An ANFIS Based Control Strategy to Improve Performance of Shunt Active Power Filter for Renewable Power Generation Systems

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Abstract: However, with the advent of the various soft computing methodologies like neural networks, the fuzzy logic and the genetic algorithm combined with modern structure optimization techniques, a wider class of systems can be handled at present. Design of an Adaptive Neuro Fuzzy Inference System controller by using voltage as feedback for significantly improving the dynamic performance of proposed Active Power Filter module. Utility distribution networks, sensitive industrial loads and critical commercial operations suffer from various types of outages and service interruptions which can cost significant financial losses. An active power filter implemented with a four-leg voltage-source inverter using a predictive control scheme is presented. The use of a four-leg voltage-source inverter allows the compensation of current harmonic components, as well as unbalanced current generated by single-phase nonlinear loads. A detailed yet simple mathematical model of the active power filter, including the effect of the equivalent power system impedance, is derived and used to design the predictive control algorithm. The compensation performance of the proposed active power filter and the associated ANFIS control scheme under steady state operating condition is demonstrated to improve the power quality is simulated using MATLAB/SIMULINK.

Keywords: ANFIS & Fuzzy Logic Controller, Active Power Filter, Current Control, Four-Leg Converters, Predictive Control Harmonics, And Power Quality.

I. INTRODUCTION

The proposed ANFIS can construct an input-output mapping based on both human knowledge (in the form of fuzzy if-then rules) and stipulated input-output data pairs. In the simulation, the ANFIS architecture is employed to model nonlinear functions, identify nonlinear components on-line in a control system, and predict a chaotic time series, all yielding remarkable results. Increasing global energy consumption and noticeable environmental pollution are making renewable energy more important. Today, a small percentage of total global energy comes from renewable sources, mainly hydro and wind power. As more countries try to reduce greenhouse gas (GHG) emissions, new power generation capacity can no longer be met by traditional methods such as burning coal, oil, natural gas, etc. However, these DG units produce a wide range of voltages due to the fluctuation of energy resources and impose stringent requirements for the inverter topologies and controls. To have sustainable growth and social progress, it is necessary to meet the energy need by utilizing the renewable energy resources like wind, biomass, hydro, co-generation, etc. In sustainable energy system, energy conservation and the use of renewable source are the key paradigm. The need to integrate the renewable energy like wind energy/PV into power system is to make it possible to minimize the environmental impact on conventional plant. The integration of wind energy into existing power system presents technical challenges and that requires consideration of voltage regulation, stability, power quality problems.

The power quality is an essential customer-focused measure and is greatly affected by the operation of a distribution and transmission network. The issue of power quality is of great importance to the wind turbine. There has been an extensive growth and quick development in the exploitation of wind energy in recent years. Although active power filters implemented with three-phase four-leg voltage-source inverters (4L-VSI) have already been presented in the technical literature [2]–[6], the primary contribution of this paper is a predictive control algorithm designed and implemented specifically for this application. Traditionally, active power filters have been controlled using pre-tuned controllers, such as PI-type or adaptive, for the current as well as for the dc-voltage loops. PI controllers must be designed based on the equivalent linear model, while predictive controllers use the nonlinear model, which is closer to real operating conditions. An accurate model obtained using predictive controllers improves the performance of the active power filter, especially during transient operating conditions, because it can quickly follow the current-reference signal while maintaining a constant dc-voltage. So far, implementations of predictive control in power converters have been used mainly in induction motor drives.
In the case of motor drive applications, predictive control represents a very intuitive control scheme that handles multivariable characteristics, simplifies the treatment of dead-time compensations, and permits pulse-width modulator replacement. However, these kinds of applications present disadvantages related to oscillations and instability created from unknown load parameters. One advantage of the proposed algorithm is that it fits well in active power filter applications, since the power converter output parameters are well known. These output parameters are obtained from the converter output ripple filter and the power system equivalent impedance. The converter output ripple filter is part of the active power filter design and the power system impedance is obtained from well-known standard procedures. In the case of unknown system impedance parameters, an estimation method can be used to derive an accurate R–L equivalent impedance model of the system. With respect to their successful methodology implementation, this kind of methodology implemented in this paper is using fuzzy logic controller & ANFIS with feedback by introduction of voltage respectively. The introduction of change in voltage in the circuit will be fed to ANFIS controller to give appropriate measure on steady state signal. The fuzzy logic controller serves as intelligent controller for this propose. This paper presents the mathematical model of the 4L-VSI and the principles of operation of the proposed predictive control scheme, including the design procedure. The complete description of the selected current reference generator implemented in the active power filter is also presented. Finally, the proposed active power filter and the effectiveness of the associated with ANFIS control scheme compensation, power quality improvement is simulated using MATLAB/SIMULINK.

