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Parallel Fuzzy Logic and PI Controller for Transient Stability and Voltage Regulation of Power System Including Wind Turbine

***Abstract**. In this paper, transient stability and voltage regulation have been studied using Fuzzy Logic (FL) and PI controller tuned by Bees Algorithm (BA). Both controllers applied to a Single Machine Infinite Bus (SMIB) power system equipped by Static Var Compensator (SVC) and small wind turbine. Transient stability has been evaluated using a relative rotor criteria and the Critical Clearing Time (CCT) which has been calculated for cases considered for different mechanical ratio. Voltage regulation has been improved using SVC controlled by PI controller which her parameters have been optimized by Bees Algorithm (BA). Obtained results have been demonstrated a better performance with FL and PI controller which CCT has been increased and decreased considerably*

Streszczenie.** W artykule analizowano system energetyczny z dołączonymi turbinami wiatrowymi pod kątem stabilności i mozliwości sterowania napieciem. Do tego celu wukoprzystano logikę rozmytą I sterowniki PI strojony za pośrednictwem algorytmu rojowego. Stabilność była poprawiona dzięki zastosowaniu metody CCT – critical cleaning time. **Poprawa stabilności i sterowalności napięcia w systemie z turbinami wiatowymi dzięki stosowaniu równolegle logiki rozmytej i sterownika PI

Keywords: Power system stability; Fuzzy Logic; PI Controller; Wind Turbine; Voltage Regulation.
Słowa kluczowe: stabilność systemu energetycznego, turbina wiatrowa, logika rozmyta

Introduction

Today, power system instability problem is taking up an important role in the study of planning and control, because instability may produce adverse effects on the robust structure of system. In especial, power oscillations with frequency between 0.2 and 2.0 Hz, i.e., Local and inter-area oscillations may risk the operation and cause the system instability. As an ending, the wide area blackout may occur [1, 2]. To solve this issue, a suitable damping controller is needed in order to call down for overall system stability. Because, without proper without proper damping, the oscillations will not decay, lead into system instability. Power System Stabilizer (PSS) is employed to supply an auxiliary control signal to an excitation system on synchronous generators to enhance the stability by damping the oscillations and extending the limit of power transfer, thus maintaining reliable operation of the system. However, due to the nonlinearity of the power system configurations and frequent changes in the operating conditions, the performance of the PSS was highly affected [3, 4].

At present days, Conventional generating units combined several renewable generating units to respond to meet the need for electric power to the consumers. The synchronous generators which that experience these devices installed is out of service to allow the system to accommodate the new wind power generation, their damping contribution is obviously lost [5]. In the last few years there has been a growing interest in SVC PID controllers in order to have the great possible performance [6, 7]. However, the structure of the electric power system is large and the design is in a complex state, and it's very difficult to find a linearized model of the system. In summary, it's laborious to apply an online controller because the electric power systems are time varying, so a fixed controller is more feasible and desirable. In the last few years, several Meta heuristic search based optimization algorithms, such as GA [8], PSO [9] attracted the attention in the field of the design of parameters optimization, but power system suffer of many problems, such as voltage fuctuation and power oscillations.

To solve these defects, this paper establishes a new Fuzzy Logic (FL) and PI Controller with the aim to improve the transient stability and voltage regulation of SMIB connected to small wind turbine and SVC. The propped Fuzzy Logic Controller (FLC) is used to control the excitation system of generator; the SVC is controlled by PI optimize by Bees Algorithm (BA) for load bus voltage improvement. Furthermore, assessment of power system transient stability is studied in case of small fluctuation of mechanical power, where relative rotor criteria and the Critical Clearing Time (CCT) are considered as index for power system transient assessment.

This paper is organized as follows: Section 2 describes the related works of different methods to analyze the transient stability and voltage improvement. In section 3, the model of power system, wind turbine and the SVC with PI controller have been presented. In section 4 design of bees algorithm has been presented in details. Fuzzy logic controller is discussed in Section 5. The implementation of the proposed design is presented in section 6 which several scenarios have studied clearly. Finally, section 7 concludes with a summary.

Related works on the stability and voltage improvement

Different methods for power system stability have proposed. The main points of this review of different method to improve the voltage and transient stability of power system are summarized in table 1.

