Robust Fuzzy Sliding Mode Control for stability analysis in decentralized hybrid power system

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Abstract: This paper discusses robust fuzzy sliding mode based UPFC controller for stability improvement in a standalone wind-diesel-fuel cell hybrid power system. Small signal model of the hybrid power system with UPFC controller has been modeled and state space equations of the system matrix is formulated for complete analysis. Performance of PI controller based UPFC has been analyzed in stability analysis and it is further improved with a fuzzy logic enhanced sliding mode controller. Variations of different parameters of the hybrid system are noticed for different wind power inputs and load variations. Results with conventional controller have been compared with Fuzzy sliding mode controller and Adaptive Fuzzy sliding mode controller. From the simulation results, the system performance is observed and vital information regarding voltage stability, damping of power oscillations and transient stability are collected.

Keywords— wind-diesel-fuel cell hybrid systems, voltage stability, Fuzzy sliding mode control, UPFC

I. INTRODUCTION

Power supply to remote places is not only challenging but takes lot of effort to set up. These are becoming popular in recent days among rural and regional communities. Penetration of renewable energy sources like wind, solar, Biomass etc. into the electricity market have improved the standalone power systems which were entirely depending on diesel generation systems [1]. The new generation hybrid power systems consisting of one or more renewable energy sources have come up in recent period which are integrated with conventional generation methods. Standalone diesel power systems are having limited use and therefore the usage of the diesel generation is minimised by increasing the renewable energy proportions in a standalone hybrid power system. The configuration of hybrid power system depends on the availability of energy resources and a suitable generation mix can be used to form a standalone hybrid power system. Control of the hybrid power system becomes to have balance between the wind power generation and load demand. It is a known fact that diesel power is considered as one of the best options for its reliability of supplying power and simplicity of operation. It provides both the inertial and reactive power support to the hybrid power system, ensuring better frequency and voltage regulation. But the operation of a diesel generator at all times is not desirable due to its operational constraints and cost, environmental concerns, etc. Therefore in a hybrid Wind-diesel operation, the hybrid system generates power during low wind penetration time periods. Many times an Energy Storage System has been added as an attractive solution to maintain system power balance. A fuel cell system can be integrated into the Wind-diesel power system to add reliability and stability to the standalone network. It offers many advantages when compared to other alternative hybrid power sources. Sometimes a dump load is a common component of hybrid power system which absorbs excess energy available in the system. A dump load can be a water heater system or an electrolyser which are used to produce hydrogen for the fuel cell system. The presented work in this paper includes the operation of a grid connected DFIG based wind-diesel Wind energy conversion system with a fuel cell. The parallel operation of a Doubly fed induction generator based wind turbine, Synchronous generator based diesel generator and fuel cell is discussed. The power quality issues such as reactive power compensation and voltage stability related issues are associated with grid connected wind turbine-fuel cell system is discussed. The small signal transfer function model of wind-diesel-fuel cell hybrid power system is modelled and a small signal transfer function model of static var compensator is considered for reactive power compensation and enhancement of power quality issues such as voltage stability. Among all the renewable energy sources, wind energy has been the fastest growing renewable energy source. But random variation of wind profiles makes the whole system unpredictable and leads to power fluctuations that cause unexpected voltage deviation.

Unified power flow controller (UPFC) plays a major role among FACTS devices, in power factor correction, harmonic compensation [2]. It also provides the much needed reactive power to the load and wind turbine in standalone electric power networks. Like other FACTS devices, the Unified power flow controller (UPFC) has been used in power systems for the purpose of regulating system’s voltage, enhancement of transient stability, and damping of power system oscillations. The small signal models of UPFC such as lead-lag and PI type are presented to improve the capability of a wind farm and enhance the transient stability of the power system. The detailed model of hybrid power system containing DFIG as the main source of energy together with diesel generator, fuel cell system and dump load has been shown with UPFC controller. The design of a sliding mode controller after modified by fuzzy control achieves reduced chattering, simple rule base, and robustness against load disturbance and nonlinearities. Fuzzy Sliding Mode Controller (FSMC) is employed to ensure the stability of the controller of nonlinear as well as linear systems[3]-[8]. It is advantageous to both
Fuzzy controller and sliding mode controller[9]. Some drawbacks of sliding mode controller like chattering phenomena due to high frequency switching near sliding surface is removed by Fuzzy sliding mode controller. It is further improved by Adaptive fuzzy sliding mode controller.

