Performance Enhancement of an Integrated Offshore Wind Farm, Marine Current Farm and PV System with Flywheel Energy Storage System

S.Ayyappan,K.Banupriya, M.Gomathi, Jebrine Melco

Abstract-**This paper represents a control strategy to instantaneously realize mitigation in power fluctuation and performance enhancement of offshore wind farm (OWF), PV system and Marine current farm (MCF) coupled to the grid with Flywheel type energy storage system (FESS). The whole configuration is implemented by MATLAB/SIMULINK environment and SimPowerSystems toolbox. From simulation results which can be decided that the offered FESS come together with the proposed PI damping controller can successfully stabilize the integrated OWF, MCF, and Photovoltaic system with different load conditions. The variations in voltage of AC bus expose to real power changes can be efficiently regulated with energy storage system.**

Keywords: **SCIG, Offshore Wind Farm, Marine Current Farm, PV System, Flywheel Energy Storage System**

I. INTRODUCTION

Ocean energy includes many forms of energy which may be used to provide a new system intended for electricity generation, they are marine current energy, tidal energy, thermal energy, offshore wind energy and wave energy. Offshore wind farm together with Marine-Current Farm (MCF) can be widely established at the specific locations of the world in the upcoming years because they covers greater than 70% surface of the earth. Energy available in Photovoltaic, Wind energy and ocean energy are extremely appropriate for power supply and have been effectively initiated in numerous cases in developing countries. Battery bank is necessary to provide backup power where in case of utility power start to fails in energy production from renewable resources.

Manuscript received November 12, 2015.

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Solar PV system arrays generate electrical energy from light energy; it can able to supply the power to electrical power grid, household appliances and other industrial applications. Offshore wind is likely to strike harder and further consistent than on ground.

Here offshore wind energy system is simulated by corresponding combined 45-KW squirrel cage induction generator (SCIG), and marine current energy transformation is also simulated by a same grouped 50KW squirrel-cage induction generator. Wind energy produces three phase AC supply is rectified by using three phase controlled rectifier (with switch IGBT because it has low switching losses & high switching frequency than SCR, MOSFET) to store the excess energy in the storage system and then the required grid power is converted into AC by using three phase converter bridge. The power generated by Marine current turbines is directly connected to the grid. If excess power is available, that will send to storage scheme through three phase converter (in demand this stored energy is retrieved and sent back to the grid). The DC power produced by PV scheme is connected across the DC link and during demand the PV arrangement steadily shared with these (OWF & MCF) powers in order to assure the uninterrupted accessibility of grid power. Additionally LC filter is connected across the transmission line to filter out the harmonics; excitation capacitor to excite the squirrel cage induction generator is employed.

A literature survey has done by referring various papers which are essential to know the existing techniques and their significance. It also has included the various supporting papers for the proposed technique and their advantages. The points presented in the papers are discussed below. Wang *et* al. [1]. have presented a strategy and control scheme for dynamic stability improvement of an integrated OWF and MCF using a FESS system (existing system), to concurrently meet power variation reduction it uses a control scheme of FESS (it is coupled with power grid). The implementation of the OWF is fabricated by doubly fed induction generator (DFIG), whereas the features of the MCF are fabricated by a squirrel-cage induction generator. The FESS is designed by using modal control theory for stability improvement and proportional integral derivative (PID) damping controller is used to control FESS. The variability behaviour in Solar and Wind creates the system not to be trusted, thus energy storage device SMES is leaded to decrease output oscillations. From simulation outputs are revealed that the system without SMES was unreliable when compared to system without SMES are addressed in [2]. The efficiency in the proposed HVDC link, use of eigenvalue analysis with respect to specific condition in operating point and steady state analysis with different speeds in wind and marine-currents also in dynamic loads and the bus voltage can be satisfactorily kept at around 1.0 pu due to the proposed HVDC link are shown in [3].

