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# **Robust Power Management Control for Stand-Alone Hybrid Power Generation System**

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Abstract. This paper presents a new robust fuzzy control of energy management strategy for the stand-alone hybrid power systems. It consists of two levels named centralized fuzzy supervisory control which generates the power references for each decentralized robust fuzzy control. Hybrid power systems comprises: a photovoltaic panel and wind turbine as renewable sources, a micro turbine generator and a battery storage system. The proposed control strategy is able to satisfy the load requirements based on a fuzzy supervisor controller and manage power flows between the different energy sources and the storage unit by respecting the state of charge and the variation of wind speed and irradiance. Centralized controller is designed based on If-Then fuzzy rules to manage and optimize the hybrid power system production by generating the reference power for photovoltaic panel and wind turbine. Decentralized controller is based on the Takagi-Sugeno fuzzy model and permits us to stabilize each photovoltaic panel and wind turbine in presence of disturbances and parametric uncertainties and to optimize the tracking reference which is given by the centralized controller level. The sufficient conditions stability are formulated in the format of linear matrix inequalities using the Lyapunov stability theory. The effectiveness of the proposed Strategy is finally demonstrated through a SAHPS (stand-alone hybrid power systems) to illustrate the effectiveness of the overall proposed method.

**Keywords**— Hybrid power system, Lyapunov function, Takagi-Sugeno fuzzy control system, Power management, Wind and photovoltaic energy system.

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# 1. Introduction

The consumption of fuels as natural gas, coal and oil threat the energy spare of our generations [1], due to a lot of problems like a high cost of operation, transportation of fuel and difficult maintenance, renewable energy is one of the most solutions to be used [2]. The hybrid system is mainly composed of renewable energy sources (i.e., wind power and solar power), and a storage battery and, a micro turbine generator may be integrated into the system as well. Because of their discontinuous and unstable production, hybrid systems expand a very level of energy security with a great efficiency by the mixture of generation systems with a permanent, and storage energy system to ensure maximum efficiency of power supply [3].

Energy management is a term that collects all the systematic procedures to control and minimize the quantity and the cost of energy used to provide a certain application with its requirements. Some of the power management studies used linear programming to implement energy management, and others used intelligent techniques [4]-[8]. Ref. [4] presented the performance of two power management strategies that use the hysteresis band in operating the hybrid power system that contains Photovoltaic Panel (PV), Wind Turbine (WT), and hydrogen as energy storage. Ref. [5] proposed a power management control strategy for a standalone PV/battery power system. In this strategy, the PV system provides the steadystate energy, while the battery compensates for the dynamic energy. The goal of the strategy is to control the unidirectional and bi-directional DC-DC converter to operate in suitable modes based on the battery SOC and weather conditions. A hybrid system consisting of PV panels, a battery system, and a micro turbine as a backup source are introduced in [6]. Ref. [7] developed an algorithm for the optimal power management of a standalone hybrid system that contains a PV, wind, diesel generator, and battery energy storage. In this strategy, the PV subsystem operates at maximum power with the aid of a maximum power point tracking algorithm to supply the load as a priority. In [8] the authors presented a method for determining the optimum power management strategy of hybrid power systems consisting of various sources of energy and storage systems. In this research, the dispatch strategy employed gives priority to the effective use of renewable energy sources (PV and wind) to meet the load demand, while other sources have no predefined priorities except for the priorities determined by the power management optimization process.

Batteries are employed to store excessive energy from renewable energy. Many of researchers proposed several State of Charge (SOC) estimation methods for the batteries based on fuzzy logic, neural network and Kalman extended filters [9]. Micro turbine with a hybrid power generation system is presented to serve the load demands in remote areas because micro turbine instead of diesel generator because of more fuel flexibility and to less: weight, maintenance, noise, and pollution. The micro turbine and the battery storage are used as a support for the hybrid system of the WT and the solar array.

Stability conditions is studied based on Lyapunov stability theory is proposed in [10], fuzzy scheduling controllers is given in [11], switching controllers is presented in [12] and other methods studied the robust fuzzy control are given in [13]-[17]. Control and maximize the wind power for variable speed wind turbines based on TS fuzzy model and Linear Matrix Inequalities (LMI) are given in [15], [17].

