OPERATION ASSESSMENT OF A WIND GENERATOR WITH A CONVENTIONAL POWER SYSTEM

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ABSTRACT

Injection of wind power into an electric grid affects the voltage quality. As the voltage quality must be within certain limits to comply with utility requirements, the effect should be assessed prior to installation. To assess the effect, knowledge about the electrical characteristics of the wind turbines is needed otherwise the result could easily be an inappropriate design of the grid connection. So, this paper aims to operate wind generator with conventional power system at some of areas of Egypt such as Egyptian coastal on Red and Mediterranean seas, Toshki and East of Oweinat that show significant promise for wind energy exploitation.

Firstly, the dynamic performance of a wind-turbine synchronous generator supplying an infinite bus- through a transmission line is study. Also, a linear model for this system is developed and proportional plus integral controller is designed. This controller is examined for some disturbances in wind speed, load and short circuit faults, and the results are compared with the open loop ones. Then, a proposed approach has been introduced to assess the energy credits of the study of wind energy system as a function of wind-turbine, generator and installation site characteristics. Also, the energy output of this wind-generator has been assessed economically to compete with conventional power systems (CPSs). Finally, the proposed approach is used to evaluate the operation of the study of wind-generator with CPSs in number of applicable applications in Egypt.

1. INTRODUCTION

Many studies had been carried out in Egypt [1] and concluded that wind energy resource has to be established as one of the economic resource pertaining the meteorological conditions of Egypt. This resource can be used for both electricity generation at large scale wind farms connected to the national grid or small scale electricity generation for development regions at coastal zones and East of Oweinat.

Wind speed is naturally random in magnitude and direction. Therefore, Control and stability of wind generating systems are of prime importance for successful operation [2]. The Mod-5 system size and features were established as a result of trade off and optimization studies driven by minimizing the system cost of energy. This led to 400′ (122 m) rotor diameter size and synchronous generator rating of 6200 kW [**3**]

So, In this paper, the nonlinear model for WTGs in Reference [4] is modified. This wind generator system consists of a wind turbine drives a three phase synchronous generator. a detailed derivation of the wind turbine torque equation is presented In Reference [5], the nonlinear equations of the system are linearised, by using Perturbation Techniques to obtain a linear state-space model [6] Also, Matlab Software Program is developed to calculate the coefficients. Also, Proportional plus integral state and output feedback controllers are designed based on this linearised model.

Furthermore, a proposed approach has been also introduced to assess the operation of wind-generator with conventional power system (CPS). The assessment includes the energy displacement of CPS, the savings in conventional generation costs and reduction in unit energy cost of the combined generation.

2- PROPOSED MODEL:

In this model, the synchronous generator equations are driven from [6]. Figure (1) shows the line diagram of the wind turbine generator. It includes; i) horizontal axis wind turbine ii) a synchronous generator, G, iii) short transmission line connected to an infinite-bus ,Vb , and , vi) a simple local concentrated reactive load, ZL at the generator terminal

2.1 Wind Turbine Model.

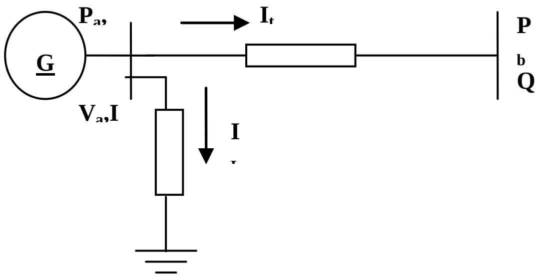

Figure (1). The line diagram of wind-turbine generator study

The regimes of wind speed for operating the wind turbine and modeling is shown in Reference (7).

The start up of the turbine occurs when the wind speed is greater than the cut-in value (Vci) and the turbine power (pt) in this regime is proportional to the cubic of wind speeds and given by :

$$P_t = 0.5\,\rho\,A\,C_P\,V_w^3 \qquad (1)$$

Where ρ is the mass density of the air, V_w is a wind speed, A the area swept by the blades and C_P is a power coefficient representing the aerodynamic efficiency.

