POWER QUALITY IMPROVEMENT IN DFIG BASED WECS CONNECTED TO THE GRID USING UPQC CONTROLLED BY FRACTIONAL ORDER PID AND ANFIS CONTROLLERS

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Abstract

This paper discusses power quality improvement in a DFIG based WECS connected to a distribution system. A WECS is usually affected by issues such as high frequency oscillations, harmonics, transients, voltage sags, swells, voltage unbalance etc., These result in malfunction or damage to the electrical equipment in the system and lead to financial losses. So in order to mitigate the power quality events a UPQC device is employed which integrates series and shunt active filters that provide satisfactory compensation for power quality problems. The performance of UPQC is compared by using Fractional-Order PID controller and Adaptive Neuro Fuzzy Logic Controller. Modeling of DFIG and WECS systems is discussed with relevant equations. Design of UPQC and controllers is also discussed in detail. The proposed DFIG based WECS employing UPQC is simulated on MATLAB/ Simulink platform. The compensation capabilities of UPQC are assessed for both controllers for the proposed system and simulation results are presented.

Keywords: DFIG (Double Fed Induction Generator), Grid, Power Quality, Voltage sag, Voltage Swell, reactive power compensation, Wind Turbine, UPQC (Unified Power Quality Conditioner).

I. Introduction

Depletion of fossil fuels, need to decrease pollution and necessity to meet the ever increasing demand of electrical energy has led the mankind to explore the effectiveness of renewable energy sources. Generation of electrical energy by using sustainable alternative energy sources has gained much importance over the past few decades. Among all the renewable energy sources used for production of electrical energy, wind energy has gained much importance due to its ability is providing pollution free, clean and unlimited power at low production price [XIV]. Wind sector
is the fastest growing division as compared to other conventional sources and also creates considerable workforce for a nation.

For achieving improved efficiency, modern generators such as DFIG were developed with variable speed operation. In addition to providing independent active and reactive power control DFIG has also has other advantages such as reduced mechanical stresses on the turbine, reduced flicker and noise as compared to the previous machines [VI], [XI]. Due to the inconstant nature of the wind, the power obtained from a wind farm is fluctuating. The integration of wind energy farms to the electric grid results in deteriorated power quality, increased losses, voltage variations and voltage instability. Power quality problems that arise due to WECS-grid integration are voltage harmonics, voltage sag, voltage unbalance etc. These issues have adverse effects on the system and cause failure or malfunction of the electrical equipment [XII]. Over a period of time these power quality issues lead to reduction in life expectancy and poor performance of load equipment [X].

A new set of devices named as Custom Power devices have been designed and developed to provide custom power to the consumers. These devices include DVR, STATCOM, and UPQC etc. Among all the devices available, UPQC is identified as modern hybrid filter which is designed to protect sensitive loads against sudden disturbances in a power system. As shown in Fig. 1 UPQC comprises of two Voltage sources converters via a DC link. In this paper the performances of Fractional Order PID controller and Adaptive Neuro Fuzzy Logic Controller for UPQC device employed in a DFIG based wind energy conversion system are investigated when it is integrated with electric grid.

Fig.1 Block Diagram of UPQC Device
II. Description And Modeling Of The System

Description of System:

Fig. 2 displays the single line diagram of the power system employing UPQC. The performance of UPQC is studied by using FOPID and ANFIS controllers. As shown in Fig.2 the system comprises of two parallel transmission lines. Capacitive, RLC and non-linear loads are connected to the first line for different intervals of time. Capacitive load causes a voltage swell and RLC load results in voltage sag. The non-linear load results in harmonics in the power system. In addition to the three different loads causing power quality issues aforementioned, it is also assumed that the first line is subjected to a three-phase fault. The second transmission line feeds a DFIG based WECS. Power quality issues occurring in the first line also affect the second line due to the loading effects and degrade the performance of DFIG based WECS. Thus it is necessary to protect second line from the adverse effects of power quality events that occur in first line [VIII].

WECS Modeling Equations:

The wind power developed by the turbine is given by the equation (1)

\[ P_m = \frac{1}{2} \rho C_p (\lambda, \theta) A_r V_w^3 \]  

(1)

\( C_p \) refers to power coefficient which can be calculated by using the following equation.

\[ C_p(\lambda, \beta) = 0.73 \frac{151}{\lambda^2} 0.58\beta 0.002\beta^{2.14} 13.2 e^{-\frac{18.4}{\lambda}} \]  

(2)

where

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(3)

\[ \lambda_j = \frac{1}{\frac{\lambda - 0.02}{\beta} - 0.003 - 1} \]

and

\[ \text{TSR}(\lambda) = \frac{\omega R_f}{V_w} \quad (4) \]

Dynamics of Double fed induction generator:

Fig. 3 shows the equivalent circuit of DFIG. Following are the design equations of DFIG obtained from Fig. 3.

