

Regulation for Wind Generation System Using Ant system Based Takagi Sugeno Fuzzy PID

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Abstract— This paper introduces a new tuning technique for the PID control scheme that is adopted for regulating the magnitude and frequency of the wind energy conversion system (WECS) output voltage which presents interesting control demands and exhibits intrinsic non-linear characteristics. The developed technique is stem from blending the ant system optimization method with Takagi Sugeno fuzzy system approach. The optimum relationship between the PID controller gains and the parameters of fuzzy modules is explored using Ant system algorithm; hence a satisfactory dynamic performance of the WECS is obtained.

Keywords-Takagi - Sugeno fuzzy control; PID control; Ant system optimization; Wind energy conversion systems

I. INTRODUCTION

In the world of today there is a need for alternatives to the large coal and oil fired power plants. Renewable energy is one way to go, and in particular wind turbines have proven to be a solution [1]. The arrival of the new power devices technologies, new circuit topologies and novel control strategies are contributing to the success of the wind generation technology.

In wind energy standalone generation systems, the frequency and the magnitude of the terminal voltage for the Self Excited Induction generators (SEIG) vary with load even when the rotor speed is maintained constant. An increase in the rotor speed due to the increase of wind speed will result in a proportionate increase in frequency, often accompanied by severe overvoltage and excessive current.

Although the slip-ring machine is more expensive and requires more maintenance, it permits rotor slip-power control when driven by a variable-speed turbine. When a grid connection is permissible, the slip-ring machine may be operated as a double-output induction generator (DOIG) using the slip-energy recovery technique. In the case of Self Excited Slip Ring Induction Generator (SESRIg), the system cost can be further reduced by the use of a simple rotor resistance controller [2], [3]. Since only a capacitor bank needs to be connected to the stator terminals, the SESRIg provides a good quality ac source with little harmonic distortion to the stator load. Another advantageous feature of the SESRIg is that independent control of the voltage and frequency can be achieved easily. Even with a wide variation in speed, the

generator frequency can be maintained reasonably constant by rotor resistance control, while the voltage can be controlled by varying the excitation capacitance. The rating of the rotor resistance controller is small compared with the generator rating; hence, the cost saving is quite significant.

Fuzzy control and tuning methodologies have emerged in last years as promising ways to approach nonlinear control problems and to deal with difficulties of conventional PID controllers [4]. The area of auto-tuning of PID controller using fuzzy systems has attracted many authors [5][6]. However, a common bottleneck encountered in fuzzy controller design is that derivation of fuzzy rules is often difficult and time-consuming, and relies on expert knowledge. To overcome this disadvantage, many automatic methods for fuzzy system design and optimization algorithms have been proposed, such as neural fuzzy systems [7] and evolutionary fuzzy systems [8].

Recently, the social inspired optimization algorithms become a successful alternative for the conventional tuning method to adapt the PID controllers. Using these new methods, the global optimal or suboptimal solutions of the optimized control scheme are found. These algorithms are adopted by many researchers for tuning PID controller in its classical and intelligent forms. One such approach is Ant System Optimization (ASO) which is founded on the foraging behavior of ants and their indirect communication based on pheromones see for instance [9]. ASO has been applied to several combinatorial problems such as job scheduling, routing optimization in data communication networks and telephone networks [10].

One of the widely used methods for optimizing a fuzzy logic controller is to modify the rule base using this self-organizing algorithm automatically according to previous responses until the desired control performance is achieved. Many works studied this problem such as [11], [8] and [12]. In [11], a tracking control problem is assumed to develop a self tuning PID control scheme with application to antilock braking system via combinations of fuzzy and genetic algorithms. While in [13], the approximation of analytical test function is performed using ant colony algorithm to tune the parameters of Takagi Sugeno (T-S) fuzzy rule base. The authors simplified their work by assuming constant

consequence part instead of the ordinary linear function consequent part of T-S fuzzy system. In [12], incremental fuzzy PID controller is used which is slightly different from the T-S fuzzy PID controller where, the scaling factors for input/output Macvicar-Whelan based fuzzy system are addressed in the ant colony optimization framework. In T-S fuzzy systems design, one challenging design task is the determination of the parameters of the consequent part. In this paper, ASO is employed to design the consequent part of a Takagi Sugeno fuzzy PID controller. The paper presents design procedures for a model free T-S fuzzy PID controller. Three independent T-S fuzzy systems are combined to tune different gains of PID controller. The optimum relationship between the PID controller parameters and the parameters of T-S fuzzy modules is explored. Using Ant system algorithm, the parameters of each T-S fuzzy system are optimally determined. The idea is to start with a tuned, conventional PID controller, replace it with an equivalent Takagi-Sugeno fuzzy PID controller and eventually fine-tune the T-S fuzzy tuner. This is relevant whenever a PID controller is possible or already implemented.

