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WIND ENERGY-GRID STABILIZATION USING A DYNAMIC FILTER COMPENSATOR

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Abstract:

Economic electric energy generation using wind energy production has been rapidly growing for the last three decades. However, the integration of a large wind scheme can pose inherent voltage instability and power quality problems. The paper presents the impact of a Novel Dynamic FACTS Compensator Scheme DFCS developed by the Second Author on voltage level stabilization and power quality enhancement of Wind-Grid connected green energy system. The Wind Energy Conversion System comprises four key parts. The wind farm, induction generator and DFCS scheme and the novel Multi loop dynamic error driven coordinated controller developed by the second Author to ensure voltage stabilization, power quality enhancement and minimal inrush transients and excursions under normal operation , wind velocity excursions and hybrid motorized-linear –nonlinear load disturbances.

The integrated wind-grid scheme with four subsystems has been digitally simulated using the Matlab Simulink/Sim-Power software environment. The DFCS scheme with the coordinated dynamic error driven hybrid controller developed was fully validated. The digital simulation results have indicated that the novel new DFCS Filter Architecture and Multi loop controller did maintain voltage stabilization, enhance power quality and improve energy utilization.

Keywords: Renewable Wind Energy, Dynamic Filter Compensator Scheme, Reactive Power Compensation, Power Quality

I. Introduction

The extensive growth of wind energy utilization is a byproduct of robust FACTS Stabilization and Novel Control Strategies. Wind energy is a clean source of electricity generation without producing harmful emission gases. Wind energy system converts the available kinetic energy in the wind into mechanical energy that can derive an electrical generator [1, 2]. Wind Energy is one of the most competitive renewable energy resources with a production cost of $ 0.05-0.06per KWH. Wind power is intermittent due to wind speed stochastic variation. In addition, the sites with economic feasible wind speed are located in remote areas, which may require substantial infrastructure improvement.

Mostly, wind powered generators are self excited induction generators. The main characteristics of induction generators is the considerable reactive power absorb during their normal operating conditions. This reactive power problem may create dynamic voltage instability in the system [3]. There are two major types of wind generators, which are widely used in wind farms. The first one is the squirrel cage induction generator while the second is doubly fed induction generator. In this squirrel cage induction generator is used due to the low cost, low maintenance rate and possible utilization under wind gusting conditions. The required reactive power of induction generator can be supplied by the grid or self capacitor bank in parallel with the generator stator terminals. The selected induction generator model is the typical two-axis reference frame (D-Q) model.

Dynamic Reactive Power Compensators are always required to stabilize the voltage and to supply required reactive power at wind generator interface bus under normal operation, load disturbances and wind speed excursions. FACTS devices can be very useful to simultaneously deliver reactive power and support bus voltage at wind generator interface. Flexible AC transmission systems (FACTS) are alternating current transmissions systems incorporating power electronic-based and static

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controllers to enhance controllability and improve power quality. FACTS will enable confinement or neutralizing of electrical disturbances such as voltage sags and fluctuations, harmonic distortion.

A Novel Dynamic FACTS Filter Compensator was developed by the Second Author as a Member of a Family of Modulated/Switched LC Compensators and Modulated Power Filters as an effective low cost solution for voltage stabilization and power quality enhancement of Grid-Wind Direct Interface. A novel multi-loop error-driven dynamic controller adjusts the pulse switching pattern of DFCS. In this paper the effectiveness of the new DFCS topology for voltage stabilization, power quality enhancement and efficient energy utilization is validated using digital simulation based on a unified sample system model, which is developed by integrating sub-system mathematical models in MATLAB/Simulink software.

II. Wind Energy Conversion System

The power extraction of wind turbine is a function of three main factors: the wind power available, the power curve of the machine and the ability of the machine to respond to wind fluctuation. The expression for power produced by the wind is given by [4-6]

$$p_m(u) = \frac{1}{2} C_p(\lambda, \beta) \rho \pi R^2 u^3 \qquad (1)$$

Where ρ is air density, R is radius of rotor, u is wind speed, C_p denotes power coefficient of wind turbine, λ is the tip-speed ratio and β represents pitch angle.