II. WIND DIESEL FUEL CELL HYBRID POWER SYSTEM MODELLING

In a typical standalone hybrid power system as shown in Figure.1 With the wind turbine (DFIG), Diesel engine, Fuel cell are connected to electrical loads and reactive power management has been done through UPFC. The model parameters are mentioned in Table.2.

The reactive power balanced equation can be formed from the above diagram

\[ Q_{SG} + Q_{UPFC} + Q_{FC} = Q_L + Q_{DFIG} \]  \hspace{1cm} (1)

During the system experiences a change of load \( Q_L \), the other parameters experience change

\[ \Delta Q_{SG} + \Delta Q_{UPFC} + \Delta Q_{FC} = \Delta Q_L + \Delta Q_{DFIG} \]  \hspace{1cm} (2)

The modified equation is

\[ \Delta V(S) = \frac{K_V}{\tau_S V} \left[ \Delta Q_{SG}(S) + \Delta Q_{UPFC}(S) + \Delta Q_{FC}(S) - \Delta Q_L(S) - \Delta Q_{DFIG}(S) \right] \]  \hspace{1cm} (3)

Where \( \tau_S = \frac{2 \pi}{f} \) and \( K_V = \frac{1}{D_V} \)

II.A-Modelling of Fuel cell

Generally the FC as shown in Figure.2 consists of three main parts: reformer, stack, and power conditioner. The complexity and very nonlinear behaviour of electrical, chemical, and thermodynamic processes result in complex models. The parameters of such models are difficult to estimate. However, for FC connected using full controlled inverters with large capacitors or some energy storage capabilities, the voltage or the reactive power is assumed to be controlled through full controlled inverters.

![Figure 2. Transfer function of Fuel cell](image-url)

II.B-Modelling of UPFC

Unified power flow controller (UPFC) is for reactive power compensation like SVC and STATCOM. It controls the power flow in the transmission system by controlling the impedance, voltage magnitude and phase angle. This controller offers advantages in terms of static and dynamic operation of the power system. The structure of the UPFC consists of two voltage source inverter (VSI), where one voltage source converter is connected in parallel to the transmission line while the other is in series with the transmission line. Fig. 3 is showing shunt and series controlled UPFC. The structure of UPFC helps to control reactive power and active power by injecting AC voltage in series with amplitude and a phase angle to the transmission line. The role of first inverter is to provide or absorb real power while the second Inverter produces and absorbs reactive power and there by provides shunt compensation. It has been assumed that the series and shunt impedances of UPFC are pure reactances. \( P_{sh} \) and \( Q_{sh} \) are with the shunt voltage sources while \( P_i, Q_i \) represent the series voltage sources. The injected powers depend on the injected voltages and bus voltages also. Buses \( i \) and \( j \) are taken as load buses in the load flow analysis. They are taken with some modifications as the injected powers are not constant. The injected powers are given as follow:

\[ P_i = \frac{V_i}{x_{sh}} \sin(\delta_i - \delta_{sh}) \]  \hspace{1cm} (4)

\[ Q_i = \frac{V_i^2}{x_{sh}} \cos(\delta_i - \delta_{sh}) \]  \hspace{1cm} (4)

\[ P_{pq} = \frac{-V_i}{x_{ij}} \sin(\delta_i - \delta_{pq}) \]  \hspace{1cm} (5)

\[ Q_{pq} = \frac{V_i}{x_{ij}} \cos(\delta_i - \delta_{pq}) \]  \hspace{1cm} (5)
Multiplying $V_j$ to the above two equations we can get

$$P_j = \frac{V_j V_{pq}}{x_{ij}} \sin(\delta_j - \delta_{pq})$$
$$Q_j = \frac{-V_j V_{pq}}{x_{ij}} \cos(\delta_j - \delta_{pq})$$

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$$Q_j = \frac{-V_j V_{pq}}{x_{ij}} \cos(\delta_j - \delta_{pq})$$

UPFC depends upon $V_{m2p}$ and angle $\delta$ which are proportional to the voltage at PCC

$$\Delta Q_{UPFC} = K_j \Delta \delta(S) + K_k \Delta V(S)$$

II. CONTROL OF THE UPFC BASED WIND-FUEL CELL HYBRID SYSTEM

A. PI CONTROLLER BASED UPFC DESIGN

Conventional controllers like PI Controller is used frequently in many power system applications. But the controller lags in many ways and fails to achieve the optimum results. A controller based UPFC has been shown in Figure.4, where the reference signal is compared with actual feedback and the output is tuned with PI Controller.