The power coefficient depends on the ratio between the turbine's angular velocity (Ω) and the wind speed (Vw). This ratio is called the tip speed ratio λ and given by [8].

$$\lambda = \Omega R / V_w \qquad (2)$$

The model of the turbine power, Equation (2-1) depends on the value of C_P, which is given by [4]:

$$Cp = (0.44 - 0.0167\beta)\sin\left[\frac{\frac{\pi}{2}(\lambda-3)}{7.5-.15\beta}\right] - (\lambda-3)(0.00184\beta) \qquad (3)$$

2.2Generator Model:

A synchronous generator is used in the study of wind generator system. Park's equations for the generator are given in reference [5]:

2.3 System Transmission Line Model:

The transmission line system can be represented by lumped series inductance (X_e), and resistance (R_e). It can be modeled as in the synchronous generator in direct and quadrature axes and given by [6]:-

$$V_d = V_b \sin\delta + P I_d X_e/\omega_o + R_e I_d - X_e I_q \omega_r/\omega_o \qquad (4)$$

$$V_q = V_b \cos\delta + P I_q X_e/\omega_o + R_e I_q + X_e I_d \omega_r/\omega_o \qquad (5)$$

2.4 Load Modeling:

The load can be modeled in terms of load currents in d - and q-axis as follows:

$$V_d = R_l I_{ld} + P I_{ld} X_l/\omega_o - X_l I_{lq} \omega_r/\omega_o \qquad (6)$$

$$V_q = R_l I_{lq} + P I_{lq} X_l/\omega_o - X_l I_{ld} \omega_r/\omega_o \qquad (7)$$

2-5 Blade Dynamics

The dynamics of the blades can be represented by a first order differential equation as shown in Figure (4) [7]:

$$P\beta = \frac{(\beta_c - \beta)}{\tau} \qquad (8)$$

Where:

β : the reference blade pitch angle.

β_c : the pitch of the controller module.

τ : the time constant of the pitch servo.

$$\delta = \omega_r - \omega_o \qquad (9)$$

ω : angular velocity

To obtain the complete model for the system, the differential equations for the synchronous generator, transmission line, and the load are augmented to give the nonlinear model .

The initial investigation on this WTG is obtained when the active and reactive power, and the voltage of the bus, Figure (1), are known. Also, the active and reactive power of the load is given.

3. LINEARISED MODEL OF THE WGS

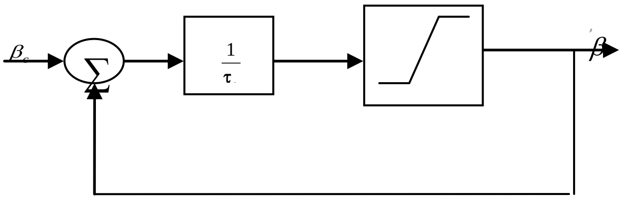

Figure (3) Block diagram of Pitch control system.

The previous non-linear model of the study generator and load are linearised as [5]:

3-1 Linearising Equations of the Wind Turbine:

$$T_m = f(\beta, \omega, V_w) \qquad (11)$$

Because the wind speed is a function of tip speed ratio which is also a function of power coefficient C_p Equation (2) . Equation (10) can be linearised as follows:

$$\Delta T_m = \frac{\partial f}{\partial \beta}\Delta\beta + \frac{\partial f}{\partial \omega}\Delta\omega + \frac{\partial f}{\partial V_w}\Delta V_w \qquad (12)$$

$$P\Delta\beta = -\frac{1}{\tau}(\Delta\beta - \Delta\beta_c) \qquad (13)$$

4- PROPOSED CONTROLLER FOR WGS

The objective of the controllers is to regulate the generator's voltage and power to be constant under load and wind speed variation [9]. So PI controller has been designed for a large (6.2MW) horizontal axis wind turbine Generator (WTG). The Matlab Software Program is used to calculate the optimal gains and its corresponding eigenvalues