The tip speed ratio is defined as

$$\lambda = \frac{R\omega}{u} \qquad (2)$$

Where ω is the rotor speed. It is seen that if the rotor speed is kept constant, then any change in the wind speed will change the tip-speed ratio, leading to the change of power coefficient C_p as well as the generated power out of the wind turbine. If, however, the rotor speed is adjusted according to the wind speed variation, then the tip-speed ratio can be maintained at an optimal point, which could yield maximum power output from the system.
From Eqs. (1) and (2) we can see that

$$P_m(\omega) = k_w \omega^3 \qquad (3)$$

Where

$$k_w = \frac{1}{2} C_p \rho \pi \frac{R^5}{\lambda^3} \qquad (4)$$

$$C_p(\lambda, \beta) = C_1 \left(\frac{C_2}{\lambda_i} - C_3 \beta - C_4 \right) e^{\frac{c_3}{\lambda_i}} + C_6 \lambda$$

$$1/\lambda_i = 1/[l+0.08\beta] - 0.035/[\beta^3+1] \qquad (6)$$

The coefficients C_1 to C_6 of equation (5) are : C_1=0.5176, C_2 = 116, C_3=0.4, C_4=5, C_5=21 and C_6 = 0.0068. In this paper, a constant pitch angle is assumed, and the value is assigned as 0.

III. Description of the System under Study

The study system model for wind energy utilization scheme shown in Fig.(1) comprises three key subsystems. The wind energy conversion system, Dynamic FACTS compensator scheme DFCS and hybrid system load connected to bus 3. The novel dynamic error driven coordinated control scheme are used to regulate the DFCS scheme. Medium voltage feeder section eac of 3 km length constitute the 11-kV (L-L) distribution grid network to interface wind generated power to the 138 kV Grid and the hybrid system load.

IV. Dynamic FACTS Compensator Scheme and its control system:

The DFCS shown in Fig.(2) is configured by 3-phase capacitors in Delta Connection between wind energy conversion system and the distribution grid. The DFCS comprises a series 3-phase capacitor with additional 2x3-phase shunt capacitors. Each phase of paralleled shunt capacitors is connected to 2-pulse diode bridge with IGBT Switching Stage on the DC Side of the bridge. The output terminals of each bridge are switched through tri-loop error driven dynamic PID controller to adjust the duty cycle ratio using the pulse width modulation technique.

The novel tri loop error driven coordinated controller shown in Figure (3) is implemented to regulate the DFCS Filter-Compensator. The Coordinated time decoupled Controller comprises three regulation loops: The load bus voltage stabilization loop, Current ripple control loop and RMS current dynamic tracking [7, 8], using the Root-Mean-Square (RMS) voltage, phase RMS current, and current ripple content minimization loop.

1. The main voltage stabilization loop is the Master Loop with the of objective of stabilizing the load voltage at the radial distribution load at Unity.
2. The second auxiliary loop is the load bus current RMS error tracking loop, which is an auxiliary loop to compensate for any sudden electrical load excursions or wind speed variations.
3. The third supplementary loop is used to limit current ripple content and reduce harmonics in the current. The loop-scaling and selected time delays of these loops were selected by an offline guided trial and error method to insure fast response and effective damping [9, 10].

This is achieved by using a minimization functional of the total error squared. The novel concept of a time decoupled and De-Scaled tri-loop regulation was developed by the Second Author to ensure robust action of the Master and auxiliary loops to limit dynamic inrush excursions at the load bus. The three loop-total error signal is driven through a PID controller that is used to compensate the dynamic total error in order to provide a stabilized minimum total error.

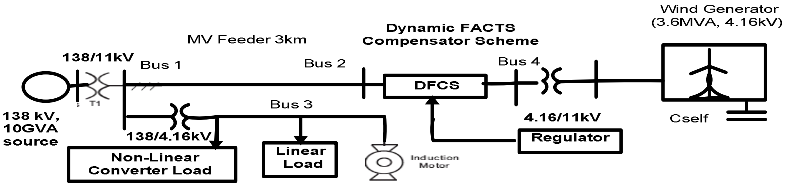

Fig. (1) Proposed Study system with DFCS

The existence of a non-linear load can complicate the operation of Wind-Grid interface. Conventional optimization methods may be ineffective to optimize the controller gain-parameters. Consequently, the weights and time delays of these loops, as well as controller proportional, integral and derivative gains ((Kp Kd and Ki) were selected by an Off-Line Guided Trial and Error method to ensure minimal Integral of Absloute Total Control Error over a settling time duration equals laegest System Time Constant [9,10].

