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Acomparison of Supplementary Controllers for Stability in Conventional With and Without Wind Turbine Farm Power Systems

A. U. Lawan Andj.S Kazaure
Department Of Electrical Engineeringbayero University Kano And Department Of Electrical & Electronic Engineering, Hussaini Adamu Federal Polytechnic, Kazaure, Jigawa State

ABSTRACT

This paper presents some polynomial approximations and pole placements control approaches to a multimachine power systems all in-cooperating a supplementary controllers designed based on the state feedback control and static synchronous compensator (STATCOM) as a primary controller. The linear mathematical model of STATCOM is used in the systems and the proposed approach is tested on power system with and without the additional controllers in two different power system; wind farm and conventional power network by digital computer simulation programs for different types of loading and disturbances. Comparisons of these results have shown the effects and advantages of feedback supplementary control introduction in power systems.

KEY-WORDS: *-STATCOM, Polynomial Algorithms, Windfarm, supplementarydamping*

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I. INTRODUCTION

Fossil fuels accounts for more than 70% of world energy needs and is still increasing, world consumption demandscurrently amountto not less than75million barrels of oil per day. It is clear that future world energy demands for oil will by outweigh the supply [1].The main objective of the European Economic Communityachieving minimum 12%of all energy produced to be from renewable wind power before 2020. This necessitates global needs ofcleaner energy, movingaway from greenhouse gases emitted from fossil fuels which are by far muchmore than that generated by wind farm plants [2].The moving energy of the wind is converted to the rotation of a shaft, which connects to anelectrical generator via control devices. Synchronous generatorsare used for constant speed rotors, if attached to thegrid network, it should be synchronized and controlled to run at the grid frequency but direct gridcoupling is possible where rotors are all rotating at the sameangular speed and frequency. However, most modern day wind farmsusedouble fed inductiongenerators(DFIG)which can be used for changing speeds as a results of constant changing wind power and speed, DFIG employs power electronics whichmaintain alternating current at 50 or 60 Hz even though the generator shaft speed isvarying. The fluctuationsof wind bring aboutfluctuations in the power generated by the wind turbine to the grid network,therefore, use of Flexible AC Transmission Systems (FACTS) devices in such networks both conventional (non-wind farm) and wind farms in cooperated networks in up grading power systemstability is a vital research. The incorporation of FACTS Controllers inwind turbines, improves stability and frequency of the voltage through their decoupled control of active and reactivepower. Power system oscillations can reach up to 46Hz due to torsional oscillation but a frequency less than 4Hz istermed lowfrequency oscillation which can occur in both non wind and wind farms and introduction of wind farms into the electrical network can be achieved by the integration FACTS devices like STATCOM and the supplementary controllers. A static synchronous compensatorSTATCOM) is a regulating device used on alternatingcurrent electricity transmission networks based on a power electronics source converter and stimulates voltage stability by reactive power regulation [3]. In the power transmission system STATCOMs concern is only a reactive power and gives voltage support to buses. However, the primary function is for voltage stability. STATCOM generates or absorbs reactive power to or fromthe power grid in compensating for small voltage deviations at the wind turbine farm –grid connection point. That is improving stability through control of voltages at the connection pointsto the grid[4], and alsohelps the wind farm system to make voltage stable especially after a voltage dip happens[5].

Traditionally power system stabilizers (PSS) are applied on some generators that generate more oscillations or have shown to have more coordinated effects on other generators in damping for damping local mode oscillation and sometimes even inter-area mode oscillation but supplementary controllers combined with STATCOMhas proven better for inter-area mode oscillation applied to the FACTS devices [6].Performance evaluation for study of STATCOM on power system stability on conventional, non-wind farmhas been studied in [7], linear quadratic regulator (LQR) also being applied for stability studies using optimal control law [8]. In this research paper, state feedback polynomial controllers have been proposed and tested using STATCOM supplementary controllers using various algorithmsand compared in different givenconditions:Multi machine windturbine farm and conventional multimachineplant system.

