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Integrating Wind Energy into Weak Power Grid Using Fuzzy Controlled TSC compensator

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Abstract. Wind energy has been developed significantly over last decade and has been noted as the most rapidly growing technology and most cost-effective ways to generate electricity from renewable sources. On the other hand, the voltage of wind turbine driven generator is variable due to intermittent nature of wind energy. Therefore, the integration of large wind scheme can pose inherent security problems such as voltage fluctuations and power quality.

Voltage control, power quality and reactive power compensation in a distribution network with embedded wind energy conversion system represent the main goal of this paper. The dynamic simulation of the proposed voltage stabilization TSC scheme is presented using fuzzy logic based controller. The Wind Energy Scheme comprises three key parts. The wind energy system, induction generator, TSC compensator with the associated fuzzy logic controller and the distribution wind-grid integrated AC system feeding the hybrid load.

The integrated wind-grid scheme with all subsystems has been digitally simulated using the Matlab Simulink/Sim-Power software environment. The fuzzy logic controlled TSC scheme was fully validated to ensure voltage stabilization and efficient wind energy utilization

Key words
Renewable Wind Energy, Reactive power compensation, Fuzzy logic controller, Voltage Stabilization and Efficient Utilization of wind Energy.

1. Introduction

Wind energy has received significant attention last decade as a consequence of strong ecological concerns of climate change and security of energy supply. Therefore, significant efforts have been made to develop wind energy conversion system as alternative renewable resource. Wind source is the better option as the power in MW range can be generated. This is a feasible power level to be interfaced to the power grid. Wind power growth with 20% annual rate has experienced the fastest growth among all renewable energy sources. It is predicted that by 2020 up to 12% of the world's electricity will have been supplied by wind power [1].

The function of wind turbine-coupled generator is providing a mean of energy conversion between mechanical torque from the wind turbine as prime mover and electric grid. Different types of generators are being used. Historically induction generator has been extensively used in commercial wind turbine units. Induction generators have considerable advantages for implementation in wind turbine systems because they provide some degree of flexibility under different wind speed and have low cost as well as low maintenance rate. Induction generators can deliver real power to electric grid, but they require reactive power for self-excitation. This can be supported by the grid or by capacitor bank connected in parallel with the generators. Therefore, large induction generators are considered as a heavy reactive power burden to utility grids.

Wind energy conversion schemes are usually planned and installed in rural, mountain and coastal areas, where the distribution grid networks are usually of radial configuration and can be considered weak with low short circuit levels [2]. For wind turbines connected to weak radial electric grid, the wind power fluctuations and voltage stabilization problems would lead to reduced quality of power supply to the loads. These weak grid systems need appropriate control schemes to smooth out the fluctuation and to efficiently utilize the wind energy. The power converter based controller is an option to maintain the quality of voltage supply to the users. As a result, necessary power conditioning devices should be employed and fully utilized to guarantee high power quality.

Generally, rectifier and line commutated inverter are used for interfacing the wind conversion system to the grid. To reduce the cost, uncontrolled rectifier is used with fully applied control on the inverter side. Thereby, the controller action is designed to generate a proper pulses sequence to ensure inverter switching. In addition PLL is added to ensure synchronization of the inverter output voltage with the AC utility voltage. The synchronization signal is obtained from the AC utility bus voltage at the wind energy conversion system interface.

This paper presents transient MATLAB/SIMULINK simulations of wind energy conversion system connected to the electric grid using fuzzy controlled TSC at load center. This paper is organized as follows. Section II introduces the wind energy conversion system. Section III describes the configuration of the studied system. Section IV depicts design procedure for fuzzy controller for the employed TSC compensator. Section V compares the digital simulations results of the studied system response with and without the designed fuzzy logic controller under wind speed variations and load excursions.

2. 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

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

$$C_p(\lambda, \beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right) e^{\frac{C_5}{\lambda_i}} + C_6\lambda$$

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

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.

The wind speed gusting conditions has a great impact on the dynamic performance of the wind scheme, a dynamic wind speed model is required to represent the stochastic nature of wind variations for the power dynamic simulations. A simplified dynamic wind speed model is developed using the MATLAB/Simulink software. This stochastic model consists of four basic key components, namely the mean wind speed, a wind speed ramp, a wind gust, and the turbulence component. The eventual wind speed to be applied to the wind turbine is the summation of all four key components as shown in fig.(1).