This approach is an extension of the work proposed in [15] and [16]. This paper proposes a new Robust Fuzzy Control of Energy Management Strategy (RFCEMS), by introducing Centralized Fuzzy Supervisory Control (CFSC) to manage the power based on TS fuzzy control for the whole stand-alone hybrid power systems (SAHPS) and generate the power references for each Decentralized Robust Fuzzy Control (DRFC) which based on Takagi-Sugeno (TS) fuzzy control as given in [15]-[17]. DRFC maximize power extraction PV and WT and stabilize a nonlinear system in the presence of the parameter uncertainties. The derived stability conditions for DRFC are used to analyze the stability of the TS fuzzy control systems with uncertainty. Sufficient design conditions are derived for robust asymptotic tracking in terms LMIs.

Based on the aforementioned works, therefore the proposed algorithm combines the merits.

- The SAHPS control model is built-up with a hierarchical modular structure. This modular control structure has the advantage that, if it is desired, is easily extendable by adding new control functions either at the centralized and/or at the decentralized level.
- The modifications approach is designed such that to maximizes the produced power by PV and WT unit and is able to maintain the system stable during the parameter uncertainties and disturbance; in addition, it optimizes and manages the total power produced by the SAHPS.
- The simulation results for SAHPS system are demonstrated to visualize the feasibility of the proposed method.
- The battery maximum and minimum SOC level are chosen so as to increase its lifetime. The dump load added to the system aims to dissipate the power product excess.

The rest of the paper is organized as follows. TS fuzzy model with parameter uncertainty is presented in section 2. Section 3 shows the proposed RFCEMS algorithm. Stability and robustness analysis of proposed DRFC control systems is provided in section 4. In Section 5, the description of the power generation system is introduced. Simulation results are given in section 6. Finally, conclusion is deduced in section 7.

## 2. Parameters uncertainty matrices based on TS fuzzy model

The overall theoretical development will be introduced in this section and its application will be applied on a hybrid system which will be presented in section 5. To study the stability, the TS fuzzy dynamic model with parameter uncertainties is given by [17],

$$\dot{x}(t) = \left[\sum_{i=1}^{q} \mu_i(Z(t))A_i + \Delta A\right]x(t) + \left[\sum_{i=1}^{q} \mu_i(Z(t))B_i + \Delta B\right]u(t)\right]$$
$$y(t) = \sum_{i=1}^{q} \mu_i(Z(t))C_i x(t)$$
(1)

Where  $Z_1(t), ..., Z_{\psi}(t)$  are the premise variables; q is the number fuzzy rules;  $\mu_i$  is a fuzzy strength, i=1,2,...,q; x(t), y(t) and u(t) are respectively the state vector, output vector and input control signal;  $A_i$ ,  $B_i$ ,  $C_i$  are system matrices and output matrix, respectively,  $\Delta A_i$ , and  $\Delta B_i$  are the uncertainties parameters for  $A_i$  and  $B_i$ . The regenerator uncertainty based on TS fuzzy is given by the following format:

$$\Delta A = \sum_{j=1}^{n} h_{j} (\Delta A, \Delta B) \Delta \overline{A}_{j} , \qquad \Delta B = \sum_{j=1}^{n} h_{j} (\Delta A, \Delta B) \Delta \overline{B}_{j}$$
(2)

 $n=2^{f}$  is the number of the parameter uncertainty regenerator fuzzy rules; f is the number of elements represented by uncertainty in  $\Delta A$  and  $\Delta B$ , which are given by  $\Delta \overline{A}_{j}$  and  $\Delta \overline{B}_{j}$ . To express the TS fuzzy plant model of (1) as a weighted sum of the corner fuzzy systems, we use the property

$$\sum_{i=1}^{q} \mu_{i} = \sum_{j=1}^{n} h_{j} = \sum_{i=1}^{q} \sum_{j=1}^{n} \mu_{i} h_{j} = 1, \text{ from (1) and (2) the TS fuzzy plant model becomes}$$
$$\dot{x}(t) = \sum_{i=1}^{q} \sum_{j=1}^{s} \mu_{i} h_{j} [(A_{i} + \Delta \overline{A}_{j}) x(t) + (B_{i} + \Delta \overline{B}_{j}) u(t)]$$
(3)

