Integration of Hybrid Offshore Wind and Wave Energy using PMSG and Linear Generator based on VSC and VSI

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***Abstract*— To combine the power from an offshore wind energy (OWE) and wave energy conversion (WEC) system, a vigorous and suitable generators are required to run the system and extract energy frequently at the maximum power point (MPP). The offshore wind energy maximum-power-point-tracking (MPPT) techniques are established via voltage source converter (VSC) to attain power from a permanent magnet synchronous generator (PMSG) based on variable speed. To get maximum power from wave energy the best choice is the linear generator with the VSC. A detailed numerical modelling analysis of the linear generator is carried out. The combined offshore wind coupled with wave energy is implemented in MATLAB Simulink environment. Furthermore, the final simulated results of offshore wind-wave energy system is analyzed and compared with each other.**

Keywords- Offshore wind Energy (OWE); Maximum power point tracking (MPPT); Voltage source converter (VSC); Hybrid offshore wind and wave energy (HOWWE); Permanent magnetic synchronous generator (PMSG); Energy conversion system (ECS); Offshore wind turbine (OWT)

I. INTRODUCTION

Hybrid offshore wind-wave energy (HOWWE) power conversion and inversion is a significant portion of the mixing of the both energy sources. The suitable selection of offshore-wind generator is PMSG and wave-energy is linear generator. These generators are linked with VSC and voltage-source-inverter (VSI). HOWWE is the double generated, enormous, steady and globally friendly source. There has been a manifest change in renewable due to HOWWE by decrease in carbon emissions and reduction of fossil fuels. To make system more efficiently many sectors of HOWWE needs to be improved such as correlation and power conversion. A detailed review on different power conversion techniques of HOWWE are discussed in [1]. Different case studies of HOWWE with generators selection using W2Power systems are analyzed by [2]. Moreover HOWWE marine-energy-converters (MEC) is developed and tested by [3]. To generate output power continuously numerical analysis and testing is important of power conversion and it is analyzed by [4]. The implementation of wave-energy converter into offshore wind system is analyzed by [5]. To simulated test of system the each part of HOWWE needs to analyzed separately such as offshore-wind VSC. Offshore-wind is most suitable and continuously power generation technologies. However it has a high demanding capacity compared with linked systems, such as hybrid solar-wind and hybrid wave-wind. In assessment of offshore-wind, wind turbines are based on fixed-speed and variable-speed. The operation of a control techniques to calculate MPPT for getting the optimal-point of action in offshore-wind ECS is essential [6]. MPPT is required to enhance the performance of offshore wind-wave ECS. The essential idea of driving the MPPT in offshore wind ECS is to adjust and manage the speed of AC generator, along with the speed of PMSG wind-turbine and coupling shaft [7]. The high power offshore wind conversion coupled with ocean energy are discussed in [8]. The offshore-wind is adjustable speed offers 10–15% output, minimized power-fluctuation, and curtail mechanical-stress than the fixed-speed [9].

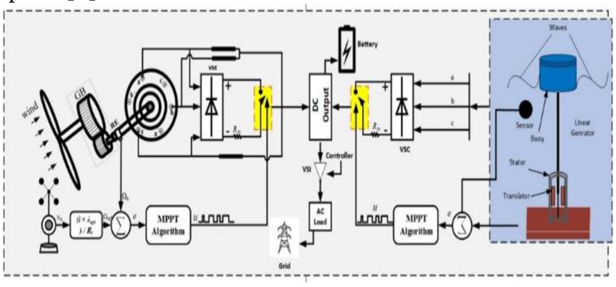

Figure. 1. Schematic diagram for hybrid wind and wave energy

However, under quick variation of wind-speed, it declines to attain MPPT. By choosing an appropriate step-size is a hard task due to a superior step-size because its provide a quicker convergence but added oscillations around the MPP, however a lesser step-size provides a slower convergence [6]. Similarly, for the maximum-power output from wave energy near the shoreline is discussed in [10]. The comparative analysis from three phase power converter and inverter from wave energy is analyzed by [11]. Different control techniques to maximize the output power such as super-twisting are tested in [12].