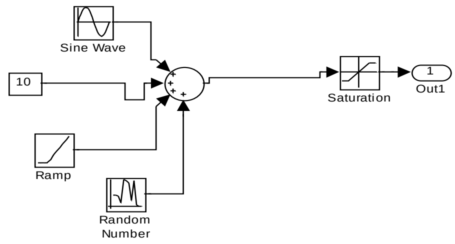


Fig. (1) Stochastic Wind-Speed Variation Model

3. Sample Wind-Grid Study System

The study system model for wind energy utilization scheme shown in Fig.(2) comprises three key subsystems. The wind energy conversion system, TSC compensator and hybrid system load. The fuzzy logic coordinated control scheme are used to regulate TSC compensator. Six radial feeder sections each of 3 km length constitute the 11-kV (L-L) distribution grid network to interface wind generated power to the system loads located at the different distribution network buses.

The voltage regulation and stabilization of the electric grid is severely degraded due to integrating wind energy conversion scheme with weak radial grid. The power obtained from wind farm is integrated with the electric grid via DC link to feed dynamic hybrid electric load. The use of the TSC compensator is essential to ensure voltage stabilization, power quality and power factor enhancement [7].

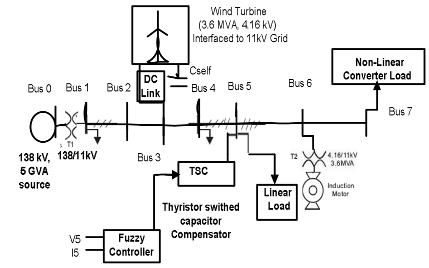
The configuration of the TSC is shown in Fig.(3) with the associated thyristor switches. In a TSC a capacitor is connected in series with two opposite pole thyristors. A current flows through the capacitor when the opposite poled thyristors are gated. The effective reactance of the TSC pack can be changed by switching a TSC on or off. For example in an n-pack TSC, the effective reactance is

$$Xeq = -j\left[\frac{1}{kwc}\right] \qquad , k = 1,2 \ldots K$$

Where K is the number of TSCs conducting

The compensator capacitor size selection is essential for the combined reactive compensation and harmonic filtering. TSC compensator is controlled using fuzzy logic algorithm to adjust the duty cycle ratio using the pulse width modulation technique.

Fig.(2) Proposed Grid Connected Wind turbine test System with TSC compensator Scheme



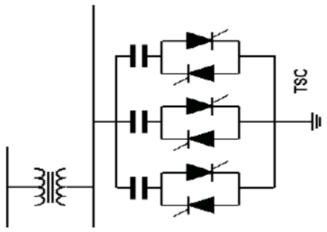


Fig. (3) Configuration of Thyristor switched capacitor TSC compensator

4. Fuzzy Logic Control Scheme

In this paper, the tri-loop error driven dynamic Fuzzy Logic controller scheme shown in Figure (4) is implemented for switching control of TSC, which comprises three basic loops, namely the load bus voltage stabilization loop, Current ripple loop and RMS current dynamic RMS loop [7,8], using the Root-Mean-Square (RMS) voltage, phase RMS current, and current ripple content minimization loop.

1. The main voltage stabilization loop functions as the reference loop using the root mean squared value of load voltage at the radial distribution load bus 5 and maintaining the voltage at 1.0 per unit.
2. The second 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 ripples and harmonic content of the current. The dynamic loops ensure energy efficient utilization and reduced current ripple content [7,8].

Table (1) Fuzzy Rule Decision Table

e \ Δe	N	Z	P
N	**NB**	**NS**	**ZE**
Z	**NS**	**ZE**	**PS**
P	**ZE**	**PS**	**PB**

The total error signal (E_t) is the sum of these three basic dynamically scaled loop errors. The Tri-loop dynamic controller compensate for any dynamic oscillations in bus voltage. The loop weighing factors are assigned to ensure loop time scaling and dominant loop (1) control action. Fuzzy Logic controller (FLC) is used to compensate the dynamic total error in order to provide control signal, which is then converted to degrees as phase angles. This phase angles are then sent to the Pulse Width Modulated (PWM) generator through saturation to adjust the sequence of thyristor switching of Figure (3). Thereby, the FLC generates the required control signal by compensating for error and change in error down to its lowest value by implementing stipulated fuzzy rule assignment. The output fuzzy space used in this paper has 9 rules defined on two input spaces, where each rule has 3 fuzzy Triangular Memberships as Negative (N), Zero (Z) and Positive (P). Table (1) shows the selected decision fuzzy rules.

