iii) Three Phase fault to ground:** Three phase faults in the grid system are likely the most severe disturbances for the HVDC Light system. A three-phase fault is analyzed to investigate the performance of HVDC Light system during such faults.

Figure 12 shows simulation results on both converters which are resulted from a three phase fault to ground at inverter side (VSC 2) of the HVDC Light system. Active power, Reactive power, Voltage and Current signal of both converter sides are shown where the fault take place at t=1.0s. For a three phase to ground fault, AC voltage at Station 2 (VSC 2) is decreased to 0.1pu during the fault and recovers within 100ms to steady state after clearing the fault. The transmitted power flow is also reduced to very low value during the fault and then recovers to steady state. On the side the phase currents at station 2 reached to their maximum transient value of about 1.5pu during the fault, but the phase currents at Station 1 side reduced to about 0.1pu to reduce the power flow, and thus maintaining power balance.

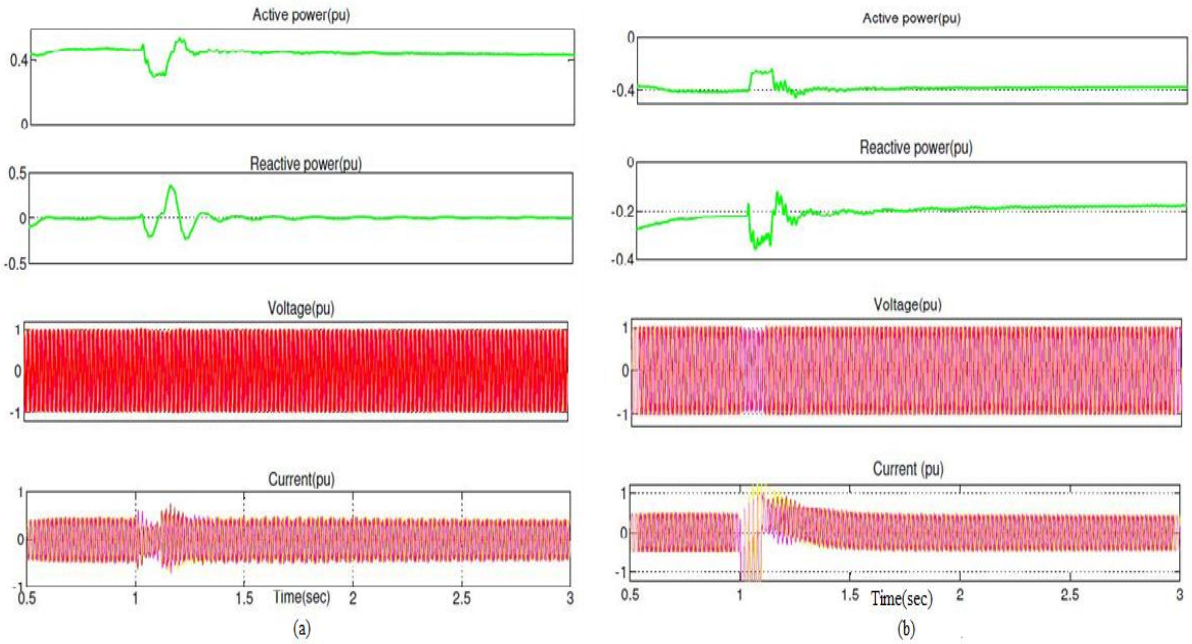


**Fig. 11 Single phase to ground waveforms for HVDC Light system for fault at t=1.0s at station 2 side end, (a) Station 1 side (Rectifier) (b) Station 2 side (Inverter)**

