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A Shunt Facts Supplemental Controller for Power Quality and Control in a Wind Farm System

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Abstract: **This research investigates the control strategies mainly a feedback controller and Genetic Algorithm tuned controllers as supplemental controllers besides a shunt a flexible a.c transmission (FACTS) devices static synchronous compensator (STATCOM) considered in damping power oscillations connected in a wind plant systems for power quality and control, a comparative study is implemented mainly considering real and reactive power at the area of connection of the wind farm and STATCOM to see the effect of power compensation. The supplemental controllers' designs were based on linear time invariant system model and state feedback control. STATCOM has been widely proven effective mainly in voltage control but this research has found it so useful in as well control of both reactive and real power of a FACTS incorporated wind farm system which is a two area four machine system modified to a two area five machine where by the fifth machine is the wind firm generator put at a load side with a fact device connected shunt, matlab/simulink and a power analysis toolbox were used .**

Keywords:* *FACTS incorporated wind farm, Supplemental controller, DFIG, and Low frequency oscillations

1. INTRODUCTION

Due to the crisis of the world continuing and progressive dependence on fossil fuels that accounts for more than 70% of world's energy demand and as its consumption presently amounts to more than 75 million barrels of oil per day. It is inevitable that the future global needs for it will by far exceed its supply and production [1].

The objective dream of EEC is by 2020 to achieve 12% of the world's energy produced from alternate wind energy. This comes from global needs for clean energy, away moving from fossil fuels that generate greenhouse gases [2].

A wind turbine could be considered as a reverse of an electric fan that its kinetic energy is converted to rotation of a shaft that connects to electrical generator for power production.

Direct grid coupling is possible when the wind farm plant's rotors are all moving /rotating at same angular velocity. However, the most of the modern day wind firms have a double fed induction generator (DFIG) which is used when there is variable speed. DFIG uses power electronics to maintain alternating current at a required frequency as the generator shaft speed is varying.

The integration of Doubly Feed Induction Generators (DFIG) and flexible a.c transmission devices (FACTS) controllers in a wind turbine has been improving voltage stability and frequency of the voltage through their control of active and reactive power that are decoupled. However, that power produced by the wind farms to electric network bring about some defects like;

a. Fluctuations of Frequency due to fluctuations of the wind power

b. Unfiltered harmonic emission due to presence of power electronic converters presents in the wind turbines.

c. Voltage flickers from aerodynamic nature of wind farm turbines [3].etc.

Power system oscillations can reach up to46Hz frequency as in the case of a torsional oscillation type but a frequency range between 0.1 and 2 Hz is termed as low frequency type. To promote the incorporation of wind farms into electrical networks, FACTS which are power electronics are widely put in. STATCOM is a regulating device that is used on alternating current (a.c) electricity transmission networks based on a power electronics source converter and enhances voltage stability by reactive power exchange. STATCOM can be employed at a distribution level and/or at a load side for power factor and voltage improvement alone is called a DSTATCOM but when is used for harmonic filtering is called active Power Filter. In a transmission system STATCOMs usually handle fundamentally reactive power and do provide voltage supports to buses, however the most common function is for load/voltage stability. STATCOMs provide/absorb reactive power to/from the grid in order to compensate the small voltage variations at the bus which connects wind turbine plant with the grid.Small signal stability such as increase in loads, loss of generation from on of the generators in the network e.t.c is improved by controlling the voltages of the connection points of the wind turbine farms in the system [4], also helps the system make voltage stable especially when there is a voltage dip [5]. Power system stabilizers (PSSs) are applied on some selected generators in power system with a wind farm to help in damping local mode oscillations and even sometimes the inter-area mode type but supplemental controllers are better for inter-area mode of oscillations applied with FACTS devices [6]. Performance evaluation of STATCOMs on stability improvement has been studied in [7]. Controllers using optimal control strategy such as linear quadratic regulator (LQR) for a linear system which it is a control based on minimizing a quadratic performance index were tested [8]. A wide attention had been displayed in investigation the use of state feedback controllers by some authors [9-11]. This paper studied besides the primary function of a STATCOM which is voltage stability also has proven also its contribution in enhancement of real and reactive power, their quality and stability using a state feedback. PID, GA-PID tuning that have been proposed based on different operating conditions in multimachine wind turbine plant system.