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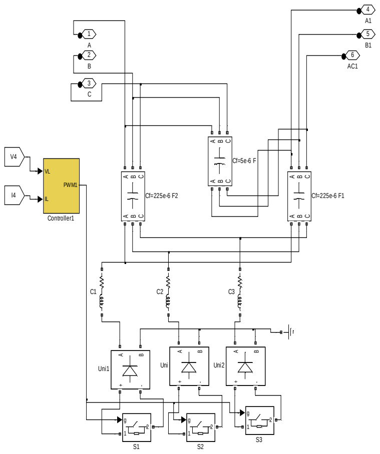

Fig.(2) Dynamic Filter Compensator Scheme

V. DIGITAL SIMULATION RESULTS

Digital simulations studies were carried out on the sample wind-grid study system shown in Fig.(1). The built-in functional blocks in SIM-POWER toolbox facilitate the simulation of such wind-grid integrated system. The DFCS scheme is connected to the radial distribution grid network at bus 4 was validated using continuous mode of digital simulation. Full digital simulation and validation were carried out without and with DFCS. A test period of 4 seconds is selected in order to show the DFCS effect on dynamic voltage stabilization, harmonic content reduction. The dynamic performance of the DFCS scheme was tested under the following load switching actions:

- At t=1.0 second, induction motor was connected at bus 3 for the rest of test period (3 seconds).
- At t=2.0 second, linear load was connected at bus 3 for the rest of the test period (2 seconds).
-At t=3.0 second, non loinear load is connected at bus 3 for the rest of test period(one second)

The comparison of the total harmonic distortion THD and harmonic content at wind interface bus 4 and hybrid load bus 3 is examined for two specified cases first without, second with the hybrid MPFC compensator. Voltage and current harmonic analysis in term of the total harmonic distortion (THD) and magnitude of certain low order harmonics are displayed in Table (1) and Table (2), respectively. It is obvious that the voltage and current harmonics are reduced by installing DFCS scheme.

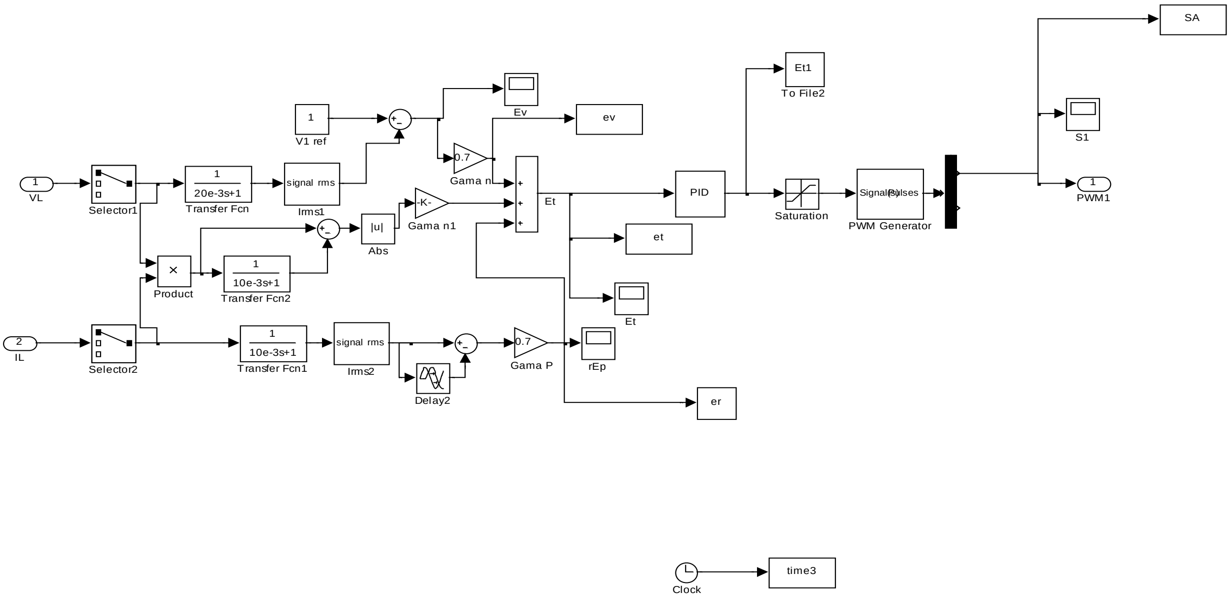

Fig. (3) Coordinated Time-Descaled Tri-loop dynamic (PID) Error Driven Controller for the Dynamic FACTS Compensator Scheme DFCS.

