2020 International Conference on Electrical Engineering (ICEE)
September 25-27, 2020, Istanbul, Turkey

Automatic Voltage Regulator Design Using Particle Swarm Optimization Technique

Fazia Ahcene (1), Hamid Bentarzi (1)*
Laboratory Signals and Systems, IGEE, University M’hamed BOUGARA
Boumerdes, Algeria
*lss@univ-boumerdes.dz

Abstract— The generation of energy in large power systems and islanded networks is ensured by the synchronous machine, the enhancement of dynamic performance during disturbances is increasingly required. This research work aims to maintain the terminal voltage constant of a 1.5 kVA synchronous laboratory power machine with salient pole under different loads. Then, a second generator of 187 $*10^3$ k VA with different exciting system is studied. A voltage regulation is ensured via a well-chosen controller named 'automatic voltage regulator’ that is based on proportional integral controller (PI). The adopted optimization method that has been used to determine the regulator parameters is the particle swarm optimization algorithm (PSO). The automatic voltage regulator (AVR) is tested under three different conditions. The obtained simulation results are encouraged the validation of the use of the designed AVR.

Keywords- Automatic Voltage Regulator; synchronous generator; Particle Swarm Optimization; excitation system; modeling and linearization.

I. INTRODUCTION

Electric energy is a vital element in our civilization. Around the world, electricity has found many applications in various areas of life. However, since energy is a scarce and precious resource, the investigation may be performed on its use in the most optimal possible way. Today most of this energy is produced by synchronous machines in thermal, gas turbine and hydraulic power plants. Synchronous machines play an important role to provide the power system with an energy reservoir making it possible to cope, in the first moments, during a transient condition of imbalances between production and consumption, by controlling the inductor of the main generator indirectly through the control of the machine exciter [1-3].

The synchronous generator has two inputs; mechanical input of the turbine and an electrical input for the excitation system. The efficiency of electric power system and the stability of the synchronous generator are highly dependent on the reliability of the exciter that is as the main power source for the whole system. Because the excitation supports the stator and the rotor, however, the loss of excitation of the generator weakens the various parts of the machine and hence leads to an imbalance of mechanical and electrical power and the speed of the rotor increases beyond the synchronous speed. This phenomenon can damage the generator and the power grid. The excitation system reduces these risks, the generator itself is a source of energy or the generator is self-excited. The significant advantage of this type of excitation system can generate negative excitation current. Thus, it allows a rapid de-excitation which may be necessary in the event of an internal fault of the generator and also reduces the response time and the size of the installation. The application of a PSO algorithm for the determination of the parameters of the corrector offered precision [2, 4, 5].

II. EXCITATION SYSTEM

The excitation system is developed to supply and regulate the inductive current of the main machine. It consists mainly of an exciter and the voltage regulator (AVR - Automatic Voltage Controller) or the power factor regulator. The rectified and filtered terminal voltage of the machine is compared with the reference voltage V_{ref} to determine the voltage error that is entering the amplifier of the regulator. This error is introduced to the main damping loop of excitation [1, 5, 6].

Another type of excitation system is Static Excitation System that may be used for the high power generator (for our case 187kVA). It is based on a rectifier using thyristors together with the control system, regulates the excitation voltage V_f. A schematic diagram of the excitation system is shown in Fig.2.

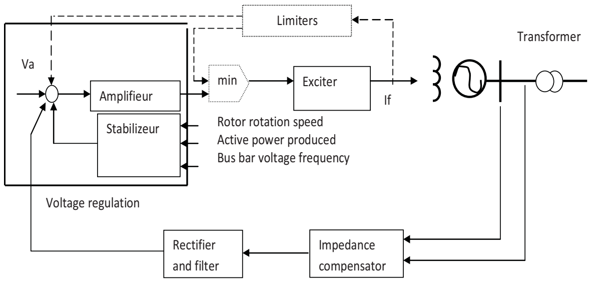


Figure 1. Schematic diagram of the excitation system of synchronous laboratory power machine.

