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Steady State Analysis of Grid Connected Hybrid Renewable Energy Conversion Systems

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Abstract

This paper presents an analysis on steady state behavior of grid connected hybrid renewable energy conversion systems (RECS). Modeling of Doubly Fed Induction Generator (DFIG) for Wind Energy Conversion system (WECS) and marine current energy system ,and modeling of PV module is presented. A procedure for incorporating WECS, marine current energy conversion system and solar energy conversion system into a power flow program is discussed. A gird interfaced power flow program is developed in MATLAB and effectiveness of developed program is tested on a standard IEEE-9 bus system. The impact of varying wind speed, marine velocity and solar irradiation values on the steady state behavior of the grid connected hybrid power system is studied and the results are presented.

Keywords: Doubly fed induction generator, marine energy conversion system, power flow analysis. solar energy conversion system, wind energy conversion system.

Introduction

Environmental concerns and exhaustion of fossil fuels have encouraged the use of renewable energy sources [1]. To avoid global warming, the consumption of fossil fuels must be reduced. Hence, the installation of renewable energy power production plants has become a burning issue to over the world [2]. Renewable energy sources have unpredictable random behaviours. However some of the renewable sources like solar radiation, wind speed and tidal velocity have complementary profiles. One of the problems that wind energy will create in electrical power systems is the dependence of the injected power on the wind speed. The wind speed cannot he predicted, but the probability of a particular wind speed occurring can be estimated [3]. The Earth receives an incredible supply of solar energy**.** The amount of solar radiation striking the earth over a three-day period is equivalent to the energy stored in all fossil energy sources. An experimental model of gird connected PV system with high voltage gain has been studied in [4, 5]. A hybrid generation system constituted by a wind power generation branch and a PV power generation branch is discussed in [6]. A small scale offshore wind and marine current farms composed of variable speed wind turbine driven doubly fed induction generators (DFIGs) and fixed speed squirrel cage induction generators (IGs) is presented in [7]. A modified N-R method considering wind power is proposed in [8] and in [9] the power flow analysis of a power grid containing photovoltaic (PV) generating system is proposed. A typical hybrid system combines two or more energy sources, from renewable energy technologies, such as photovoltaic panels, wind or small hydro turbines. This paper deals with an integration of wind, tidal and solar energy conversion system to perform power flow analysis and thereby analyses the effect of change in wind speed, marine velocity and solar irradiation to the operating point of power systems.

This paper is organized as follows: Section 2 describes modelling of hybrid power systems components for steady state analysis. Section 3 presents power flow analysis of grid connected hybrid power systems. Section 4 describes about test system used for steady

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state analysis. In section 5, the results of power flow analysis of gird connected hybrid power systems are presented and the variation of voltage real power and reactive power with varying network parameters are analysed. Conclusion is presented in section 6.

Modeling for steady state analysis

In this section, modelling of wind turbine, marine turbine, DFIG and for steady state analysis is presented

Wind Turbine Model

The power obtained by the turbine is a function of wind speed. The simple model used commonly to represent the turbine is based on the power coefficient C_p versus the tip speed ratio λ [10]. The mechanical power extracted from the wind turbine is given by

$$P_{mech} = \frac{1}{2}\rho A U_w^3 C_p \quad (1)$$

C_p is a function of the blade pitch angle θ and the tip speed ratio λ defined as,

$$\lambda = \frac{\omega R}{U_w} \quad (2)$$

The variation of C_p with the variation of U_w and λ is non-linear in nature [11].The C_p is generally represented as,

$$C_p(\lambda, \theta) = C_1\left(\frac{C_2}{\Lambda} - C_3\theta - C_4\theta^x - C_5\right)e^{\frac{-C_6}{\Lambda}} \quad (3)$$

$$\frac{1}{\Lambda} = \frac{1}{\lambda + 0.08\theta} - \frac{0.035}{\theta^3 + 1} \quad (4)$$

where, ω- Rotational speed of rotor; R– Radius of swept area; θ- Pitch angle (in degree) ; C_1 to C_6 and x are constants