II. MODELING THE STATCOM- POWER SYSTEM

Shown in Figure1, the FACTS device STATCOM is connected to the power transmission line through an in cooperated step-down transformer, STATCOM has a three phase gate turn-off (GTO) – based voltage source converter (VSC) and a DC capacitor which is a reactive current source and assumed positive. The difference in voltage between the STATCOM bus AC voltage and output voltage *p*roduces active and reactive power exchange between the STATCOM and the power system, which can be controlled by adjusting the magnitude V_0 and the phase ψ

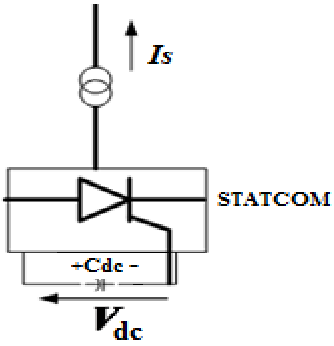


Figure 1.0 STATCOM Device

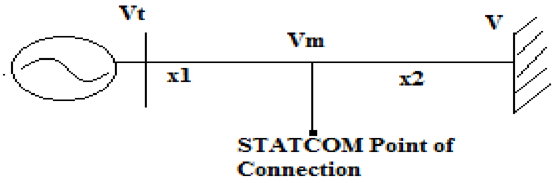


Figure 2.0 SMIB power system for STATCOM connection

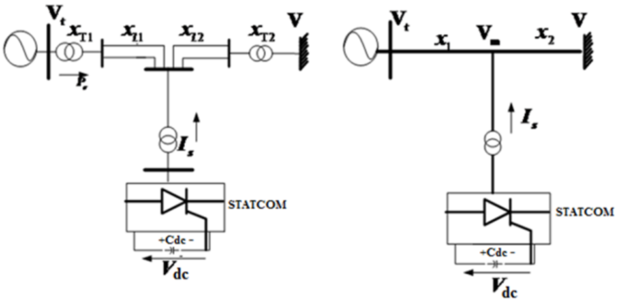


Figure 3.0 Network and its equivalent SMIB with a STATCOM for conventional power system

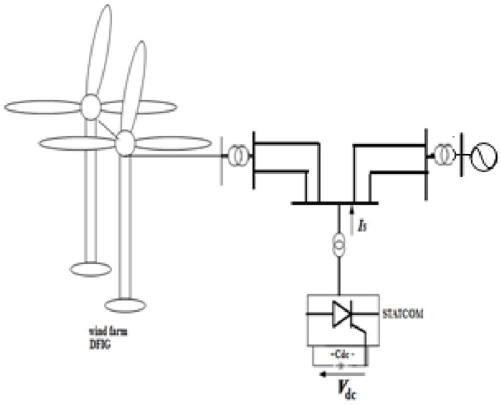


Figure 4.0 STATCOM integrated Wind farm Turbine power System

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

Where

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

K_ris the stabilizing signal gain

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

From Fig.2, $I_2 = I_1 - I_s$ $\qquad \bar{V}_t = jx_1\bar{I}_1 + jx_2\bar{I}_2 + \bar{V}$ (3)

Substituting eqn. I$_2$ into eqn. **3** gives

$\bar{V}_t = jx_1\bar{I}_1 + jx_2(\bar{I}_1 - \bar{I}_s) + \bar{V} = j\left(x_1 + x_2\right)\bar{I}_1 - jx_2\bar{I}_s + \bar{V}$ (4)

That is

$j\left(x_1 + x_2\right)(I_d + jI_q) = \bar{V}t + jx_2\bar{I}_s - \bar{V} \Rightarrow j\left(x_1 + x_2\right)(I_d + jI_q) = x_q I_q + (E_q' - x_d' I_d) - jx_2 I_s(\cos\theta + j\sin\theta) - V(\cos\delta + j\sin\delta)$ Expansion gives rise to

$$I_d = \frac{E_q' + x_2 I_s cos\theta - V\, sin\delta}{x_1 + x_2 + x_d'} \qquad (5)$$

$$I_q = \frac{Vcos\delta + x_2 I_s sin\theta}{x_1 + x_2 + x_q} \qquad (6)$$

$\bar{V}_m = jx_2\bar{I}_2 + \bar{V} = \bar{V} + jx_2(\bar{I}_d + j\bar{I}_q - \bar{I}_s) = V_{md} + jV_{mq}$ Therefore