978-1-7281-8292-6/20/$31.00 ©2020 IEEE

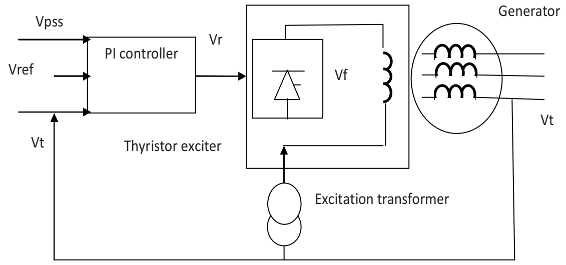


Figure 2. Schematic diagram of the excitation system in power plant

The input voltages to the PI controller block V_t and V_{pss} are compared for each iteration of the algorithm with the voltage reference V_{ref}. The output voltage V_r of the PI controller without internal feedback controls the thyristors of the rectifier using a pulse width modulation (PWM) signal. The regulator is supplied by the generator armature circuit via an excitation step down transformer, adjusted to the parameters of the excitation system. The excitation transformer is used to supply the rectifier as well as a galvanic separator of the rotor circuit, as shown in the schematic diagram of the excitation system Figure.2 [2, 6, 7].

III. MATHEMATICAL MODEL OF THE SYSTEM

For good mathematical modeling of a system, all the transfer functions of its main elements should be linearized, by taking into account the major time constants and ignoring the saturation and other non-linearities. The transfer functions of the main elements of the studied system will be represented as follows.

A. The Excitation System Model

The excitation system model is given from the relationship between the amplification, excitation and compensation functions.

The transfer function is:

$$G_E(s) = \frac{K_f}{1+sT_f} \tag{1}$$

B. The Sensor Model

The role of the sensor circuit is to rectify, filter and reduce the terminal voltage; it is given by a first order transfer function:

$$H(s) = \frac{K_r}{1+sT_r} \tag{2}$$

Where, T_r range from of 0.001 to 0.06 s.

C. Generator Model

The simplified transfer function describing the SG is of the form:

$$G(s) = \frac{K_G}{1+sT_G} \tag{3}$$

Finding K_G and T_G can be done as follow:

$$G(s) = \frac{K_G\,(1+sT_{kd}\,)}{(1+sT_{d0}^{'})(1+sT_{d0}^{''})} \tag{4}$$

Where, $K_G = \frac{x_{md}}{r_f}$, $T_{d0}^{'} = \frac{x_{md}+x_f}{r_f}$, $x_{md} = x_f$ and $T_G = T_{d0}^{'} = \frac{x_f}{r_f}$.

With T_{kd} and $T_{d0}^{''}$ are neglected.

D. Automatic Voltage Regulator Model

An automatic voltage regulator (AVR) ensuring the internal stability of the closed loop system as well as the attenuation of the influence of disturbances on the output of the controlled system.

The PID controller synthesis may be used to improve the dynamic response as well as reduce or eliminate the stationary state error.

The transfer function of a PID-controller is:

$$G_{PID}(s) = K_P(1+\frac{1}{sT_I}+sT_D) = K_P(\frac{1+sT_I+s^2T_IT_D}{sT_I}) \tag{5}$$

With: KP – proportional gain, TI – integral constant time, TD – derivative constant time.

These parameters are given from experimental determination of the laboratory synchronous generator parameters and according to IEEE mathematical relations between leakage inductances.

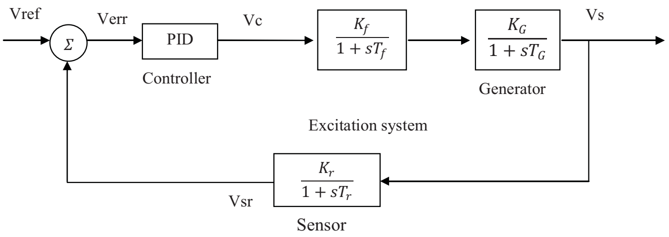


Figure 3. Simplified model of the voltage regulation principle.