In the proposed T-S Fuzzy Ant System PID, structure of T-S fuzzy system is well adapted via defining the optimum parameters of its consequence part. Once new rules are generated, the PID controller parameters are calculated from the defuzzification process. This paper has two main contributions. Firstly, a PID controller has been designed for WECS using a blending tuning mechanism namely Takagi – Sugeno fuzzy Ant system algorithm. Secondly, a satisfactory closed loop performance is achieved with respect to the conventional ZN frequency response tuning method. The objective of Ant System Optimization in this paper is to improve both the design efficiency of Takagi – Sugeno fuzzy systems and its performance to get optimal PID parameters. In this paper the voltage and frequency control of a three phase SESRIG is investigated by varying the external rotor resistance and the excitation capacitance using the proposed Ant Takagi Sugeno Fuzzy PID controller.

This paper is organized as follows: section II shows the main feature of the control characteristic for SESRIG used in the proposed standalone WECS. Takagi Sugeno fuzzy tuner for PID controller is presented in section III. Section IV introduces ant system optimization algorithm for optimal parameter determination for Takagi Sugeno fuzzy systems. The proposed control strategy is applied to WECS in section V. Finally, a conclusion is set in section VI.

II. SESRIG VOLTAGE AND FREQUENCY CONTROL

Normalized equivalent circuit of the steady state model of SESRIG can be proposed as seen in Fig. 1 [14]. Where a is per unit frequency (actual frequency/base frequency), b per-unit speed (rotor speed/synchronous speed) corresponding to base frequency, C excitation capacitance per phase, E_1 air-gap voltage per phase referred to base frequency, R_1 & R_2 stator and rotor winding resistances per phase. R_L stator load

resistance per phase. V_I Load voltage per phase, X_1 & X_2 Stator and rotor leakage reactances per phase, X_c Excitation capacitive reactance per phase and X_L Load reactance per phase.

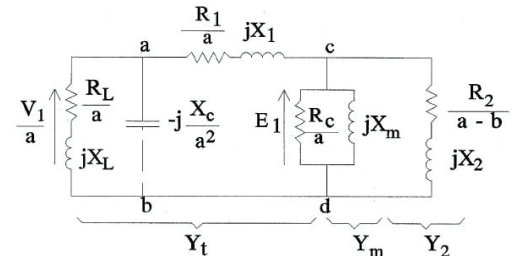


Figure 1 Normalized equivalent circuit of SESRIG[14]

For convenience, all of the machine parameters, except the excitation capacitance, are expressed in per unit. The solution of the SEIG equivalent circuit have been developed using various methods. Among them, the nodal admittance method [15], is considered very simple and easy to follow, hence it will be adopted in this paper. The main feature of the control characteristic for SESRIG used in standalone WECS is deduced in this section by performing laboratory experiments on 1.1 KW machine. The effect of changing the external rotor resistance with constant excitation capacitance and vice versa on the output terminal voltage and frequency at loading condition is presented. Fig's. 2 & 3 show the effect of changing the external rotor resistance with constant excitation capacitance at loading conditions ($R_L = 8$ p.u.) on the SESRIG output terminal voltage and frequency.

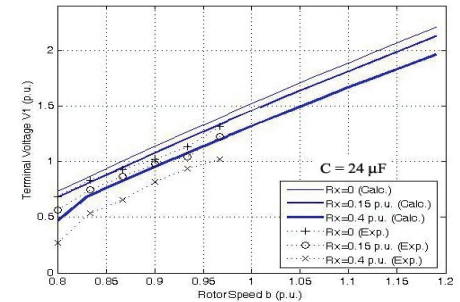


Figure 2 Terminal Voltage (V_I) versus Rotor Speed (b) at different external resistance (R_x) at $R_L = 8$ p.u.

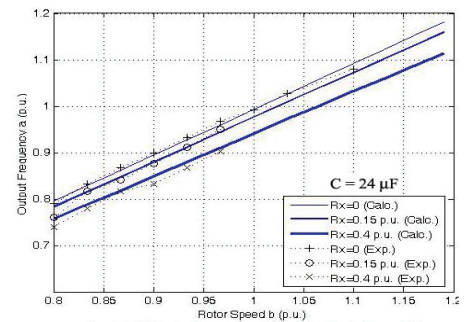


Figure 3 Output Frequency (a) versus Rotor Speed (b) at different external resistance (R_x) at $R_L = 8$ p.u.