5. Digital Simulation Results

Digital simulations studies were carried out on the sample wind-grid seven bus study system shown in Fig. (2). The built-in functional blocks in SIM-POWER toolbox facilitate the simulation of large and complicated power system. The TSC scheme is connected to the radial distribution grid network at bus 5 and the system was validated using continuous mode of digital simulation. Full digital simulation and validation were carried out with and without TSC located at bus 5. A test period of one second is selected in order to show the TSC effect on dynamic voltage stabilization and harmonic content reduction. The dynamic performance of the distribution system was tested under the following load switching actions:

- At t=0.6 second, induction motor was removed at bus 6 for a duration of 0.1 second.
- At t=0.25 second, linear load was removed at bus 5 for 0.15 second.
-In addition, the wind speed model described in fig.(1) was implemented to display the dynamic response of the system parameters for stochastic wind speed excursion.

The dynamic responses of voltages at different buses of the distribution grid are shown from Figure (5-7) with TSC compensator. The voltage profile along the radial distribution system with TSC compensator was improved. The largest voltage variations are reduced to its one third value using TSC compensator. This can be attributed to the reasonable amount of reactive power injected by TSC into the grid according to its demand. All power factors along the feeder are improved with introducing TSC compensator above 0.8 lagging.

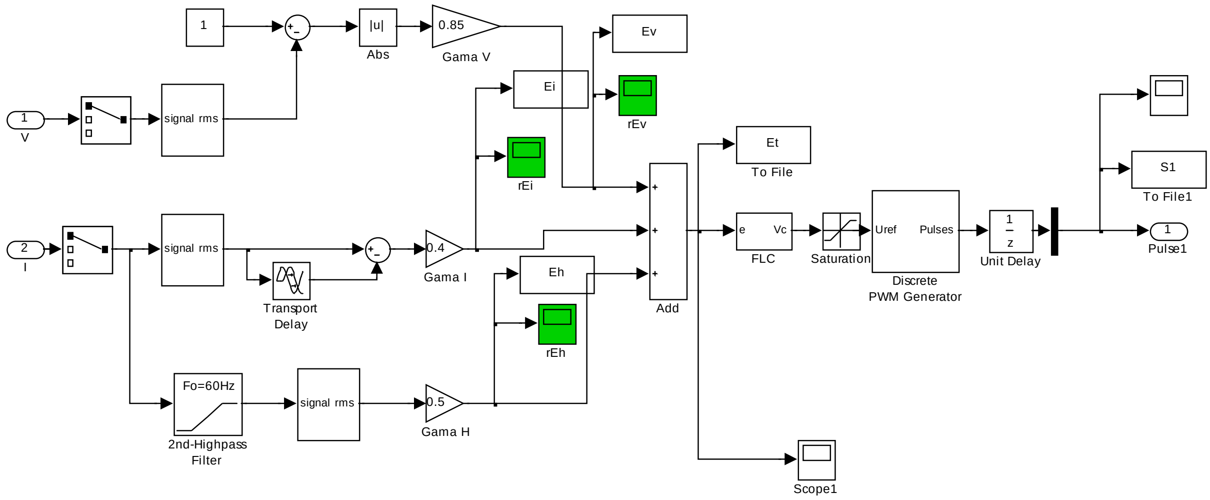


Fig (4) Coordinated Tri-loop dynamic error driven Fuzzy logic Controller for TSC compensator

Table(2) Voltage harmonics and $(THD)_v$ at distribution network buses for the four case studies

Bus	Case	THD	3rd	5th	7th	9th
3	1	0.04952	0.00763	0.03541	0.00266	0.0004141
	2	0.11143	0.00273	0.07354	0.05444	0.0013905
	3	0.05000	0.00947	0.04352	0.03962	0.0005237
5	1	0.02325	0.006983	0.03753	0.00767	0.0003265
	2	0.11376	0.028911	0.07482	0.05113	0.0028526
	3	0.02679	0.01401	0.04802	0.01191	0.0007504
7	1	0.02391	0.01016	0.04026	0.01171	0.0006873
	2	0.10947	0.02744	0.06721	0.05276	0.003447
	3	0.02713	0.01598	0.02647	0.01890	0.0009982