The analysis in performance & comparison between fixed speed (SCIG) and variable speed wind generators coupled with power grid and the ability of variable speed systems to extract maximum power from the available wind power has demonstrated in [4]. By the application of power electronic devices and Flexible AC Transmission System (FACTS) devices (can ensure more improvement in the ride-through ability of the wind generators while disturbance conditions), effective static and dynamic stability control of voltage, power and also PQ control is possible in distribution and transmission network has presented in [5]. Distributed generation with power flow control problem of grid-connected inverter in which phase locked loop algorithm has established to get conditioning in line and grid current and produce harmonic free current were carried out by [6]. Energy from solar and wind energy system with a model of Pulse width modulation voltage source inverter (PWM-VSI) connected to grid has suitable converter control technique not only able to transmit direct current from system but also can have improved power factor and quality power system has discussed [7].

With the help of unified power flow controller the power system can be made as stable and also real & reactive power flow in transmission and distribution network control within the limit has possible by [8]-[9]. Dynamic stability improvement and reduction of bus voltage variation in power system network (it has comprised of renewable wind farm and marine current farm as energy source) by means of STATCOM which was designed through a pole-assignment approach based PID damping controller has addressed in [10]-[11]. The steady state analysis in wind energy system (using fixed speed & variable speed on wind turbine) with various wind velocities and maximum power point tracking in DFIG have performed in [12]. The improvement of configuration of marine current turbine depends upon speed & pitch control and the use of this model were dynamic load assessment with various operating points and performance enhancement has discussed by [13]. The line to line procedure for model of Photovoltaic system interconnected with power system and maximum power point algorithm has performed for this configuration to extract high power from the PV module against changes in solar irradiance is explained in [13].

From the above discussions it can be concluded that renewable sources have power fluctuations and voltage variations due to variations in wind/tide speed, solar irradiation and climate changes. By using proper energy-storage system or FACTS devices with suitable control techniques, variable speed induction generators (to improve efficiency and power output) and with suitable converter control, it has possible of performance enhancement of the system, minimization in the power fluctuations and variations of bus voltage.

II. EXISTING AND PROPOSED SYSTEM

The disadvantage of existing system of only two renewable sources (or less no of resources), thus it may not able to meet the required demand on time and has the complexity of controlling doubly fed induction generator. Now a days with the recent advances in power electronics devices variable speed squirrel cage induction generators (SCIG) are possible. A WT with variable speed SCIG can make variable speed generation by lesser price than PMSG, besides resolve the difficulty of thin generation part happened in current static speed generation. Performance enhancement of an integrated PV system, offshore wind and Marine current farm with a Flywheel energy storage system (proposed system) has overcome the intermittent form of these energy sources by using variable speed SCIG instead of DFIG, interconnecting PV system with the grid and storage device. During wind power is subject towards temporary variations, PV production varies with insolation level then marine power has used to compensate for these deviations. The FESS joined by means of the considered PI damping controller can efficiently stabilize the power system through OWF, MCF & PV system under several load settings.

III. SYSTEM CONFIGURATION AND MODELS

The configuration of the proposed system through incorporated OWF and MCF based on SCIG with the suggested FESS controller is shown in figure 3.1. The OWF with 45-KW and MCF with 50-KW capacity power generation have denoted by an equivalent SCIG driven by variable speed wind turbine through an equivalent gearbox. The PV system with 60KW has connected with the grid through charge controller and inverter to enhance the continuous power supply & to maintain the system as stable. The OWF, MCF, PV system, FESS and load have coupled with an AC bus that was fed to the power grid by means of step-up/step down transformer, transmission lines and underground cables.