Table 1. Summury of different methods to improve the voltage and transient stability

Reference	Year	Technique	Remarks
Mohanty et al [10]	2015	ANN	The artificial neural network (ANN) based SVC controller for voltage stability improvement in an isolated wind-diesel-micro hydro hybrid system. Simulation result justifies the working of the isolated systems performance which shows that the system parameters attend steady state value with lesser time and complexities.

Amoozegar [11]	2016	FL-PI	The Distribution Static Synchronous Compensator (D-STATCOM) is an inverter based power quality conditioner device used to improve the power quality issues in distribution systems with fuzzy logic (FL) - PI current controller. Fuzzy-PI controller is employed for the better performance and the transient stability. Further, the work can be done by using neuro-fuzzy control.
Bian et al [12]	2016	PMT	The identification and improvement of probabilistic voltage instability modes of power system with wind power integration using based on plug-in modeling technology (PMT). The results validate the efficiency and feasibility of the proposed approach.
Fereidouni et al [13]	2016	SSFCL-LR	The performance of inductive (L), resistive (R) type solid-state fault current limiter (SSFCL) can improving power quality and transient stability of power network with wind turbine generators. PSCAD/EMTDC is used to analyze the power system characteristics of the SSFCL-LR unit.
Hossain et al [14]	2016	PRBFCL	The parallel-resonance bridge type fault current limiter (PRBFCL) is used to augment the transient stability of a hybrid power system consisting of a photovoltaic (PV), wind energy based doubly-fed induction generator (DFIG) and a synchronous generator (SG). The performance of the PRBFCL is better than other controllers during the grid fault.
Milla et al [15]	2016	POA-PSS	The Predictive Optimized Adaptive PSS (POA-PSS) is used to improve the oscillations in a Single Machine Infinite Bus (SMIB) power system. Simulation results illustrate that the proposed POA-PSS approach has better performance than the classical PSS.
Mohanty et al[16]	2016	FOPID	The application of fractional order PID controller (FOPID) for reactive power compensation and stability analysis in a stand-alone micro grid for enhancement of voltage stability and reactive compensation of the isolated system using SVC. The proposed controller is found effective and it shows robustness in improving the voltage stability under different wind power input and 5% step increase in reactive load demand.
Ni et al [17]	2016	GrHDP	The adaptive neuro-control approach, namely goal representation heuristic dynamic programming (GrHDP) to study the nonlinear optimal control on the multi-machine power system. Simulation results verify that the investigated neuro controller can achieve improved performance in terms of the transient stability and robustness under different fault conditions.
Saxena et al [18]	2016	GA, ANN, ANFIS	The Genetic Algorithm (GA), Artificial Neural Network (ANN) and Adaptive Neuro Fuzzy Inference System (ANFIS) are used to control in decentralized hybrid power system with STATCOM. Results comparison through all tuning methods show that advanced tuning methods are able to preserve optimal performances over wide range of disturbances.
Singh et al [19]	2016	GA	The Genetic algorithm (GA) is used to optimize the impact assessment of optimally placed distributed generations DGs and FACTS controller with different load models from minimum total real power loss viewpoint. The effectiveness of the proposed methodology is tested on IEEE 37-bus distribution test system.
Oubbati et al [20]	2016	TSCOPF	The transient stability constrained optimal power flow (TSCOPF) is used minimize the total cost of fuel for all generators which The proposed method is tested on the IEEE 30-bus system.
Bakhshi et al [21]	2017	LFDC	The local fuzzy based damping controller (LFDC) for thyristor controlled series capacitor (TCSC) to improve transient stability of power systems. The simulation results confirm that the proposed LFDC is an efficient tool for transient stability improvement since it utilizes only local signals, which are easily available.
Labdelaoui et al [22]	2017	(MOGA)	The multiobjective genetic algorithms (MOGA) approach is used to design the optimal of power system stabilizer (PSS). The effectiveness of the proposed methodology is tested using single-machine infinite bus (SMIB). The simulation results demonstrate the best trade-off according to Pareto dominance by the dual-input of PSS.
Abdelaziz et al [23]	2017	TSMC	The terminal sliding mode control (TSMC) is used to improve the speed deviation and electrical power generated by single-machine infinite bus (SMIB). The simulation results confirm the robustness of the proposed method which compared by conventional that means a lead lag compensator, and a classical sliding mode power system stabilizer.