Fig. 4, shows that as the rotor speed (b) increase the external rotor resistance (R_x) required to maintain the frequency constant at 1 p.u. increases. It is noted that unity per-unit frequency is only achievable at rotor speeds above 1 p.u.

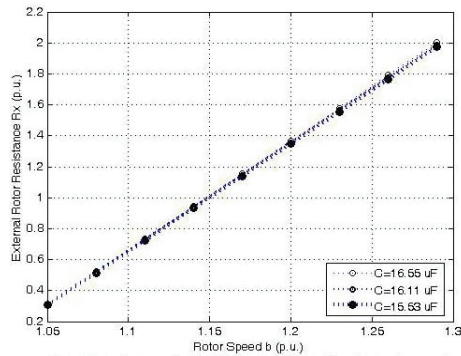


Figure. 4 External Rotor Resistance (R_x) required to maintain rated frequency as the rotor speed varies at different excitation capacitance ($R_L=8$)

Fig. 5 shows the corresponding terminal voltage. The terminal voltage (V_t) is constant as the rotor speed increases. At the same rotor speed, increasing the excitation capacitance increases the voltage. At a certain value of excitation capacitance, unity per-unit voltage can be obtained. For example, at rotor speed $b = 1.1$ p.u. and load resistance $R_L = 8$ p.u., the external rotor resistance required to achieve $a = 1$ p.u. is 0.66 p.u. To keep the voltage at 1 p.u. at the same time, the external capacitance is adjusted to 16.11 μF .

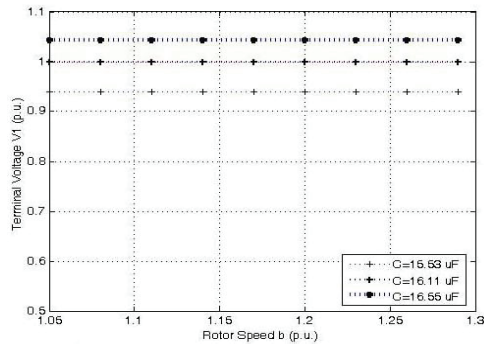


Figure 5 Terminal voltage (V_t) at rated frequency as the rotor speed varies at different excitation capacitance ($R_L=8$)

Fig.'s 6&7, show the external resistance and excitation capacitance needed to maintain nominal voltage and frequency at a constant rotor speeds (b) of 1.1 p.u. and 1.2 p.u. as the load current increases. For example, when rotor speed (b) is 1.1 and load current (I_L) is 0.25 p.u., the values of the external resistance and excitation capacitance which are needed to maintain the frequency and voltage at 1 p.u. are 0.7 p.u. and 16.55 μF respectively.

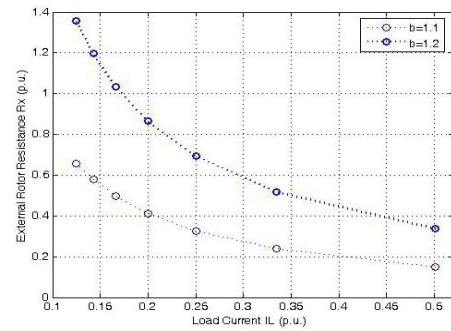


Figure 6 Variation of external resistance (R_x) to operate at rated voltage and frequency as the load current increases

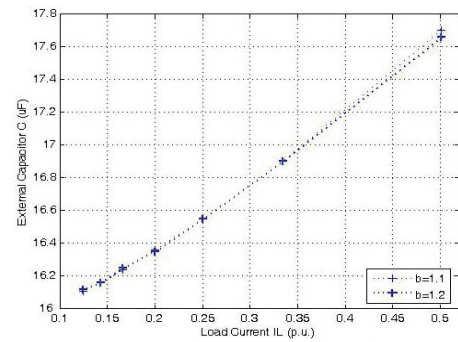


Figure 7 Variation of excitation capacitance (C) to operate at rated voltage and frequency as the load current increases

From the above figures and discussions the following points can be concluded:

Remark 1:

- (1) Comparison between the computed and experimental results reflects their close matching that reflects the adequateness of the circuit model and the solution method proposed in [16] and [17].
- (2) At constant load conditions, changing the external rotor resistance will affect the standalone WECS terminal output voltage and frequency while the excitation capacitance remains unchanged (i.e. increasing rotor speed (i.e. wind speed) should accompany with increasing the external rotor resistance while the excitation remains nearly constant)
- (3) At variable load conditions, simultaneous change in the external rotor resistance and the excitation capacitance is required in order to keep the standalone WECS working at the rated voltage and frequency (i.e. increasing the loading condition (the output power required from the standalone WECS) to be delivered to the load) should accompany with decreasing the external rotor resistance and increasing the excitation capacitance).

