Hybrid PSO-Optimized ANFIS-Based Model to Improve Dynamic Voltage Stability

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Abstract—**The objective of this paper is to perform a hybrid design for an Adaptive Neuro-Fuzzy Inference System (ANFIS) optimized by Particle Swarm Optimization (PSO) to improve the dynamic voltage stability of a grid-connected wind power system. An onshore 99.2MW wind farm using Doubly Fed Induction Generator (DFIG) is studied. To compensate the reactive power absorbed from the power grid of the wind farm, a Static VAR Compensator (SVC) is proposed. To demonstrate the performance of the proposed hybrid PSO–ANFIS controller, simulations of the voltage response in time-domain are performed in Matlab to evaluate the effectiveness of the designed controller. From the results, it can be concluded that the proposed hybrid PSO-optimized ANFIS-based model can be applied to enhance the dynamic voltage stability of the studied grid-connected wind power system.**

Keywords-adaptive neuro-fuzzy inference system; particle swarm optimization; static var compensator; voltage stability

I. INTRODUCTION

Renewable energy is important nowadays and wind generators or solar panels are used in many countries, while wind generators are applied more widely than before. An offshore wind farm can include many wind turbines and wind driven generators. The output power of the wind generators can be connected to form a wind farm and they can feed a power grid using a step-up transformer. In relevance to a wind generator, DFIG (doubly fed induction generator) is the most prevalent generator because of its high efficiency compared to other types of wind generators such as permanent magnet synchronous generator (PMSG) and induction generator (IG) [1]. Moreover, DFIG has the capability of controlling both active and reactive power for better grid integration to the transmission line [2]. However, connecting the stator windings directly to the power grid, makes it very sensitive to power grid faults. Besides, the randomness of wind energy affects the power quality of the connected power systems. Some power quality problems such as voltage fluctuations, flicker, harmonic and voltage deviation of the Baolian wind farm have been studied in [3]. The measurements of a wind farm located in the south-east part of Poland were analyzed and compared with the acceptable values in [4]. In [5], a power quality study of a large-scale wind farm with and without storage was studied. Authors showed that with the proposed storage system, voltage drops, and harmonic voltage and current distortion at the wind farm output can be improved when a short circuit occurs in the connection with the power grid. Flexible AC Transmission Systems (FACTS) devices have been proposed and applied in power transmission systems and in this situation, Static Var Compensator (SVC) is used to enhance the voltage stability [6, 7]. In large systems, the SVC is located in the middle of the transmission line to reduce the oscillation of the system and thus improve grid stability [8, 9].

In today's control devices, the controller plays an important role in improving the operability and flexibility of the device. PID (proportional-integral-derivative) is a linear controller and is used in many control systems. The main disadvantage of this controller is that it does not respond well when the input is large. Recently, many algorithms have been applied to improve the efficiency of the device, such as a fuzzy logic controller used in vibration reduction control when linking generator systems in two large areas [10]. In addition, the fuzzy controller is used to replace the PID controller using the voltage deviation as the feedback signal in the voltage control at the link bus [11]. However, the main disadvantage of fuzzy logic controllers is that they depend on the programmer's experience. To improve the accuracy of the algorithms, combining algorithms together to exploit the advantages of each algorithm is a good solution that is being widely researched. In [12], authors proposed an algorithm combining fuzzy logic and an artificial neural network called ANFIS (Adaptive-Network-based Fuzzy Inference System). ANFIS is also a good structure for designing a controller of FACTS devices [13] because of its simplification and its ease of designing. ANFIS is used for replacing controllers that are not obvious or cannot be calculated by definite equivalence.

In this research paper, a Particle Swarm Optimization (PSO) algorithm is proposed to optimize the parameters of the ANFIS controller for improving voltage stability. The proposed approach is based on the combination of PSO and ANFIS controller. The idea of combining PSO and ANFIS was applied to examine the electricity market of mainland Spain [14] as well as for short-term electricity prices prediction [15] with many advantages.