#### 3. Proposed hierarchical supervisory control algorithm

#### 3.1. Control system structure

Based on Matlab/Simulink and the analysis of the mathematical model of the SAHPS, a simulation model of the control system is established in this paper, with the block diagram of the control system being shown in Fig.1. The goal is to design a centralized controller to management and optimization the active power injected by the whole SAHPS. A DRFC for a PV and WT will be designed and will be tested in simulations. The proposed control system is based on a complex hierarchical control

architecture. A CFSC manages the power production of the whole SAHPS by sending out reference power signals to PV and WT, while the DRFC ensures that this reference power signal is reached. In addition, this strategy has the ability to keep the PV and WT system states stable in the presence of parameter uncertainties, wind disturbance and irradiance. First of all, we need to calculate the reference and the total power which are given by PV and WT. Error (*e*) is given by  $e(t)=P_{Load} - P_{total}$  and  $\Delta e$  its derivative, where  $P_{Load}$  is the load power and  $P_{total}$  is given by  $P_{total} = P_{PV} + P_{WT}$ , where  $P_{PV}$  and  $P_{WT}$  are the PV and WT power at maximum point of the operation, respectively. In order to obtain optimality for the WT, the  $r(t)=\Omega_{gref}=\Omega_{g(opt)}=\lambda_{opt}V/R$  profile is chosen in such a way as to follow the optimal tip speed ratio ( $\lambda_{opt}$ ), V is the wind speed, R is the rotor-plane radius, and  $\Omega_{g(opt)}$  is the optimal mechanical generator speed at  $\lambda_{opt}$ .

# 3.2. Proposed decentralized controller

The objective in this sub-section is to design a DRFC for WT-generator unit and PV unit. The control is performed such that the power is maximized and gives good tracking of the reference power generated by the centralized CFSC control.

# 3.2.1. Nonlinear fuzzy controller

Final output of the modified fuzzy controller for the fuzzy model (3) becomes [17]

$$u(t) = \sum_{k=1}^{c} \mu_{k} (Z(t)[-G_{k} x(t) + r(t)]$$
(4)

Where  $G_k \in \Re^{mxn}$  are local feedback gains for DRFC of rule *k*, r(t) is the reference input and *c* is the number of the fuzzy rules (k=1,2,...c).



Figure 1: Simplified control structure of the overall SAHPS

# 3.2.2. Decentralized robust fuzzy controllers

The number of rules and the antecedents of the fuzzy scheduler are the same as those of the fuzzy uncertainty rules. The inferred output of the DRFC is given by:

$$u(t) = \sum_{k=1}^{c} \sum_{j=1}^{n} \mu_{i} h_{j} [-G_{kj} x(t) + r(t)]$$
(5)

With the DRFC (5) employed, the TS fuzzy system (3) has the following closed-loop:

$$\dot{x}(t) = \sum_{i=1}^{q} \sum_{k=1}^{c} \sum_{j=1}^{n} \mu_{i} \mu_{k} h_{j} [((A_{i} - B_{i}G_{kj}) + (\Delta \overline{A}_{j} - \Delta \overline{B}_{j}G_{kj})) x(t) + (B_{i} + \Delta \overline{B}_{j})r(t)]$$
(6)

#### 3.3. Proposed centralized supervisory controller

SAHPS is energy generation systems which are autonomous and controllable generating units. Given the current technological status, turbine-generator-power converter and PV converter set should be considered as a unit. These units work as an individual system for variable speed systems and solar irradiance. Consequently, through the controller and conditions of different wind regimes and solar irradiance, it is possible to establish an optimum point of operation for each generation system. The control method is based in the aim of its control on a fuzzy controller as shown in Fig. 1. After we design the DRFC for WT and PV unit, the CFSC is developed as the following. In the first step summing of the entire active power produced  $(P_{total})$  by each unit is done. Then, with this value and with the load power ( $P_{Load}$ ), the error and its derivative are calculated. Next, these two variables with SOC variable are the inputs of a CFSC that produces a control output variable. This output variable is then used to determine the optimal reference input for each subsystem PV and WT control unit, battery charging/discharging and set point for the micro turbine operation. Finally, PV and WT control unit adjusts its operation in order to obtain the reference imposed by the CFSC. The rules 'IF' part describes the situation for which the rules are designed. The "Then" part describes the response of the fuzzy system in this situation. The degree of support is used to weigh each rule according to its importance. The CFSC is constituted by 27 rules. With the following significance: e has 3 membership function N (Negative), Z (Zero), P (Postive).  $\Delta e$  can be represented by N (Negative), Z (Zero), P (Postive). SOC is introduced by 3 membership function L (Low), M (Medium), H(High). Where  $\Delta e$  is the derivative of the error. As examples, it is presented below some of the fuzzy rules which are used for the proposed CFSC.