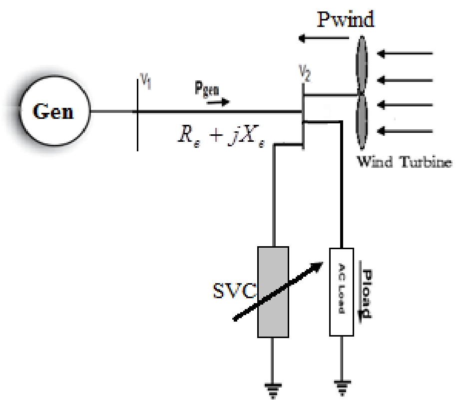

Fig.1. SMIB equipped by SVC and wind turbine

Power system modeling under study

The efficiency of the proposed method has been tested using Single Machine Infinite Bus (SMIB) equipped by SVC and a small wind turbine connected in bus 2 shown in figure1. The transmission line parameters are R_e and X_e to connect synchronous generator in infinite bus which the load, wind turbine and the SVC are connected shown.

The stator voltage equations with the external impedance included is: [2]

$$v_q = -(r_s + R_e)I_q - (x_d^{'} + X_e)I_d + E_q^{'} \qquad (1)$$
$$v_d = -(r_s + R_e)I_d - (x_q^{'} + X_e)I_q + E_d^{'}$$

(2) $$\dot{\delta} = (\omega - \omega_b)$$

(3) $$\dot{\omega} = \frac{\omega_b}{2H}\left[P_m - P_e - D(\omega - \omega_b)\right]$$

(4) $$\dot{E}'_q = \frac{1}{T'_{d0}}\left[V_{ex} - E'_q + (x_d - x'_d)I'_d\right]$$

(5) $$\dot{E}'_d = \frac{1}{T'_{q0}}\left[-E'_q - (x_q - x'_q)I'_q\right]$$

The electrical power at the bus 2 is given by:

(6) $$P_e = P_{gen} + P_{wind}$$

where: P_{gen} is the electrical power generated by the synchronous generator, P_{wind} is the electrical power generated by the wind turbine which the captured power (in W) by a Wind turbine (WT) can be written by: [3]

(7) $$P_{wind} = \frac{1}{2}\rho_w.A_{rw}.V_w^3.C_{pw}(\lambda_w, \beta_w)$$

where ρ_w the air density (kg/m3), A_{rw} is the blade impact area (m2), V_w is the wind speed (m/s), the WT λ_w the tip speed ratio, β_w is blade pitch angle (degrees) and C_{pw} power coefficient. The tip speed ratio (TSR) is the ratio of turbine speed at the tip of a blade to the free stream wind speed and given by:

(8) $$\lambda_w = \frac{A_{rw}\omega_{WT}}{V_w}$$

The power coefficient curve has been described in the literature by different fitted equations. In this paper, the power coefficient curve is approximated analytically by: [3]

(9) $$C_{pw}(\lambda, \beta) = 0.5109\left(\frac{116}{X} - 0.4\beta - 5\right)\exp\left(-\frac{21}{X}\right) + 116\lambda_w$$

where: $X = \dfrac{1}{\lambda_w + 0.08\beta_w} - \dfrac{0.035}{1 + \beta_w^{\ 3}}$

Where $r_s, H, D, \omega, \delta$, P_m, P_e, ω_b, T'_{d0}, T'_{q0}, E'_d, E'_q, x'_d, x'_q, I'_{d0}, I'_{q0}, V_{ex} are the parameters of synchronous machine given in reference [2].

