DPC Based on ANFIS Super-Twisting Sliding Mode Algorithm of a Doubly-Fed Induction Generator for Wind Energy System

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ABSTRACT

Conventional direct power control (DPC) using two hysteresis comparators and switching table for a doubly fed induction generator (DFIG) integrated in a wind turbine system (WTS) have some drawbacks such as harmonic distortion of voltages, reduced robustness and powers ripples. In order to resolve these problems, a super-twisting sliding mode control (STSMC) scheme based on adaptive-network-based fuzzy inference system (ANFIS) algorithm is employed. The validity of the employed approach was tested by using Matlab/Simulink software. Interesting simulation results were obtained and remarkable advantages of the proposed strategy were exposed including simple design of the control system, reduced powers ripples as well as the other advantages.

1. INTRODUCTION

The use of doubly fed induction generator (DFIG) has increased tremendously due to its easy maintenance with good reliability, low cost, and simple construction. Various control strategy for DFIG have been introduced in literatures [1-4]. Initially for the DFIG the direct power control (DPC) scheme was introduced by Takahashi in 1998 [5]. DPC has various advantages like fast response of active and reactive powers and it is simple to implement. To control the frequency and output voltage of the drives the pulse width modulation (PWM) and space vector pulse width modulation (SVPWM) switching techniques are used [6, 7]. The SVPWM technique has the ability to reduce harmonic content and low switching losses with satisfactory performance. To reduce complex online computation the intelligent techniques based SVPWM are also used [8-10]. The DSPs, FPGA, and dSPACE are used as controller platform to implement the control strategy in order to control and regulate the DFIG [11-13].

DPC strategy of control implies a direct control of the active and reactive powers which must fall into two separate certain bands to be applicable. The simple objective is to control two quantities which are the stator active and reactive powers. In DPC strategy those quantities are directly controlled by selecting the proper vector state converter. Various research papers are published on DPC scheme of permanent magnet synchronous generator (PMSG) [14, 15] and DFIG [16-18]. DPC control scheme based on an estimated stator flux has been proposed [19]. As the stator voltage is relatively harmonics free, the accuracy of the stator flux estimation can be guaranteed. However, an unfixed switching frequency is considered the main drawback of conventional DPC strategy. DPC strategy based on super-twisting sliding mode (STSM) algorithm [20]. DPC control scheme based on artificial neural networks (ANNs) of a DFIG-based wind energy system (WES) [21]. A discrete sliding mode control is designed to regulate the real and active power of DFIG-based WES [22]. Second order sliding mode control (SOSMC) and fuzzy logic controller (FLC) are combined to control DFIG [23]. DPC technique of a DFIG based-wind power generation systems by using seven-level SVPWM strategy was presented [24].

The original contribution is the application of the adaptive-network-based fuzzy inference system-STSM algorithms (ANFIS-STSM) in the DPC control with three-phase induction generator and simulation investigation of this novel control system. In this paper, the DPC system with the application of the ANFIS-STSM algorithms has been considered. based on for a DFIG-based wind turbine system (WTS) by using two-level SVPWM technique. The main advantages of the DPC-ANFIS-STSM scheme are the simplicity to implement and the reduced ripples of active and reactive powers compared to another control schemes. The ANFIS-STSMC controller is used in order to reduce the ripple content in reactive and active powers.

2. MODEL OF DFIG

In order to establish vector control of DFIG, we remind here the modeling in the Park [25, 26].

Rotor flux components:

\[
\begin{align*}
\psi_{dr} &= L_r I_d + M I_r \\
\psi_{qr} &= L_r I_q + M I_r
\end{align*}
\]

(1)

where, \( \psi_{dr} \) and \( \psi_{qr} \) are the two components of rotor fluxes, \( L_r \) is the rotor inductance, \( M \) is the mutual inductance, \( I_d \) and \( I_q \) are the rotor currents.

Stator flux components:
\[ \begin{align*}
\psi_{ds} &= L_s I_{ds} + M I_{qr} \\
\psi_{qs} &= L_s I_{qs} + M I_{qr}
\end{align*} \tag{2} \]

where, \( \psi_{ds} \) and \( \psi_{qs} \) are the stator fluxes and \( L_s \) is the stator inductance.