Marine Current Turbine Model

The marine current turbine (MCT) is assumed to be driven by tide speeds and the marine-current speed is determined by spring and neap tides. The marine-current speeds are given at hourly intervals starting at 6 hour before high waters and ending 6 hour after. Therefore, it is easy to derive a simple and practical model for marine-current speed under the known tide coefficients [12]. The marine current speed is given by

$$V_{mr} = V_{nt} + \frac{(C_{mr} - 45)(V_{st} - V_{nt})}{95 - 45} \quad (5)$$

The mechanical power produced by an MCT is given by

$$P_{mr} = \frac{1}{2}\rho_{mr} A_{mr} V_{mr}^3 C_{pmr}(\lambda_{mr}\beta_{mr}) \quad (6)$$

The C_{pmr} can be expressed as

$$C_{pmr} = d_1\left[\frac{d_1}{\psi_{mr}} - d_3\beta_{mr} - d_4(\beta_{mr})^{d_5} - d_6\right]e^{\left(-d_7/\psi_{mr}\right)} \quad (7)$$

in which,

$$\frac{1}{\psi_{mr}} = \frac{1}{\lambda_{mr} + d_8\beta_{mr}} - \frac{d_9}{(\beta_{mr})^3 + 1} \quad (8)$$

$$\lambda_{mr} = \frac{R_{B\omega r}\,\omega_{Bmr}}{V_{mr}} \quad (9)$$

where,

Cmr – marine coefficient

Vst – spring marine-current speed (in m/sec)

Vnt – neap marine-current speed (in m/sec)

95 and 45 is the spring and neap tide medium coefficient respectively

ρ_{mr} – water density (1025 kg/m^3)

A_{mr} – blade impact area (in m^2)

V_{mr} – marine velocity (in m/sec)

d_1 to d_9 are the constant coefficients of power coefficient of C_{pmr}

Doubly Fed Induction Generator Model for Wind and Marine Energy System

`A doubly fed induction machine is a wound-rotor doubly fed electric machine. The steady state equivalent circuit of DFIG [13] is shown in fig.1.

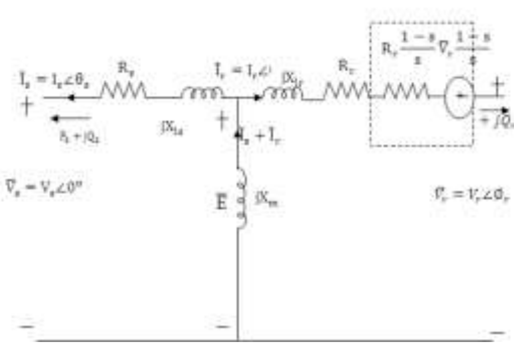

Fig. 1 Steady-state equivalent circuit of DFIG

The equations for stator and rotor real and reactive power are employed as given in [13].The stator real power (P_s) and reactive power (Q_s) can be written as equations (10) and (11) respectively,

$$P_s = R_e\left(\overline{V_s}\overline{I_s^*}\right)$$

$$P_s = \frac{-V_s^2}{A^2+B^2}(BR_r + AsX_r) + \frac{V_sV_r}{A^2+B^2}(AX_m\cos\emptyset_r - BX_m\sin\emptyset_r) \quad (10)$$

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$$Q_s = \mathrm{Im}(\overline{V}_s \overline{I}_s^*)$$

$$Q_s = \frac{-V_s^2}{A^2+B^2}(AR_r - BsX_r) - \frac{V_s V_r}{A^2+B^2}(BX_m \cos\emptyset_r + AX_m \sin\emptyset_r) \quad (11)$$

The rotor real power (P_r) and reactive power (Q_r) can be written as equations (12) and (13) respectively,

$$P_r = R_e(\overline{V}_r \overline{I}_r^*)$$

$$P_r = \frac{-V_r^2}{A^2+B^2}(BR_s + AX_s) + \frac{sV_s V_r}{A^2+B^2}(AX_m \cos\emptyset_r + BX_m \sin\emptyset_r) \quad (12)$$

$$Q_r = \mathrm{Im}(\overline{V}_r \overline{I}_r^*)\ Q_r$$

$$Q_r = \frac{-V_r^2}{A^2+B^2}(AR_s - BX_s) - \frac{sV_s V_r}{A^2+B^2}(BX_m \cos\emptyset_r - AX_m \sin\emptyset_r) \quad (13)$$