A. Wind turbine

In practice, using principles of aerodynamics that the power extracted by wind turbine can be expressed as

$$P_{meh} = \frac{1}{2} \rho_w A_w V_w^3 C_{pw} \tag{1}$$

Where ρ_w is the air density(which is equal to 1.225 kg/m^3 at sea level at temperature T=288 K), A_w is swept area of the blades (m^2), V_w is wind velocity (m/s) and C_{pw} is the power coefficient of the wind turbine parameters (The power coefficient reaches an extreme rate equivalent to C_p = 0.593 [12] which means that due to several losses by machine's construction, power from wind turbine is constantly fewer than 59.3%) and the parameter C_{pw} is expressed with [1, 12]

$$C_p(\lambda,\theta) = C_1\left(\frac{C_z}{\Lambda} - C_3\theta - C_4\theta^x - C_5\right)e^{\frac{-c_e}{\Lambda}} \quad (2)$$

From which

$$\frac{1}{\Lambda} = \frac{1}{\lambda + C_7\theta} - \frac{C_3}{\theta^2 + 1} \quad (3)$$

$$\lambda = \frac{W_w R}{V_w} = \frac{2\pi NR}{V_w} \quad (4)$$

Where λ is tip speed ratio, R is the radius of wind turbine (in m), N is rotor rotational speed (rpm), ω_w is angular velocity (rad/s), θ is pitch angle (in deg) and C_1 to C_8 & x are constant coefficients of power coefficient C_{pw} of the wind turbine. The quantity of aerodynamic torque τ_w (in Nm) is assumed to be the ratio of power obtained from the wind P_w (in W) and rotor speed ω_w, as follows

$$\tau_w = \frac{p_w}{w_w} \quad (5)$$

Torque is given by,

$$\tau_w = \frac{\rho_w \pi R^2 V_m^2 C_{tw}}{2} \quad (6)$$

Where $C_{tw} = \frac{C_{vw}}{\lambda}$ is called the torque coefficient.

A. Marine current model

The MCTs are driven through tide speeds and determination of the marine-current speed is by spring and neap tides. The marine-current speeds are fixed on periodically intervals beginning at 6 hours before high waters and ending 6 hours afterwards. With the help of aerodynamic principle the following equations are obtained from marine current turbine are [15]

$$P_{mr} = \frac{1}{2}\rho_{mr} A_{mr} V_{mr}^3 C_{pmr}(\lambda_{mr}, \beta_{mr}) \quad (7)$$

Where ρ_{mr} is the water density in kg/m^3 (ρ_{mr}=1025), A_{mr} is swept area of the marine turbine [m^2] ($A_{mr}=\pi R^2$, being R is the radius of blade[m]), C_{Pmr} is power coefficient (part of the power the turbine extracts, usually in the order of 0.35-0.8) and fluid speed [m/s] V_{mr} associated with marine power is given by eqn 6.

$$V_{mr} = V_{nt} + \frac{(C - 45)(V_{sc} - V_{nc})}{(95 - 45)} \quad (8)$$

Where C is tide coefficient, V_{st} is spring tide current speed, V_{nt} is neap tide current speed and 45 & 95 in turn are the neap & spring medium coefficients. To obtain an easy and practical model of marine-current speed, the known tide coefficients are needed. Equation for C_{pm} is described as below:

$$C_{pm}(\Psi_m, \beta_m) = [d_1(\frac{d_z}{\psi_m} - d_3\beta_m - d_4\beta_m^{dz} - d_6)]e^{\frac{-d_7}{\psi_m}} \quad (9)$$

The link among λ_m, β_m and Ψ_m are

$$\frac{1}{\psi_m} = \frac{1}{\lambda_m + d_B + \beta_m} - \frac{a_0}{\beta_m^2 + 1} \quad (10)$$

Where λ_{mr} is tip speed ratio, β_{mr} is pitch angle [degree], ω_{bm} is blade angular velocity [rad/s], R_{bm} is blade radius [m] and d1-d9 is constant coefficients of C_{pm}.