The dynamic responses of voltage and active power at wind turbine-generator interfacing bus 4 are shown in Figures (4, 5) with DFCS. Fig (6) displays the voltage response at hybrid load bus 3. Moreover, Figures (7) shows the dynamic response of voltage at wind interface bus 4 without DFCS. The voltage level along the distribution feeders are dramatically improved by using proposed DFCS. This is attributed to the capability of DFCS for regulating voltage profile along the feeder, since reasonable amount of reactive power can be injected by DFCS into the grid according to its demand.

Fig (8) shows the dynamic response of voltage at wind interface bus 4 with DFCS for 40% wind speed reduction for a period of one second between time equals 2 and 3 s. Fig. (9) displays the power factor response under load excursion with DFCS. The simulation results indicated that DFCS improves the voltage level, power factor and reduce the fluctuation range in voltage and current waveforms for load and wind speed excursions.

VI. CONCLUSIONS:

The paper presents a novel Dynamic Filter Compensator Scheme with an Error Driven Control Strategies developed by the Second Author for Wind-Grid Voltage Stabilization, Power Quality Enhancement, Energy utilization and robust interface. The connection of large wind energy conversion systems may results in voltage INSTABILITY and Severe Power Quality problems The use of new

FACTS Architecture and control strategies with Distributed Generation and Hybrid Wind-Small Hydro-Tidal-Wave renewable resources promise to ensure seemless and robust interface.

The paper presents a DFCS with dynamic error driven tri-loop controller for wind-grid utilization scheme. The DFCS is digitally simulated and validated using the Matlab/ Simulink/ Sim-Power Software environment. PID control signal drives sinusoidal SPWM switching controller to stabilize the voltage at the wind interface bus by regulated pulse width switching of IGBT switches. The voltage stabilization is fully validated as well as power quality (PQ) enhancement.

The integrated wind-grid scheme with all four key subsystems has been digitally simulated using the Matlab Simulink/Sim-Power software environment. The DFCS scheme with the coordinated dynamic error driven hybrid controller developed by the Second Author was fully validated. The simulation results have indicated that the DFCS maintain the voltage level of the system and enhance its power quality.

VII.References:

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Appendix

Wind Energy

-Wind Turbine (3.6 MVA), Base wind speed 10m/s

-Induction Generator V_r = 4.16 kV (L-L) S_r = 3.6 MVA, Cself=225 uf

AC System Loads

-Linear Load 1.2 MW at 0.8 PF, 4.16 kV (L-L)

-Induction motor dynamic load 600 kW at 4.16 kV (L-L), Nsynch=1800 r.p.m

-Non-Linear Converter Load 1.2 MW at 0.8 PF, 11 kV (L-L) connected to Universal 6 pulse converter with 540 Hz carrier frequency, 0.7 modulation index and 60 Hz output frequency

Modulated Power Filter (MPFC)

$C_s = 5\ \mu f$

$C_{f1} = C_{f2} = 225\ \mu f$

$R_f = 0.5\ \Omega$

$L_f = 15$ mH

PID controller gains:

Kp =50 K_I =5 K_d =5 E-3

Loop scaling weights: γ_v=0.7, γ_p= 0.25 and γ_i=0.7

Delay = 20 ms

PWM Switching Frequency:

F s/w 1750 Hz

Table(1) Voltage harmonics and $(THD)_v$ at distribution network buses 3 and 4

Case1:With DFCS & Case2: Without DFCS

Bus	Case	THD	3rd	5th	7th
3	1	0.02999	0.000231	0.007208	0.00598
	2	0.03095	0.000309	0.007401	0.00614
4	1	0.01132	0.000035	0.000029	0.00008
	2	0.01178	0.000091	0.000154	0.00009

Table(2) Current harmonics and $(THD)_i$ at distribution network buses 3 and 4

Bus	Case	THD	3rd	5th	7th
3	1	0.02955	0.000168	0.009795	0.00606
	2	0.03075	0.000348	0.001029	0.00574
4	1	0.01168	0.000616	0.000469	0.00025
	2	0.01187	0.000791	0.000554	0.00039

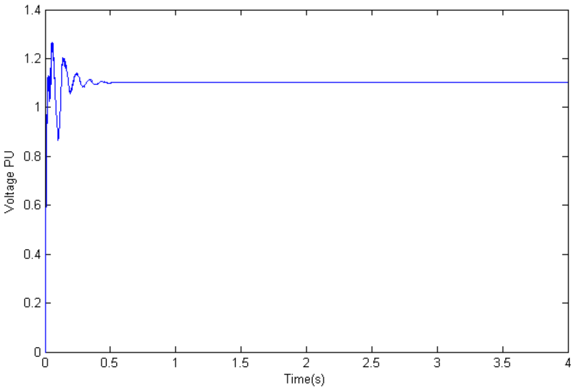

Fig.(4) Dynamic Response of voltage at interface Bus-4 with DFCS
For Load excursion (Switching Induction Motor at time =1 s and Linear load at 2 s and Non-linear load at 3s)