The expression for the electrical power can be obtained as

$$P_e = -I_r^2 R_r \frac{1-s}{s} - \frac{1-s}{s} R_e(\overline{V}_r \overline{I}_r^*)$$

$$P_e = \frac{(s-1)}{A^2+B^2}(C + D + E) \quad (14)$$

$$A = sR_s X_r + R_r X_s \,,$$

$$B = R_r R_s + s(X_m^2 - X_r X_s),$$

$$C = sR_r X_m^2 V_s^2 - R_s X_m^2 V_r^2$$

$$D = (A - 2R_r X_s) X_m V_s V_r \cos\emptyset_r$$

PV Array Modeling

DC Part Model

PV arrays are built up with combined series/parallel combinations of PV solar cells, which are usually represented by a simplified equivalent circuit model such as the one given in fig.2.

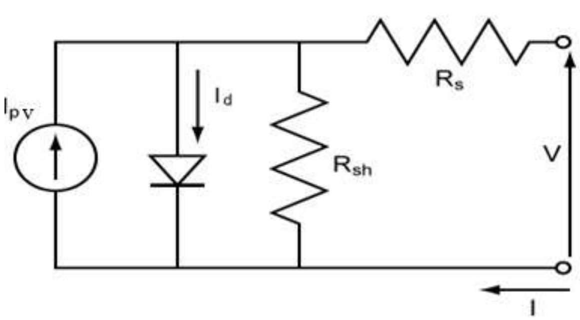

Fig.2. Equivalent circuit of PV cell

The voltage and current relationship of the simplified solar cell based on Kirchoff's current law can be expressed by the mathematical equation for the output current of single cell as

$$I = I_{pv} - I_0\left[\exp\left(\frac{V+R_s I}{V_t a}\right) - 1\right] - \frac{V+R_s I}{R_{sh}} \quad (15)$$

where,

I_{pv} –photovoltaic current of PVarray

I_0 –leakage or reverse saturation current of PV array

V–PV cell voltage

V_t– $N_s kT/q$ is the thermal voltage of array with N_s cells connected in series

R_s–equivalent series resistance of array (in ohms)

R_{sh}–equivalent parallel resistance (in ohms)

k – Boltzmann constant (1.3860503×10^{-23}J/K)

q– electron charge (1.60217646×10^{-19}C)

a– ideality factor

The light generated current of the PV cell depends linearly on the solar irradiation and is also influenced by the temperature according to equation (16)

$$I_{pv} = (I_{pv,n} + K_1 \Delta T)\frac{G}{G_n} \quad (16)$$

Here, ΔT –T-T_n

The power of PV array can be calculated as

$$P_{pv} = V_{pv}\left\{I_{pv} - I_o\left[\left[\exp\left(\frac{q}{kT}\frac{V+R_s I}{aN_s}\right)\right] - 1 - \frac{V+R_s I}{R_{sh}}\right\} \quad (17)$$

AC Part Model [14]

The average real power and average reactive power output of the PV inverter to the grid can be expressed as equations (18) and (19),

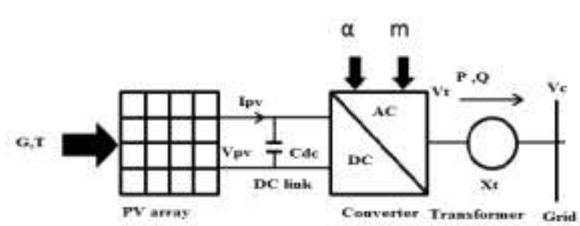

Fig. 3 Schematic diagram of single stage PV inverter

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$$P = \frac{V_t V_c}{X_t} \sin\alpha \quad (18)$$

$$Q = \frac{V_t}{X_t}(V_c \cos\alpha - V_t) \quad (19)$$

where,

V_t –RMS value of terminal voltage
V_c –RMS value of inverter output voltage
X_t –equivalent reactance of transformer
α –phase angle difference of V_c and V_t
m – modulation index

Power flow analysis of grid connected hybrid RECS

The power flow study is to determine complete voltage angle and magnitude information for each bus in a power system for specified load and generator real power and voltage conditions. Once this information is known, real and reactive power flow on each branch as well as generator reactive power output can be analytically determined [15].