B. Fuzzy sliding mode controller

Fuzzy Sliding Mode Controller (FSMC) is employed to ensure the stability of the controller of nonlinear as well as linear systems. Basically a Sliding Mode Controller as shown in Figure.5 is a Variable Structure Controller (VSC) which includes several different continuous functions which can map plant state to a control surface. Switching among different functions is determined by plant state which is represented by a switching function. As the sliding surface and switching never depend upon the system operating point, the circuit parameters and converter dynamics offer good robustness.

\[ x = f(x,t) + B(x,t)u \] (8)

\[ x \in \mathbb{R}^n \] is the state variable of dimension n and \( u \in \mathbb{R}^m \) is the controller force

\[ f(x,t), B(x,t) \] are the non linear

\[ x_d \] is the reference state trajectory and the error between the reference and system

\[ s(x) = 0 \] denotes the sliding surface in the space of the error state. If the condition \( s(x)s(x)(0) \) is satisfied then x always goes to sliding surface

\[ \mathbf{u}_eq = \left[ \frac{\partial s}{\partial x}(x_d - x) \right] (f(x,t) + B(x,t)u) = 0 \]

(9)

\[ u = u_{eq} + \left[ \frac{\partial s}{\partial x}(x_d - x) \right]^{-1} (f(x,t) + B(x,t)u) \]

(10)

\[ \mathbf{Q} = diag \; q_1, q_2, q_3, ..., q_n \]

general equation proposed earlier to determine the desired sliding surface \( \sigma(x) \) is equal to

\[ \sigma(x) = \left( \frac{d}{dx}(x) + k_i \right)^{-1} er(x) \] (12)

\[ v(x) = \frac{\sigma^T(x)\sigma(x)}{2} \] (13)

\[ u(t) = u_{eq}(t) + u_f(t) \] (14)
The inputs to the fuzzy controller to calculate $u_f$ of sliding surface $\sigma$ and its derivative $\dot{\sigma}$ membership values $\mu_{\sigma}(\sigma)$ and $\mu_{\dot{\sigma}}(\dot{\sigma})$.

### III.C. Adaptive Fuzzy sliding mode controller

Fuzzy systems can approximate any nonlinear function in a particular sphere of accuracy, where enough rules are used. This indicates the importance of using expert knowledge in the form of large number of rules with suitable membership functions. Usually trial and error procedure has been needed for achieving the requested accuracy. With all the parameters assigned by the fuzzy systems, the system becomes adaptive and the performance is enhanced.

An adaptive control law has been derived, where consequent part of the fuzzy system is used to approximate the unknown nonlinear dynamics of the system. The proposed scheme delivers expert knowledge to assign parameters of the fuzzy system. Later on disturbances, approximation errors and uncertainties have been found out to compensate and helps to achieve stability of the closed loop system. Most important approach like Lyapunov stability has been repeatedly used to find out and evaluate the convergence property of nonlinear controllers like sliding mode control, fuzzy control etc. The Lyapunov analysis has been utilized to investigate the stability property of the proposed control system. With universal approximation theorem, there exists a fuzzy controller $\tau_f(s, \hat{\theta})$ such that

$$\tau_f(t) = \tau_f(s, \hat{\theta}) + \epsilon_i = \hat{\theta}^T \vec{\varepsilon} + \epsilon_i, \quad i = 1, ..., n$$

$\epsilon_i$ is the approximate error and it is bound by $\epsilon_i \leq E_i$. Employing fuzzy controller $\tau_f(s, \hat{\theta})$, we get

$$\tau_f(s, \hat{\theta}) = \Theta^T \vec{\varepsilon}$$

Now the sliding mode controller can be derived as

$$\tau(t) = \tau_f(s, \hat{\theta}) + \tau_{ad}(s)$$

where fuzzy controller has been designed as $\tau_f(s, \hat{\theta})$ and the equivalent controller is $\tau_{eq}(t)$.