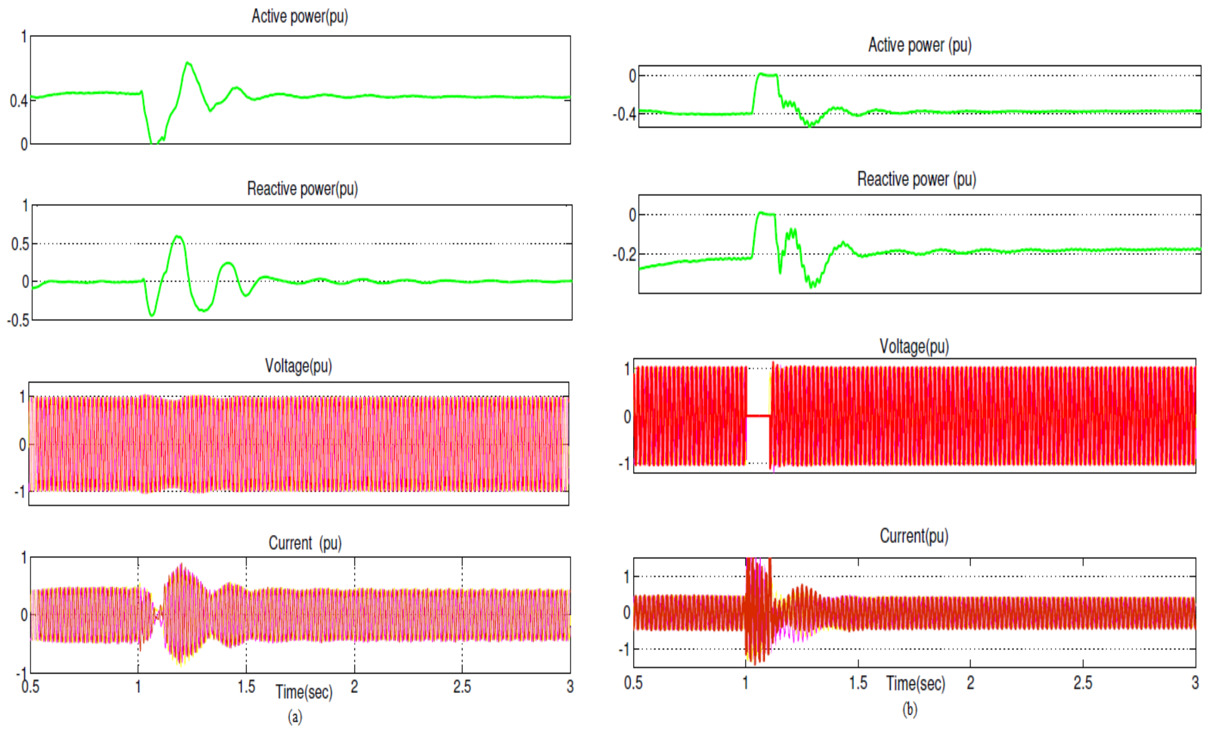


**Fig. 12. Three phase fault waveforms for HVDC Light system for fault at t=1.0s at station 2 side end, (a) Station 1 side (Rectifier) (b) Station 2 side (Inverter).**

## VI. CONCLUSIONS

This study presented the HVDC Light system as proposed to be applied to supply electricity at Mafia Island from the National Grid. HVDC Light technology is environmentally friendly for this case because the proposed system will replace fossil fuelled diesel generators without cost disadvantage. MATLAB/Simulink software has been used to simulate the proposed system. The simulation results conducted under steady state condition and when the system is under fault condition for both, single phase to ground and three phase to ground faults has shown that the performance operation of the envisaged HVDC Light system is viable.

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## APPENDICES

**Table 1. Customer connection trend for Mafia island**

| S/No. | Months | Years | | | | |
|---|---|---|---|---|---|---|
| | | 2008 | 2009 | 2010 | 2011 | 2012 |
| 1 | January | 1 | 1 | 5 | 5 | 10 |
| 2 | February | 1 | 4 | 1 | 9 | 10 |
| 3 | March | 0 | 2 | 6 | 6 | 29 |
| 4 | April | 0 | 0 | 2 | 4 | 16 |
| 5 | May | 1 | 2 | 3 | 3 | 9 |
| 6 | June | 6 | 1 | 6 | 2 | 9 |
| 7 | July | 1 | 5 | 2 | 6 | 8 |
| 8 | August | 0 | 3 | 5 | 8 | 2 |
| 9 | September | 0 | 0 | 15 | 6 | 6 |
| 10 | October | 1 | 5 | 5 | 3 | 15 |
| 11 | November | 5 | 4 | 3 | 9 | 23 |
| 12 | December | 4 | 2 | 4 | 7 | 1 |
| Total | | 20 | 29 | 57 | 68 | 138 |

**Table 2. Extended forecast load demand power**

| S/No. | Years | Electrical Power Distributed in (GWh) | Growth Rates (%) | Maximum Demand in MVA | Growth Rates (%) |
|---|---|---|---|---|---|
| 1 | 2008 | 2.06 | | 0.518 | |
| 2 | 2009 | 2.56 | 24.3 | 0.587 | 13.32 |
| 3 | 2010 | 2.66 | 3.9 | 0.593 | 1.02 |
| 4 | 2011 | 3.57 | 34.2 | 0.714 | 20.40 |
| 5 | 2012 | 4.04 | 13.2 | 0.839 | 17.51 |
| 6 | 2013 | 4.832 | 19.6 | 0.989 | 17.88 |
| 7 | 2014 | 5.712 | 18.2 | 1.177 | 19.01 |
| 8 | 2015 | 6.702 | 17.3 | 1.397 | 18.69 |
| 9 | 2016 | 7.802 | 16.4 | 1.649 | 18.04 |
| 10 | 2017 | 9.012 | 15.5 | 1.933 | 17.22 |
| 11 | 2018 | 10.332 | 14.6 | 2.249 | 16.35 |
| 12 | 2019 | 11.762 | 13.8 | 2.597 | 15.47 |
| 13 | 2020 | 13.302 | 13.1 | 2.977 | 14.63 |
| 14 | 2021 | 14.952 | 12.4 | 3.389 | 13.84 |
| 15 | 2022 | 16.712 | 11.8 | 3.833 | 13.10 |
| 16 | 2023 | 18.582 | 11.2 | 4.309 | 12.42 |
| 17 | 2024 | 20.562 | 10.7 | 4.817 | 11.79 |
| 18 | 2025 | 22.652 | 10.2 | 5.357 | 11.21 |
| 19 | 2026 | 24.852 | 9.7 | 5.929 | 10.68 |
| 20 | 2027 | 27.162 | 9.3 | 6.533 | 10.19 |
| 21 | 2028 | 29.582 | 8.9 | 7.169 | 9.74 |
| 22 | 2029 | 32.112 | 8.6 | 7.837 | 9.32 |
| 23 | 2030 | 34.752 | 8.2 | 8.537 | 8.93 |
| 24 | 2031 | 37.502 | 7.9 | 9.269 | 8.57 |
| 25 | 2032 | 40.362 | 7.6 | 10.033 | 8.24 |
| 26 | 2033 | 43.332 | 7.4 | 10.829 | 7.93 |
| 27 | 3034 | 46.412 | 7.1 | 11.657 | 7.65 |
| 28 | 2035 | 49.602 | 6.9 | 12.517 | 7.38 |
| 29 | 2036 | 52.902 | 6.7 | 13.409 | 7.13 |
| 30 | 2037 | 56.312 | 6.4 | 14.333 | 6.89 |