The power-flow analysis with the hybrid power systems is complex compared to the analysis without hybrid power system, because, the power injected into the grid by hybrid power system depends on the instantaneous wind speed, marine velocity and solar irradiation, which varies continuously. N-R power flow algorithm is reconstructed for the power flow formulation with hybrid power systems as,

$$\begin{bmatrix} \Delta P \\ \Delta Q \\ \Delta P_W \\ \Delta P_T \\ \Delta P_S \end{bmatrix} = \begin{bmatrix} \frac{dP}{d\theta} & \frac{dP}{dV} & \frac{dP}{dS_W} & \frac{dP}{dS_M} & \frac{dP}{d\alpha} \\ \frac{dQ}{d\theta} & \frac{dQ}{dV} & \frac{dQ}{dS_W} & \frac{dQ}{dS_M} & \frac{dQ}{d\alpha} \\ \frac{dP_W}{d\theta} & \frac{dP_W}{dV} & \frac{dP_W}{dS_W} & \frac{dP_W}{dS_M} & \frac{dP_W}{d\alpha} \\ \frac{dP_T}{d\theta} & \frac{dP_T}{dV} & \frac{dP_T}{dS_W} & \frac{dP_T}{dS_M} & \frac{dP_T}{d\alpha} \\ \frac{dP_S}{d\theta} & \frac{dP_S}{dV} & \frac{dP_S}{dS_W} & \frac{dP_S}{dS_M} & \frac{dP_S}{d\alpha} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta V \\ \Delta S_W \\ \Delta S_M \\ \Delta\alpha \end{bmatrix} \quad (20)$$

where,
$[\Delta P_w]$ is power mismatch matrix of WT ,which is given by $\Delta P_w = P_{mech} - P_e$ from equations (1) and (14)
$[\Delta P_T]$ is power mismatch matrix of MCT ,which is given by $\Delta P_T = P_{mr} - P_e$ from equations (6) and (14)
$[\Delta P_s]$ is power mismatch matrix of PV module ,which is given by $\Delta P_s = P_{pv} - P$ from equations (17) and (18)

Description of test system

In this paper, standard IEEE 9 bus system is considered for power flow analysis.
The single diagram of standard IEEE- 9 bus system interfaced with hybrid RECS at 5th bus is shown in fig.4.

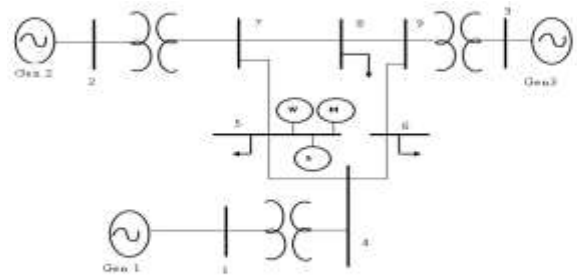

Fig. 4 Single line diagram of hybrid RECS interfaced with IEEE-9 bus system

Power flow analysis with grid connected hybrid RECS

The power flow analysis is carried out by interfacing hybrid RECS including WT, MCT and PV module into 5th bus of IEEE 9 bus system. The power flow result is analysed by varying the wind speed ,marine velocity and solar irradiation values. The voltage magnitude, real power and reactive power for varying RECS parmeter obtained using power flow anlaysis is tabuletd in table 1.

Table 1.Power flow Analysis with Varying RECS Parameters

Interval	Wind speed (m/sec)	Marine velocity (m/sec)	Irradiation (W/m^2)	Voltage (p.u.)	Real Power (KW)	Reactive power (KVar)
A	5	5	200	0.948	192.4	97.455
B	10	10	400	0.949	199.9	95.784
C	15	15	600	0.953	224.6	91.631
D	20	20	800	0.949	223.4	96.250
E	25	25	1000	0.940	201.2	98.716

The variation of voltage, real power generation and reactive power consumption based on table 1 is plotted in figs 4, 5 and 6, respectively.