B. Photovoltaic system model

The equivalent circuit of PV cell consist of a current source connected across a diode with series (R_s) and parallel resistance (R_{sh}) in which an ideal PV cell has $R_s=R_{sh}=0$. The output current from photovoltaic cell is directly proportional to the illumination level (incident light current) and sensitive to temperature. At 1000W/m^2 solar irradiation and 28^{0}C, the cell gives output current up to 4.95A. The various parameters and equations associated with PV system modeling are given by the following equations [14] and these equations are used to model the simulation of grid connected photovoltaic system of subsystems for generating cell saturation current, light generated current, cell output current and PV cell voltage.

$$I = I_L - I_0[\exp^{q((V+IRs)/AKT)} - 1] - (V + IRs)/R_{sh} \quad (11)$$

$$I_0 = I_{rr}\left(\frac{T}{Tr}\right)^3 e[qE_g(\frac{1}{Tr} - \frac{1}{T})/AK] \quad (12)$$

$$I_L = [I_{SCR} + K_1(T_C - 28)]\lambda/100 \quad (13)$$

Where I & V is Output current/voltage, I_0 /I_L is saturation current/current generated by incident light (A), q is electron charge (1.6*10^{-19}Cb), λ is cell illumination (mW/cm^2), K is boltzmann constant (1.38*10 $^{-23}$J/K), K_I is short circuit current temperature coefficient at I_{SCR} 0.0017 A/°C, I_{SCR} is short circuit current at 1000W/m^2 solar irradiation and 28^{0}C, A_{pvg} is PV generator area (m^2), G_t is solar irradiation in tilted module plane (W/m^2), I_{rr} is saturation current at T_r, T/T_c&T_r is cell temperature & referred temperature (298K), E_G is band gap energy of semiconductor, η_{pc}/η_r is power conditioning/reference module efficiency and P_{pv} is power output from this model.

C. A model of scig

The system (both MCF & OWF) being modeled includes a three-bladed turbine connected to variable-speed SCIG. In which back-back converter consist of two voltage sources converters, in-between them dc-bus capacitor is connected. One converter called GSC is placed between SCIG and the DC-bus capacitor. This GSC is used to yield machine flux for SCIG also towards best energy capture from the wind. The other converter called as GCC is keep on among the DC-bus capacitor and the grid. The purpose of this converter is to standardize the DC-bus voltage and active as well as reactive powers flows. While dc-bus voltage is gets reduced, the GCC functioned now as in rectifying method to adjust the dc-bus voltage by charging the capacitor. If energy in the wind is available, the DC-bus voltage progresses and the GCC worked in inverting manner to control the DC link voltage and the power flows also gives energy from DC-bus to the utility grid. The AC voltages and currents are transformed into d-q components also phase locked loop circuit is employed to match the frequency between grid side and system side voltages and to make voltage and currents are in phase. The objective of the machine ($SCIG_w$) side converter is to attain ideal torque via MPT also to deliver essential magnetizing current to $SCIG_w$. The control approach for machine side converter of (MCF & OWF) is shown in Fig 1 .