III. T – S FUZZY TUNER FOR PID CONTROLLER

Many PID controllers were presented in literature, the expression of PID control law for a continuous time system is given as follows:

$$u(t) = K_p e(t) + \frac{K_p}{T_i} \int_0^t e(t) dt + K_p T_d \frac{de(t)}{dt} \quad (1)$$

where $e(t)$ is the error between the input and the output of the system; $u(t)$ is the control action generated by the PID controller; K_p is the proportional gain; T_i is the integral time constant; and T_d is the derivative time constant.

In this section, three independent T-S fuzzy systems are used to tune different gains of PID controller. Each fuzzy module is assigned to obtain each PID gains. The typical T-S fuzzy systems studied in this paper have two inputs and one output. The input variables are error and rate of change of the error. We denote $e(t)$, $\dot{e}(t)$ and $y(t)$ as error, rate of change of error and system output, respectively. A fuzzy set for $e(t)$ (or $\dot{e}(t)$) is denoted as M (or L) and the corresponding membership is designated as $\mu_i(e(t))$ or $(\mu_i(\dot{e}(t)))$. Throughout this work, a Gaussians membership functions for the two inputs of the premise part of T-S fuzzy system are used. The error $e(t)$ and the rate of change of the error $\dot{e}(t)$ are normalized using three Gaussian membership functions; negative N , zero Z , and positive P , so that nine rules constitute the rule base for each module. For simplicity, the consequent part has been chosen to be a first order function of $e(t)$ and $\dot{e}(t)$. The rule bases have the following form:

Rule j : If $e(t)$ is M and $\dot{e}(t)$ is L then $k_i = a_{ij}e(t) + b_{ij}\dot{e}(t)$

where $k_i = f(e(t), \dot{e}(t))$ is the gain to be tuned, i.e. K_p , K_i or K_d . a_{ij} and b_{ij} are the constants, and $j=1, 2, \dots, 9$ is the rule number. In this paper, the weighted average technique is utilized to get the overall fuzzy output as follows:

Given a pair of $e(t)$, $\dot{e}(t)$, the final output of the fuzzy system is inferred as follows [18]:

$$k^i = \frac{\sum_{j=1}^r w_j(e(t), \dot{e}(t)) (a_{ij}e(t) + b_{ij}\dot{e}(t))}{\sum_{j=1}^r w_j(e(t), \dot{e}(t))} \quad (2)$$

$$w_j(e(t), \dot{e}(t)) = \prod_{j=1}^2 \mu_{A_j^i}(e(t), \dot{e}(t)),$$

$$h_j(e(t), \dot{e}(t)) = \frac{w_j(e(t), \dot{e}(t))}{\sum_{j=1}^r w_j(e(t), \dot{e}(t))}$$

Where $\mu_{A_j^i}(e(t), \dot{e}(t))$ is the grade of membership of $(e(t), \dot{e}(t))$ in A and B . In this paper, we assume that,

$$w_j(e(t), \dot{e}(t)) \geq 0 \quad \text{for } j = 1, 2, \dots, r$$

$$\sum_{j=1}^r w_j(e(t), \dot{e}(t)) > 0 \quad \text{for all } t. \text{ Therefore we obtain}$$

$$h_j(e(t), \dot{e}(t)) \geq 0 \quad \text{for } j = 1, 2, \dots, r \text{ and}$$

$$\sum_{j=1}^r h_j(e(t), \dot{e}(t)) = 1$$

Remark 3: Our approach is different from those of [11], [13] and [12] in the following ways.

- i. A Takagi – Sugeno type of the fuzzy PID control system is assumed instead of incremental fuzzy PID control system.
- ii. The input Gaussian membership functions of T-S fuzzy tuner are assumed to be constant (i.e. the membership function's center “ c ” and its spread “ σ ” are constant over each rules and fuzzy system).
- iii. The total no. of free parameters to be tuned in is 117 parameters while in our proposed design procedures are 54 parameters (i.e. smaller computational burden).