- If *e* is *N* and  $\Delta e$  is *N* and SOC is *L* Then WT is work at  $\Omega_{opt}$  and PV is work at  $V_{PV(opt)}$  and battery is charging.
- If *e* is *N* and Δ*e* is *N* and SOC is *H* Then WT is work at Ω<sub>opt</sub> and PV is work at V<sub>PV(opt</sub>) and battery is natural and *e* is dissipated in dump load.
- If *e* is P and  $\Delta e$  is P and SOC is *H* Then WT is work at  $\Omega_{opt}$  and PV is work at  $V_{PV(opt)}$  and battery is discharging.
- If *e* is P and  $\Delta e$  is P and SOC is low Then WT is work at  $\Omega_{opt}$  and PV is work at  $V_{PV(opt)}$  and battery is natural and micro turbine generator operates.

#### 4. Stability analysis of DRFSC

This section presents the stability conditions for the decentralized controlled system (6) and the calculation of the DRFSC gains (5). The robustness analysis and the stability conditions for the uncertain fuzzy control system (6) are summarized in the following theorem.

**Theorem:** The fuzzy control system as given by (6) is stable if the controllers set to  $G_k = M^{-1}Y_k$  with the matrices M, and  $Y_k$  satisfying the following LMIs.

$$MA_{i}^{T} + A_{i}M - (B_{i}Y_{kj})^{T} - (B_{i}Y_{kj}) < 0$$
<sup>(7)</sup>

The proof can be given directly from [17].

#### 5. Description of the proposed hybrid controlled system

The proposed hybrid energy generation system is depicted in Fig.2. This system consists of variable speed WT, a solar array as renewable sources, a micro turbine which has a permanent source power to provide the load of the overall required energy, a battery storage storing the power that exceeded from the load, and a dump load which saves the battery from over charging. The HRFCSEMS is used for obtaining maximum power from renewable sources, managing between different power sources and stabilize the system in the presence of the parameters uncertainties.



Figure 2. The schematic of the proposed hybrid system.

#### 5.1. PV model system

To show the effectiveness of the proposed controller design techniques, PV model System [18] are simulated. The current-voltage characteristic of a PV array conducts as a function of solar irradiance and cell temperature is described as follows:

$$P_{pv} = I_{PV} V_{PV} = n_{p} I_{ph} V_{PV} - n_{p} I_{rs} V_{PV} (\exp(qV_{PV} / n_{s} \phi KT) - 1)$$
(8)

where  $n_p$  and  $n_s$  are the number of the parallel and series cells, respectively, K is the Boltzmanns' constant, T is the cell temperature,  $\varphi$  is the *p*-*n* junction characteristic, *q* is the electron charge,  $I_{PV}$  and

 $V_{PV}$  are the output current and the PV array voltage on the capacitance  $C_I$ ,  $I_{ph}$  and  $I_{rs}$  are the photocurrent and reverse saturation current, respectively. When the power slope  $dP_{PV}/dV_{PV} = 0$ , the system operates at the maximum power generation. The dynamic equation can be expressed by the following differential equations given in [18].

## 5.2. Dynamic model of wind turbine generator unit

If the air density is  $\rho$ , R is turbine radius, power coefficient is  $C_p(\lambda,\beta)$ , and tip speed ratio  $(\lambda)$  is given by  $\lambda = \Omega_l R / V$ , the WT mechanical power is given by [19].

$$P_m = 0.5\rho\pi R^2 \, V^3 C_p(\lambda, \beta) \tag{9}$$

From (16) if we maximized  $C_p(\lambda,\beta)$ , the maximum power from the WT will obtain.  $C_{p(max)}(\lambda_{opt},\beta)$  can obtained at  $\lambda = \lambda_{opt}$ . The state space of the WT using Doubly-Fed Induction Generator (DFIG) is given by [19]. The WT system parameters are defined in the appendix. The stator active ( $P_s$ ) and reactive ( $Q_s$ ) power of the WT with DFIG are given by [19].

$$P_s = -\frac{L_m V_s}{L_s} i_{qr} \qquad , \ Q_s = \frac{V_s^2}{\omega_s L_s} - \frac{L_m V_s}{L_s} i_{rd} \qquad (10)$$

Where  $V_s$  is the stator voltage

#### 5.3. Battery model

In this paper, we use the battery model presented in [20]. During the loaded condition, the electrical model of the battery can be expressed as

$$V_{bat} = V_{oc} + IR_{o} + IR_{1}(1 - \exp(-t/C_{1}R_{1})) + IR_{2}(1 - \exp(-t/C_{2}R_{2}))$$
(11)

where *I* is the current and *t* is time,  $R_1$ ,  $R_2$  and  $C_1$ ,  $C_2$  are the *RC* branch resistors and capacitors, respectively,  $V_{oc}$  is the open circuit voltage. The quantity that describes the ratio of the remaining capacity to the nominal capacity of the battery is known SOC and is computed by

$$SOC = SOC_{i} + \frac{\int \eta I dt}{C_{n}} , \qquad (12)$$

where  $SOC_i$  is the initial value of the SOC,  $C_n$  is the nominal capacity and  $\eta$  is the Coulombic efficiency.