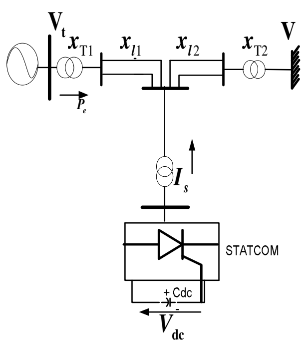

Fig.1 SMIB with STATCOM device

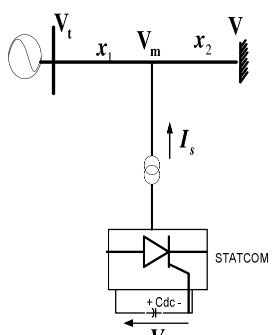

Fig.2 Equivalent SMIB with STATCOM device

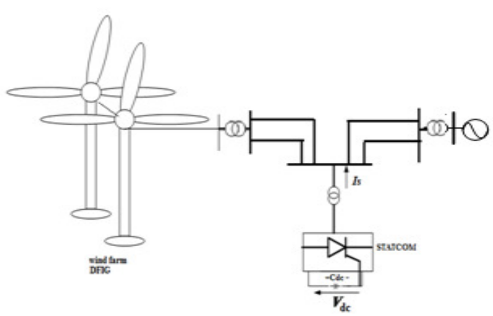

Fig. 3 STATCOM controller in cooperated Wind farm power System

2. MODELING THE POWER SYSTEM WITH A STATCOM

Shown in Fig.1, STATCOM is put unto the transmission line through a step-down transformer. The STATCOM consists of three- phase gate turn-off (GTO) – based voltage source converter (VSC) and a storage DC capacitor. It is a reactive current source with some time delay, this reactive current generated by the STATCOM isassumed positive.

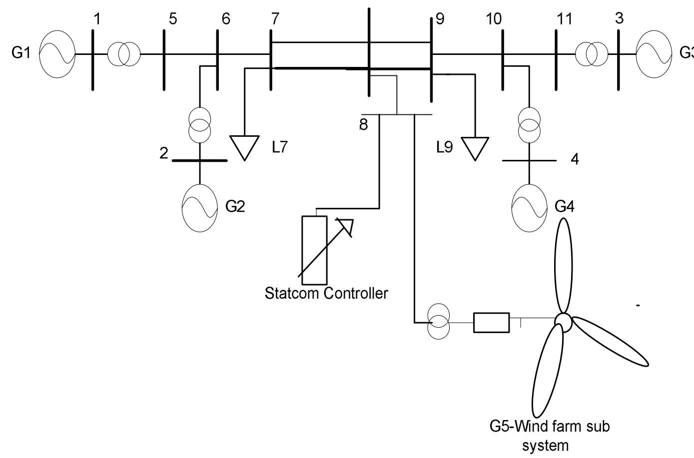

Fig. 4. Proposed Two Area STATCOM-WIND farm incorporated System

$$\dot{I}_s = (K(Vref - V) - Is)/T \text{ Where}$$

$$I_s = I_{sd} + I_{sq} = (I_s\cos\theta + jI_s\sin\theta) \quad (1)$$

Where

$K_r$is gain of the stabilizing signal.

$$\frac{dV_{DC}}{dt} = \frac{I_{DC}}{C_{DC}} = \frac{mk}{C_{DC}} I_s \quad (2)$$

From Fig.2,

$$I_2 = I_1 - I_s \; \bar{V}_t = jx_1\bar{I}_1 + jx_2\bar{I}_2 + \bar{V} \quad (3)$$

Substituting eqn. I_2 into equation.3 gives

$$\bar{V}_t = jx_1\bar{I}_1 + jx_2(\bar{I}_1 - \bar{I}_s) + \bar{V} = j(x_1 + x_2)\bar{I}_1 - jx_2\bar{I}_s + \bar{V}$$