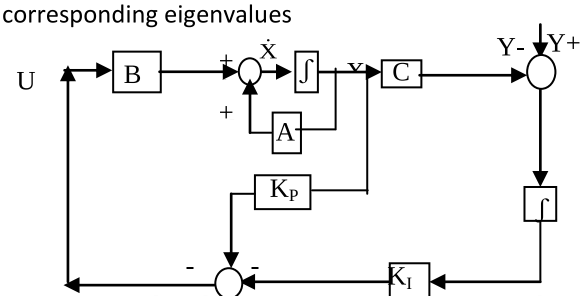

Figure (4) Closed-loop system configuration with state feedback controller.

4.1 CONTROLLER DESIGN:

Based on the linearized developed model, its state space form can be written as:

$$\dot{X} = A.X + B.U \qquad (14)$$

Where:

A : is the open loop transition matrix (n×n).

B : is the driven matrix (n × r).

U : is a control signal (r× 1) and given by: $\begin{bmatrix}\Delta V_f \\ \Delta\beta_c\end{bmatrix}$

$$X^T = [\Delta e'_q, \Delta\lambda_d, \Delta e''_q, \Delta\lambda_q, \Delta e''_d, \Delta\delta, \Delta\omega, \Delta I_{ld}, \Delta I_{lq}, \Delta\beta] \qquad (15)$$

4-2 State Feedback Controller Design:

Based on Equation (14), optimal state feedback controllers have been designed.

Design of a multivariable state feedback regulator can be mathematically stated as minimizing the performance index in the form:

$$J = 1/2\int_o^\infty (X^T Q X + U^T R U)dt \qquad (16)$$

An important part of the design process is choosing the weighting matrices Q and R. For any values of Q and R matrices, the optimal solution to the LQR (Linear quadratic regulator) problem is obtained by minimizing J with respect to U. The optimal solution is obtained by finding the symmetric positive definite matrix M by solving the following equation[11]:

$$A^T M + MA - MBR^{-1}B^T M + Q = 0 \qquad (17)$$

$$U = -R^{-1}B^T MX = -K_x * X \qquad (18)$$

The corresponding closed loop system is:

$$\dot{X}(t) = (A - BR^{-1}B^T M)X(t) = (A + BK_x)X(t) \qquad (19)$$

Once M has been obtained by this manner, the optimal state feedback matrix can be calculated .

4-3 PI Output Feedback Controller Design:

The system with output controller is preferred, because some of the state variables are not available for measurement, which requires extensive digital control hardware and software requirements [9].

The PI output feedback controller can be designed from PI state feedback controller as follows:

$$Y = C.\ X \tag{20}$$

, and Y is given by:

$$Y = [\Delta P_a; \Delta V_a; \Delta\delta; \Delta\omega_r; \int \Delta V_a dt; \int \Delta P_a dt]^t \tag{21}$$

$$Y = [y_1, y_2]^t$$

$$Y_1 = [\Delta P_a; \Delta V_a; \Delta\delta; \Delta\omega_r]^t$$

$$Y_2 = [\int \Delta V_a dt; \int \Delta P_a dt]^t$$

$$K_o = -K_x * \text{pinv}(C) \tag{22}$$

$$\text{Pinv}(C) = [C' * C]^{-1} * C' \tag{23}$$

5- SIMULATION STUDIES:

The selected weighting matrices for the state controller are ,and their corresponding optimal state feedback matrix are given as :

Q = diag[900 ;800 ;80 ;80 ;80 ;80 ;200 ;1 ; 10 ;1000 ; 100000 ;20000]

R = diag[6;.1] and K_x :

$$\begin{bmatrix} 43.1 & -146.8 & -11.4 & 178.8 & 0.1 & 0.0 & 15.4 & -0.1 & -0.0497 & 0.0 & 126.9 & 33.4 \\ 0.1 & -1267.9 & -12.7 & -287.3159.7 & 183.91.9204.1 & -0.2 & & -991182.9 & 1390.4 \end{bmatrix}$$