The comparison of the total harmonic distortion and harmonic content at each AC bus is made for three specified cases first with, second without TSC compensator for deterministic and third with stochastic wind speed model and TSC. Voltage harmonic analysis in term of the total harmonic distortion (THD) and magnitude of certain low order harmonics are displayed in Table (2) for the three different cases, respectively. It is obvious that the voltage harmonics are significantly reduced by installing TSC compensator. Moreover, the total harmonic distortion using TSC is not greater than 5% which is the legal limit described in the IEC-61000-2 norm series standard of harmonic contents. Fig. (8) shows the produced torque of the wind turbine for stochastic wind speed model. To justify the effectiveness of fuzzy logic controller, the dynamic response of the voltage loop and current loop errors are displayed in Fig.(9,10), respectively.

6. Conclusions

The paper presents a fuzzy logic control scheme for TSC compensator for voltage stabilization and quality improvement of wind-grid utilization system. The Test system is digitally simulated and validated using the Matlab/ Simulink/ Sim-Power Software environment. The TSC Compensator Scheme is controlled by a dynamic error driven action regulator using SPWM-pulsing control strategy. The voltage stabilization is fully validated as well as power quality (PQ) enhancement.

The FACTS schemes can be extended to other distributed/dispersed hybrid renewable green energy interface systems including hybrid AC-DC common bus collection scheme using (Photo-voltaic, Wind, Fuel Cell, Micro-hydro, Wave and Tidal) renewable energy systems. The application of FACTS devices in loss reduction and dynamic energy management, demand side management DSM is currently investigated

7. References

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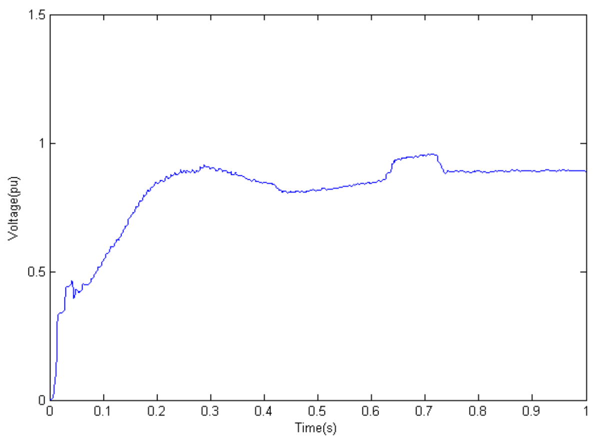

Fig.(5) Dynamic Response of voltage at Bus-3 For Load excursion and stochastic wind speed (Removing Linear load between 0.25-0.4s and Induction Motor between 0.6-0.7s)

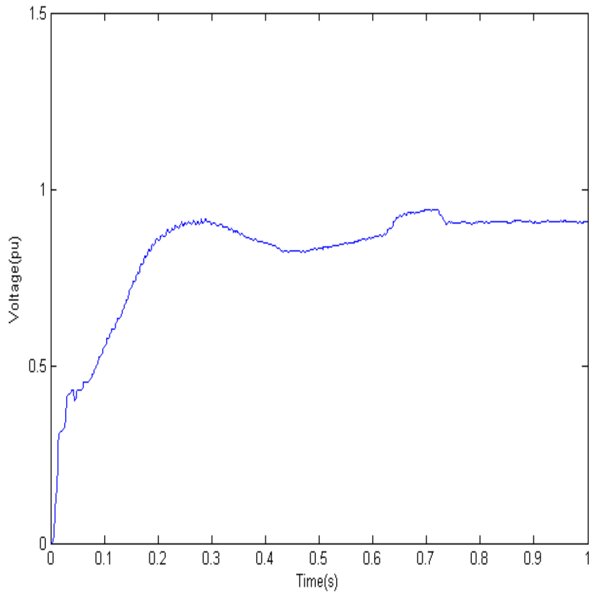

Fig.(6) Dynamic Response of voltage at Bus-5 For Load excursion and stochastic wind speed (Removing Linear load between 0.25-0.4s and Induction Motor between 0.6-0.7s)