That is

$$j(x_1 + x_2)(I_d + jI_q) = \bar{V}t + jx_2\bar{I}_s - \bar{V} \quad (4)$$

Expanding the real and imaginary parts of the above equations, the expressions of *Iq* and *Id* becomes,

$$I_d = \frac{E'_q + x_2 I_s cos\theta - V\, sin\delta}{x_1 + x_2 + x'_d} \quad (5)$$

$$I_q = \frac{V\cos\delta + x_2 I_s \sin\theta}{x_1 + x_2 + x_q} \quad (6)$$

Therefore

$$V_{md} + jV_{mq} = V(\cos\delta + j\sin\delta) + jx_2\{I_d + jI_q - I_s(\cos\theta + j\sin\theta)\} \quad (7)$$

The STATCOM voltage is assumed in phase with the bus voltage. Putting equation. 5 and equation 6 into equation.7 andthen separating the real and imaginary parts gives

$$V_{mq} = \frac{(x_1 + x_d')V\cos\delta + E_q' x_2 + I_s\cos\theta x_2 (x_1 + x_d')}{x_1 + x_d' + x_2} \quad (8)$$

$$V_{md} = \frac{(x_1 + x_q)V\sin\delta + I_s\sin\theta x_2 (x_1 + x_q)}{x_1 + x_q + x_2} \quad (9)$$

$$P_e = \frac{E_q' V_m}{x_1 + x_d'}\sin\theta + \frac{V_m^2}{2}\frac{x_d' - x_q}{(x_1 + x_q)(x_1 + x_d')}\sin 2\theta \quad (10)$$

3. STATCOM ACTIVE AND REACTIVE POWER CONTROL IN A POWER SYSTEM

The difference in voltage between the STATCOM bus AC voltage($v_L(t)$) and the output voltage($v_{0}(t)$) produces active - reactive power exchange between the STATCOM and the power system network, which is controlled by adjusting the magnitude(V_0) and the phase(ψ). but since the two voltages are in phase the ψ is assumed to be 0^0 and the control is implemented through the modulation ratio '*m*' and phase angle 'ψ' as shown by Fig. 5 [8],

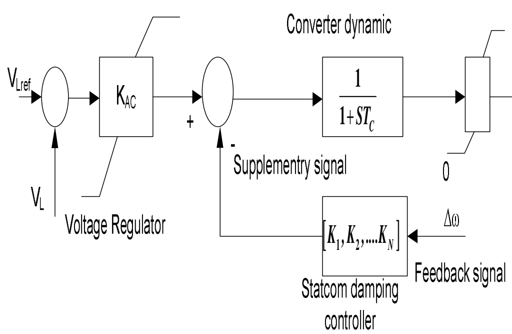

Fig. 5 STATCOM control circuit

4. REAL AND REACTIVE POWER INJECTED IN A BUS

For the formulation of the real and reactive power entering a bus, where the wind turbine is connected and other buses, the voltage at the i^{th} bus be denoted by

$$V_i = |V_i|\angle\delta_i = |V_i|(\cos\delta_i + j\sin\delta_i) \quad (11)$$

the self-admittance at bus-*i* as

$$Y_{ii} = |Y_{ii}|\angle\theta_{ii} = |Y_{ii}|(\cos\theta_{ii} + j\sin\theta_{ii}) = G_{ii} + jB_{ii} \quad (12)$$

Similarly the mutual admittance between the buses *i* and *j* can be written as

$$Y_{ij} = |Y_{ij}|\angle\theta_{ij} = |Y_{ij}|(\cos\theta_{ij} + j\sin\theta_{ij}) = G_{ij} + jB_{ij} \quad (13)$$

the power system contains a total number of *n* buses. The current injected at bus-*i* is given as

$$I_i = Y_{i1}V_1 + Y_{i2}V_2 + \cdots + Y_{in}V_n = \sum_{k=1}^{n} Y_{ik}V_k \quad (14)$$