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

STATCOM voltage should be in phase with the bus voltage. Putting eqn. 5 &eqn 6 into eqn.**7** and separating the real and imaginary parts give

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

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

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

The dynamic equations of the generator and the excitation system are expressed as

$\Delta\dot{\delta} = \omega_b \Delta\omega$ (11)

$$\Delta\dot{\omega} = -(\Delta P_e + D\Delta\omega)/M \qquad (12)$$

$$\Delta\dot{E}'_q = (-\Delta E'_q + (x_d - x'_d)\Delta i_d + \Delta E_{fd})/T'_{d0} \qquad (13)$$

$$\Delta\dot{\boldsymbol{E}}_{fd} = -\frac{\boldsymbol{K}_A}{\boldsymbol{T}_A}\Delta\boldsymbol{V}_t - \frac{1}{\boldsymbol{T}_A}\Delta\boldsymbol{E}_{fd} \qquad (14)$$

$$\dot{\boldsymbol{I}}_s = (\boldsymbol{K}_r\Delta\boldsymbol{u} - \Delta\boldsymbol{Is})/\boldsymbol{T} \qquad (15)$$

Let the input of STATCOM controller to be

$$\Delta\boldsymbol{u} = (\boldsymbol{V}_{ref} - \boldsymbol{K}_u\Delta\boldsymbol{V}_m + \boldsymbol{K}_\omega\Delta\omega) \qquad (16)$$

$K_u$and $K_\omega$are gainsof the voltage and damping control loop, respectively.

FEED BACK CONTROLLERS

A. Pole placements and PID Algorithms

Assume single-input system dynamics given by

$$\begin{aligned}\dot{x}(t) &= Ax(t) + Bu(t),\\ y(t) &= Cx(t)+Du(t).\end{aligned} \qquad (17)$$

Taking a control law of the form:

$$u(t)=-Fx(t) \text{ or } u(t)=r(t)-Fx(t) \qquad (18)$$

Is the state feedback that brings the system to the form of a closed loop transfer function

$$\begin{aligned}x(t) &= (A - BF)x(t) + Br(t),\\ y(t) &= (C - DF)x(t) + Dr(t)\end{aligned} \qquad (19)$$

So we have

$$x = (SI-A)^{-1}B(r-Fx) \Leftrightarrow sx-Ax= Br-BFx \qquad (20)$$

Taking y = Cx, the new closed loop transfer function is

$$s_d(s) = C(sI-A_F)^{-1}B \text{ where } A_F = A-BF \qquad (21)$$

Closed loop polynomial is

$$x_{cl} = det(sI-A_F) \qquad (22)$$

There exists state feedback gain Kso that $x_{cl}(s)$ is closed loop characteristic polynomial.

B. Butterworth and ITAE polynomials Algorithms

In this controller design, table 1.0 is used which is a standard control approximation procedure where by coefficients of the power system under consideration which is first reduced to seventh order were used andcompared with the standard table (table 1.0), then the controllers, K's are determined

Mat labalgorithms for finding the K's algorithm is summarized as follows: –

K= [K$_1$, K$_2$, K$_3$…….Kn] where n is the order of thereduced power system matrix'A'A = $\begin{matrix} a11 & a12 & a13 \\ a21 & a22 & a23 \\ a31 & a32 & a33 \end{matrix}$

$$‘B=\begin{matrix} b1 \\ b2 \\ bn \end{matrix},$$

B is the input to the both conventional and wind farmpower system and is taken from the output of the STATCOM.