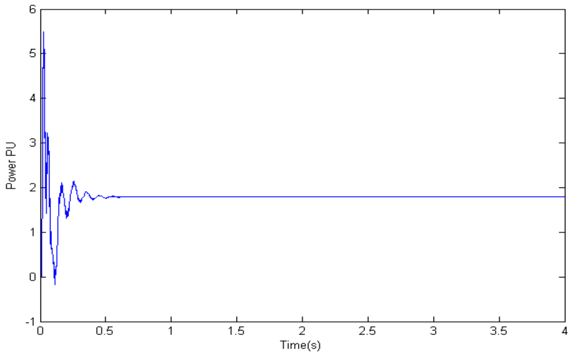

Fig.(5) Dynamic Response of active power into interface Bus-4 with DFCS
For Load excursion (Switching Induction Motor at time =1 s and Linear load at 2 s and Non-linear load at 3s)

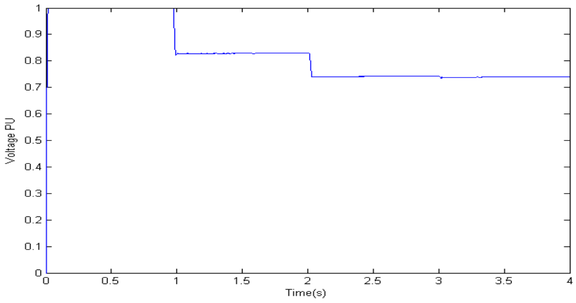

Fig.(6) Dynamic Response of voltage at hybrid load Bus-3 with DFCS
For Load excursion (Switching Induction Motor at time =1 s and Linear load at 2 s and Non-linear load at 3s)

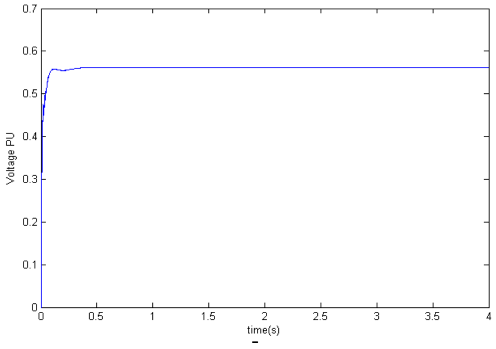

Fig.(7) Dynamic Response of voltage at interface Bus-4 without DFCS
For Load excursion (Switching Induction Motor at time =1 s and Linear load at 2 s and Non-linear load at 3s)

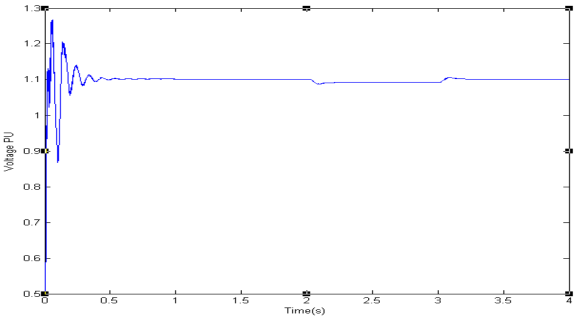

Fig.(8) Dynamic Response of voltage at interface Bus-4 with DFCS and 40% wind speed reduction.
For Load excursion (Switching Induction Motor at time =1 s and Linear load at 2 s and Non-linear load at 3s)

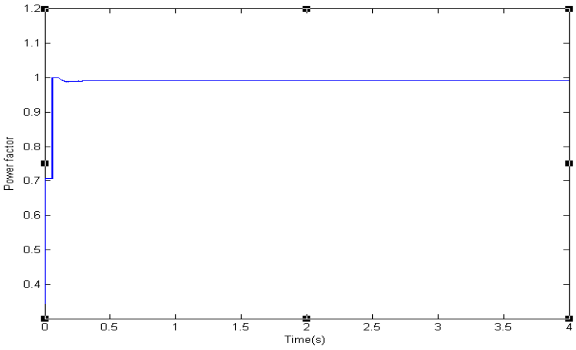

Fig.(9) Power Factor -vs- Time at wind interface Bus-4 DFCS
For Load excursion (Switching Induction Motor at time =1 s and Linear load at 2 s and Non-linear load at 3s)