For the regulation of the voltage at bus 2, we connect a SVC which the reactive power injected Q_{SVC} given by the expression [11]:

(10) $$Q_{SVC} = -b_{SVC}V_2^2$$

where b_{SVC} is the susceptance. The value of b_{SVC} is obtained by PI controller (figure .2)

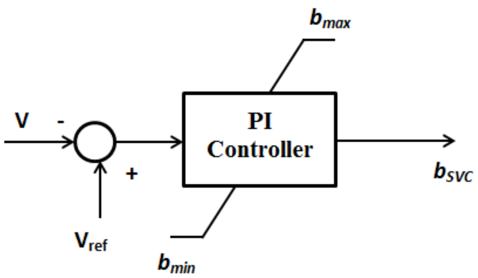

Fig.2. SVC with PI controller

The Figure 1 represent of synchronous generator V_1 and an impedance of the transmission line $R_e + jX_e$. The voltage across the compensating impedance at the bus 2 can be written as follows:

(11) $$V_2 = \frac{1}{y_{22} + y_{SVC}}\left[\frac{(P - P_{wind}) - j(Q \pm Q_{SVC})}{V_2} - y_{12}V_1\right]$$

where y_{SVC}, y_{22}, y_{12} are the admittance of the SVC, bus 2 and the line. To resolve and calculate and the bus voltage V2 Gauss-Sidel method have been used.

Therefore, there is a need for an effective method for tuning the parameters of the PI controllers so as to maximize the voltage regulation of power system. Bees Algorithm (BA) is a global searching technique based on the operations observed in natural selection.

Proposed bees algorithm

A colony of honey bees thrives by propelling its foragers to a good field. The colony can extend itself over 10 km in multiple directions in order to find a large number of food sources. Basically, flower patches with plentiful amounts of nectar or pollen that can be collected with less effort should be visited by more bees, whereas patches with less nectar or pollen should receive fewer bees [24]. After the dancing, the follower bees that were waiting inside the hive will follow the scout bees to the flower patch, allowing the food to be gathered quickly and efficiently. More following bees will be sent to promising field. As the food level is being monitored, the colony will decide based on the waggle dance upon the next returning to the hive. If the food source from the patch is still good enough.

As mentioned, the BA inspired by the natural foraging behavior of honey bees is an optimization algorithm which aims to find the optimal solution [25]. The simplest form of pseudo code for the algorithm is shown in Figure. 3. The best bee can be selected directly based on the fitness value associated with the sites they are visiting. Promising solution provided by the bees search in the neighborhood of the best e sites is made more detailed by recruiting more bees to the selected best e sites. Meanwhile, the remaining bees in the population are assigned randomly around the search site scouting for new potential solutions.

1. Initialize population with random solutions.
2. Evaluate fitness of the population.
3. While (stopping criterion not met)
// forming new population.
4. Select sites for neighbourhood search.
5. Recruit bees for selected sites (more bees for best e sites) and evaluate fitnesses.
6. Select the fittest bee from each patch.
7. Assign remaining bees to search randomly and evaluate their fitnesses.
8. End While.

Fig.3. Pseudo code of the basic Bees Algorithm.

Design of Fuzzy Logic Controller (FLC) proposed

To achieve the best dynamical response of power system, the structure of excitation system of generator is displayed in Figure. 4. The FLC can be used to add damping to the rotor oscillations of the synchronous generator by controlling its excitation. The FLC input signal can be the rotor speed deviation of generator ω. The disturbances occurring in a power system induce electromechanical oscillations of the electrical generators. These oscillations, also called power swings, must be effectively damped to maintain the system stability. The output signal of the FLC is used as an additional input Vsup to the excitation system. To ensure a robust damping; the FLC should provide a moderate phase advance at frequencies of interest in order to compensate for the inherent lag between the field excitation and the electrical torque induced by the FLC action as shown in Fig. 5.

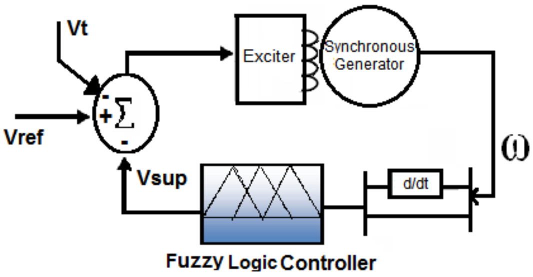

Fig.4. Proposed FLC

The excitation system of the synchronous machine is represented by the following transfer function:

$$\frac{V_{ex}}{E_f} = \frac{1}{K_E + sT_E} \quad , \tag{12}$$

where K_E and T_E are respectively constant gain and time constant of exciter.

In order to automatically control the terminal voltage V_t of the synchronous machine, a transducer voltage must be compared to a reference voltage and amplified to produce the exciter input signal V_{ref}. The amplifier may be characterized by a gain K_A and with a time constant T_A.