Assuming the current entering a bus be positive and that leaving the bus be negative also the power and reactive power entering a bus will also be positive. The power at bus-*i* is then given by

$$P_i - jQ_i = V_i^* I_i = V_i^* \sum_{k=1}^{n} Y_{ik}V_k \quad (15)$$

Then real and reactive power as

$$P_i = \sum_{k=1}^{n} |Y_{ik}V_iV_k|\cos(\theta_{ik} + \delta_k - \delta_i) \quad (16)$$

$$Q_i = -\sum_{k=1}^{n} |Y_{ik}V_iV_k|\sin(\theta_{ik} + \delta_k - \delta_i) \quad (17)$$

1. STATE FEEDBACK SUPLEMENTAL CONTROLLERS

A. GA-PID CONTROLLER

Genetic Algorithms (GAs) are heuristic procedures for a search inspired by mechanisms of biological evolution and genetics. Combining the survival of the fittest principle with information exchange between individuals. Gas is a simple but a powerful tool for system optimization and applications. In GAs, candidates' solutions to a problem are similar to individuals in a population. A population of individuals is considered and maintained within the search space of GAs, each represents a possible solution to a given problem [12]. The individuals are randomly taken to form the initial population from which the improvement is sought [13]. The individualsare then considered according to their level of fitness within the problem domain and are bred together. The population breeding is achieved by the use of the operators borrowed from the natural genetic to produce future generations termed off springs. The population is successively improved with respect to the search objective. The least fit individuals are changed with the new and fitter off springs [12] from previous population generation. Over the recent years, GAs have been at the core center for researches especially in the optimization processes. . GA-PID controller for STATCOM is introduced for damping oscillations which has been elaborated and applied on this modified two area five machine with a STATCOM

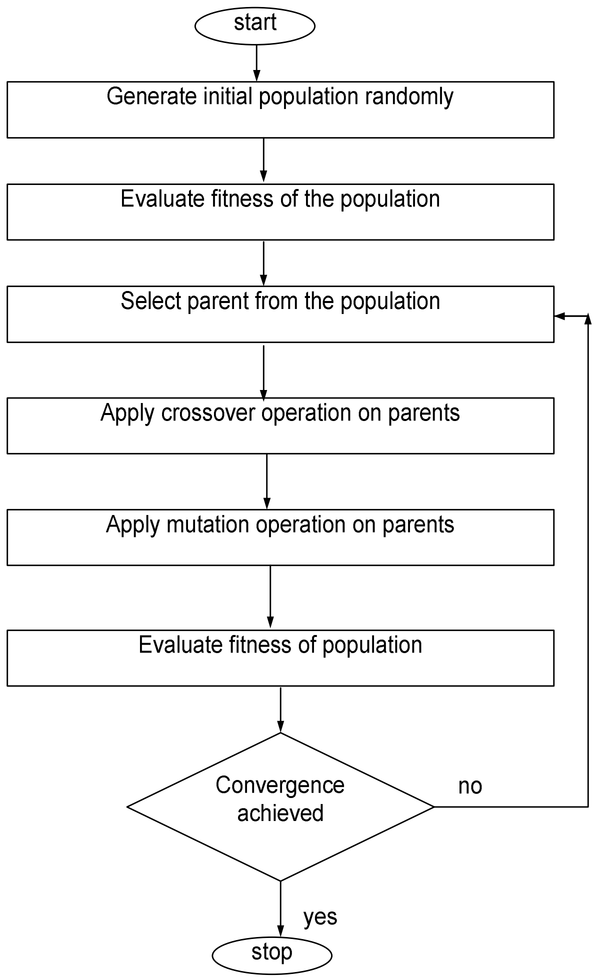

Fig.6 Simple G.A Flow Chart

B. PID-STATCOM POLE PLACEMENT APPROACH

In the use of a PID controller, gain settings could be computed by placement of the Eigen values at a pre-specified locations, this is what is known as the pole placement where K_p, K_I, K_D, are the gains of the PID controller and T_W is the wash out time constant shown in fig 3,This starts with thelinearization of the non-linear model around a nominal point to obtain a desired linearized model described by input-output system equations.

