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Research Article

Fractional Order PID Controller Design for Automatic Voltage Regulator

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Abstract In this study, the Fractional Order PID (FOPID) controller is used in the optimal design of the automatic voltage regulator (AVR). FOPID controller offers superior control features and flexible adjustment with the help of its five parameters. The adjustment process of the FOPID controller, which has two additional parameters (λ and μ) compared to the PID controller, is relatively more difficult than the PID controller. A wound healing algorithm developed to overcome this problem has been proposed. Integral Time Absolute Error (ITAE) was used as the fitness function in the optimum design of the parameters of the FOPID controller. The FOPID controller parameters obtained as a result of the developed wound healing algorithm were compared with other meta-heuristic algorithms. For this, a program was written in the Matlab Simulink environment. The results show that the proposed AVR design is more stable and durable than the other compared AVR designs.

Keywords Automatic voltage regulator (AVR), Fractional order PID (FOPID) controller, Wound healing algorithm, Optimal control system design

1. Introduction

PI and PID controllers have been used frequently in many industrial control systems in recent years due to their simplicity and reliability [1]. PID controller is one of the oldest control methods with its simple control structure and has a wide place in industrial control applications. There are many useful PID design techniques in the literature. The most frequently used ones are; Ziegler-Nichols adjustment method, Aström Hagglund method, Chien-Hrones-Resnick method and Cohen-Coon methods [2].

The reason why PID controller is frequently used in control systems is; simplicity of design processes and success in improving system performance. In recent years, modern control theories have introduced the idea of fractional order computing to improve PID controller performance in different industrial systems. In recent years, fractional computing has been used frequently in system modeling and control systems [3,4]. The characteristic of real-world systems can be modeled perfectly using fractional mathematical models. The fractional order PID (FOPID) controller is obtained by adding two parameters (λ and μ) to the conventional PID controller. This increases the number of parameters that need to be set from three to five. FOPID controllers provide better response and stability than integer PID controllers for fractional and integer systems in many applications [5]. In recent years, many studies have been carried out on fractional order systems and their applications. Fractional computing provides a complete mathematical model for many systematic operations and events associated with physics, biology, and control theory [6]. However, the FOPID controller ($PI^{\lambda}D^{\mu}$) has better control performance than the conventional PID controller; because 2 control parameters are added next to the integral and derivative terms. However, 2 parameters added according to the PID controller made the $PI^{\lambda}D^{\mu}$ controller more complex. Many methods have been proposed to overcome this complexity [7]. The Ziegler-Nichols method is one of these methods to set the parameters of the $PI^{\lambda}D^{\mu}$ controller [8]. In recent years, evolutionary optimization algorithms have been developed to tune fractional order controller (FOPID) parameters. Examples of these algorithms are genetic algorithm [9], particle swarm optimization algorithm [10] and hybrid optimization algorithms [11]. In addition to the PID controller, the FOPID controller, which provides more flexible design possibilities in many engineering fields, is also used in the AVR system to improve the generator voltage quality. Although the FOPID controller has more design flexibility due to its two additional parameters compared to the traditional PID controller, it is a more difficult controller to design as five independent parameters must be set. Ant colony algorithm [12], genetic algorithm [13], particle swarm algorithm [14], whale optimization algorithm [15], chaos optimization algorithm [16] and harmony search [17] algorithms are used to adjust these parameters in the AVR system.

By using the wound design of the automatic voltage regulator were tried to be optimized. The work consists of the following parts:

Fractional systems are discussed in chapter 2, the wound healing algorithm developed in chapter 3, obtaining optimum FOPID controller parameters for automatic tension regulator in chapter 4, and conclusion in chapter 5.

2. PID and Fractional Order PID (FOPID)

Fractional PID (FOPID) is an extended version of the PID controller. The structure of FOPID is shown in equation (1). K_p, K_I and K_D show proportional, integral and derivative gains, respectively. λ and μ are positive fractional gains. If $\lambda=1$ and $\mu=1$, classical PID controller is obtained. The representation of the classical PID controller is given in equation (2). The FOPID is shown as equation (1), with U being the controller output and E being the controller input.

$$C_{FOPID}(s) = \frac{U(s)}{E(s)} = K_p + \frac{K_I}{s^{\lambda}} + K_D s^{\mu}, \ (\lambda, \mu > 0) \tag{1}$$

$$C_{PID}(s) = \frac{U(s)}{E(s)} = K_p + \frac{K_I}{s} + K_D s \tag{2}$$

2.1. Fractional Order Calculation

Fractional computing is a branch of mathematics that includes derivative and integral terms and describes the real world better than systems with integer degrees [18]. Fractional computation can be thought of as a generalization of the integral and differentiation operator with non-integer orders. This situation can be seen in Equation 3. Equation 3, where k is the degree of operation $t0$ and t the lower and upper limits, is as follows:

$$t0D_t^k = \begin{cases} \dfrac{d^k}{dt^k} & k > 0 \\ 1 & k = 0 \\ \displaystyle\int_{t0}^{t} (dt)^{-k} & k < 0 \end{cases} \tag{3}$$