It can be noted that, even with well-defined systems, tunneling the parameters of the correctors is not always easy especially with real systems. The modeling does not always represent the behavior of the system very well over the entire range of use; phenomena of non-linearity and / or saturation appear very quickly. Whatever we do, we will always have a more or less precise idea of the mathematical model (s) that describes the synchronous machine. In order to facilitate the adjustments of the correctors, identification techniques have been developed; formulas may be developed to determine approximately the parameters of the desired corrector [3, 8, 9, 10].

E. Static Excitation System Model of the generator

The input voltages to the PI controller block generator terminal voltage V_t and power system stabilizer V_{pss} are compared for each iteration of the algorithm with the voltage reference V_{ref}. The output voltage V_r of the PI controller without internal feedback controls the thyristors of the rectifier using a PWM signal. The regulator is supplied by the generator armature circuit via an excitation step down transformer, adjusted to the parameters of the excitation system.

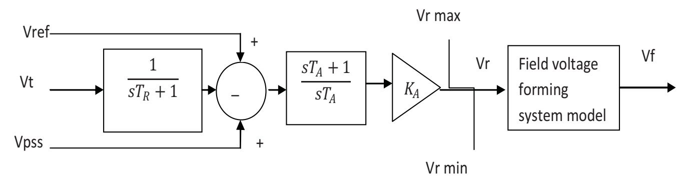


Figure 4. Block diagram of the generator static excitation system

The excitation transformer is used to supply the rectifier as well as a galvanic separator of the rotor circuit, as shown in the schematic diagram of the excitation system Figure 4 [3, 7, 10].

IV. ZERO/POLE CANCELATION TECHNIQUE FOR TUNING THE PID-CONTROLLER

The pole compensation method is the frequently used synthesis method. It consists in imposing the zero of the regulator equal to a slow pole of the transfer function of the system to be controlled; then seek the gain so as to have an optimal response from the point of view of the set point.

The control signal is given by:

$$V_c = K_P\left[e(t) + \frac{1}{T_I}e(t)dt + T_D\frac{de(t)}{dt}\right] \tag{6}$$

Where: e(t) is the error voltage.

The transfer function of (excitation system +generator) is then obtained:

$$G_{EG}(s) = \frac{K_f K_G}{(1+sT_f)(1+sT_G)} = \frac{K_{EG}}{1+s(T_f+T_G)+s^2T_fT_G} \tag{7}$$

After applying Zero/Pole cancelation eliminating the poles of equation (6) by the zeros of equation (3), we can deduce the gains:

$$\begin{cases} K_P = \dfrac{\left(T_f+T_G\right)T_r\omega_n^2}{K_rK_fK_G} \\ or \\ K_P = \dfrac{\left(T_f+T_G\right)}{4K_fK_GT_rK_r\xi^2} \end{cases} \qquad K_I = \frac{1}{T_f+T_G} \qquad \& \qquad K_D = \frac{T_fT_G}{T_f+T_G} \tag{8}$$

The idea of canceling the zero/pole may seem academic since the exact cancellation of the zero/ pole is practically impossible. Experience shows that the designed controller parameters give an acceptable performance for most alternators with time constant of the exciter of about one tenth of the generator time constant. For this task, an advanced method has been used such as the PSO which has the advantage of finding a global solution for tuning the PID controller parameters [3, 10, 11, 12].

V. PARTICLE SWARM OPTIMIZATION

PSO is an evolutionary computation algorithm which is founded upon the principles of biological evolution and is inspired by the study and investigation of swarm patterns occurring in nature [13, 14]. PSO was first introduced by Eberhart and Kennedy in 1995 [15, 16], many researchers have expanded on the original idea with alterations ranging from minor parameter adjustments to complete reworking of the algorithm [17].

PSO is used to explore the search space of a given problem to find the settings or parameters required to maximize or minimize an objective function. It is found to be robust in solving problems featuring nonlinearity and non-differentiability, multiple optima, and high dimensionality problems [14].