Comparing;

$A(s) = SI-(A-BK)$ (23)

Withnth order equation from either
to find Butterworth and ITAE constants K,s from thetablegives;
The numerical values of K1, K2, K3….Kn. where n is seven(7)
MATLAB COMMANDS

- Form the desired polynomials equationsΦd(s) and ,
- Use place command to determine the feedback gains. –
- Simulate andcheck the performance and control effects.

Butterworth isan approximation techniques where by poles are positioned on a circle centred at the origin with a given radius, *R.* These poles are gotten from the solution of the nth order equation(24)below, Butterworth approximation has only poles, i.e., no finitezeros and gives a maximally flat response around zero and infinity, to guarantee stability,
the poles that lie in the left half-plane are identified

$$\left(S/R \right)^{2n} = (-1)^{n+1} \qquad (24)$$

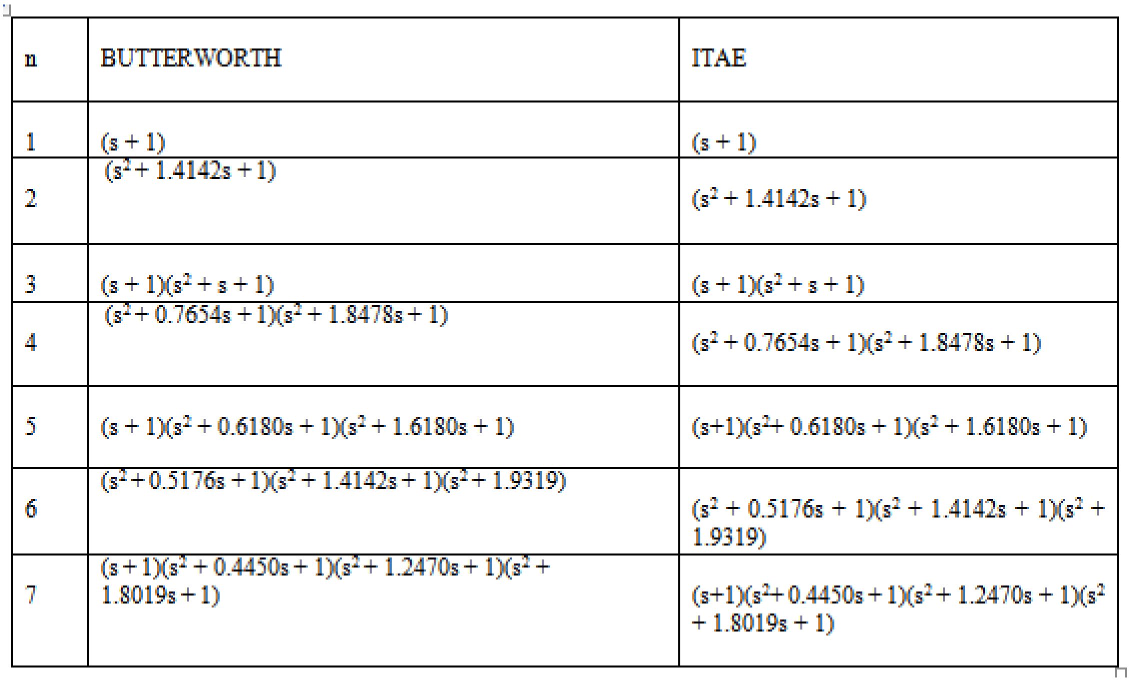
While **ITAE** choose those poles that exactly match the

nth polynomial equation denominators which are designed to minimize the **ITAE** “integral of time multiplied by absolute value of the error” as in (25)

$$J_{ITAE} = \int_0^{\infty} t\,|\,e(t)\,|\,dt \qquad (25)$$

Where e(t) shows the deviation in speed and time t is the time of simulation.