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II. SYSTEM CONFIGURATION

A. Studied System Configuration

The structure of the studied system in this paper is a practical 99.2MW wind farm in Bac Lieu province, Vietnam including 62×1.6MW wind turbineS as shown in Figure 1. This project, panning an area of 1,000ha, transmits power to the national grid through two parallel 63MVA transformers and two 110kV transmission lines. The wind farm has an estimated electricity output of 300GWh per annum. The wind turbine model is GE 1.6 XLE – 1.6MW supplied by General Electric using a DFIG-based wind turbine with a single-line diagram [16]. The stator windings of the DFIG are directly connected to the low-voltage side of the 0.69/22kV step-up transformer while the rotor windings of the DFIG are connected to the same 0.69kV side through a rotor-side converter (RSC), a DC link, a grid-side converter (GSC), and a connection line. For normal operation of a DFIG, the input AC-side voltages of the RSC and the GSC can be effectively controlled to achieve simultaneous output active power and reactive power control [17].

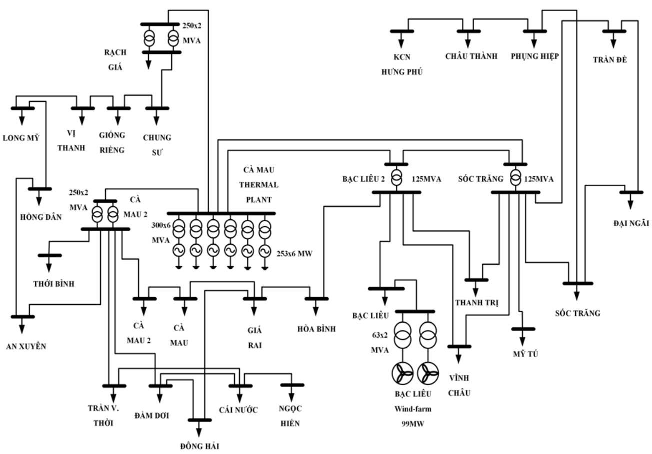


Fig. 1. Single-line diagram of the studied system.

For normal operation of a wind DFIG, the input AC-side voltages of the RSC and the GSC can be effectively controlled to achieve the aims of simultaneous output active power and reactive power control. The control block diagram of the RSC of the studied DFIG and the control block diagram of the GSC of the studied wind DFIG can be seen in [18].

B. SVC Model

For improving voltage stability, a 40 MVAr SVC is proposed for adjusting the voltage at the connected bus by compensating the reactive power to the power grid. The equivalent model of SVC is shown in Figure 2. It consists of a thyristor switched capacitor (TSC) and thyristor controlled reactors (TCRS). The control scheme of the studied SVC is presented in [19]. In the SVC model, if the bus voltage is lower than the reference value, the value of the equivalent susceptance (B_{SVC}) of the SVC is positive and on the contrary, if the bus voltage is higher than the reference value, the B_{SVC} is negative. The relationship between the firing angle (α) and the steady state value of B_{TCR} is given as:

$$B_L(\alpha) = \frac{2(\pi - \alpha) + \sin(2\alpha)}{\pi X_L} \quad (1)$$

where $\alpha = [\frac{\pi}{2} \div \pi]$.

The equivalent susceptance of SVC (B_{SVC}) is:

$$B_{SVC}(\alpha) = \frac{1}{X_C} - B_L(\alpha) \quad (2)$$

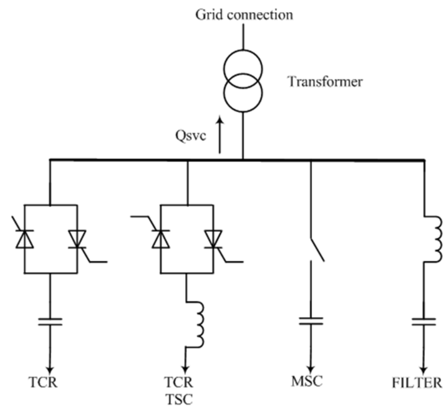


Fig. 2. Single-line diagram of SVC

III. HYBRID PSO–ANFIS CONTROLLER DESIGN

An ANFIS is a class of adaptive multi-layer feedforward network. It incorporates the self-learning ability of neural networks with the linguistic expression function of fuzzy inference. The structure of the ANFIS controller is depicted in Figure 3. The ANFIS network is composed of five layers.