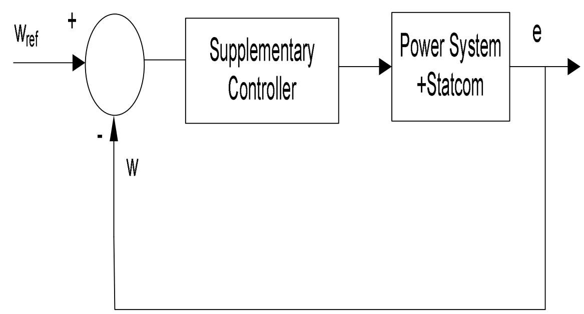

Fig. 7 PID-STATCOM Based power system closed loop block diagram

$$\dot{x}(t) = Ax(t) + Bu(t), \quad (18)$$

$$y(t) = Cx(t) + Du(t) \quad (19)$$

Where the x, y and u form state vector variables, output signal and control signal respectively, take in the Laplace transform, substituting output equations into the state equation gives

$$X(s) = (sI - A)^{-1}BU(s) \quad (20)$$

If the system output variable *'Y'* is inputted into the PID controller as shown in fig 4, the PID controller is having a transfer function *H(s),* therefore write the control signal as

U(s)=H(s)Y(s) thus

$$H(s) = \frac{sT_w}{1+sT_w}\left(k_p + \frac{K_i}{S} + k_{ds}\right) \quad (21)$$

Putting (21) into (20), we have:

$$X(s) = (sI - A)^{-1}BH(s)CX(s) \quad (22)$$

Or $[1 - (sI - A)^{-1}BH(s)C]\,X = 0$ (23)

If λ is the eigen value of the closed loop system, then
$\mathrm{Det}[1 - (\lambda I - A)^{-1}BH(\lambda)C = 0$ (24)

Equ.24 can be re-written as
$1 - C(\lambda I - A)^{-1}BH(\lambda) = 0$ (25)
or

$$H(\lambda) = \frac{1}{1 - C(\lambda I - A)^{-1}B} \quad (26)$$

Equ.21=Equ.26, thus

$$\frac{\lambda T_w}{1+\lambda T_w}k_p + \frac{T_w}{1+\lambda T_w}k_i + \frac{\lambda^2 T_w}{1+\lambda T_w}k_d = \frac{1}{1 - C(\lambda I - A)^{-1}B} \quad (27)$$

Selection of the dominant eigen values at the desired location, considering $\lambda=\sigma+j\omega_d$, and separating imaginary parts from the real of (27) brings in two equations in terms of three(3) gain parameters, A third equation can be obtained by pre-specifying another real pole.

5. RESULTS AND DISCUSSION

The results were obtained and presented under the operating condition that is normal loading: Pe=1.0pu at unity pf.; Vt=1.0 p.u. and it also presents a comparison of the responses from the feedback approaches namely Butterworth, ,ITAE,PID and GA tuned PIDs based on the compensated closed loop system, the controller parameter aswere found to be K_p, K_i and $K_p$and [K_1, K_2, K_3, K_4] for the settling time of Ts=5s and w_0=1 rad/s.

The research also investigated another means of alternative for solving the above issues; namely Genetic Algorithm (GA-PID) controller for STATCOM Wind farm power system and introduced for damping oscillations which has been applied on the two area five machineusing genetic algorithm optimization technique.