Furthermore, the producing capacity of distribution generation system (DGS) relating with large-synchronous-generators is smaller. So, the DC micro-grid is used to convert the energy and DGS into dc-electricity smoothly.

The DC electricity is again converted back into AC [13], [14]. The intermittence of HOWWE and DGS, connected loads with bidirectional dc/dc converters are required to get smooth power [15]. To simulate the ac/dc grid system using photo-voltaic and wind-power with inverter model were developed in [16]. The modelling and outcomes of Archimedes-wave-swing (AWS) with a linear-generator were presented and associated with 2-MW AWS system [17]. A modelling and arrangement of a marine-power AWSs linking to a power-grid was discussed in [18]. The detailed analysis of the WEC integration technologies into offshore windmills are presented in [19]. The site and co-location of wind-wave energy utilization is investigated in the Italian seas [20]. The spar-type OWT and a WEC by performing numerical simulations in operational conditions is presented in [21].

As the scope of hybrid offshore wind and wave farms has greater than before, challenges linked to installation, construction, operation and transportation have also increased. Hybrid wind and wave farms are typically located far away from the shore and are challenging to access, particularly in bad weather. Hence, fixing the technical issue could be complicated and expensive. Additional challenging factors in offshore wind and wave are power deployment relate to supply characterization, operation and grid interconnection. Hence, the more capital costs and issues linked with the transportation, operations, maintenance and logistics restrain the global offshore wind and wave market.

The intent of this project is to consider and implement the linear generators and their prospective uses for HOWWE. A design model is created in MATLAB Simulink. The linear generator used for the wave energy model has following features: non-salient, 12-pole, non-sinusoidal, three-phase with back electromotive force (EMF). A selection of these technologies is generically modeled and their results are discussed and contrasted against one another. The idea establishes the tasks of using linear generators for HOWWE scenarios. It also demonstrates a valuable tool in investigating and refining the performance under a diversity of conditions. The remaining parts of the paper is presented as follows; section II covers the configuration of the system and modelling of OWT. In section III, the numerical implementation of linear generator for wave energy is carried out. In section IV, the power conversion and inversion of HOWWE is presented while the comprehensive results, conclusion and the future work are presented in sections V, VI and VII respectively.

II. System Configuration and OFFSHORE WIND ENERGY

The Fig. 1 illustrates the configuration of the HOWWE system linked to an AC-grid through a DC conversion. The offshore wind system implemented by PMSG and wind turbine (WT) is linked to the VSC. The OWT basically signifies WT based on PMSG, where GB represents the gearbox, RE represent a rotational-encoder, i_s, X_s, V_{PMSG} are the current, inductance and voltages across PMSG. The wave energy is implemented by linear generator using buoy through VSC. The translator motion is produced when the sea waves hits the buoy and i_{LG}, X_{LG}, V_{LG} are the current, inductance and voltages are produced across linear generator. Both energy sources are linked each other with VSC system. The inverter is used to convert back the DC into AC for AC-grid and load, as shown in Fig. 1.

A. Wind-Turbine Modeling

The output-power that is accessible at the turbine shaft is signified as [13]:

$$P_s = \frac{1}{2}\rho\pi {R_{blade}}^2 {v_s}^3 C_{pr}(\lambda) \quad (1)$$

where R_{blade} is represents the radius of blade, wind-speed is signified by v_s, ρ represents the air-mass-density, while power-coefficients is denoted as C_p and it is considered as:

$$C_p(\lambda) = [\lambda(0.0060 - 0.0014\,\lambda + 0.0081\lambda^2 - 0.00097477\lambda^3] \quad (2)$$

where λ is represented as:

$$\lambda = \frac{w_s R_{blade}}{v_s q} \quad (3)$$

where the w_s shows the shaft-angular-speed of OWT while, q is the gear-transmission-ratio.