Particle Swarm Optimization (PSO) is an iterative global search algorithm its goal is to optimize a predefined function called the "fitness" cost criterion or function. It allows an initial set of solutions to evolve towards a final set.

This method is based on the collaboration of individuals with each other. The particles are the individuals and they move in the search hyperspace, while the population is known as (swarm). Each particle moves with each iteration and it closes to the optimum, communicates its position to the others so that they can modify their trajectories. This idea is that a group of less intelligent individuals can have a complex global organization. The particle can benefit from the movements of other particles in the same population to adjust its position and speed during the optimization process. Each individual uses the local information they can access about the whereabouts of their nearest neighbors to decide on their own next move.

To maintain the cohesion of the whole group, very simple rules like “stay close to other particles”, “go in the same direction”, “go at the same speed” must be respected.

To initiate the algorithm, we use randomness, each particle having a random speed and a position. Then, at each time step:

1) Each particle can assess the quality of its position and it has a memory that allows it to memorize the best point through which it has already passed and it can return back via that point.

2) Each particle is informed of the best point known by its neighborhood.

3) Each particle chooses the best of the best performances of which it knows, modifies its speed according to this information and its own data and moves accordingly. From the disposal information, a particle can decide its next movement as well as its new speed [13].

VI. INTEGRAL TIME MULTIPLIED BY SQUARE ERROR (ITSE) CRITERIONS

The objective function is defined from some specifications and desired constraints on the test input signal and some output specifications such as overshoot, rise time, stabilization time and steady state error.

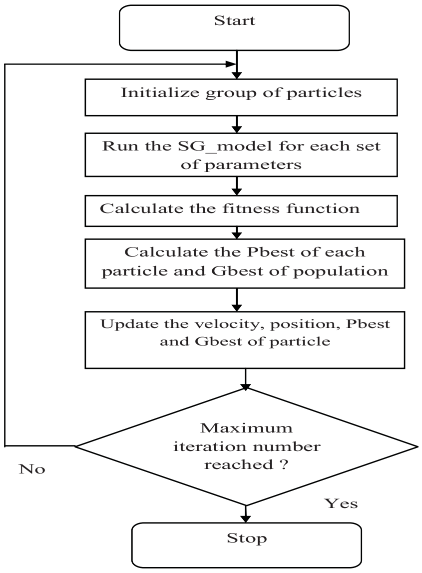


Figure 5. Flowchart for the PSO based PI-controller

Each performance index has its own advantages and disadvantages and will result in a different system of equation.

The performance criterion used in our work for the design of the PI controller is the integrated square error of the time weighting (ITSE).

$$ITSE = \int t.e(t)^2 \quad (9)$$

It averages the ISE and ITAE criteria, which amounts, through the action of the time parameter, to a fine analysis of the error at the end of the transient regime, while the start is not penalized. It is minimized for a 2nd order of which z = 0.58 [6, 10].

VII. SIMULATION RESULTS AND DISCUSSION

The objective of AVR is to maintain a constant voltage at the terminals of the synchronous generator SG by eliminating external disturbances (loads, load shedding, etc.). To test the developed AVR, Simulink model of the complete system has been implemented as close as possible to the real one. The SG is first used at no load and then at nominal conditions. At t = 1s, a load is connected across the machine (pure resistors in series with inductors, while inductive loads are modeled as pure inductors in series with small value resistors). The system response to varying loads leads to he rejection of disturbances due to the connected load is not guaranteed. To give better performance in closed loop, a PI controller is introduced.

A. PSO Tuning Results of First Generator

The combination between the SG model and the PSO algorithm allows calculating the error and the dynamic characteristics of the system at each position and each particle for each iteration.

The PSO parameters are given in table 1.

TABLE I. PSO PARAMETERS SETTINGS.

Number of variables (Dimension of the problem)	2
c1	2
c2	2
Velocity updating method	Inertia weight
Wmax	0.9
Wmin	0.4
Correction factor	2.0
Lower bound (position)	[-5.12 -5.12]
Upper bound (position)	[5.12 5.12]
Fitness function	ITSE

The idea is to have the best solutions for K_p and K_i with graphs of PSO convergence characteristics for different parameters, population size and number of iterations as shown in Fig.6.