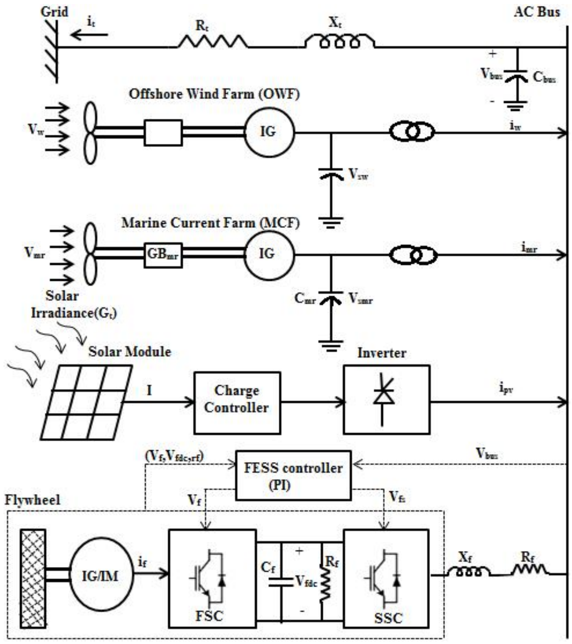

Fig 1: Control scheme of machine-side converter

Speed-control loop for MPPT, reference d-q axis $SCIG_W$ stator-current generation and generation of PWM signal for machine-side converter are employed in figure 2. The references for d − q components of $SCIG_\omega$ stator currents (I^*_{dsw} and I^*_{qsw}) are converted to three-phase reference $SCIG_\omega$ stator currents (i^*_{swa}, i^*_{swb}, and i^*_{swc}), by d − q to abc transformation using angle $\theta_{rotorfluxw}$(θ_{rf}) as

$$i^*_{swa} = I^*_{dsw} \sin \cos(\theta_{rf}) + I^*_{qsw} \cos(\theta_{rf})$$

$$i^*_{swb} = I^*_{dsw} \sin \cos(\theta_{rf} - 2\pi/3) + I^*_{qsw} \cos(\theta_{rf} - 2\pi/3)$$

$$i^*_{swc} = I^*_{dsw} \sin \cos(\theta_{rf} + 2\pi/3) + I^*_{qsw} \cos(\theta_{rf} + 2\pi/3) \quad (15)$$

The three-phase reference $SCIG_\omega$ stator currents ($i^*_{swa}, i^*_{swb}, and\ i^*_{swc}$) ,are compared with sensed $SCIG_\omega$ stator current ($i^*_{swa}, i^*_{swb}, and\ i^*_{swc}$)to compute $SCIG_\omega$ errors, and these current errors are amplified with a gain and the amplified signals are compared with a fixed frequency triangular carrier wave of unity amplitude to generate gating signals for the IGBTs of the machine-side VSC.

D. Flywheel storage and convertors

The anticipated flywheel energy-storage scheme in this paper Consists of spinning mass attached to the shaft of

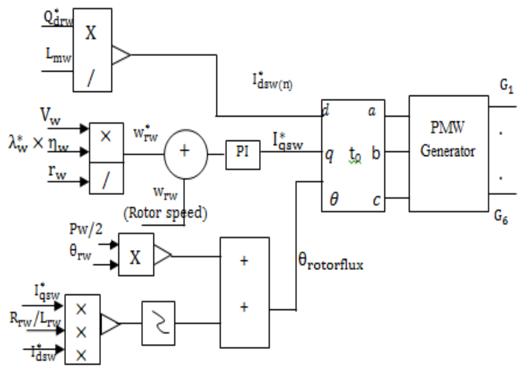

Figure 2: Configuration of the Integrated OWF, MCF and PV system with FESS

Power/photovoltaic system/wind energy. Depends upon inertia and speed of the revolving mass the certain amount of kinetic energy is stored as rotational energy. Kinetic energy is conveyed between the flywheel and with electrical machine that can function either as a motor or generator. When acting as motor, electric energy is brought to the stator winding transformed to torque then applied to the rotor it results it to gain kinetic energy. In generator mode kinetic energy stored in the rotor applied a torque is converted to electric energy. To control the power in- and output, speed, frequency the power converters are necessary to meet the grid side requirements.

an induction machine which is coupled to two bi-directional converters. A flywheel stores rotational energy by converting electrical into mechanical energy when excess energy is available in marine

IV. SIMULATION AND RESULTS

The simulation of an integrated PV system, offshore wind and marine current farm with flywheel energy storage system is implemented using MATLAB Simulink model.