Table 1.0 Polynomial algorithms coefficient



n	BUTTERWORTH	ITAE
1	$(s + 1)$	$(s + 1)$
2	$(s^2 + 1.4142s + 1)$	$(s^2 + 1.4142s + 1)$
3	$(s + 1)(s^2 + s + 1)$	$(s + 1)(s^2 + s + 1)$
4	$(s^2 + 0.7654s + 1)(s^2 + 1.8478s + 1)$	$(s^2 + 0.7654s + 1)(s^2 + 1.8478s + 1)$
5	$(s + 1)(s^2 + 0.6180s + 1)(s^2 + 1.6180s + 1)$	$(s+1)(s^2+ 0.6180s + 1)(s^2 + 1.6180s + 1)$
6	$(s^2 + 0.5176s + 1)(s^2 + 1.4142s + 1)(s^2 + 1.9319)$	$(s^2 + 0.5176s + 1)(s^2 + 1.4142s + 1)(s^2 + 1.9319)$
7	$(s + 1)(s^2 + 0.4450s + 1)(s^2 + 1.2470s + 1)(s^2 + 1.8019s + 1)$	$(s+1)(s^2+ 0.4450s + 1)(s^2 + 1.2470s + 1)(s^2 + 1.8019s + 1)$

The performance of the control stability in is in terms of the rise time, settling time, overshoot and steady-state error by J-criterion optimization of equation (26)

Considering system with a transfer function

$$G(s)\,\frac{\alpha_0}{s^n+\alpha_{n-1}s^{n-1}+\cdots+\alpha_2 s^2+\alpha_1 s+\alpha_0} \quad (26)$$

Has no zero, so the position error is zero and the system tracks any step reference input,
in the optimisation Table 1.0 Polynomials with a zero-position error is referred to choose the nth order denominator tallying with the order of the system transfer function, .
In this case 7th order and get the seven controller constants K's

III. RESULTS AND DISCUSSION

This section also investigates the multi-machine power systems stability improvement by means of STATCOM additional controllers in multi machine power systems with and without a wind turbine, the three-area five machine system is used, the STATCOM was inserted along the source of oscillations, which is between buses. The voltage at oscillation source bus and the reactive power flowsinto thebus receiving the oscillation is controlled by the statcom element. There were five (5) Generators 1 to 4 have static exciters each with power system stabilizers, but generator 5 has a dc exciter.

There is one under damped low frequency electro-mechanical mode in which generator 5 oscillates against generators 1 to 4.

All the five (5)have thermal turbines with governors but additional turbine which is wind turbine is inserted for case 2 studies and the stability of each was studied.

(A) For the conventional power without wind turbine pole algorithm detailed in section 3 the controller constants are found to be [K1, K2, K3, K4, K5] = [-0.9056 57.84 -38.87 -0.2316 0.1658] while in the ITAE method the controller parameter are: [K1, K2, K3, K4, K5] = [0.57; 0.79; -253; 0.53 -1.707].

(B) For wind turbine farm system, Reactive Power ofinfinite Bus and the speed responses were simulated taking:
ts=5s , we have -1.7064, -0.8672 ±*j* 1.7504, -1.3143±*j* 1.1357, -1.5365±*j* 0.5616i

The ITAE supplementary controller constants for the same system but wind turbine integrated are [K$_1$, K$_2$, K$_3$, K$_4$, K$_{5,}$ K6, K7] = [22.9, -10.1, 332.9,-19.3, 3260, -5340, -9891]. Figure 4 shows the response of real power in line where statcom is injecting reactive power from bus where there is generation of oscillation for different methods.

IV. CONCLUSIONS

STATCOM supplementary Controller based on various state feedback polynomial concepts are proposed for damping power system oscillations, effectiveness of these proposed control methods are compared with each other that is pole placement algorithm, pole placement PIDs, ITAE and Butterworth under some disturbances. The controllers are tested multimachine system, From the studies it could be concluded that the polynomial state feedback algorithms which are ITAE and Butterworth have effectively produce least steady state error within acceptable overshoots, and their responses die almost completely under with and without wind turbine that both cases but they track unity and zero as the case may be perfectly in conventional than the wind farm case.