Stator voltage components:

\[ \begin{align*}
V_{ds} &= I_{ds} R_s - \omega_s \psi_{qs} + \frac{d}{dt} \psi_{ds} \\
V_{qs} &= I_{qs} R_s + \omega_s \psi_{ds} + \frac{d}{dt} \psi_{qs}
\end{align*} \tag{3} \]

where, \( V_{ds} \) and \( V_{qs} \) are the stator voltages, \( \omega_s \) is the electrical pulsation of the stator and \( R_s \) is the stator resistance.

Rotor voltage components:

\[ \begin{align*}
V_{dr} &= I_{dr} R_r - \omega_r \psi_{qr} + \frac{d}{dt} \psi_{dr} \\
V_{qr} &= I_{qr} R_r + \omega_r \psi_{dr} + \frac{d}{dt} \psi_{qr}
\end{align*} \tag{4} \]

where, \( V_{dr} \) and \( V_{qr} \) are the rotor voltages, \( R_r \) is the rotor resistance.

The stator active and reactive powers are defined as:

\[ \begin{align*}
P_s &= 1.5(V_{ds} I_{ds} + V_{qs} I_{qs}) \\
Q_s &= 1.5(V_{qs} I_{ds} - V_{qs} I_{qs})
\end{align*} \tag{5} \]

where, \( P_s \) is the active power and \( Q_s \) is the reactive power.

The electromagnetic torque can be written as follows:

\[ T_e = \frac{3}{2} p M (I_{ds} \psi_{qs} - I_{qs} \psi_{ds}) \tag{6} \]

where, \( T_e \) is the electromagnetic torque.

\( p \) is the number of pole pairs.

The electrical model of the DFIG is completed by the following mechanical equation:

\[ T_e - T_r = J \cdot \frac{d\Omega}{dt} + f \cdot \Omega \tag{7} \]

where, \( f \) is the viscous friction coefficient.

\( J \) is the inertia.

\( T_r \) is the load torque.

\( \Omega \) is the mechanical rotor speed.

3. DESCRIPTION OF THE STSM ALGORITHM

Super twisting sliding mode controller has been widely used for control nonlinear systems. This algorithm based on the theory of variable structure systems. However, this algorithm was proposed by Utkin et al., in 1999 [27]. The STSM algorithm maintains the advantages of the traditional SMC techniques. On the other hand, this algorithm is simple and easy to implement compared to another strategies. The output signal from controller of this type is comparable with the control signal obtained from linear proportional integral (PI) controllers.

The control law of the STSM algorithm can be defined as follows:

\[ \begin{align*}
u &= K_1 \left[ \text{sgn}(S) + u_1 \right] \\
\frac{d u_1}{dt} &= K_2 \text{sgn}(S)
\end{align*} \tag{8} \]

where, \( K_1 \) and \( K_2 \) are the coefficients of the proportional and integral parts of the STSM algorithm; \( S \) is the switching function determined for the STSM algorithm, respectively; \( r \) is the exponent defined for the STSM algorithm.

The graphical representation of the control law of the STSMC algorithm is shown in Figure 1.

**Figure 1.** Block diagram of STSMC algorithm

The values of the \( K_1 \) and \( K_2 \) of all analyzed STSMC algorithm and value of the exponent \( r \) have been determined according to the procedure presented in detail in the paper [28].

The value of the exponent \( r \) has an impact on the dynamics of the control structure with STSM algorithms. This exponent can have a value between zero and one. In the analyzed control structure, its value was assumed as 0.5. The applied tuning procedure allows for ensuring the stability of the control system [29].

The procedure for determining the coefficients \( K_1 \) and \( K_2 \) of the STSM algorithm is based on the analysis of equations for the nonlinear control system and the equations of the output signals. These equations in the matrix form are presented as follows [30]:

\[ \frac{dx}{dt} = a(x,t) + b(x,t)u, \quad y = c(x,t) \tag{9} \]

where, \( u \) is the vector of input control signals; \( x \) is the state vector of the system; \( y \) is the vector of output control signals; \( a(x, t), b(x, t) \) and \( c(x, t) \) are the vector functions.