Also, the shaft-torque of offshore-turbine as a function of measurement of torque as:

$$T_{mec} = \frac{1}{2}\rho\pi {R_{blade}}^3 {v_s}^2 C_T(\lambda) \quad (4)$$

The coefficient of torque $C_{Torque}(\lambda)$ is:

$$C_{Torque}(\lambda) = \frac{C_{PR}(\lambda)}{\lambda} \quad (5)$$

B. PMSG Modeling in d-q axis

A modeling of PMSG is presented as follows [13].

$$\left.\begin{aligned} \dot{i_d} &= \frac{-R_{stator} i_d + p(L_q - L_{chopper})\omega_h i_q - R_{chopper} i_d}{L_d + L_{chopper}} \\ \dot{i_q} &= \frac{-R_{stator} i_q - p(L_q + L_{chopper})\omega_s i_d - R_{chopper} i_q}{L_q + L_{chopper}} + p\Phi_m \Omega_h \\ \dot{\omega_s} &= \frac{1}{J}\left(-p\Phi_m i_q + \frac{b_1 {v_{wd}}^2}{q} + \frac{b_2 v_{wd}\omega_s}{q^2} + \frac{b_3 {\omega_s}^2}{q^3}\right) \end{aligned}\right\} \quad (6)$$

where R_{stator} represents resistance across stator L_d, L_q represents inductances and i_d, i_q are currents across dq axis. Other expressions p are the pole numbers, ω_h represents angular rotor speed and ω_s signifies the shaft angular speed of the generator. The Ω_h and Φ_m signify the angular-speed and flux of permanent-magnets. The symbol J signifies the generator-shaft-inertia, $R_{chopper}$ signifies the chopper-resistance and b_1, b_2, b_3 are constant parameters.

The state-variables becomes in simplified form by taking the values of constant parameters as mentioned in Table I.

$$x_1 = i_d$$
$$x_2 = i_q$$
$$x_3 = \omega_s$$

$$\begin{bmatrix} \dot{x_1} \\ \dot{x_2} \\ \dot{x_3} \end{bmatrix} = \begin{bmatrix} -(l_1 + l_3 R_{chopper}) - (l_3 x_3) + 0 \\ -(m_2 x_3) - (m_1 + m_4 R_{chopper}) + m_3 \\ -\frac{n_1 {v_{wd}}^2}{x_1} - n_4 - (n_2 v_{wd} + n_3 x_3) \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \quad (7)$$

where $l_1, l_3, m_1, m_2, m_3, n_1, n_2, n_3$ and n_4 represents the constant terms.

III. WAVE ENERGY CONVERSION USING LINEAR GENERATOR

In the preceding sections, the numerical modelling for wave energy system is assessed. The initial target is to find the maximum power for wave energy, which can be accomplished by appropriate generator selection and MPPT control technique. This is done via using linear generator for hybrid offshore wind and wave energy system.

A. Linear Generator Variable Equations

It is simple to model linear generator by using rotating machine or generator variables and equations. The torque is linked to force by:

$$P = \tau\omega_{rm} \quad (8)$$

and

$$P = FV \quad (9)$$

where F is force, V is the velocity and P is the power. The electrical power for the three phase linear generator can be calculated by:

$$P = v_{xs}i_{xs} + v_{ys}i_{ys} + v_{zs}i_{zs} \quad (10)$$

The stator voltage equation of the linear generator. In a three phase generator with stator phases x, y and z, the voltage in the stator can be defined by:

$$v_{xyzs} = r_s i_{xyzs} + \frac{d}{dt}\lambda_{xyzs} \quad (11)$$

where v_{xyz} , i_{xyz} and λ_{xyzs} are generalized in the form:

$$f_{xyzs} = \begin{bmatrix} f_{xs} \\ f_{ys} \\ f_{zs} \end{bmatrix} \quad (12)$$

where f_{xs} , f_{ys} and f_{zs} are the stator voltage, current linkage and flux linkage phases of x, y and z. In the linear generator the back sinusoidal back EMF, the total flus linking the translator and stator is achieve by combining flux from windings and translator. The flux depend on translator electrical angle θ_{re} .The position of translator θ_{re} is linked with the mechanical translator angle θ_{rm} by the number poles. The $\theta_{re}$is defined as:

$$\theta_{re} = \theta_{rm}\frac{p}{2} \quad (13)$$

So the flux linkage matrix is represented as:

$$\lambda_{xyzs} = L_s i_{xyzs}\lambda'_m \begin{bmatrix} \sin\theta_{re} \\ \sin\theta_{re} - \frac{2\pi}{3} \\ \sin\theta_{re} + \frac{2\pi}{3} \end{bmatrix} \quad (14)$$

where λ'_m is the peak flux linkage. The stator self-inductance matrix is defined as:

$$L_s = \begin{bmatrix} L_{ls} + L_{ms} & -\frac{1}{2}L_{ms} & -\frac{1}{2}L_{ms} \\ -\frac{1}{2}L_{ms} & L_{ls} + L_{ms} & -\frac{1}{2}L_{ms} \\ -\frac{1}{2}L_{ms} & -\frac{1}{2}L_{ms} & L_{ls} + L_{ms} \end{bmatrix} \quad (15)$$

The L_{ms} is mutual inductance and L_{ls} is the stator leakage. The translator speed of linear generator ω_{rm} related to electrical counter-torque τ_e and mechanical input torque τ_m by

$$\tau_e - \tau_m = J\frac{d}{dt}\omega_{rm} + D_m\omega_{rm} \quad (16)$$

where J is translator inertia of the translator and create resistance and D_m is the mechanical damping due to friction. The electric torque produced by linear generator is specific to the geometry of HOWWE. It is complicated by the system design such as winding distribution and the air gap between the translator and stator. By assuming the generator winding distribution as constant then the τ_e is expressed as:

$$\tau_e = \frac{p}{2}\left\{\frac{\sqrt{3}}{2}\left(i^2{}_{ys}i^2{}_{zs} - 2i_{xs}i_{ys} + 2i_{xs}i_{zs}\right) + \lambda'_m\left[\left(i_{xs} - \frac{1}{2}i_{ys} - \frac{1}{2}i_{zs}\right)\cos\theta_{re} + \frac{\sqrt{3}}{2}\left(i_{ys} - i_{zs}\right)sin\theta_{re}\right]\right\} \quad (17)$$

while the flux linkage equation is defined as:

$$\lambda_{xyzs} = L_s i_{xyzs} + \lambda'_m \sum_{n-1}^{\infty} k_{2n-1} \begin{bmatrix} \sin((2n-1)\theta_{re}) \\ \sin((2n-1)(\theta_{re} - \frac{2\pi}{3})) \\ \sin((2n-1)(\theta_{re} + \frac{2\pi}{3})) \end{bmatrix} \quad (18)$$

where magnitude of harmonic coefficient is k_n . So, the torque equation is become as:

$$\tau_e = (\tfrac{3}{2})(\tfrac{p}{2})\,\lambda'_m \textstyle\sum_{n-1}^{\infty} k'_{2n-1}\,[i_{xs}\; i_{ys}\;\; i_{zs}] \begin{bmatrix} \cos((2n-1)\theta_{re}) \\ \cos((2n-1)(\theta_{re} - \frac{2\pi}{3})) \\ \cos((2n-1)(\theta_{re} + \frac{2\pi}{3})) \end{bmatrix} \quad (19)$$

B. Translator Reference Frame using dq0 variables

In order to find the translator variables, the transformation of variables through translator reference frame. The Park's transformation was used to find three phase system variable transformation. The dq0 transformation has replaced standard transformation. The dq0 transformation replaced the phase variables x, y, z into d, q, 0 axes. The graphical representation is shown in the figure where f_{xs} , f_{ys} and f_{zs} are x, y and z axes while f_{ds} and f_{qs} are d and q axis. The 0 axis will be originate from other axes and it is not shown in the figure. The main advantages for using the dq axes for the linear generator because it gives simplified direct torque.