In standard excitation systems, to achieve the desirable dynamic performance and to shape the regulator response, a stabilizing circuit is used, which characterized by a gain K_F and with a time constant T_F as can be seen in Fig. 5.

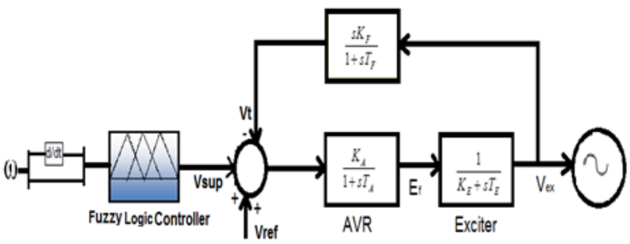

Fig.5. Proposed FLC

The proposed strategy of control is composed a fuzzy logic controller, adaption law, hitting controller and bound estimation. The inputs of this controller are oscillation of ω and its derivative. Figure 6 shows normalized membership functions for input and output variables.

The rule Table 2 was then designed and used with a triangular membership function inputs-output in the fuzzy logic controller and was implemented in the simulation.

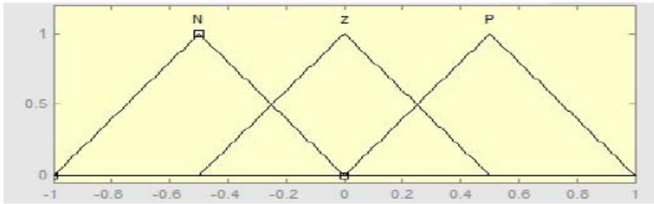

Fig.6. Membership representation

Table 2. Rule base of the fuzzy controller

Δuf[k]		ė[k]		
		N	Z	P
e[k]	N	N	N	Z
	Z	N	Z	P
	P	Z	P	P

Simulation results

In order to demonstrate the effectiveness of the proposed controllers, the system being studied is simulated by MATLAB software shown in figure 7.

SVC and wind turbine are connected to the bus load which the system has been designed to study the electromechanical oscillations in large interconnected power systems. It has also been modified to include FACTS devices for studying the damping voltage improvement which the SVC will maintain the load voltage profile to close to 1 p.u.