The second time derivative of equations for the output signals has the matrix form presented as follows:
\[ \frac{d^2 y}{dt^2} = A(x, t) + B(x, t) \frac{du}{dt} \] (10)

The bounds of \( B(x, t) \) and \( A(x, t) \) of the second derivative of \( y \) can be labelled as \( A_M, A_m, B_M \) and \( B_m \), where \( B_M \) and \( A_M \) are upper bounds and \( A_m \) and \( B_m \) are lower bounds. The \( K_1 \) and \( K_2 \) are determined for all STSM algorithms according to the equations presented as follows [31]:

\[
K_1 > \frac{A_m}{B_m}, \quad K_2 > \frac{4A_m}{B_m^2}, \quad \frac{B_m(K_1 + A_m)}{B_m(K_1 - A_m)}
\] (11)

In this work, the procedure for determining the coefficients \( K_1 \) and \( K_2 \) for the STSM algorithm of the DFIG has been presented. The same principle has been used to determine the values of the \( K_1 \) and \( K_2 \) for the STSM algorithm of the magnitude of the stator reactive and active powers used in the DPC system with three-phase DFIG.

4. WIND TURBINE MODEL

In wind turbine, the kinetic energy of wind is converted into mechanical power, the mechanical torque developed by the wind turbine is expressed by Benbouhenni et al. [32, 33]:

\[
T_m = \frac{P_m}{\Omega} = \frac{C_p(\lambda, \beta) \rho \pi R^2 V_w^3}{2\Omega}
\] (12)

where, \( V_w \): The wind speed (m/s),
\( \rho \): The density of the air (kg/m),
\( R \): The radius of the turbine in (m),
\( C_p \): The aerodynamic coefficient of power.
\( \lambda \): The blade pitch ratio.
\( \beta \): The blade pitch angle in a pitch-controlled wind turbine.

The fundamental principle of the dynamics is applied to know the evolution of the mechanical speed:

\[
J \frac{d\Omega_m}{dt} = T_m - T_{em} - f \cdot \Omega_m
\] (13)

where, \( J \) and \( f \) are the system moment of inertia and the friction coefficient respectively.

Figure 2 shows the mathematical model of the mechanical part of the wind turbine with MPPT algorithm.

In this work, the proportional-integral (PI) of the wind speed MPPT algorithm is replaced by STSM algorithm, as shown in Figure 3.

The output signal for the electromagnetic torque controller is determined by the following system of equations:

\[
\begin{align*}
T_e &= K_{pe} \left| S_{Te} \right|^{\frac{r}{r}} \text{sgn}(S_{Te}) + T_{el} \\
\frac{dT_{el}}{dt} &= K_{te} \text{sgn}(S_{Te})
\end{align*}
\] (14)

where, \( K_{pe} \) and \( K_{te} \) are the coefficients of the proportional and integral part of the STSM electromagnetic torque regulator, respectively. On the other hand, the stability of the STSM algorithm is proven using Lyapunov stability theorem.

The torque STSM algorithm gains (Ki and Kp) were found after performing simulations in Matlab/Simulink software. Table 1 shows the constants values.

![Figure 2. Wind turbine model with the wind speed MPPT algorithm](image)

![Figure 3. MPPT with STSM algorithm](image)

![Figure 4. Wind speed](image)

![Figure 5. Mechanical power](image)

**Table 1. STSM controller gains**

<table>
<thead>
<tr>
<th>Kp</th>
<th>Ki</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>250000</td>
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<td>0.9</td>
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</table>

Figures 4-10 show the obtained simulation results. We can observe that the MPPT with STSMC algorithm minimize clearly the ripples presents in power and tip speed ration compared to the MPPT with conventional PI controller.
The DPC performances can be ensured by using a switching table (Table 2) to select the switching voltage vector [34]. The inverter connected to the DFIG must provide the necessary complimentary frequency in order to maintain a constant stator frequency.

\[
\Psi_s = \sqrt{\Psi_{s\alpha}^2 + \Psi_{s\beta}^2}
\]

(16)

where,

\[
\Psi_s = \frac{V_s}{w_s}
\]

(17)

The stator flux angle is calculated by:

5. TRADITIONAL DPC CONTROL

Traditional DPC scheme controls independently the stator active and reactive powers at the same time. There are six switching configurations for any selected VSI output vector, and these six switching configurations can be applied to the two-level converter to generate the same output voltage vector, as shown in Figure 11. On the other hand, the DPC control goal is to regulate the reactive and active powers of the DFIG. The traditional DPC, which is designed to control stator reactive and active powers of the DFIG, is shown in Figure 12.