IV. ASO ALGORITHM BASED T-S FUZZY OPTIMAL PARAMETER DETERMINATION

A. Ant System Optimization

The ant system is the first member of a class of algorithms called Ant Colony Optimization (ACO) that was initially proposed by Colomni, Dorigo and Maniezzo [19]. This technique is adopted in this paper due to its simplicity. The main underlying idea, loosely inspired by the behavior of real ants, is that of a parallel search over several constructive computational threads based on local problem data and on a dynamic memory structure containing information on the quality of previously obtained result. In this algorithm, computational resources are allocated to a set of artificial ants that exploit a form of indirect communication mediated by the environment to find the shortest path from the ant nest to a set target. Ant algorithms have been proved to be a quick global optimal solution finder when compared to other heuristic methods such as simulated annealing and genetic algorithms. It also states that the ant algorithms have the quality to find new optimal solution without reinitiating the computations from scratch.

B. T-S Fuzzy PID optimization problem

Usually, the optimization process consists of finding the controller parameters such as to minimize or maximize a given cost function of the closed loop system consisting of a fuzzy PID controller and an unknown plant. The optimization of step response of the system under control by minimizing a suitable performance criterion is the aim of this work.

Each T-S fuzzy module consists of constant premise parameters (that is needn't to be optimized) and 18 free consequence parameters (that will be optimized). The total number of free parameters to be optimized for the overall fuzzy system is 54. The AS algorithm is applied to optimize two different parameter matrices (A & B). These parameters matrices are driven by the consequence parts of fuzzy rule base. The dimension of both parameter matrices is “ 3×9 ”. The effectiveness of the proposed T-S Fuzzy controller is quantified by the following performance criteria that are evaluated at the end of a step response experiment. It includes the overshoot ζ , settling time t_s and steady state error e_{ss} of the system unit step response. The performance criterion of the system F is designed as follows:

$$F = \lambda_{\zeta} f_1 + \lambda_{t_s} f_2 + \lambda_{e_{ss}} f_3 \quad (3)$$

where λ_{ζ} , λ_{t_s} and $\lambda_{e_{ss}}$ are three weighting coefficients and f_1 , f_2 & f_3 are defined as follows:

$$f_1 = \frac{\zeta}{\zeta_o}, f_2 = \frac{t_s}{t_{so}} \text{ and } f_3 = \begin{cases} \frac{e_{ss}}{e_{ss0}} & \text{if } e_{ss0} \neq 0 \\ 0 & \text{if } e_{ss0} = 0 \end{cases}, \quad (4)$$

Where ζ_o , t_{so} and e_{ss0} are the performance values obtained from ZN tuning formula. The parameters matrices for the problem of tuning T-S fuzzy PID controller are defined as:

$$A = \begin{bmatrix} a_{11} & \cdots & a_{19} \\ \vdots & \ddots & \vdots \\ a_{31} & \cdots & a_{39} \end{bmatrix} \& B = \begin{bmatrix} b_{11} & \cdots & b_{19} \\ \vdots & \ddots & \vdots \\ b_{31} & \cdots & b_{39} \end{bmatrix} \quad (5)$$

Now, the control problem in this paper can be formulated as follows:

Given a plant $G(s)$ to be controlled (Fig.8), **determine** the optimum values of the parameters in (2) using ant system algorithm, hence, **find** the optimal PID parameters K_p , T_i and T_d **so that** the control system has the minimum value of given performance criterion “ F ” (3).

Fig. 8 depicts the closed loop control system used in this paper.

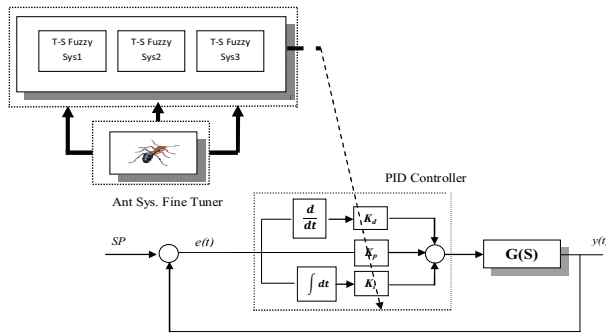


Figure 8 The Proposed Closed loop Control System

A. Proposed Algorithm

Using the same technique used in [20] or the ant system optimization, we can modify the design algorithm presented in [12] to take into account the presence of T-S fuzzy system. The proposed AS Algorithm based T-S Fuzzy optimal PID parameter determination can be summarized as follows:

Step 1: Determine K_{po} , K_{io} and K_{do} using the classical Ziegler-Nichols tuning formula for a given control system with a PID controller and compute the system's performance indexes ζ_o , t_{so} and e_{ss0} .