PV output graph model:

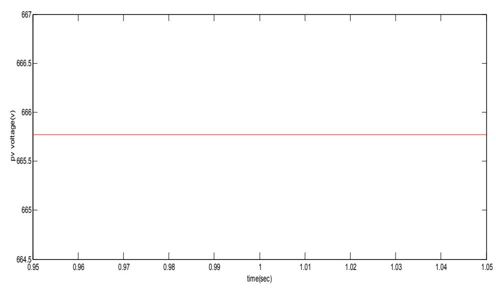

Fig 3: Output waveforms for PV voltage

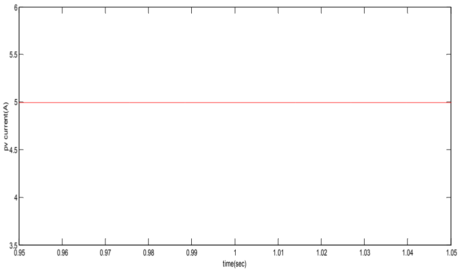

Fig 4: Output waveforms for PV current

The output waveforms for PV voltage and PV current are shown figure 4.1 and 4.2. The values for PV voltage and PV current obtained are,
PV voltage = 665V

PV current =4.9A

A. Wind farm output waveforms

Wind output power waveform is shown in figure 4.3 and output power is changes with wind speed fluctuations. In simulation result gave nearly 45KW wind generated power for given constraints and is used to meet the required power in stand-alone power system.

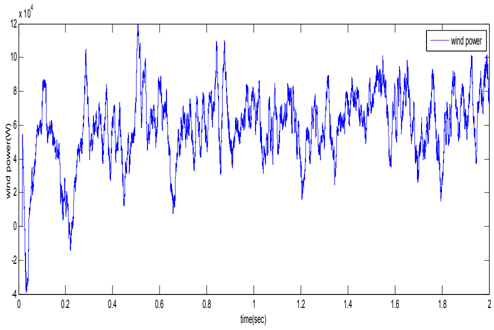

Fig 5: Wind power output waveform

B. Marine current farm waveform

Simulation output waveform of marine current and marine voltage is shown in figure 4.4 and 4.5. In simulation, Marine current farm has directly connected to the grid since marine voltage/current matches with the grid frequency and in phase. The marine current farm output power varies with tide speeds and the optimum speed to produce efficient power will be between 11m/s to 15m/s.

The load voltage and load current must be in phase with the marine current farm, wind energy output voltage and current. The power output from PV system is DC power, which is converted into AC supply through employed converters. Hence the converter output voltage and current also must be in phase with load voltage and current. These requirements are satisfied in simulation results. From the discussions Marine current farm, load, Offshore wind and converter corresponding voltage and current waveforms they clearly shows that whatever may be the changes in the load,

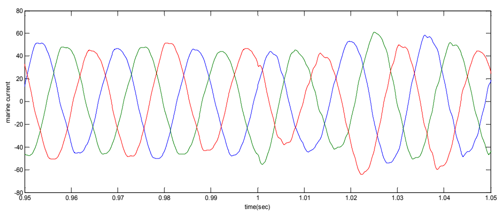

Fig 6: Simulation waveform of marine current output

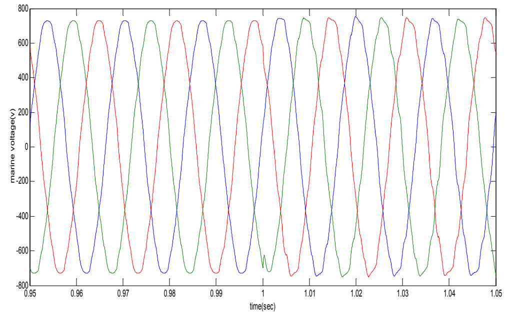

Fig 7: Simulation waveform of marine voltage output

The system voltage and current were be in phase/balanced condition. During changes in load, the real and reactive powers were effectively controlled by proper control mechanism using energy storage device under different loading conditions.

V. CONCLUSION

This paper is reported the model of performance enhancement of an integrated grid connected PV system OWF and MCF with FESS. Responses of the this system is subjected to various loading conditions have established the usefulness of the suggested FESS joint by means of the considered PI damping controller going on suppressing bus voltage deviations, active-power changeability of the test system. Results have obtained clearly reveals that modeling and performance of an integrated grid connected PV system, OWF and MCF is enhanced with the introduction of FESS.

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