Table 2. Traditional switching table of DPC strategy

<table>
<thead>
<tr>
<th>N</th>
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<th>4</th>
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<th>6</th>
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<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>1</td>
</tr>
</tbody>
</table>
\[
\theta_s = \arctan\left(\frac{\Psi_{s\beta}}{\Psi_{s\alpha}}\right)
\]  

(18)

Reactive and active powers is estimated using (19) and (20) [35].

\[
P_s = -\frac{3}{2} \frac{L_m}{\sigma L_s L_r} (V_s \varphi_s)
\]  

(19)

\[
Q_s = -\frac{3}{2} \frac{V_s}{\sigma L_s} \varphi_s - \frac{V_s L_m}{\sigma L_s L_r} \varphi_m
\]  

(20)

where,

\[
\sigma = 1 - \frac{M^2}{L_s L_r}
\]  

(21)

\[
\Psi_{s\alpha} = \sigma L_s I_{s\alpha} + \frac{M}{L_r} \Psi_s
\]  

(22)

\[
\Psi_{s\beta} = \sigma L_s I_{s\beta}
\]  

(23)

The reactive and active powers can be reformulated by inducing angle \(\lambda\) between the rotor and stator vectors as follows [36]:

\[
P_s = -\frac{3}{2} \frac{L_m}{\sigma L_s L_r} w_r |\psi_r| \sin(\lambda)
\]  

(24)

\[
Q_s = -\frac{3}{2} \frac{w_r}{\sigma L_s} |\psi_r| \frac{M}{L_r} |\cos(\lambda)| - |\psi_r|
\]  

(25)

The derivation of the active and reactive powers can give by:

\[
\frac{dP_s}{dt} = -\frac{3}{2} \frac{L_m}{\sigma L_s L_r} w_r |\psi_r| \frac{d(|\psi_r| \sin(\lambda))}{dt}
\]  

(26)

\[
\frac{dQ_s}{dt} = -\frac{3}{2} \frac{M w_r}{\sigma L_s L_r} |\psi_r| \frac{d(|\psi_r| \cos(\lambda))}{dt}
\]  

(27)

A two-level hysteresis comparator is used for reactive error (see Figure 13). For stator active power error, the hysteresis comparator used is three level as shown in Figure 14.

**Figure 13.** Reactive power hysteresis comparator

**Figure 14.** Active power hysteresis comparator

6. ANFIS-STSM DPC METHOD

The DPC strategy of three-phase DFIG with the application of ANFIS-STSM algorithm is shown in Figure 15. In this control system, the stator reactive and stator active powers are controlled by the ANFIS-STSM algorithms.

**Figure 15.** DPC system of three-phase DFIG with the application of ANFIS-STSM algorithm

In the outer control loop of the stator active, the reference value of the magnitude of the stator active is compared with the estimated value. The switching function for stator active vector controller can be specified as follows:

\[
S P_s = P_{s\text{ref}} - P_s
\]  

(28)

The output signal from the controller of the magnitude of the stator active vector is determined by the following system.
function definition is shown in Fig 3 [48]. The stator currents and measured voltages. DFIG based on the measured stator currents and measured phase VSI converter. The disadvantage of STSM algorithms of the DFIG is that the active power ripple, electromagnetic torque ripple, reactive power ripple, and harmonic distortion of stator current.

In order to improve the STSM algorithms performances, a complimentary use of the ANFIS controller is proposed. The main goal of this work is to control independently the reactive and active powers both of them using the ANFIS-STSM algorithms.