To find transformation, there is multiplication between K matrix transformation and generator variables. By taking electrical translator angle θ_{re} , so transformation matrix will become as:

$$K_s^r = \frac{2}{3}\begin{bmatrix} cos\,\theta_{re} & cos\,(\theta_{re} - \frac{2\pi}{3}) & cos\,(\theta_{re} + \frac{2\pi}{3}) \\ sin\,\theta_{re} & sin\,(\theta_{re} - \frac{2\pi}{3}) & sin\,(\theta_{re} + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (20)$$

The new translator variables in dq0 frame are generalized as:

$$f^r{}_{qdos} = \begin{bmatrix} f^r{}_{qs} \\ f^r{}_{ds} \\ f^r{}_{os} \end{bmatrix} \quad (21)$$

and

$$f^r{}_{qdos} = K_s^r f_{xyzs} \quad (22)$$

The inverse transformation from qd0 to xyz variables the inverse transformation matrix is applied:

$$f_{xyzs} = (K_s^r)^{-1} f^r{}_{qdos} \quad (23)$$

and

$$(K_s^r)^{-1} = \begin{bmatrix} \cos\theta_{re} & \sin\theta_{re} & 1 \\ \cos(\theta_{re} - \frac{2\pi}{3}) & \sin(\theta_{re} - \frac{2\pi}{3}) & 1 \\ \cos(\theta_{re} + \frac{2\pi}{3}) & \sin(\theta_{re} + \frac{2\pi}{3}) & 1 \end{bmatrix} (24)$$

So voltage becomes

$$v^r{}_{qs} = r_s i^r{}_{qs} + \omega_{re}\lambda_{ds}^r + \frac{d}{dt}\lambda_{qs}^r \quad (25)$$

$$v^r{}_{ds} = r_s i^r{}_{ds} + \omega_{re}\lambda_{qs}^r + \frac{d}{dt}\lambda_{ds}^r \quad (26)$$

$$v^r{}_{0s} = r_s i^r{}_{0s} + \frac{d}{dt}\lambda_{0s}^r \quad (27)$$

and the equation (11) becomes

$$\lambda_{qs}^r = \left(L_{ls} + \frac{3}{2}L_{ms}\right) i^r{}_{qs} + \lambda'_m \sum_{n-1}^{\infty}(k_{6n-1} + k_{6n+1})\sin(6n\,\theta_{re}) \quad (28)$$

$$\lambda_{ds}^r = \left(L_{ls} + \frac{3}{2}L_{ms}\right) i^r{}_{ds} + \lambda'_m + \lambda'_m \sum_{n-1}^{\infty}(k_{6n-1} - k_{6n+1})\cos(6n\,\theta_{re}) \quad (29)$$

$$\lambda_{0s}^r = (L_{ls} + \frac{3}{2}L_{ms}) i^r{}_{0s} + \lambda'_m \sum_{n-1}^{\infty} k_{6n-3}\sin((6n-3)\,\theta_{re}) \quad (30)$$

and (12) becomes:

$$\tau_e = (\tfrac{3}{2})(\tfrac{p}{2})\,\lambda'_m [i^r{}_{qs}(1 + \sum_{n-1}^{\infty}(k''{}_{6n-1} + k'{}_{6n+1})\cos(6n\,\theta_{re})) + i^r{}_{ds}\sum_{n-1}^{\infty}(k'{}_{6n-1} + k'{}_{6n+1})\sin(6n\,\theta_{re}) + 2i^r{}_{0s}\sum_{n-1}^{\infty}(k'{}_{6n-3})\cos((6n-3)\theta_{re})] \quad (31)$$

In equation (10), power can be calculated using xyz variables. So, using dq0 variables power can be calculated as

$$P = \frac{3}{2}(v^r{}_{qs} i^r{}_{qs} + v^r{}_{ds} i^r{}_{ds} + 2v^r{}_{0s} i^r{}_{0s} \quad (32)$$

TABLE I

CONSTANT TERMS [12]

Constants	Value	Constants	Value	Constants	Value
$l_1 = m_1$	27.146	l_2	0.94867	$l_3 = m_4$	8.2265
m_2	3	m_3	1.3147	n_1	9.946
m_3	0.1333	n_3	0.00507	n_4	23.807

IV. POWER CONVERSION AND INVERSION OF HOWWE

The integration of HOWWE transmission systems are established on current-fed VSC converters. This innovative converter technique minimize the priced for HOWWE system based on VSC-VSI using fast-switching semiconductors. There are following advantages for VSC-VSI are the fast switching and capability to autonomously control of both active-reactive power. Mostly VSC-VSI are based on point-to-point links such as offshore wind farm converter is linked with AC grid by using DC cable. The connection of HOWWE offshore wind and wave energy can be achieved with a shared dc grid based in a multi-terminal grid, where the terminals are wind-wave and grid connections as shown in Fig. 2.