The expression for sliding mode controller is

$$\dot{s}(x,t) = \dot{v}(t) - \dot{\beta}(t) = x(t) - \dot{x}(t) - \beta(t)$$

$$= M^{-1}(x)\tau - M^{-1}(x) f(x) - x - \dot{\beta}(t)$$

$$= M^{-1}(x)(\tau_{ad} + \tau_{eq}) - M^{-1}(x) f(x) - x - \beta(t)$$

Substituting

$$\dot{s} = M^{-1}(x)(\alpha - \Theta - \varepsilon)$$

where

$$\Theta = [\hat{\theta}_1 \ \hat{\theta}_2 \ \hat{\theta}_3 \ \cdots \ \hat{\theta}_n \ \hat{\varepsilon}_1 \ \hat{\varepsilon}_2 \ \cdots \ \hat{\varepsilon}_n]$$

$$s_i = M_i(x)(\alpha - \hat{\theta}_i \ \hat{\varepsilon}_i - E_i), \quad i = 1, ..., n$$

Estimation error is $\dot{E}_i(t) = E_i - \dot{E}_i(t), \quad i = 1, ..., n$

If we define a lyapunov function as

$$V_2(s(t), \hat{\theta}, \dot{E}) = \sum_{i=1}^{n} \left( \frac{1}{2} \dot{E}_i^2 + \frac{\dot{\theta}_i^2}{2\eta_i} + \frac{\dot{E}_i}{2\eta_i} \right)$$

$$V_2(s_i, \dot{\theta}_i, \dot{E}_i) = \sum_{i=1}^{n} \left( s_i + \dot{M}_i s_i \dot{\theta}_i \dot{\theta}_i + \dot{E}_i \dot{E}_i \right)$$

$$= \sum_{i=1}^{n} \left( s_i \dot{M}_i (s_i^2 - \dot{\theta}_i \dot{\theta}_i) + \dot{E}_i \dot{E}_i \right)$$

For satisfying $\dot{V}_2 \leq 0$, the adaptive law can be made as

$$\dot{\theta}_i = -\eta_i \frac{\dot{E}_i}{s_i^2}$$

### IV. SIMULATION RESULTS

The proposed fuzzy sliding mode controller has been simulated in MATLAB environment. The performance of the parameters of standalone wind–diesel–fuel cell system is tested under various operating conditions in a wide variation of wind inputs and loads. Different plots like terminal voltage, reactive power delivered by SG, FC and UPFC are plotted for Fuzzy sliding mode controller, PI Controller and Lead-lag controller and are shown in Figure.6(a-d) and subsequently mentioned in Table.1.
Fig. 6 (a-d). Figures showing the parameter variations with Fuzzy, PI and Lead lag controllers with constant wind and load.

Fig. 7 (a-d). Figures showing the parameter variations with Adaptive Fuzzy sliding and Fuzzy sliding controllers.

Table 1. Comparison between PI, Fuzzy Sliding & Adaptive Fuzzy sliding mode controller

4.1. System Stability analysis of the system:

The stability analysis is performed based on the encirclements of the poles on the imaginary axis, gain and phase margins. Usually spirals shown in the right hand plane do not overlap with the polar plot. Based on the no of encirclements about the poles the stability of the hybrid system is determined. Further stability study based on Nyquist Criterion has been shown in Fig. 8(a). According to this criterion, hybrid system becomes stable for the range of k. Further Popov and bode diagrams have been plotted in Fig 8(b-c). The minimum and maximum of an auxiliary function is found out to know the stability of the system. The magnitude and frequency bode plots are shown in Fig. 8(c) where the gain margin and phase margin define the stability of the hybrid system.
Fig. 8(a,b,c). Stability analysis of the system based on (a) Nyquist method (b) Popov Criterion and (c) Bode plot

5. CONCLUSION
In this paper, a nonlinear controller based on fuzzy sliding mode control for UPFC is proposed for the isolated hybrid power system modelling. The sliding mode controller based UPFC takes into account the parametric uncertainties and cancels the nonlinearities. The proposed controller has been found robust and improves damping and overshoots for a variety of operating conditions which includes variable wind power input and load, torque variation, short circuit, and variation of frequency. From the results it is clear that the isolated hybrid power system with fuzzy sliding mode controller based UPFC performs better than the system having PI and Lead-lag controller based UPFC.

Appendix

Table 2. Parameters of Wind-diesel-fuel cell hybrid system

<table>
<thead>
<tr>
<th>Parameters of Wind-Diesel-Fuel cell hybrid System</th>
<th>Wind-Diesel-Fuel cell System</th>
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<tbody>
<tr>
<td>Wind Capacity (In KW)</td>
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<tr>
<td>Diesel Capacity (In KW)</td>
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<tr>
<td>Fuel cell Capacity (In KW)</td>
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<td>Load Capacity (In KW)</td>
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<tr>
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REFERENCES