The obtained results are shown in figures 7, 8 and 9 [6, 9].

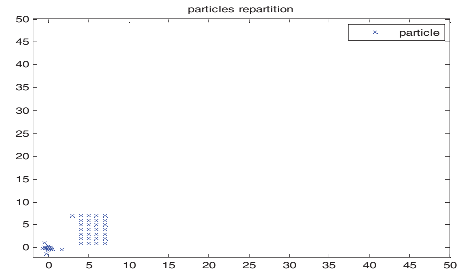
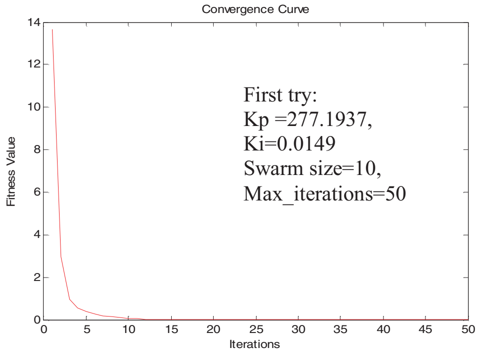
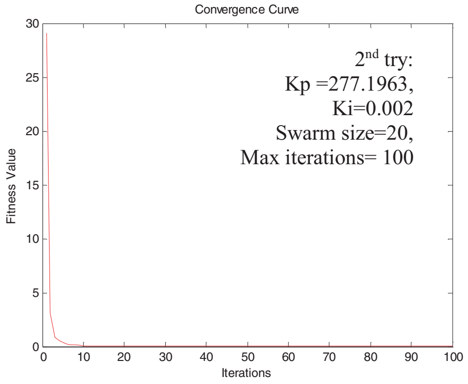


Figure 6. Population repartition





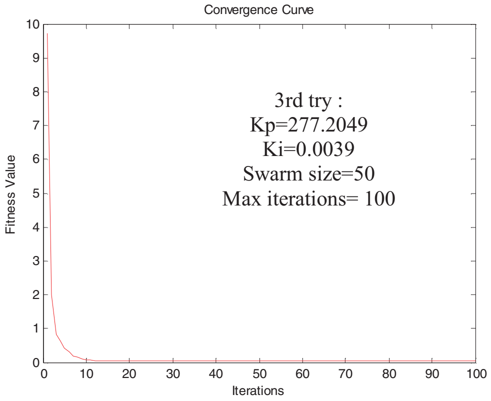


Figure 7. PSO convergence characteristics and best solutions

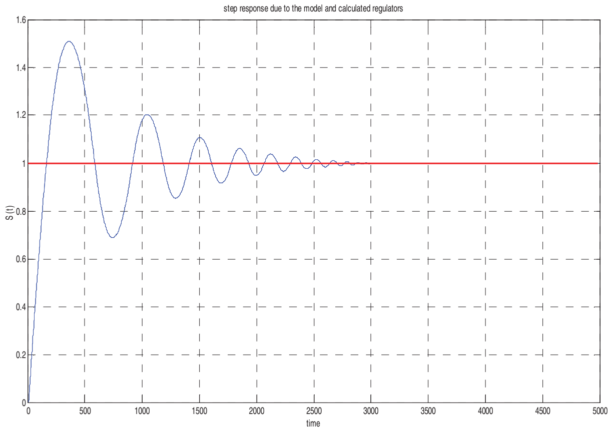


Figure 8. Plot of the step response due to the model and calculated regulator

The obtained results in the first part encouraged us to extend the study for another excitation system and another synchronous machine with nominal power is in the order of $187 * 10^3$ kVA.

VIII. PSO Tuning Results Of The Second Generator

The two figures 10 and 11 represent the application of the load at the instant 1 s.

Figures 12 and 13 show the voltage when applying a fault on phase A.