Step 2: Specify the initialization parameters of our proposed problem that contain the following:

- Values of α , β , ρ , τ_o and m .
- The maximum number of iterations t_{max} .
- A one-dimensional array $Path_k$ with 108 elements. Array $Path_k$ can be used to denote the moving path of ant k .

Step 3: Set the iteration counter $t=1$ and then place all of the m ants at the origin O.

Step 4: Set $i=1$.

Step 5: Set $k=1$.

Step 6: Compute the transition probability of each node on line L_i using the following formula

$$P_k(i, j, t) = \frac{\tau^\alpha(i, j, t) \eta^\beta(i, j, t)}{\sum_{j=0}^9 \tau^\alpha(i, j, t) \eta^\beta(i, j, t)}$$

Where $\eta(i, j, t)$ is the visibility of node (i, j) and defined as:

$$\eta(i, j, t) = \frac{10 - |j - j^*|}{10}$$

Where the values of j^* are set in the following way:

- In the first iteration of the AS algorithm, the values of j^* ($i=1-108$, $j=0-9$) are assigned from the different values of the one dimensional array $Path_{k-initial}$.
- In each of the following iterations, j^* are determined from the calculated one dimensional array $Path_k$ (it contains different entities of matrices A & B) that is corresponding to optimal traveling path generated in the previous iteration by the ant

α & β represent respectively the relative importance of the pheromone concentration and visibility in transition probability

Step 7: Based on the calculated transition probability in the previous step and using Roulette wheel selection method, select a node on line L_i for ant k and move ant k to this node, then save the y coordinate of the node into the i^{th} element of $Path_k$.

Step 8: Set $k \leftarrow k+1$. If $k \leq m$, go to Step 6; Otherwise, continue.

Step 9: Set $i \leftarrow i+1$. If $i \leq 108$, go to Step 5; Otherwise, continue.

Step 10: For each ant k ($k=1, 2, \dots, m$): according to $Path_k$, compute different entities values of matrices A & B using formula (5).

Step 11: For each ant k ($k=1, 2, \dots, m$): evaluate the PID gain values from the T-S fuzzy system according to formula (2).

Step 12: For each ant k ($k=1, 2, \dots, m$): perform a simulation experiment using the calculated matrices A & B and compute the system's performance indexes ζ^k , t_s^k and e_{ss}^k then compute the performance criterion F_k using formula (3).

Step 13: Compare all of the obtained F_k values and find the optimal ant path of this iteration ($Path_{k-optimal}$), that has minimum value of the performance criterion (i.e. $\min_k F_k$, $k=1, 2, \dots, m$). Save the $Path_{k-optimal}$ and the corresponding optimal PID gains.

Step 14: Set each element of $Path_k$ to zero, $k=1, 2, \dots, m$.

Step 15: Update the pheromone concentration of each node on the moving ant path using the following updating rule:

$$\tau(i, j, t+1) = \rho \tau(i, j, t) + \Delta \tau(i, j)$$

$$\Delta \tau(i, j) = \sum_{k=1}^m \Delta \tau_k(i, j)$$

Where $0 < \rho < 1$ is the pheromone decay parameter; $\tau(i, j)$ is the amount of pheromone laid at n_{ij} by ant k in the iteration just completed and computed by the following formula:

$$\Delta \tau_k(i, j) = \begin{cases} \frac{Q}{F_k} & \text{if ant } k \text{ passed through } n_{ij} \text{ in previous iterat.} \\ 0 & \text{Otherwise} \end{cases}$$

Where Q is a positive constant, F_k is the value of performance criterion of ant k in the iteration just completed and computed by (3).

Step 16: Set $t \leftarrow t + 1$. If $t < t_{max}$ and all of the m ants do not make the same tour, place all the ants at the origin O and go to Step 4; if $t < t_{max}$ but all of the m ants make the same tour or $t = t_{max}$; stop.

V. STANDALONE WECS SIMULATION USING THE PROPOSED TECHNIQUE

In this section, based on the results drawn from the above sections, the proposed technique namely Ant System based Takagi Sugeno Fuzzy PID (ASTSFPI) Control is applied to the standalone WECS configured in Fig. (9) to automatically control the terminal output voltage and frequency of SESRIG when either the stator load impedance or the rotor speed changes. The goal is to keep the voltage and frequency at the value of 1 p.u. This is achieved by simultaneously changing the excitation capacitor and the added rotor resistance.