II. FOUR-LEG CONVERTER MODEL

Fig 1 shows the configuration of a typical power distribution system with renewable power generation. It consists of various types of power generation units and different types of loads. Renewable sources, such as wind and sunlight, are typically used to generate electricity for residential users and small industries. Both types of power generation use ac/ac and dc/ac static PWM converters for voltage conversion and battery banks for long term energy storage. These converters perform maximum power point tracking to extract the maximum energy possible from wind and sun.

The electrical energy consumption behavior is random and unpredictable, and therefore, it may be single- or three-phase, balanced or unbalanced, and linear or nonlinear. An active power filter is connected in parallel at the point of common coupling to compensate current harmonics, current unbalance, and reactive power. It is composed by an electrolytic capacitor, a four-leg PWM converter, and a first-order output ripple filter, as shown in Fig. 2. This circuit considers the power system equivalent impedance $Z_s$, the converter output ripple filter impedance $Z_f$, and the load impedance $Z_L$. The four-leg PWM converter topology is shown in Fig. 3. This converter topology is similar to the conventional three-phase converter with the fourth leg connected to the neutral bus of the system. The fourth leg increases switching states from improving control flexibility and output voltage quality [19], and is suitable for current unbalanced compensation.

![Fig. 2. Three-phase equivalent circuit of the proposed shunt active power filter.](image)

![Fig. 3. Two-level four-leg PWM-VSI topology](image)
Where $R_{eq}$ and $L_{eq}$ are the 4L-VSI output parameters expressed as Thevenin’s impedances at the converter output terminals $Z_{eq}$. Therefore, the Thevenin’s equivalent impedance is determined by a series connection of the ripple filter impedance $Z_f$ and a parallel arrangement between the system equivalent impedance $Z_s$ and the load impedance $Z_L$.

$$Z_{eq} = \frac{Z_s Z_L}{Z_s + Z_L} + Z_f \approx Z_s + Z_f$$  
(3)

For this model, it is assumed that $Z_L \sim Z_s$, that the resistive part of the system’s equivalent impedance is neglected, and that the series reactance is in the range of 3–7% p.u., which is an acceptable approximation of the real system. Finally,

$$R_{eq} = R_f \text{ and } L_{eq} = L_s + L_f.$$  
(4)

III. REFERENCE CURRENT GENERATION SCHEME

A $dq$-based current reference generator scheme is used to obtain the active power filter current reference signals. This scheme presents a fast and accurate signal tracking capability. This characteristic avoids voltage fluctuations that deteriorate the current reference signal affecting compensation performance [20]. The current reference signals are obtained from the corresponding load currents as shown in Fig. 4. This module calculates the reference signal currents required by the converter to compensate reactive power, current harmonic, and current imbalance. The displacement power factor $(\sin \varphi(L))$ and the maximum total harmonic distortion of the load $(\text{THD}(L))$ defines the relationships between the apparent power required by the active power filter, with respect to the load, as shown below.

$$\frac{S_{APF}}{S_L} = \sqrt{\frac{\sin \varphi(L) + \text{THD}(L)}{1 + \text{THD}(L)^2}}$$  
(5)