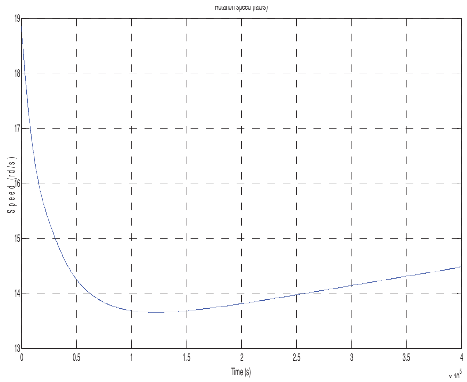


Figure 9. Rotation speed (rd/s)

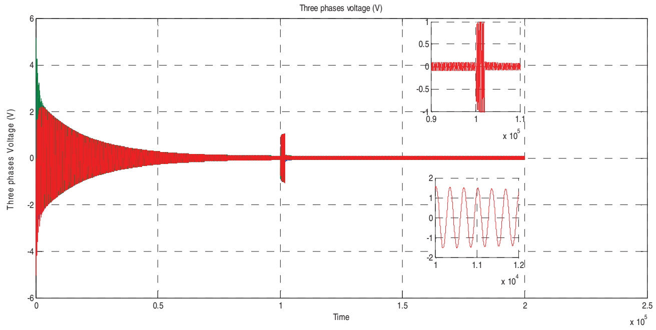


Figure 10. Three phase voltage (V)

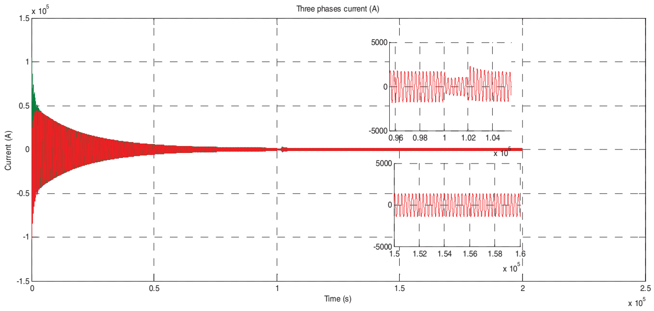


Figure 11. Three phase current (A)

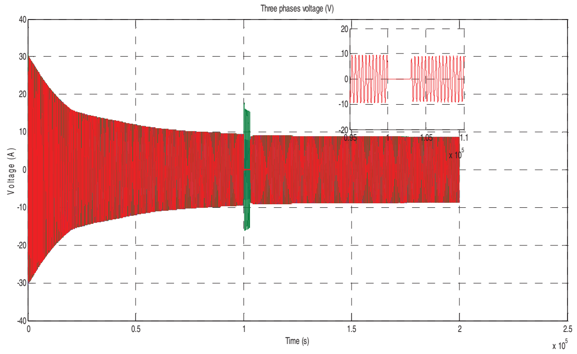


Figure 12. Three phase voltage when a fault is applied to phase A at 1 s

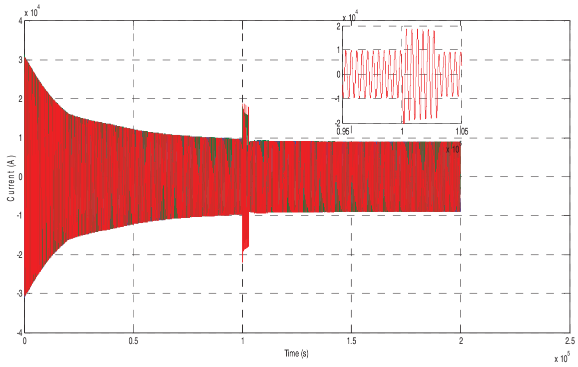


Figure 13. Three phase current when a fault is applied to phase A at 1 s

IX. CONCLUSIONS

Minimum frequency deviation and good voltage response at the terminals are both characteristics of a reliable power supply. The used conventional controllers have significant rise time, overshoot. Therefore, when advanced algorithms are applied to control systems, their typical characteristics show faster and smoother response.