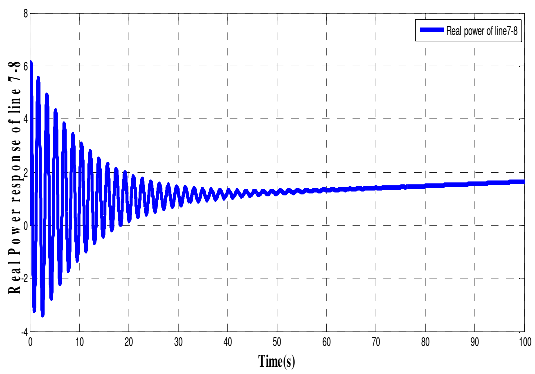

Fig. 8. Real power response of line 7-8 using PID

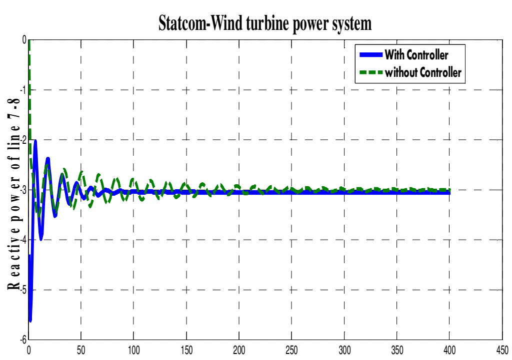

Fig. 9. Reactive Power response of line 7-8using PID

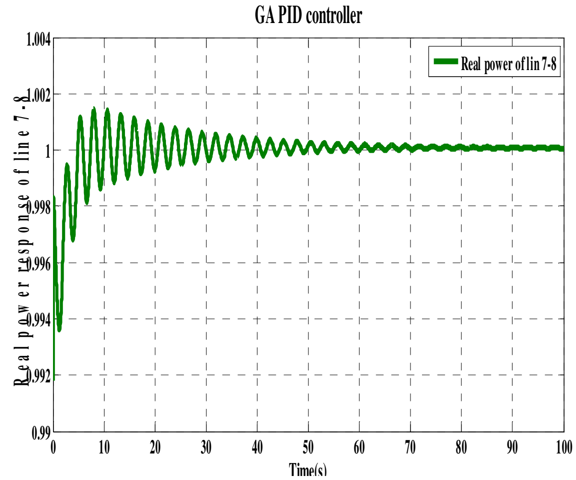

Fig. 10 Real Power Response of line 7-8using G.A PID

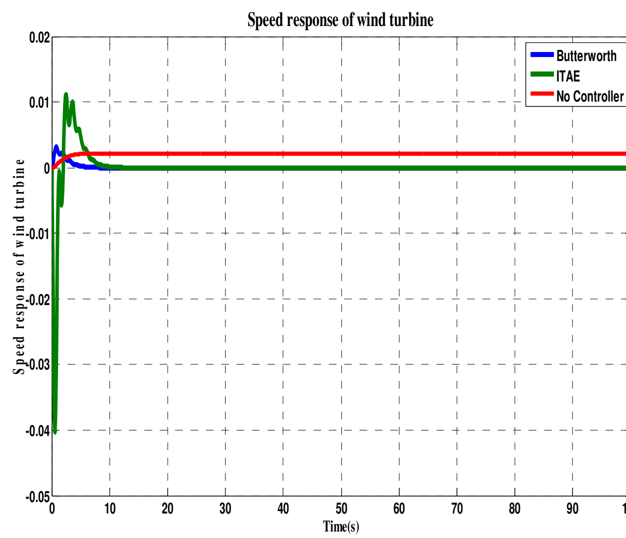

Fig. 11. Speed Response of The Wind Turbine Generator

6. CONCLUSIONS

In this paper, STATCOM Controller based on state feedback concepts are proposed for damping oscillations and the effectiveness of the proposed control methods are compared with G.A. PID and the pole placement PIDs, from the results of the real and reactive power on line 7-8 where the controller and STATCOM were connected has shown that the state feedback controllers both the PID and G.A PID least over shoot and small steady state error, and the response approaches unity better than the response without controller

Also the speed difference between the generator 1 and the turbine generator is better approaching zero when using the controller.

The GA-PID constants were found to be $K_p = 99.4$, $K_i = 99.8$ and$K_p = 90.5$ using genetic algorithm optimization technique and the Ks were found to be[0.45 3.32 14.7 73.9] . Fig.9 to Fig 10 show the responses for the reactive power in line 7-8 with GA Controller, without controller and with PID controller. Figure 11 shows the response for speed deviation between Generator 1 and Turbine Generatorwith and without controllers,

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APPENDIX

Generator: H = 3.642, D = 0, Xd=1.8572, Xq=1.4845, X'd =0.4245, X'q =1.04, T'do = 6.66, T'qo=0.44, Ra=0, δ0=44.370.

Exciter: KA=400, TA=0.027 s

Transmission line: R=0, XL = 0.8135, XT=0.1464, XTH=0.1363, G=0, B=0;