#### 5.4. Micro turbine model

Micro turbine is small gas turbine produce high energy gas stream that turns an electrical generator based on burns gaseous or liquid fuels [21], [22]. In this paper, we will use the Micro turbine model presented in [21],[22].

#### 5.5. Dump load

When the storage battery are fully charged and the power produced by the PV and WT is greater that the required load power, in this case we need to dissipate the difference through the dissipative resistance which known as the dump load.

# 6. Simulation and results

The simulation model of the hybrid energy system has been developed using MATLAB/Simulink. The performance of the proposed supervision and energy management has been verified by simulation studies for 50 seconds under various scenarios using the wind speed, irradiance, and temperature profiles as shown in Figures 3, 4 and 5, respectively. The control objective of this paper is to design a robust fuzzy control law for the PV and WT system to ensure that all signals in the closed-loop system are bounded and the parametric uncertainties are considered within 40% of their nominal values for WT and PV, which are not time varying.



Figure 3. Wind speed profile.



Figure 4. Irradiation profile.



Figure 5. Temperature profile.

The WT, generator rotational speed and the active power  $P_s$  are shown in Figures 6, 7 and 8, respectively, in the presence of parametric uncertainties Fig. 9 and 10 show the PV array voltage and power, respectively. From the simulation results, it can be observe that, the outputs tracking of the PV and WT subject to parameter uncertainties are bounded and good performance for the proposed control strategy.

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**Figure 6**. The trajectories of rotational speed  $\Omega_r$ 



**Figure 7**. The trajectories of generator  $\Omega_g$ 











Figure 10. PV array output power (W)

Load power profile is shown in Fig.11. It is variable to ensure that the hybrid energy system can serve the load in any case. In Fig.12, SOC of battery changed from charging and discharging depending on the need of load. Fig.13 is presented the dump load which is used to dissipate the exceeded power to save the battery and the load. Fig. 14 is clarified the operation of micro turbine generator which operates when the load need power more than (WT+PV) power and SOC is low.





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Figure 15. Power generated for each element.

Power generated for each element is shown in Fig.15. In Fig.15, from  $t = 2 \sec to 20 \sec the total power from renewable (WT+ PV) energy is higher than the load demand so the battery charged even max. SOC, at t = 12.5 sec the dump load takes the exceeded power to secure the battery from damaging. After that the battery discharged to supply the required energy to the load when renewable energy has not ability to serve the load, then micro turbine generator gives the load of the required power.$ 

From the simulation results of the proposed strategy, with those given by the previous algorithms, it can be noticed that the proposed strategy has the following features:

- It maximizes the produced power by PV and WT unit and is able to maintain the system stable even with parameter and disturbance uncertainties up to 40% compared with [15]-[17]. In addition, it optimizes and manages the total power produced by the SAHPS.
- The simulation results demonstrate the effectiveness and the reliability of the proposed control approach.

# 7. Conclusion

New algorithm strategy is applied on a stand-alone hybrid power systems, equipped with: photovoltaic panel and WT (as renewable sources), a micro turbine generator and a battery storage system. The proposed control strategy is based on a complex hierarchical control architecture which consists of two levels named centralized and decentralized fuzzy control. Centralized fuzzy control level derives the active power references for PV and WT based on fuzzy control. A decentralized control level is based on TS fuzzy models, gives a good tracking for the reference power signal sent by the centralized control level and is robust for a wide range of parameter uncertainties and wind disturbances. The battery maximum and minimum SOC level are chosen so as to increase its lifetime. The dump load added to the system aims to dissipate the power product excess. The proposed robust power management strategy satisfy the load and battery bank SOC and it is tested in simulation using theoretical profiles of weather conditions to illustrate the performance of the proposed strategy. A set of sufficient conditions for robust stabilization of the TS fuzzy model are formulated in the LMI format based on Lyapunov stability. The concept of PDC is employed to design fuzzy control from the TS fuzzy models. Simulating control actions imposed on the SAHPS controller has been tested the performance of the control system. An extension of the SAHPS controller with fault tolerant control is in the implementation stage and it will be described in detail in a future paper.

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