A. Closed loop control

The stator terminal voltage and the output frequency are chosen as the feedback variable since any change in speed and stator load impedance will result in a corresponding change in the terminal voltage and output frequency. The stator terminal voltage signal is compared with the voltage reference signal. The voltage error signal is fed to a proportional-plus-integral (PI) controller that outputs a signal for the firing angle of the thyristor controlled inductor (TCR). The output frequency signal is compared with the frequency reference signal. The frequency error signal is fed to another PI controller that outputs a signal for the duty cycle of the chopper controlled resistance.

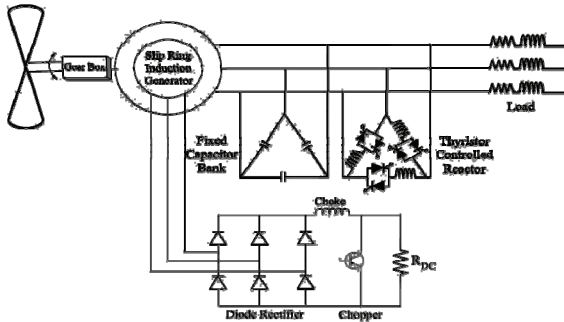


Figure 9 Schematic Diagram for the system configuration

In [17], since no electrical dynamics is involved the SESRIG was approximated as a first-order delayed system, the parameters of the proposed transfer function were determined using the open-loop step response method. Proper tuning of the PI controller is required in order to give satisfactory dynamic performance of the proposed standalone WECS. Hence, same approximation for SESRIG performed in [17] will be adopted in this paper.

Among different traditional tuning methods, the Ziegler-Nichols (ZN) technique has been very influential. The idea is to start the proposed algorithm with ZN PI gains then enhance the dynamic response of the closed loop system according to

the performance index in (3) via the steps of the algorithm. Finally, the algorithm will reach to the optimal parameters of the PI controller that can be used in controlling the voltage and the frequency of the standalone WECS.

B. Closed Loop Control Simulation Results

This section contains the results of three simulation experiments using MATLAB/SIMULINK environment to study the dynamic response of SESRIG based standalone WECS with Takagi Seguno Fuzzy based Ant System PI closed loop control. For the sack of comparison, the results with ZN-PI controller designed in [17] are also presented. Firstly the response for changing the rotor speed (b) while the stator load resistance kept constant is presented. Secondly the response for changing the stator load resistance (R_L) while the rotor speed (b) kept constant is studied. Thirdly the response for changing the rotor speed (b) followed with a change in the stator load resistance (R_L) is introduced. Fig's. (10-15) show the dynamic response (output voltage and frequency) of the standalone WECS subjected to the proposed and traditional control method. The proposed PI controllers (ASTSFPI) after a short transient time restored both the output terminal voltage and frequency to the reference value (i.e. 1 p.u.) with reasonable overshoot and zero steady state error irrespective of changing the rotor speed and the stator load resistance. As seen from the following figures, the proposed control method outperforms the traditional control method.

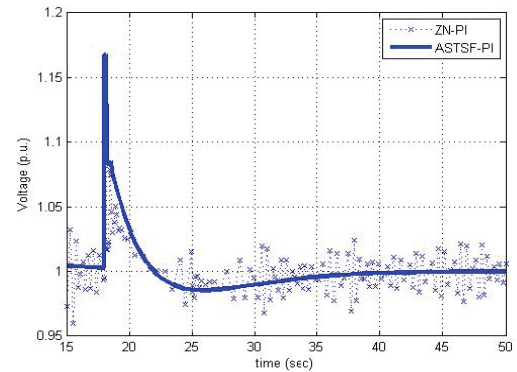


Figure 10 Dynamic Response of the voltage as the rotor speed increases from 1.2 to 1.3 p.u. at $R_L = 4$ p.u. with the proposed and the traditional control

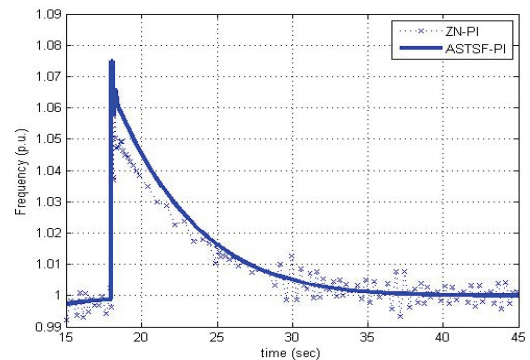


Figure 11 Dynamic Response of the frequency as the rotor speed increases from 1.2 to 1.3 p.u. at $R_L = 4$ p.u. with the proposed and the traditional control