\[ V_{ds} = R_s i_{ds} + \frac{d}{dt} \psi_{ds} + \omega_s \psi_{qs} \quad (5) \]
\[ V_{qs} = R_s i_{qs} + \frac{d}{dt} \psi_{qs} + \omega_s \psi_{ds} \quad (6) \]
\[ V_{dr} = R_f i_{dr} + \frac{d}{dt} \psi_{dr} + (\omega_s \omega_r) \psi_{qr} \quad (7) \]
\[ V_{qr} = R_f i_{qr} + \frac{d}{dt} \psi_{qr} + (\omega_s \omega_r) \psi_{dr} \quad (8) \]

III. Proposed Control Approaches Of Upqc Device

Fractional Order PID (FOPID) Controller:

For achieving good control and obtaining appropriate results, it is essential to select suitable parameter values by proper tuning. For a controller to achieve optimum results, it should exhibit minimum overshoot, settling time and robustness to load disturbances. In industrial applications, usage of PID controller is more common as it is simple and easy to implement. However, PID control is not efficacious for complex nonlinear systems as it is difficult to obtain desired results.
Controllers based on fractional calculus have become more prevalent and advantageous than other controllers. These controllers use fractional-order derivatives and integrals and have proved to be more robust in nature than traditional controllers by providing desired and improved results. The block diagram of FOPID controller as shown in Fig.4. FOPID controller requires tuning of five parameters which results in design of advanced control system with improved frequency response [II], [IV], [V], [VII]. Disadvantage of FOPID controller is its complexity and difficulty in tuning the controller parameters.

Fig.4 Block Diagram of FOPID Controller

The differential equation applicable in a fractional order PID controller is

\[ u(t) = K_p e(t) + K_i D_t^{-\mu} e(t) + K_d D_t^{\lambda} e(t) \]  

(7)

Transfer function of FOPID Controller is given by :

\[ G_c(s) = \frac{u(s)}{e(s)} = K_p + \frac{K_i}{s^\lambda} + K_d s^\mu \]  

(8)

Where \( G_c(s) \) is controller transfer function, \( e(s) \) is error, and \( s \) is the output. \( K_p, K_i, \) and \( K_d \) are the gains for proportional, integral, and derivative terms. The term \( \lambda \) is the fractional component of integral parts and \( \mu \) is the fractional component of derivative parts. It is evident that five fractional order based nonlinear equations exist and tuning of five parameters \( (K_p, K_i, K_d, \lambda, \mu) \) for a fractional order PID (PI\(^D\)) controller is quite difficult. In this paper Ziegler-Nichols tuning method is used for tuning of a FOPID Controller. From this method parameters of the FOPID controller are \( K_p = 2.19277, K_i = 3.07272, K_d = -0.1721, \mu = 0.9 \) and \( \lambda = 0.01 \).

Adaptive Neuro – Fuzzy Inference System (ANFIS) Controller:

Conventional controllers have become obsolete due to their inability to perform satisfactorily when subjected to nonlinearities. With the introduction of intelligent controllers such as Fuzzy Logic controllers the dynamic performance of a system is improved. But determination of membership functions (MF) and the rules is a complex task. Later Artificial Neural Network (ANN) based controllers were introduced that did not require any predefined model. However, proper approach for selection of parameter values and number of training sets is still unknown. To

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overcome the drawbacks of FL and ANN controllers, a hybrid controller named as ANFIS controller has been designed. [X]

The advantages of ANN and Fuzzy logic such as efficient learning capabilities, ability in combining expert’s knowledge and data interpretation have been incorporated in ANFIS controller [XI]. ANFIS uses neural networks to tune a Fuzzy Logic Sugeno type controller. To obtain the membership functions and the rules it presents hybrid learning with back propagation algorithm to tune them and the least-squares method to identify them. Thus, performance ANFIS controller is satisfactory with improved estimation efficiency.[II],[VII]. MATLAB/SIMULINK Software is used in order to design of ANFIS Controller. The ANFIS editor toolbox is used to train the ANFIS Controller.

The following are the steps to be followed for designing the converter control circuit.

Step 1: Training data obtained from conventional SVPWM technique is loaded into ANFIS controller.

Step 2: ANFIS output is evaluated.

Step 3: FIS data from ANFIS controller is imported.

Step 4: FIS data is exported to Fuzzy Logic Controller which is used in the proposed converter control circuit.

The schematic structure of an ANFIS controller is as shown in Fig.5. The circles represent fixed nodes and squares represent adaptive nodes [I], [III].

As shown in Fig.5 ANFIS has two input nodes X1 and X2 which indicate DC link voltage(Vdc) and change in DC link voltage (ΔVdc) of converter control circuit respectively. The controller structure has five layers and one output. In the first layer, the inputs X1, X2, are expressed as Triangular Membership Functions (MF). Bell-Shaped MF is also generally chosen for ANFIS controllers. In the second layer, the weights of Membership Functions (MF) are determined by accepting the inputs from first layer and combining with corresponding weights.
The membership functions thus obtained are used as fuzzy sets to represent the input parameters $X_1$ and $X_2$ [IX]. The third layer is also termed as Rule Layer. Fuzzy rule matching is performed based on the assumption that the number of layers and fuzzy rule count are equal. Then activation level of each rule and normalized weights for each node are evaluated. Defuzzification process is carried out in Layer 4. Fuzzy rules are deduced, and outputs are obtained. A set of Neuro-Fuzzy parameters are obtained by Fuzzy Singletons which are indicated by weighted connections between Rule Layer and Defuzzification Layer. Finally, in the fifth layer all the incoming signals are summed up and outputs are evaluated. In this paper, the adaptive error back-propagation method is used to update the weights in each epoch. The total number of epochs used in this work is 200.