ANFIS algorithm is a technology based on engineering experience and observations. ANFIS architecture was first proposed by Jang [37] in 1993. This strategy is a widely applied artificial intelligent that combines the advantages of both ANN controller and fuzzy logic (FL) it is generally used for nonlinear and complex systems in various fields [38, 39]. Garcia et al. [40] designed an ANFIS based energy management system which consists of battery, renewable energy sources and hydrogen. Hysteresis comparator based on ANFIS controllers was proposed to control induction motor (IM) [41]. ANFIS controller were designed to regulate the speed of IM controlled by direct torque control (DTC) [42]. Vector control scheme based on neuro-fuzzy was proposed to control DFIG-based wind turbine systems [43]. A novel rotor current controller based on ANFIS controllers is developed to control DFIG [44]. The ANFIS controllers-based control scheme is developed for standalone operation mode of DFIG [45]. SMC and ANFIS controllers are combined to control the DFIG-based wind energy conversion systems [46]. ANFIS-SOSMC controllers is proposed to regulate the reactive and active power of the DFIG [47]. A new nonlinear control has been proposed in this paper. This proposed nonlinear control is based on ANFIS algorithm and STSM control theory.

The ANFIS-STSM algorithms is a modification of the STSMC algorithms, where the switching controller term sgn(S(x)), has been replaced by an ANFIS controller as shown in Figure 16. Both of them do not need advanced mathematical models. The DPC with ANFIS-STSM algorithms goal is to control the stator reactive and the active powers of the DFIG. The stator reactive power is controlled by the direct axis voltage \( V_{dr} \), while the active power is controlled by the quadrature axis voltage \( V_{qr} \).

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Table 3. ANFIS rules

<table>
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</tr>
</tbody>
</table>

7. RESULTS AND ANALYSIS

The simulation results of DPC with ANFIS-STSM algorithms of the DFIG are compared with conventional DPC control scheme. For this end, the control system was tested under different tests.

The DFIG used in our study has the following parameters: nominal active power of the stator: P_m=1.5 MW, stator voltage: 380/696V, two poles, stator voltage frequency: 50Hz; R_s=0.012 Ω, R_r=0.021 Ω, L_s=0.0137H, L_r=0.0136H, J=1000 kg.m² and f_s=0.0024 Nm/s [51, 52].

The trajectory of the measured magnitude of the stator current is shown in Figure 22. It can be stated that the active power tracks almost perfectly their reference value (P_r-ref). On the other hand, the amplitudes of the oscillations of the active power are smaller and occur in a shorter time period in comparison with the oscillations obtained for the conventional DPC with hysteresis comparators (see Figure 23).

For the DPC-STSM algorithms with the performance of the conventional DPC system with application of the ANFIS-STSM algorithms with comparative analysis of THD values.

Table 4. Comparative analysis of THD value

<table>
<thead>
<tr>
<th>Stator current</th>
<th>DPC</th>
<th>DPC-ANFIS-STSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>THD (%)</td>
<td>0.88</td>
<td>0.29</td>
</tr>
</tbody>
</table>

The simulation waveforms of the reference and measured active power of the DFIG-based WTS are shown in Figure 20 in order to compare the performance of the DPC system with application of the ANFIS-STSM algorithms with the performance of the conventional DPC system with application of the switching table. The active power tracks almost perfectly their reference value (P_r-ref). On the other hand, the amplitudes of the oscillations of the active power are smaller and occur in a shorter time period in comparison with the oscillations obtained for the conventional DPC with hysteresis comparators (see Figure 23).

For the DPC-ANFIS-STSM and conventional DPC control scheme, the reactive power track almost perfectly their reference value (see Figure 21). Moreover, the DPC-ANFIS-STSM control scheme minimized the reactive power ripple compared to the conventional DPC control scheme (See Figure 24).