Where the value of THD(L) includes the maximum compensable harmonic current, defined as double the sampling frequency $f_s$. The frequency of the maximum current harmonic component that can be compensated is equal to one half of the converter switching frequency. The $dq$-based scheme operates in a rotating reference frame; therefore, the measured currents must be multiplied by the $\sin(wt)$ and $\cos(wt)$ signals. By using $dq$-transformation, the $d$ current component is synchronized with the corresponding phase-to-neutral system voltage, and the $q$ current component is phase-shifted by 90°. The $\sin(wt)$ and $\cos(wt)$ synchronized reference signals are obtained from a synchronous reference frame (SRF) PLL. The SRF-PLL generates a pure sinusoidal waveform even when the system voltage is severely distorted. Tracking errors are eliminated, since SRF-PLLSs are designed to avoid phase voltage unbalancing, harmonics (i.e., less than 5% and 3% in fifth and seventh, respectively), and offset caused by the nonlinear load conditions and measurement errors [3], the relationship between the real currents $i_L(x) = i_u, v, w$ and the associated $dq$ components $(i_d$ and $i_q)$.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{2}{\sqrt{3}} \begin{bmatrix} \sin \omega t & \cos \omega t \\ \cos \omega t & -\sin \omega t \end{bmatrix} \begin{bmatrix} i_u \\ i_v \\ i_w \end{bmatrix}$$  
(6)

A low-pass filter (LFP) extracts the dc component of the phase currents $i_d$ to generate the harmonic reference components $id$. The reactive reference components of the phase-currents are obtained by phase-shifting the corresponding ac and dc components of $iq$ by 180°. In order to keep the dc-voltage constant, the amplitude of the converter reference current must be modified by adding an active power reference signal $ie$ with the $d$-component. The resulting signals $i^*d$ and $i^*q$ are transformed back to a three-phase system by applying the inverse Park and Clark transformation. The cut off frequency of the LPF used in this paper is 20 Hz.

Fig.4. $dq$-based current reference generator block diagram.

The current that flows through the neutral of the load is compensated by injecting the same instantaneous value obtained from the phase-currents, phase-shifted by 180°, as shown next.

$$i_{sn}^* = -(i_{L_u} + i_{L_v} + i_{L_w})$$  
(8)

One of the major advantages of the $dq$-based current reference generator scheme is that it allows the implementation of a linear controller in the dc-voltage control loop. However, one important disadvantage of the $dq$-based current reference frame algorithm used to generate the current reference is that a second order harmonic component is generated in $id$ and $iq$ under unbalanced operating conditions. The amplitude of this harmonic depends on the percent of unbalanced load current (expressed as the relationship between the negative sequence current $i_{L,2}$ and the positive sequence current $i_{L,1}$). The second-order harmonic cannot be removed from $id$ and $iq$, and therefore generates a third harmonic in the reference current when it is converted back to abc frame. Since the load current does not

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have a third harmonic, the one generated by the active power filter flows to the power system.

**A. DC Link Voltage Control**

The dc-voltage converter is controlled with a traditional PI controller. This is an important issue in the evaluation, since the cost function is designed using only current references, in order to avoid the use of weighting factors. Generally, these weighting factors are obtained experimentally, and they are not well defined when different operating conditions are required. Additionally, the slow dynamic response of the voltage across the electrolytic capacitor does not affect the current transient response. For this reason, the PI controller represents a simple and effective alternative for the dc-voltage control. The dc-voltage remains constant (with a minimum value of sqrt of 6/π(rms) ) until the active power absorbed by the converter decreases to a level where it is unable to compensate for its losses. The active power absorbed by the converter is controlled by adjusting the amplitude of the active power reference signal \( i_e \), which is in phase with each phase voltage. In the block diagram shown in Fig. 5, the dc-voltage \( v_{dc} \) is measured and then compared with a constant reference value \( v_{ref} \). The error \( (e) \) is processed by a PI controller, with two gains, \( K_p \) and \( T_i \). Both gains are calculated according to the dynamic response requirement. Fig. 5 shows that the output of the PI controller is fed to the dc-voltage transfer function \( Gs \) which is represented by a first-order system.

\[
G(s) = \frac{v_{dc}}{i_e} = \frac{3}{2} \frac{K_p v_s \sqrt{2}}{C_{dc} v_{dc}^*}
\]  

(9)

The equivalent closed-loop transfer function of the given system with a PI controller

\[
C(s) = K_p \left(1 + \frac{1}{T_i s}\right)
\]

\[
\frac{v_{dc}}{i_e} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}
\]  