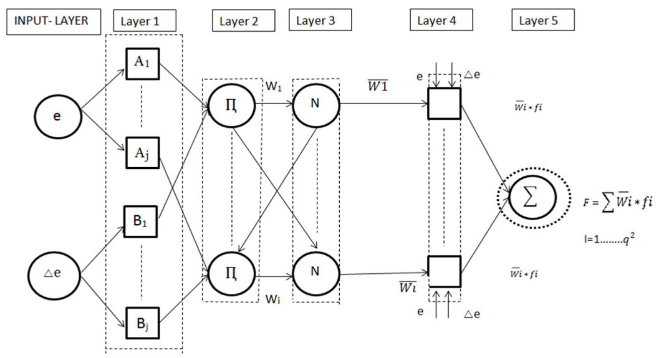


Fig. 3. Structure of the ANFIS

Each layer contains several nodes which described as the following node equations:

In Layer 1, the output function O_i^1 shows the membership grade of a fuzzy set A1, A2 , B1, or B2 and it specifies the degree to the given input e or Δe.

$$O_i^1 = \mu A_i(e),\ i = 1 \div 2 \quad (3)$$

or

$$O_i^1 = \mu B_{i-2}(\Delta e),\ i = 3 \div 4 \quad (4)$$

The membership functions for A and B are usually described by a generalized bell functions as described bellow:

$$\mu A_i(e) = \frac{1}{1 + \left| \frac{e - r_i}{p_i} \right|^{2q_i}} \quad (5)$$

where p_i, q_i, r_i are the values of the bell function.

In Layer 2, the product output value O_i^2 is formed by multipling the incoming signals. In this layer, each node output represents the firing strength of a rule.

$$O_i^2 = w_i = \mu A_i(e).B_i(\Delta e),\ i = 1 \div 2 \quad (6)$$

In Layer 3, the outputs of this layer, O_i^3, are called normalized firing strengths:

$$O_i^3 = \overline{w_i} = \frac{w_i}{w_1 + w_2},\ i = 1 \div 2 \quad (7)$$

In Layer 4, the output O_i^4 is the contribution of the i^{th} rule to the overall output:

$$O_i^4 = \overline{w_i} z_i = \overline{w_i}(a_i.e + b_i.\Delta e + c_i),\ i = 1 \div 2 \quad (8)$$

where a_i, b_i, c_i are consequent parameters.

In Layer 5, the output O_i^5 is the final output as the summation of all incoming signals

$$O_i^5 = F = \sum \overline{w_i} z_i,\ i = 1 \div 2 \quad (9)$$

In an ANFIS system, neural networks extract automatically fuzzy rules from numerical data and, through the learning process, the membership functions are adaptively adjusted. For improving the training process, PSO is applied to optimize the parameters of the membership functions of the ANFIS controller [20]. The objective of this method is to discover the particle location that outcomes the finest assessment of a specified fitness function to minimize the training errors of ANFIS. In PSO, a swarm specifies the number of probable solutions to a complex problem, where each probable solution is known as a particle. Every particle set has its opening parameters in random fashion and is flown throughout the multi-dimensional search space during the initialization phase of swarm optimization [21]. As sketched in Figure 4, an updating mechanism of the PSO technique is presented, where *x(t)* and *v(t)* denote a particle's position and flight velocity over a solution space, respectively. The following equations present the search mechanism:

Velocity update rule:

$$v_i(t) = \omega v_i(t-1) + \rho_1\left[x_{Pbesti} - x_i(t)\right] + \rho_2\left[x_{Gbesti} - x_i(t)\right] \quad (10)$$

where ω is an inertia weight, ρ_1, ρ_2 are random variables, G_{best} is the best particle among all particles in the swarm, and P_{best} is the personal best position of each particle.

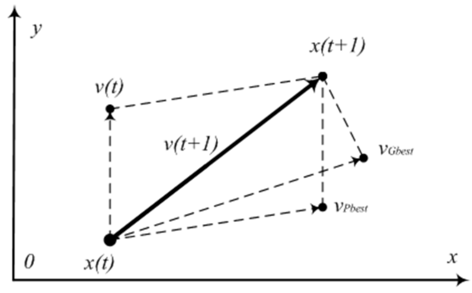
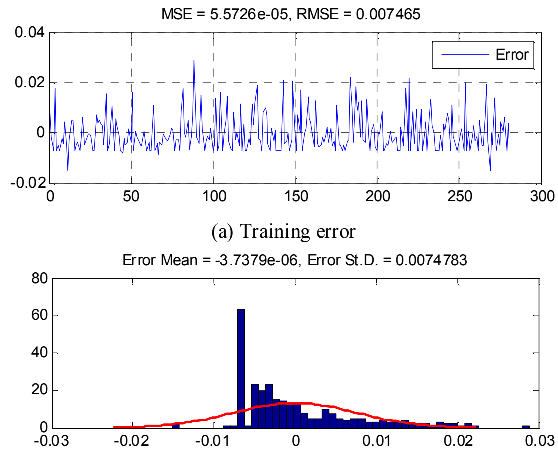