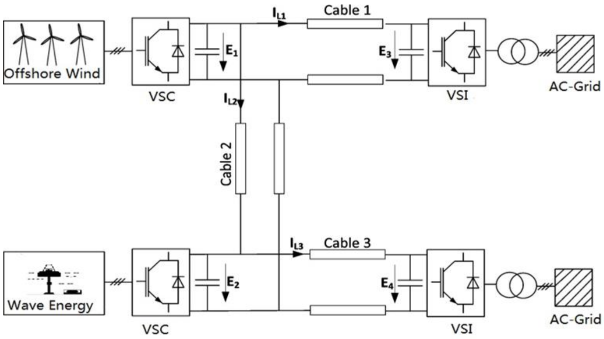

Figure. 2. Multi-terminal VSC-VSI for HOWWE

The integrated model for HOWWE using VSC and VSI based with four terminals: first one for offshore wind, second for wave energy source and two AC grid supply. The integrated offshore wind and wave energy with VSC inject the power generated in each hybrid farm into the grid, however the VSI inject the power from the DC-grid into the AC side grid. From the above cases, it is to clear that multisource converter and VSI inverter supplied stable fed AC voltage to the AC-grid by keeping constancy and stability of the HOWWE system.

V. SIMULATION RESULTS

An OWT and wave energy numerical modelling are simulated in MATLAB. The wind-speed is supposed as 12m/s. The comparison and simulation of both energy sources are made among the designed schemes separately. In case of OWT guarantee the extraction of maximum output. To find energy conversion from wave energy the numerical modelling is presented in the section III. The output of both energy sources goes through voltage source converter, separately. On the other hand, the integration of HOWWE in MATLAB notices a steady output power flow by adding both energy sources. To obtain the maximum power, and operate the OWT and wave energy at the MPPT, the power should be maintained in such a way to guarantee the system efficiency at its optimum-value as shown in the control signal of DC offshore wind Fig. 3. and Fig. 4. The HOWWE system is programmed and tuned to reach a steady state of final output power. The filter bus stations are applied sequentially on both wind and wave energy section and the results are shown in Fig. 5 and Fig. 6. The inverted power is stabilizes and reference DC voltage of the inverter is decreased from 1 p.u. to 0.95 p.u. at time t = 2.5 s in Fig. 7. The transformer is use to step up the voltage of inverted power for the load connectivity and the smooth resultant waveform are shown in Fig. 8.