The trajectory of the measured magnitude of the stator current is shown in Figure 22. It can be stated that the amplitudes of the stator currents depend on the state of the drive system and the value of the load active/reactive power of the DFIG-based WTS. In addition, the DPC-ANFIS-STSM method reduced the stator current ripple compared to the DPC strategy (See Figure 25).
Stator current (A)

Active power $P_s$ (W)

<table>
<thead>
<tr>
<th>1320</th>
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Active power $P_s$ (DPC-ANFIS-STSMC)

<table>
<thead>
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<th>0.6949</th>
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<td>5</td>
</tr>
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Active power $P_s$ (DPC)

<table>
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</table>

Figure 19. Spectrum harmonic of stator current (DPC-ANFIS-STSMC)

Figure 20. Active power (RTT)

Figure 21. Reactive power (RTT)

Figure 22. Stator current (RTT)

B. Robustness test (RT)

Figure 23. Zoom in the active power (RTT)

Figure 24. Zoom in the reactive power (RTT)

Figure 25. Zoom in the stator current (RTT)

Figure 26. Spectrum harmonic of stator current (DPC)
In this section, the nominal values of $R_s$ and $R_r$ are multiplied by 2. Simulation results are presented in Figures 26-30. As it’s shown by these figures, these variations present an apparent effect on stator powers and currents curves such as the effect appears more significant for the conventional DPC control scheme compared to DPC-ANFIS-STSM (See Figures 31-33).

**Figure 27.** Spectrum harmonic of stator current (DPC-ANFIS-STSM)

**Figure 28.** Active power (RT)

**Figure 29.** Reactive power (RT)

The THD value of stator current in the DPC-ANFIS-STSM control scheme has been minimized significantly (See Figures 26-27). Table 5 shows the comparative analysis of THD values. Thus, it can be concluded that the proposed DPC with ANFIS-STSM algorithms is more robust than the conventional DPC control scheme.

**Table 5.** Comparative analysis of THD value (RT)

<table>
<thead>
<tr>
<th></th>
<th>DPC</th>
<th>DPC-ANFIS-STSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator current</td>
<td>1.02</td>
<td>0.46</td>
</tr>
</tbody>
</table>
8. CONCLUSIONS

The main objective of this work was to develop an improved DPC control of a DFIG integrated into a wind energy system. The basic idea was to use ANFIS-STSVM hybrid controllers associated with a DPC-SVM strategy. Numerical simulations by Matlab/ Simulink have been developed to test the performances provided by the techniques used. The results of simulation obtained show well the superiority of the proposed technique (DPC-ANFIS-STSVM) compared to the classical one (DPC) especially in the attenuation of the fluctuations of the powers supplied and the robustness against parametric variations.

REFERENCES


NOMENCLATURE

| STSM         | Super-twisting sliding mode |
| DPC          | Direct power control        |
| DFIG         | Doubly fed induction generator |
| SVPWM        | Space vector pulse width modulation |
| ANFIS        | Adaptive Network-Based Fuzzy Inference System |
| NPC          | Neutral point clamped       |
| ANN          | Artificial neural network   |
| FLC          | Fuzzy logic controller      |
| GSC          | Grid side converter         |
| SOSMC        | Second order sliding mode controller |
| PI           | Proportional-integral       |
| r, s         | Rotor, stator               |
| d, q         | Synchronous d-q axis        |
| SVM          | Space vector modulation     |
| L, L_s       | Stator and rotor self-inductances |
| L_m          | Mutual inductance           |
| R, R_s       | Stator and rotor resistances |
| ψ, ψ_s       | Rotor and Stator flux vectors |
| I, I_s       | Rotor and stator current vectors |
| V, V_r       | Rotor and stator voltage vectors |
| P, Q          | Active and reactive powers  |

APPENDIX

1. The coefficients of the STSM stator active/reactive power controllers

Table 6 shows the constants values of the reactive/active power STSM algorithm gains (K1, K2, K3 and K4).

<table>
<thead>
<tr>
<th>Reactive power</th>
<th>Active power</th>
</tr>
</thead>
<tbody>
<tr>
<td>K3</td>
<td>K4</td>
</tr>
<tr>
<td>200</td>
<td>1000</td>
</tr>
</tbody>
</table>

2. Block diagram of ANFIS controller

The block diagram of ANFIS controller is shown in Figure 34.

![Figure 34. ANFIS controller](image)

The structure of the ANN controller is illustrated in the Figure 35. The block diagram of layer 1 and layer 2 is shown in Figure 36 and Figure 37 respectively.

![Figure 35. Block diagram of the ANN controller](image)

![Figure 36. Layer 1](image)

![Figure 37. Layer 2](image)