Fig. 4. Updating new position mechanism of PSO

Position update rule:

$$x_i(t) = x_i(t-1) + v_i(t),\ t = t + 1 \quad (11)$$

The results after training of the proposed hybrid PSO-ANFIS are shown in Figure 5. It can be seen that the training error between the target and the output of the training data is very close to zero (Figure 5(a)) and the error mean and error StD are also very small (Figure 5(b)). It means the proposed PSO can optimize the parameters of the ANFIS controller.



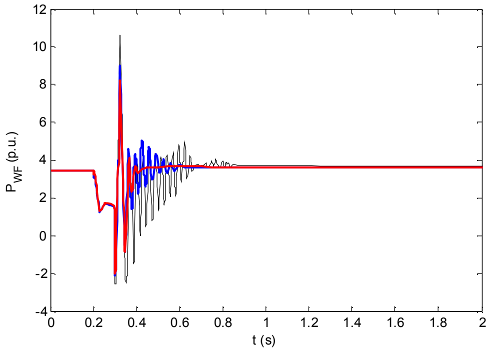
(a) Training error

(b) Error mean

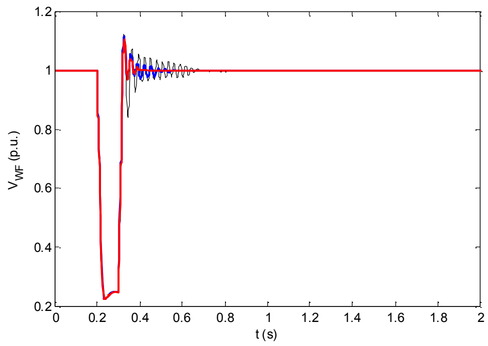
Fig. 5. Training results of the proposed hybrid PSO-ANFI

IV. SIMULATION RESULTS

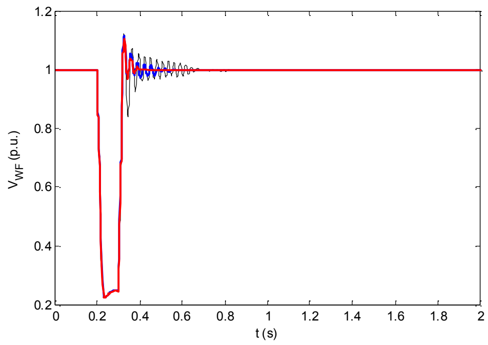
The simulation results of the studied Bac Lieu power system with a wind farm and a proposed SVC with hybrid PSO-ANFIS controller are presented in Figure 6 in which a severe three-phase short circuit fault happened at the 220kV bus in 0.1s. In Figure 6, the black lines are the responses of the system with SVC and PI controller, the blue lines are the responses of the system with SVC and ANFIS controller which is trained by applying the ANFIS Toolbox in Matlab while the red lines are the ones with SVC and the proposed hybrid PSO-ANFIS controller. Active power and voltage of the wind farm are represented in Figures 6(a) and 6(b).