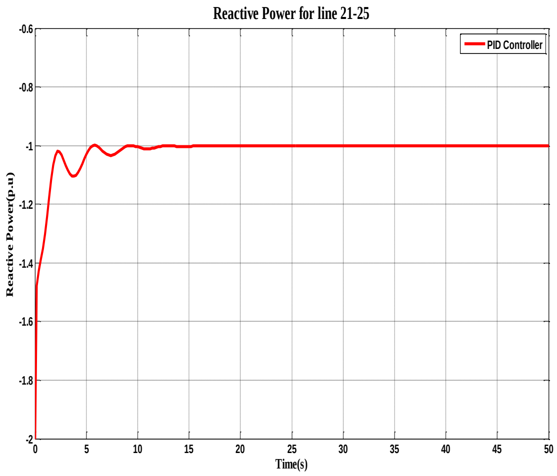


Fig. 5 reactive power for oscillation source line 21-25 using PID controller for Conventional power system

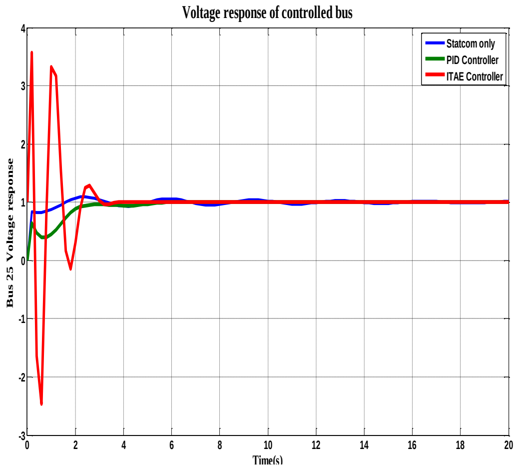


Fig. 6Voltage response for Oscillation source bus 25 using various controller algorithms for Conventional power system