For the output controller, the selected weighting matrices and their corresponding optimal output feedback matrix for the case of wind speed greater or equal to the rated value are:

Q = diag [10 ; 10 ; 500 ;0;5000;13000]

R = diag [0.4; 1] ,

$$[K_0] = \begin{bmatrix} -0.0695 & 0.1567 & 1.4828 & 3.7847 & 168.3476 & 35.7731 \\ 0.0105 & 0.0775 & 24.1955 & 10.2178 & 40.7877 & -59.0602 \end{bmatrix}$$

6- OPERATION OF WIND GENERATORS WITH (CPS)

This approach is based on the estimation of output energy and capacity values of wind generation in CPSs, conventional energy displacement, and economy of the generation system.

6.1 Output Energy and capacity values of WG

The annual energy output of a wind-generator depends on the WG and installation site characteristics. This energy is given as follows:

$$E_{WG} = 8760 * P_{WG} * CWG \tag{24}$$

$$CWG = \frac{e^{-(v_{ci}/c)^k} - e^{-(v_r/c)^k}}{(v_r/c)^k - (v_{ci}/c)^k} - e^{-(v_{co}/c)^k} \tag{25}$$

Wher,

E_{WG} : the annual energy output of the wind-generator

P_{WG} : the rated power of the wind-generator

V_{ci}, V_r, V_{co} : the cut-in, rated and cut-out wind speed of the considered WG.

C, k, CWG : the scale , shape parameters and capacity factor of the wind-generator

6.2. Conventional Energy Displacement :

The output of combined generation system on a chronological hourly basis and required energy is specified as input as:

$$P_L = P_{CG} + P_{WG} \tag{26}$$

Where, $P_{CG} = \sum_{i=1}^{NC} P_{CG_i}$, $P_{WG} = \sum_{i=1}^{NW} P_{WG_i}$

$$P_{li} + P_{ri} - \sum^{NW} P_{WG_i} = \sum^{NC} P_{CG_i} \tag{27}$$

$$CGD = P_{WG}\ (CWG / CCG) \tag{28}$$

$$SGD = A_i * CGD + B_i * CGD \tag{29}$$

$$F = 860 * E_{WG} / (H_f * \sigma_o) \tag{30}$$

$$FC = C_f * F \tag{31}$$

Where, CG, P_{Li}, P_{fi} P_{WGi}, P_{CGi} are conventional generation ,the load, spinning reserve through, the output of WG and thermal generation units through the i th hour.

CGD,SGD : capacity and saving displacement of CG

CWG, CCG :are the capacity of WG &CG

where A_i, B_i: are the capital and fixed operation cost of 1 kW per year.

H_f is the heat value of conventional fuel , C_f is the cost per 1 ton of F and is the overall efficiency of CGS