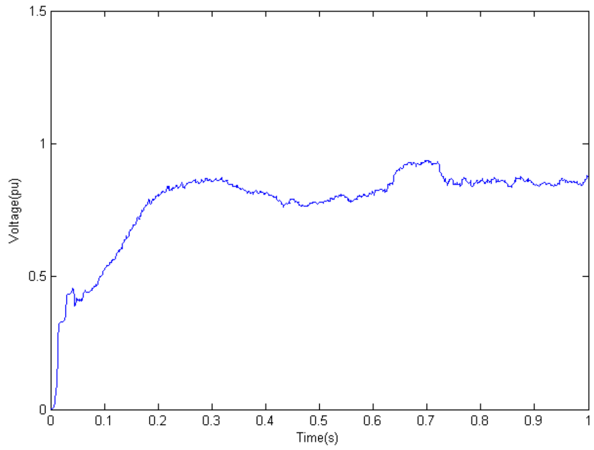

Fig. (7) Dynamic Response of voltage at Bus-7 of Non-Linear load for Load excursion and stochastic wind speed (Removing Linear load between 0.25-0.4s and Induction Motor between 0.6-0.7s)

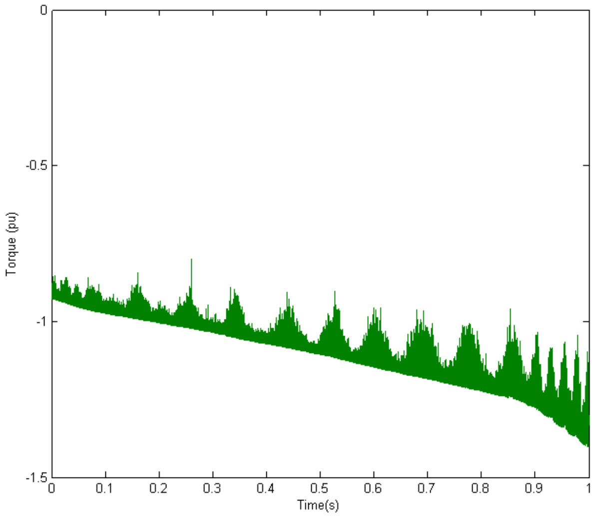

Fig.(8) Torque_vs_ime of the Wind Stochastic Speed Model with a start speed of 10 m/s, a wind speed ramp of one m/s , a wind gust of one m/s at frequency of 100 r/s, and a turbulence component of 0.5 m/s.

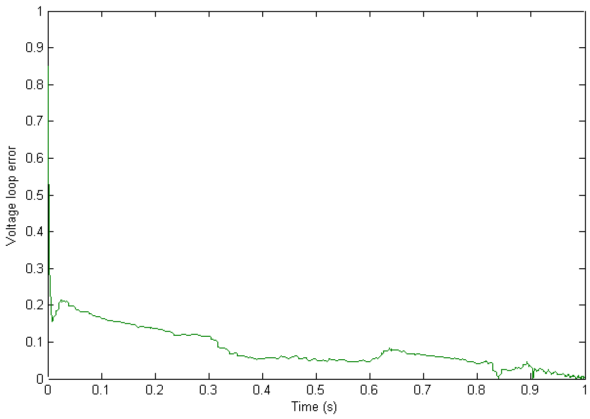

Fig. (9) Variation of the supplementary voltage loop error signal in the coordinated fuzzy logic controller of TSC compensator

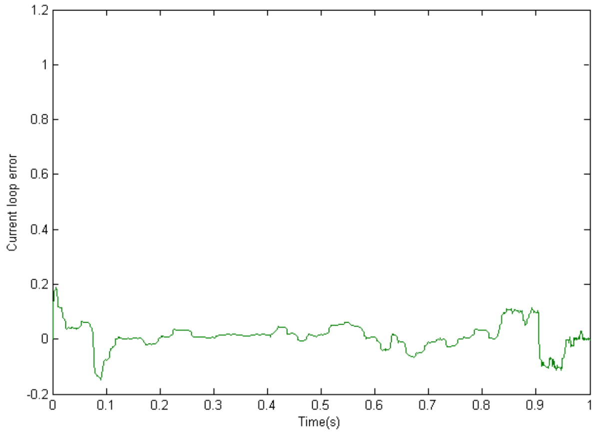

Fig. (10) Variation of the supplementary current loop error signal in the coordinated fuzzy logic controller of TSC compensator