The PI gains have been identified based on two tuning methods: a conventional method where zero / pole cancellation and a PSO heuristic algorithm. The connection between the control unit and the power circuit for the first machine is made by a firing circuit which is designed and implemented on the basis of a ramp comparator strategy during operation. For the second self-exciting machine, the PI controller based the AVR is implemented using Simulink.

The simulations were carried out using Matlab software. The obtained simulation results are finally discussed. Every part of the used excitation system is functioning correctly and satisfactorily for both generators.

REFERENCES

[1] A, M. Barakat, “Contribution à l’amélioration de la régulation de tension des générateurs synchrones: nouvelles structures d’excitation associées à des lois de commandes H∞ ”, Poitiers university, 2011.

[2] A.Ygzaw, B. Banteyirga and M. Darsema, “Generator excitation loss detection on various excitation systems and excitation system failure”, ICST 2020 ,Springer nature swizerland AG, LNICST 308, pp382-394, 2020.

[3] J. M. Ramirez, E. T. Montalvo and C. I. Nuno, “Modelling synchronization and implementation of the virtual synchronous generator: a study of itsreactive power handling”, Springer – verlag GmbH germany, part of springer nature, 2020.

[4] S. Wei, and Z. Xu, “Excitation System Parameters Setting for Power System Planning”. Power Engineering Society Summer Meeting, IEEE 2002.

[5] S. Paszek, A. Bobon, S. Berkausen, L. Majka, A. Nocon and P. Pruski, “Synchronous generator and excitation systems operating in power system”, Springer, Vol. 631, pp49-149, 2020.

[6] T. V. Custem, Introduction to electric power and energy systems, Montefiore, Liège : univerité science appliquées, 2019.

[7] Y. Shi and R. Eberhart, “A modified particle swarm optimizer”, Proceedings of IEEE World Congress on computational intelligence, international conference on evolutionary computation, pp 69-73, 1998.

[8] A. Derrar, “Résolution du problème d’optimisation H∞ des stabilisateurs PSS robustes par les approches métaheuristiques”, Sidi bel abbes university, 2016.

[9] M. Teodor Wisniewski, “Modélisation non-lieaire des machines synchrones pour l’analyse en régime transitoires et les études de stabilité”, université Paris-Saclay, 2018.

[10] F. Hashemi and M. Mohammadi, “Combination of continous action reinforcement learning automata on PSO to design PID controller for AVR system”, IJE TRANSACTIONS A, Vol.28, pp.52-59, January 2015.

[11] A. Ouadi, F. Ahcene, H. Bentarzi, “PI-Controller Parameters Tuning Using Particle Swarm Optimization for Automatic Voltage Regulator”, the International Conference on Computational Methods in Applied Sciences (ICCMAS 2019), 12-16 July, Istanbul, Turkey.

[12] F. Mudry, “Ajustage des parameters d’un régulateur PID”, eivd ecole d’ingénieurs du Canton de Vaud, 2006.

[13] M. Clerc and J. Kennedy, “The particle swarm explosion, stability and convergence in a multidimensional complex space”, IEEE Transactions on Evolutionary Computation, Vol. 6, pp. 58-73, (2002).

[14] B. Ccristian, D. Merkele, “Swarm Intelligence: Introduction and Applications”, Natural Computing Series, Springer-Verlag, Berlin Heidelberg, 2008.

[15] J. Kennedy, R. Eberhart, “Particle swarm optimisation”,Proc IEEE IntConf Neural Netw 4:1942–1948, 1995.

[16] A. Carlisle, G. Dozier, “An off-The-Shelf PSO”, Workshop particle swarm optimization, Indianapolis, 2001.

[17] A. L. Kouzou, H. Bentarzi, R. D. Mohammedi, M. Laoumer, “Optimal Placement of Phasor Measurement Unit in Power System using MetaHeuristic Algorithms”. Journal Electrotehnica, Electronica, Automatica, Vol.67, N°2, 2019.