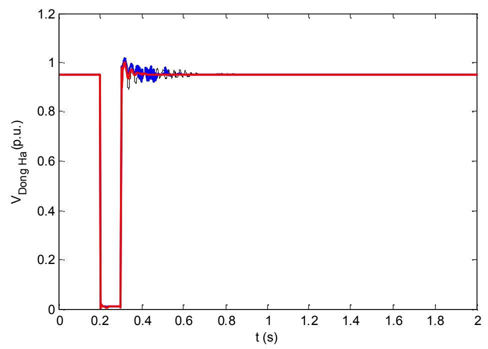
(a) Active power of the wind farm



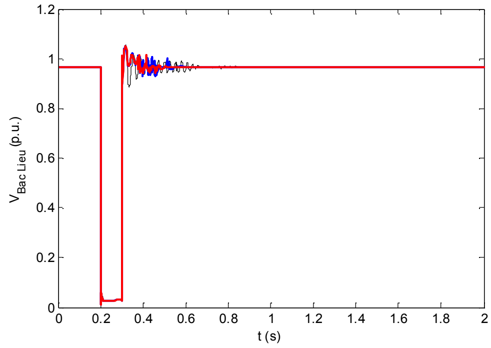
(b) Voltage of the wind farm bus



(c) Voltage of Tra Noc bus

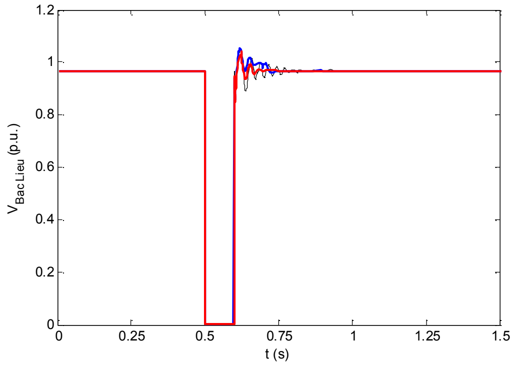


(d) Voltage of Dong Hai bus

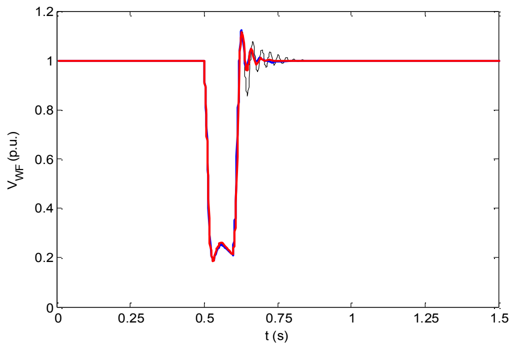


(e) Voltage of Bac Lieu bus

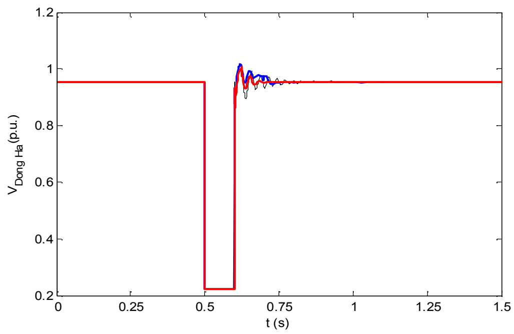
Fig. 6. The response of the system when a three-phase short circuit fault happens at 220kV level. Legend: PI ANFIS PSO-ANFIS



(a) Voltage of Bac Lieu bus



(b) Voltage of the wind farm bus



(c) Voltage of Dong Hai bus

Fig. 7. The response of the system when a three-phase short circuit fault happens at 110kV level. Legend: PI ANFIS PSO-ANFIS

The voltage of the three buses i.e. Tra Noc, Dong Ha and Bac Lieu are shown in FigureS 6(c)-6(e) respectively. From these figures, it is easily to see that by applying the hybrid PSO-ANFIS controller for the SVC device, the output values of these parameters are more stable and more effective. The voltage of each node is improved and the number of oscillations and the overshoot after a three-phase short circuit fault occurred, are also reduced. For more details, Figure 7 exhibits the simulation results of the studied system when a three-phase short circuit fault happened at the Bac Lieu bus working at 110kV level and lasting 5 cycles. By obseving the response of the voltage at Bac Lieu bus shown in Figure 7(a) it can be seen that voltage drop to zero occurred during the fault. However, with the response plotted in Figures 7(b) and 7(c) the voltage magnitude of the wind farm bus and the voltage at Dong Ha bus only dropped to 0.2p.u. Thanks to the operation of the SVC and its designed controller, a large amount of reactive power was supplied in order to improve the voltage level of these buses.

V. CONCLUSIONS

In this paper, a hybrid PSO-ANFIS controller for SVC was designed and applied in a grid-connected wind power system. SVC can support fast response to the system to balance reactive power in the grid which helps to improve dynamic voltage stability. The results showed that the proposed controller can be used to improve the voltage quality and reduce the number and amplitude of oscillations in hard operating conditions such as a three-phase short circuit fault occurrence. It can be concluded from the time-domain simulation results on Matlab that the hybrid PSO-ANFIS designed controller has more advantages compared to the ANFIS controller and can enhance power quality of the studied system under severe operating conditions.

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