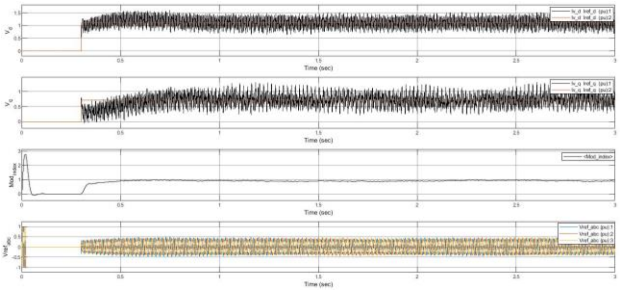

Figure. 4. Control Signals across the DC Offshore Wind

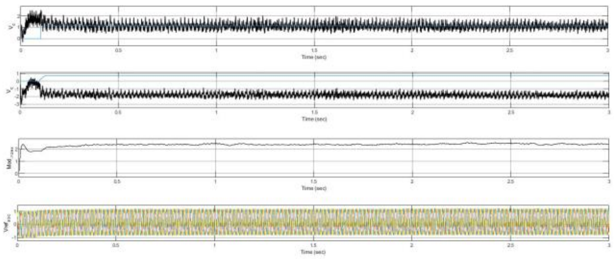

Figure. 5. Control Signals across DC Wave Energy

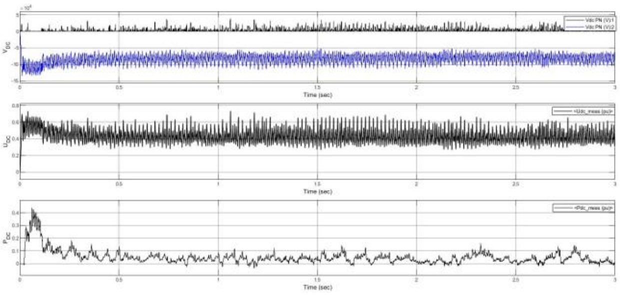

Figure. 6. Filter Bus Station of Offshore Wind

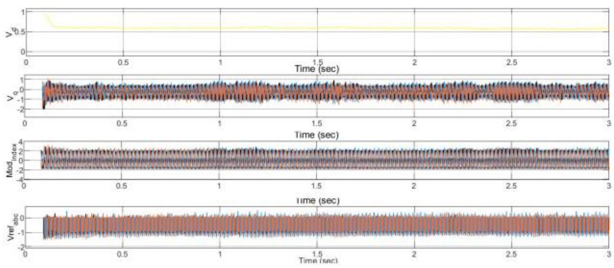

Figure. 7. Filter Bus Station of Wave Energy

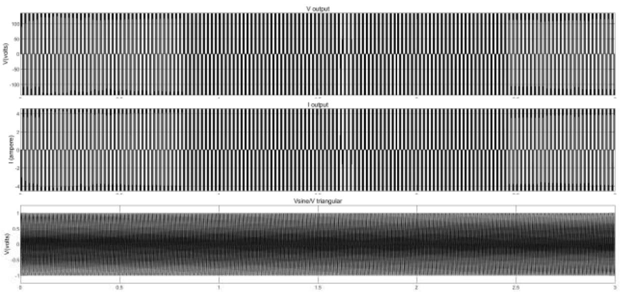

Figure. 7. Power Inversion of HOWWE

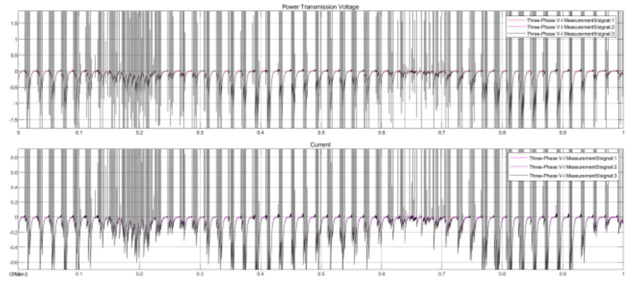

Figure. 8. Power Transmission across the Load

VI. CONCLUSIONS

In this paper, an integration of HOWWE using PMSG and linear generator has been proposed. The PMSG OWT with three state variables are converted into two-states to simplify the system. The wave energy numerical and simulated modelling is presented and the integration of both sources are carriedout using the voltage source inverter . During the simulations, it is demonstarted that offshore wind and wave energy are modelled separately and than their AC power is integrated via VSC. The power inversion is carried out for the AC grid connectivity. Finally, the proportional simulated and measured results of offshore wind and wave energy under a grid and load switching have been implemented, and it illustrates the system with the proposed techniques are functioned steadily under different conditions.

VII. FUTURE WORK

The HOWWE system can also be enhanced by adding battery and a resistive DC load to link with the DC micro-grid through a load DC-DC converter. To attain steady power-flow and fulfill DC micro-grid load under functional circumstances, the battery can also be connected to the DC micro-grid with bidirectional DC-DC converter. The AC grid can also linked to the DC micro-grid through a bidirectional grid-tied inverter. The accessible OWE and wave energy powers will be injected into the DC micro-grid with a completely charged battery, the additional power of the DC micro-grid is delivered to the AC-grid using bidirectional grid-tied inverter. Furthermore, artificial intelligence based back stepping technique for OWT will able to manage the maximum power at the optimal point and the multipoint wave energy will be helpful for getting the maximum power for the HOWWE system.

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