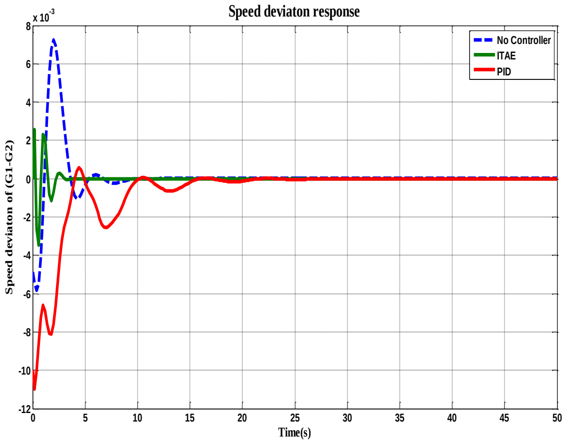


Fig.7 Speeddeviations of G1-G2 for Conventional power system

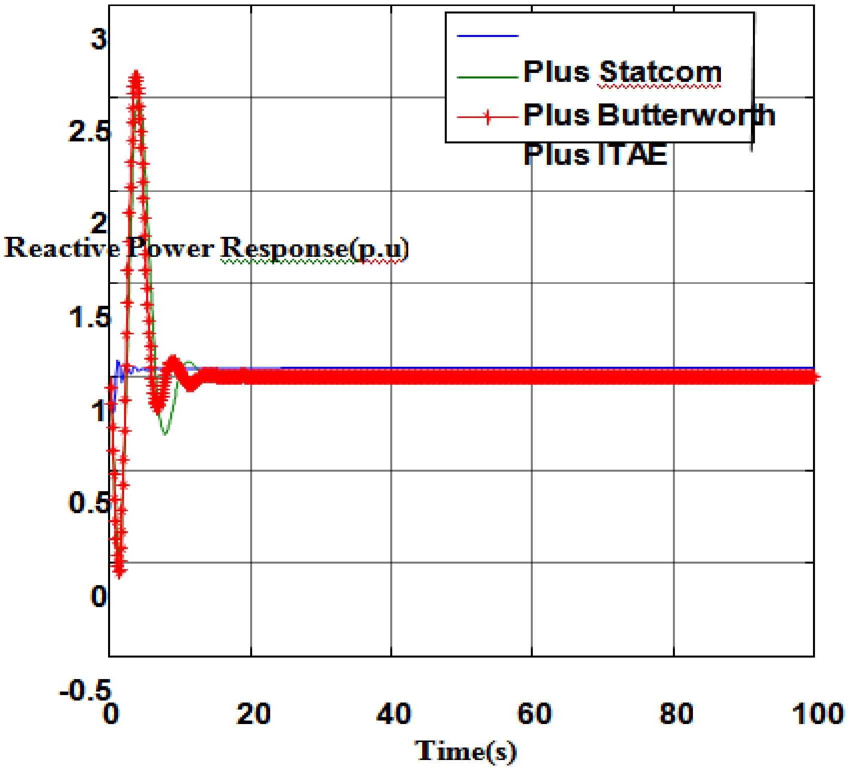


Fig. 8Response of Reactive Power ofinfinite Bus of wind Turbine power system

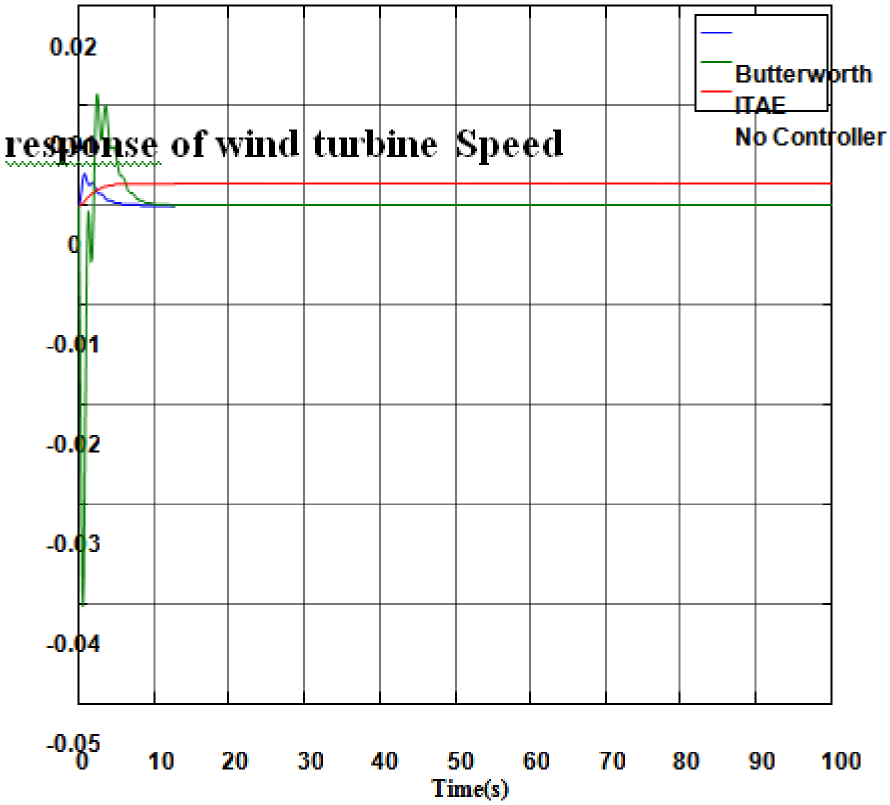


Fig. 9Speed response of wind TurbineFarm Power system

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APPENDIX

Generator: D = 0, H = 3.542, Xd=1.7672, Xq=1.5845, X’d =0.4245, X’q =1.05, Ra=0, δ0=44.370.T’do = 6.70, T’qo=0.44,
Exciter: KA=400, TA=0.02 s
Transmission line: R=0, XL = 0.8125, XT=0.1364, XTH=0.13636, G=0, B=0;