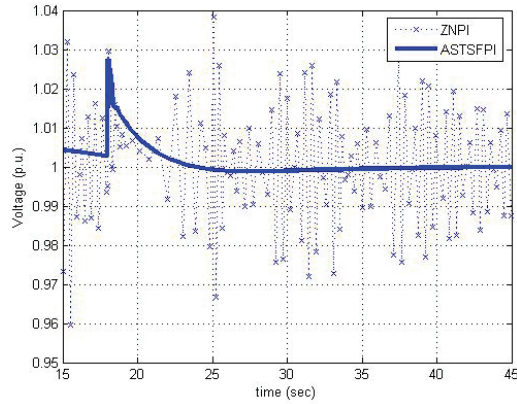


Figure 12 Dynamic Response of the voltage as the load increases from 4 to 4.3 p.u. at $b = 1.2$ p.u. with the proposed and the traditional control

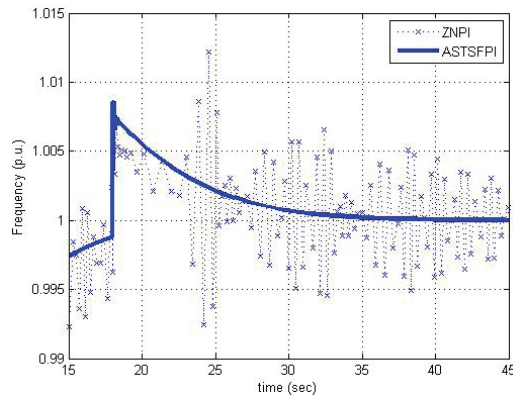


Figure 13 Dynamic Response of the frequency as the load increases from 4 to 4.3 p.u. at $b = 1.2$ p.u. with the proposed and the traditional control

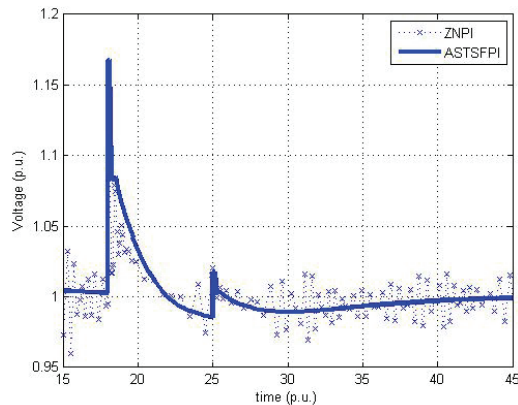


Figure 14 Dynamic response for the voltage as rotor speed & Stator load resistance change from $b = 1.15$ to 1.3 p.u. and from $R_L = 4.5$ to $R_L = 4.3$ p.u. with the proposed and the traditional control

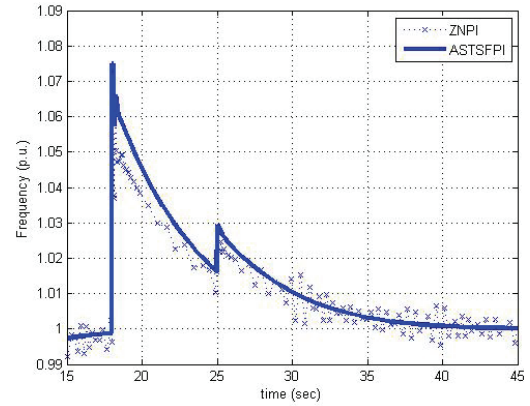


Figure 15 Dynamic response of the frequency as rotor speed change & stator load resistance change from $b = 1.15$ to 1.3 p.u. and from $R_L = 4.5$ to $R_L = 4.3$ p.u. with the proposed and the traditional control

VI. CONCLUSION

In this paper, an optimal Takagi Seguno fuzzy PID controller is determined using ant system algorithm. The proposed controller is used to control the output voltage and frequency for standalone WECS at the sending end of self-excited slip-ring induction generator. The ant system algorithm search for the optimal parameters of the consequent part of the Takagi Seguno fuzzy system that is in turn produces the optimal PID gains. It is shown that with varying rotor speed and load impedance both the frequency and the output voltage of the SESRIG can be maintained constant by rotor resistance control and excitation capacitance control over a wide range of speeds without exceeding the stator current limit. The proposed algorithm is easily implemented, has a good convergence property and has an efficient searching ability for the optimal PID controller. Moreover the proposed technique is very effective and useful for making the self excited induction generator feasible for remote windy areas.

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