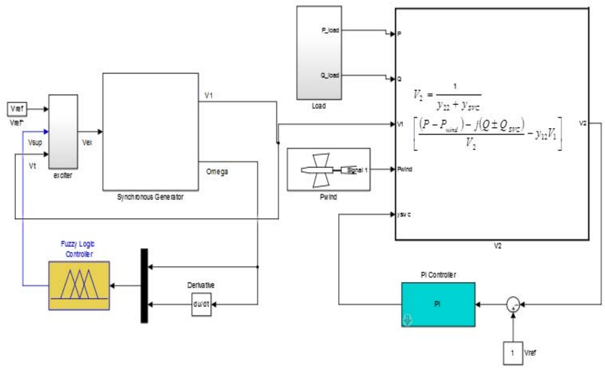

Fig.7. System being studied simulated by MATLAB software

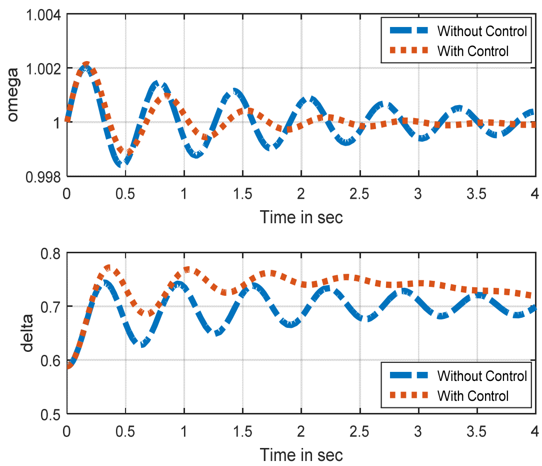

Fig.8. Simulation results

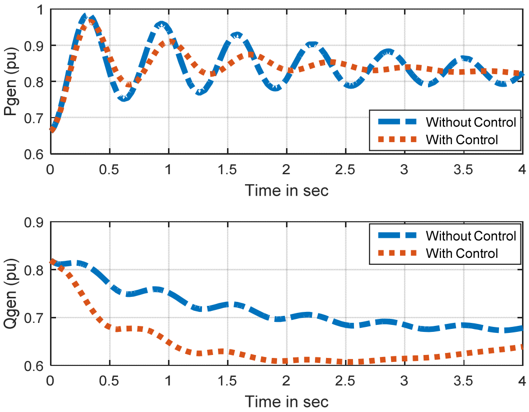

Fig.9. Simulation results

Transient stability analysis

The simulation results show the principle of CCT calculation are presented in figure 7 ,in which we increase and decrease the duration of the mechanical damping until the relative rotor angles become not oscillators weakened.

The figure 8 and 9 represent the speed, the relative rotor angles, the active power and reactive power of synchronous machine in the case of fault duration Tf = 0.1s and the size of the torque perturbation about operating point is 5% of nominal torque.
Simulation results of different scenarios and CCT are shown in table.3 and table 4.

Table 3. Decreasing of DT

Decreasing of DT (%)	CCT (sec) With Controller	CCT (sec) Without Controller	Improved Ratio (%)
5	0.93	0.1	93
10	0.95	0.15	63
15	0.90	0.12	75
20	0.88	0.20	44
30	0.84	0.21	40
40	0.86	0.21	40

Table 4. Increasing of DT

Decreasing of DT (%)	CCT (sec) With Controller	CCT (sec) Without Controller	Improved Ratio (%)
5	0.94	0.10	94
10	0.96	0.15	64
15	0.90	0.11	81
20	0.88	0.18	48
30	0.85	0.20	42.5
40	0.88	0.20	44

Table 5. Parameters set for BA

Designation	Value
Number of scout bees, n	150
Number of sites selected for neighborhood search, m	19
Number of best "elite" sites out of m selected sites, e	11
Number of bees recruited for best e sites, nep	29
Number of bees recruited for the other (m-e) selected sites, nsp	16
Number of iterations, R	100

The results presented in table 3 and 4 have shown the efficiency of the proposed method and the superiority of CCT with controller has been proved. The CCT is the minimum that shows the weakness of network requiring strengthening.

Voltage Regulation

The performance of the PI controller to regulate voltage of power system after subjected to a disturbance was examined. The parameters used for the BA is shown in Table 5.

In this section, we present the voltage improvement using SVC controlled by conventional PI optimize by BA, Figure. 10 show the voltage profile at the bus 1 and 2 for both cases: with and without of SVC device. It can be observed that the performance of voltage with SVC is better. So, the proposed strategy can be as one of the best methods for power system voltage control.

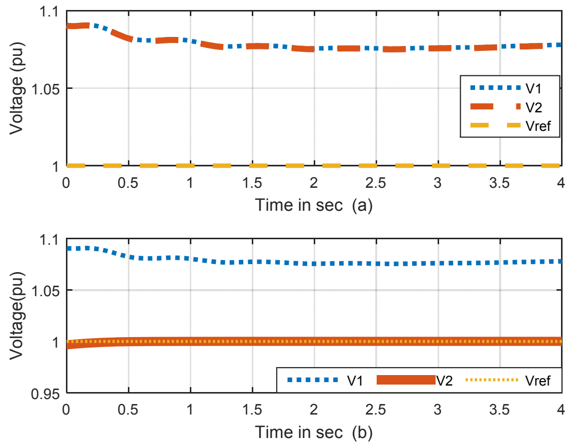

Fig.10. Voltage regulation a. Without SVC, b. With SVC

Conclusion

In this paper, transient stability and voltage control have been studied using two novels controls, the first one uses the Fuzzy Logic (FL), the second uses PI Controller tuned by Bees Algorithm (BA) to control voltage. Both controllers applied to Single Machine Infinite Bus (SMIB) power system equipped by Static Var Compensator (SVC) and small wind turbine. Transient stability has been investigated in which the mechanical power increase and decrease the mechanical ratio in which the (CCT) has been calculated for cases considered. In addition, obtained results of voltage control demonstrate the efficiency of developed PI-BA in which the voltage profile has been improved and track the reference perfectly. From these results, the major contribution of this work can be completed using multi machine power system and the online optimization of PI controller using others technics.

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