(10)

Since the time response of the dc-voltage control loop does not need to be fast, a damping factor \( \zeta = 1 \) and a natural angular speed \( \omega_n = 2\pi \cdot 100 \text{ rad/s} \) are used to obtain a critically damped response with minimal voltage oscillation. The corresponding integral time \( T_i = 1/\zeta \) (13) and proportional gain \( K_p \) can be calculated as

\[
\zeta = \sqrt{\frac{3}{8} \frac{K_p v_s \sqrt{2}}{C_{dc} v_{dc}^*} T_i}
\]

\[
\omega_n = \frac{3}{2} \frac{K_p v_s \sqrt{2}}{C_{dc} v_{dc}^* T_i}
\]  

(11)

**IV. INTRODUCTION TO FUZZY LOGIC CONTROL**

L. A. Zadeh presented the first paper on fuzzy set theory in 1965. Since then, a new language was developed to describe the fuzzy properties of reality, which are very difficult and sometime even impossible to be described using conventional methods. Fuzzy set theory has been widely used in the control area with some application to power system [5]. A simple fuzzy logic control is built up by a group of rules based on the human knowledge of system behavior. Matlab/Simulink simulation model is built to study the dynamic behavior of converter. Furthermore, design of fuzzy logic controller can provide desirable both small signal and large signal dynamic performance at same time, which is not possible with linear control technique. Thus, fuzzy logic controller has been potential ability to improve the robustness of converters. The basic scheme of a fuzzy logic controller is shown in Fig 6 and consists of four principal components such as: a fuzzy fication interface, which converts input data into suitable linguistic values; a knowledge base, which consists of a data base with the necessary linguistic definitions and the control rule set; a decision-making logic which, simulating a human decision process, infer the fuzzy control action from the knowledge of the control rules and linguistic variable definitions; a de-fuzzification interface which yields non fuzzy control action from an inferred fuzzy control action [10].

![Fuzzy Logic Controller Diagram](image-url)

The fuzzy control systems are based on expert knowledge that converts the human linguistic concepts into an automatic control strategy without any complicated mathematical model. A neuro-fuzzy technique called Adaptive network based fuzzy inference system (ANFIS) has been used as a prime tool in the present work. Adaptive network based fuzzy inference system (ANFIS) is a neuro fuzzy technique where the fusion is made between the neural network and the fuzzy inference system. In ANFIS the parameters can be estimated in such a way that both the Sugeno and Tsukamoto fuzzy models are represented by the ANFIS architecture. Again with minor constraints the ANFIS model resembles the Radial basis function network (RBFN) functionally. This ANFIS methodology comprises of a hybrid system of fuzzy logic and neural network technique. The fuzzy logic takes into account the imprecision and uncertainty of the system that is being modeled while the neural network gives...
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it a sense of adaptability. Using this hybrid method, at first an initial fuzzy model along with its input variables are derived with the help of the rules extracted from the input output data of the system that is being modeled. Next the neural network is used to fine tune the rules of the initial fuzzy model to produce the final ANFIS model of the system. In this proposed work ANFIS is used as the backbone for the identification of real world systems.

Fig.7. Block diagram of the Fuzzy Logic Controller (FLC) for proposed converter

A. ANFIS Structure

For simplicity, it is assumed that the fuzzy inference system under consideration has two inputs and one output. The rule base contains the fuzzy if-then rules of Takagi and Sugeno’s type as follows:

\[ \text{If } x \text{ is } A \text{ and } y \text{ is } B \text{ then } z \text{ is } f(x,y) \quad (12) \]

Where A and B are the fuzzy sets in the antecedents and z = f(x, y) is a crisp function in the consequent. Usually f(x, y) is a polynomial for the input variables x and y. But it can also be any other function that can approximately describe the output of the system within the fuzzy region as specified by the antecedent. When f(x, y) is a constant, a zero order Sugeno fuzzy model is formed which may be considered to be a special case of Mamdani fuzzy inference system where each rule consequent is specified by a fuzzy singleton [24]. If f(x, y) is taken to be a first order polynomial a first order Sugeno fuzzy model is formed. For a first order two rule Sugeno fuzzy inference system, the two rules may be stated as:

Rule 1: If x is A1 and y is B1 then f1 = p1x + q1y + r1

Rule 2: If x is A2 and y is B2 then f2 = p2x + q2y + r2

Here type-3 fuzzy inference system proposed by Takagi and Sugeno is used. In this inference system the output of each rule is a linear combination of the input variables added by a constant term. The final output is the weighted average of each rule’s output. The corresponding equivalent ANFIS structure is shown in Fig. 8. With the hysteresis control, limit bands are set on either side of a signal representing the desired output waveform [6]. The inverter switches are operated as the generated signals within limits. The control circuit generates the sine reference signal wave of desired magnitude and frequency, and it is compared with the actual signal. As the signal exceeds a prescribed hysteresis band, the upper switch in the half bridge is turned OFF and the lower switch is turned ON. As the signal crosses the lower limit, the lower switch is turned OFF and the upper switch is turned ON. The actual signal wave is thus forced to track the sine reference wave within the hysteresis band limits.

Fig. 8. ANFIS Structure

VI. MATLAB MODELEING AND SIMULATION RESULTS

Here simulation is carried out in several cases, in that 1) proposed Active Power Compensation at Grid Interfaced RES using Fuzzy System, 2) Proposed Active Power Compensation at Grid Interfaced RES using ANFIS System.

Case 1: Proposed Active Power Compensation at Grid Interfaced RES using Fuzzy System
Fig.10. Matlab/Simulink Modeling of Proposed Active Compensation Scheme at Grid Interfaced RES Using Fuzzy System

Fig11. Grid Voltage as a Source Component.

Fig12. Load Current for Phase A

Fig13. Shunt Current when SAPF.

Fig.14. Neutral Current for Single Phase A

Fig15. Source Current.

Fig.16. DC Link Voltage.

**THD Calculation:**

The FFT analysis is done for wind energy and pv cell on grid side current to calculate the THD before and after the interfacing of the SAPF. It is seen that the THD is high before interfacing the SAPF. After interfacing the SAPF at t=0.72s, the THD is maintained at the same level for both the cases. Here using ANFIS controller, to minimize the sudden disturbances coming from the load, due to these disturbances DC Link voltage may goes to changes that’s why using advanced controller to minimize the disturbances & improve the THD response.
Fig. 17. FFT Analysis of Source Current under No Compensation Scheme, here attain 18.29%.

Fig. 18. FFT Analysis of Source Current under Compensation Scheme using Fuzzy Controller, here attain 0.44%.

Case 2: Proposed Active Power Compensation at Grid Interfaced RES using ANFIS System

Fig. 19. Input membership function after training (a) Error membership functions (b) Change in error membership function

Fig. 20. DC Link Voltage

Fig. 21. FFT Analysis of Source Current under Compensation Scheme using ANFIS Controller, here attain 0.22%.
V. CONCLUSION

In this thesis, a de System has been studied with the photo voltaic system. To improve the power quality at point of common coupling with 3-phase 4-wire distributed generation. It has been shown that the grid interfacing inverter can be effectively utilized for power conditioning without affecting its normal operating of real power transfer. The basic principle of the ANFIS method is the use of the network neuron to optimize the membership’s functions of the fuzzy controller in other words; an ANFIS is one optimized fuzzy inference system (FIS). In the Neuro- Fuzzy controller, the simplicity of a Fuzzy controller is combined with the intelligent and adaptive nature of the Neuron Network optimization. To design the ANFIS controller, variables which can represent the dynamic performance of the plant is chosen as the inputs to the controller. This approach thus eliminates the need for additional power conditioning equipment to improve the quality of power at PCC. The MATLAB/SIMULINK simulation model of the proposed system with the connection of renewable energy sources is shown and validated. The control circuit is operated with phase lock loop, proportional integral controller and hysteresis controller which is used to generate the gating pulses for the 4-leg inverter and is carried out at load side with non-linear unbalanced load. Thus the current unbalance, current harmonics and load reactive power, due to unbalanced and non-linear load connected to the PCC, are compensated effectively such that the grid side currents are always maintained as balanced and sinusoidal at unity power factor.

VI. REFERENCES

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