IV. Simulation Results

In this paper, power quality improvement by means of UPQC device is studied when DFIG based WECS is connected to electric grid. UPQC device comprises of Shunt and Series compensators with independent control circuits. The performance of UPQC device is investigated by observing its ability in mitigating power quality issues such as voltage sag, voltage swell and harmonics.

It is assumed that the first transmission line is subjected to the following conditions:

(i) A three-phase fault during the time period $t=0.3$ to $0.5$ sec as a result of which the line suffers voltage sag.

(ii) Switching on of a capacitor bank for the time interval $t=0.7$ to $0.9$ sec due to which the line experiences a voltage swell.

(iii) Due to the incoming non-linear load during the time interval $t=1.1$ to $1.3$ sec, the line experiences harmonics.

Due to the integration of DFIG based WECS to the electric grid, the second transmission line also experiences the voltage sag, voltage swell and harmonics for the same time intervals as that of first line. The voltage and current waveforms at the load point B3 in second transmission line before connecting UPQC device to the system are as shown in Fig.9 & Fig 10.

Fig.9 Voltage Waveform at B3 point before UPQC connected
Simulation Results of FOPID Controller based UPQC

Fig. 11 and Fig. 12 show voltage and current waveforms at load point B3 in the second transmission line of the system controlled by FOPID Controller (as shown in Fig. 6). Fig. 13 shows that required active and reactive powers of 10MW and 5MVar respectively are supplied by DFIG machine at the load point B3.

Fig. 14, Fig. 15 and Fig. 16 shows the harmonic spectra of load voltage (B3 point) at different time instants. %THD at t = 0.3 sec (Voltage sag harmonic) is 5.31%, at t = 0.7 sec (Voltage swell harmonic) is 5.94% and at t = 1.1 sec (harmonics due to nonlinear load) is 5.01% respectively.
Fig. 13 Active and Reactive powers at B3 point of the system with UPQC controlled by FOPID controller

Fig. 14 Harmonic Spectrum of load voltage at $t = 0.3$ sec

Fig. 15 Harmonic Spectrum of load voltage at $t = 0.7$ sec

Fig. 16 Harmonic Spectrum of load voltage at $t = 1.1$ sec
Fig. 17 Voltage Waveform at B3 point of the system with UPQC controlled by ANFIS controller.

Fig. 18 Current Waveform at B3 point of the system with UPQC controlled by ANFIS controller.

Fig. 19 Active and Reactive powers at B3 point of the system with UPQC controlled by ANFIS controller.

Fig. 20 Harmonic Spectrum of load voltage at t = 0.3sec.
Fig.17, Fig.18 show voltage and current waveforms at load point B3 in the second transmission line of the system controlled by ANFIS Controller (represented in Fig.6). Fig.19 shows that required active and reactive powers of 10MW and 5MVar respectively are supplied by DFIG machine at the load point B3. Fig.20, Fig.21 and Fig.22 show the harmonic spectra of load voltage (B3 point) at different time instants. %THD at $t = 0.3$ sec (Voltage sag harmonic) is 2.61%, at $t = 0.7$ sec (Voltage swell harmonic) is 2.78% and at $t = 1.1$ sec (harmonics due to nonlinear load) is 2.29% respectively.

Tabel.1 %THD Comparison between UPQC with FOPID Controller and ANFIS Controller

| %THD | UPQC With FOPID Controller | UPQC With ANFIS Controller |
|------|----------------------------|----------------------------|
| % THD for $V_{load}$ at $t = 0.3$ sec | 5.31% | 2.61% |
| % THD for $V_{load}$ at $t = 0.7$ sec | 5.94% | 2.78% |
| % THD for $V_{load}$ at $t = 1.1$ sec | 5.01% | 2.29% |

V. Conclusion

The performance of UPQC device with FOPID Controller and ANFIS Controller has been analyzed when a DFIG fed WECS is subjected to power quality variations.
issues such as sag, swell and harmonic conditions when it is integrated with electric grid. The harmonic content is also measured at instants where sag, swell and harmonic have been completely compensated (i.e. at $t=0.3, 0.7, 1.1$ sec respectively). From simulation results obtained, it is observed that ANFIS Controller has better compensation capabilities and reduces harmonic distortion more effectively than FOPID Controller. The active and reactive powers are also measured at B3 load point. From the above simulation results the ANFIS controller also provide the desired active and reactive powers compensation compared to FOPID controller.

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