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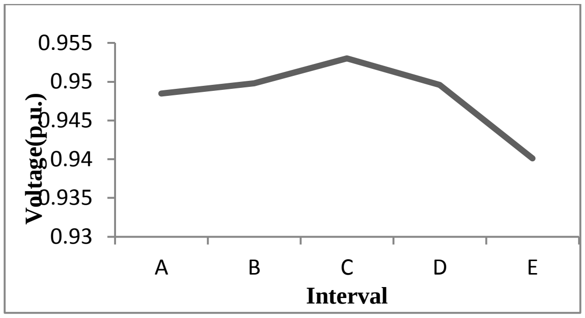

Fig.4. Voltage variation with varying RECS parameter

From fig.4 its clear that there is a increase in voltage profile up to wind speed and marine velocity of 15 m/sec and irradiation value of 600 w/m^2. The voltage profile is gradually decreasing after the interval C i.e. when the wind speed reaches speed of 15m/sec, marine velocity is 15m/sec and irradiation is 600 w/m^2 .

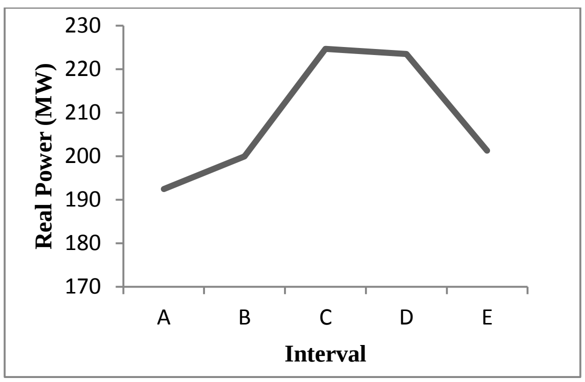

Fig. 5. Real power variation with varying RECS parameter

From fig 5 its observed that the real power generation is high for high values of network parameter. A gradual decrease in real power generation is observed from 15 m/sec of wind speed, 15 m/sec of marrine velocity and 600w/m^2 of solar irradiation.

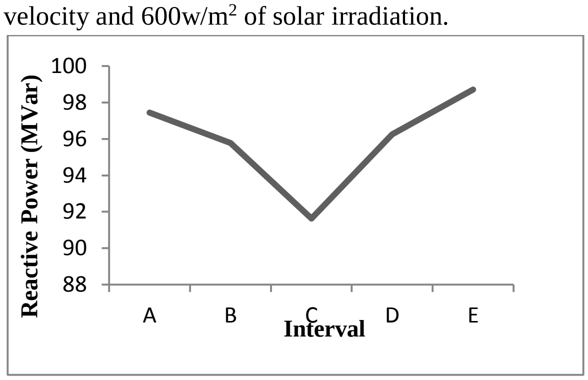

Fig 6. Reactive power variation with varying RECS parameter

Conclusion

In this paper, Power flow analysis is performed for hybrid RECS interfaced with the standard IEEE 9-bus system.. A program is developed using MATLAB .The effectiveness of the developed program is tested using a standard IEEE-9 bus system. The power flow results show that the voltage and real power increases for an optimum value of wind speed, marine velocity and irradiation values, after which a gradual decrease is observed. Hence it is suggested that the performance of grid connected hybrid RECS can be improved with the introduction of a controller for tracking maximum power. The reactive power consumption is high in the system, hence it is concluded that there is a need for reactive power compensation devices to reduce the reactive power and to improve the voltage profile.

Appendix

Hybrid RECS Data

Wind Turbine Data

Air density=1.223Kg/ m^3; Blade pitch angle =30 degree; Power coefficients C_1=0.5, C_2=116, C_3=0.4, C_5=5, C_6=21 ;P=2MW; Rs=0.00706 p.u.; Xls=0.171 p.u; Xm=2.9p.u; Rr=0.005p.u; Xlr=0.156 p.u .

2) Marine Current Turbine Data:

Water density=1025 Kg/ $m^{3;}$ Blade pitch angle =0 degree;Power coefficients d1=0.18;d2=85;d3=0.38; d4=0.25;d5=0.5;d6=11;d7=10.9;d8=0.08;d9=0.01; P=2.5MW; Rs=0.01619p.u; Xls=0.1335 p.u; Xm=3.99p.u; Rr=0.12p.u; Xlr=0.1121p.u.

PV Generation System Data

Rs=0.221p.u; Rsh=0.415p.u; a=1.3; Isc=8.21A, m=1; Xl=0.9 p.u; Gn=1000 w/m^2,T_n =25°C;I_{pvn}=8.214A Ns=54;K1=0.0032A/K;V=26.3V;k=1.3806503×10^{-23} J/K; q= 1.60217646×10^{-19}

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