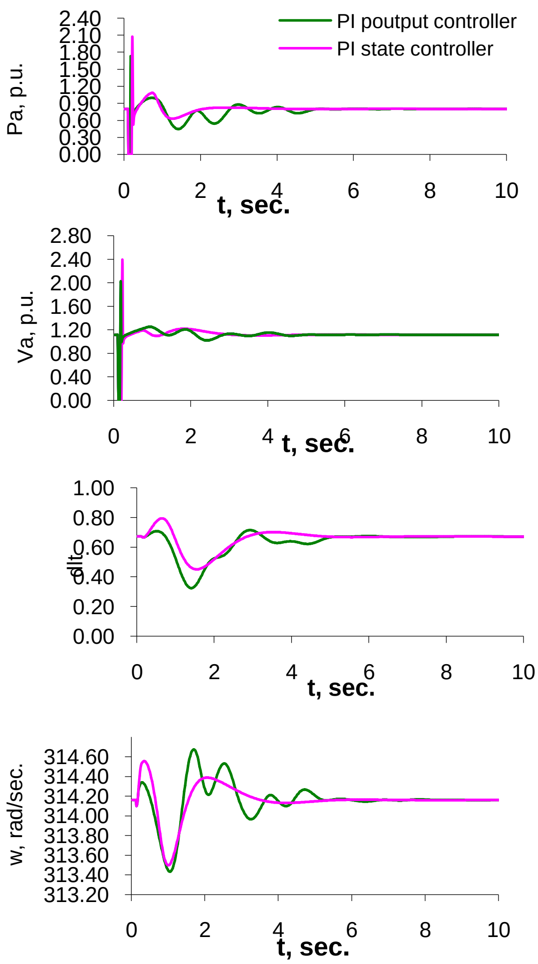

Figure (6) Comparison between the two controllers and when the system subjected to three phase short circuit

6.3 Economy of the Generation System:

The economic value of operating WGS with CGS is determined here in terms of the savings in total system generation cost. Therefore, the total conventional generation cost is defined without wind generators as a base case. The conventional generation is represented here by thermal generation units and the total annual generation cost (TAC_c) of these units is given by:

$$TAC_c = A_i * P_{rc_i} + B_i * P_{rc_i} + C_i * E_{CGi} \quad (31)$$

$$U_c = TAC_c / E_{CG} \quad (32)$$

$$U_{cw} = [U_c (E_L - E_{WG}) + U_W * E_{WG}] / E_L \quad (33)$$

Where EL is the annual energy supplied to the load.

7- APPLICATION

Figure (6) illustrates comparison between the two controllers when the system is subjected to three phase short circuit. The proposed approach, is applied for operating the study wind-generation with conventional generation units to supply the load .

1-Thermal generation units are used to represent the CPS. These unit are similar and have the characteristics as [10].

2-The heat value of the fuel used is 11500 kcal / kg and its cost is 120 $ / ton .

4- The capacity factor is varied from 0.6 to 0.9.

5- The reserve margin is taken as 10% of the generation.

Figures (7,8) depict The total annual savings and unit energy cost in convention generation at different penetration levels of WG and for different capacity factors of CPS .

8- CONCLUSION:

Equations 24 and 25 are used with the study of wind-generator characteristics, [5] to develop the capacity factor ,and annual energy output and given as 0.225 and 12.2 GWh. Also, the proposed model in section 6 is applied to assess the operation of this wind-generator with conventional power system

.This application resultant in the unit energy cost of conventional, wind and combined generation are 8.33, 3.8, and 8.27 c/kWh respectively at 0.9 CPS capacity factor. Also; the capacity displacement of conventional generation is 1.55 MW and the corresponding saving is 150350 $/yr .

The savings in fuel and fuel cost are 2856 tons and 493070 $ /yr.

-The total savings in CGS cost is 493070 $/yr.

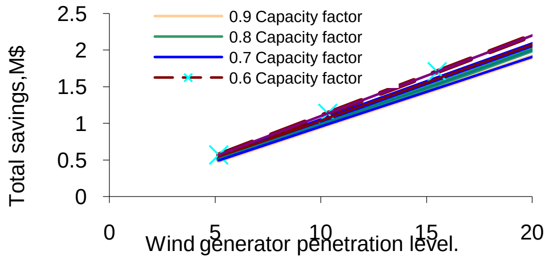

Figure (7) The total annual savings at different penetration levels of WG

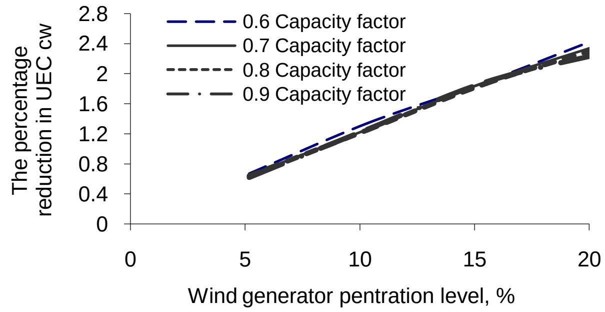

Figure (8) The percentage reduction in unit energy cost of the combined generation system at different penetration levels

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