There are many definitions of fractional calculus. Generally, the Riemann-Lioville (RL), Caputo and Grunwald-Letkinov notations are used in fractional calculations. Riemann-Liouville's second-order fractional definition is given in Equation 4 [19]. If n is an integer defined as $n-1 < k < n$, it gives Euler's gamma function as shown in Equation (5).

$$^{RL}_{t0}D_t^k f(t) = \frac{1}{\Gamma(n-k)} \frac{d^n}{dt^n} \int_{t0}^{t} \frac{f(\tau)}{(t0-\tau)^{k-n+1}} d\tau \tag{4}$$

$$\Gamma(k) = \int_{0}^{\infty} e^{-u} u^{k-1} du, \quad k > 0 \tag{5}$$

Caputo's definition of fractional calculation is given in equation 6. The Laplace transform of Caputo and Riemann-Liouville's definitions are equivalent under initial conditions.

$$^{C}_{t0}D_t^k f(t) = \frac{1}{\Gamma(n-k)} \int_{t0}^{t} \frac{f^{(n)}(\tau)}{(t0-\tau)^{k-n+1}} d\tau \tag{6}$$

Grunwald-Letnikov's definition of fractional calculation is given in equation (7). It is the same as the Riemann-Liouville definition in Equation (4).

$$ {}^{GL}_{t0}D_t^k f(t) = \lim_{h \to 0} \frac{1}{h^k} \sum_{i=0}^{[(t-t0)/h]} (-1)^i \binom{k}{i} f(t-ih) $$

$$ \binom{k}{i} = \frac{\Gamma(k+1)}{\Gamma(i+1)\Gamma(k-i+1)} \quad (7) $$

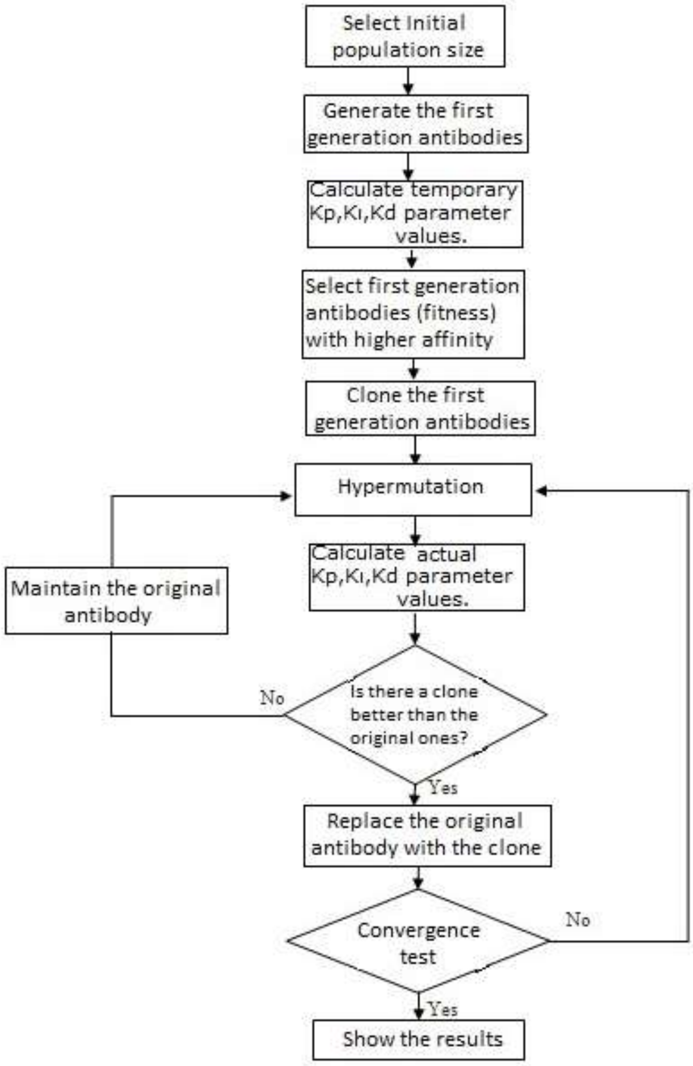

Figure 1: Wound healing algorithm flow chart

3. Developed Wound Healing Algorithm

The clonal selection algorithm is an algorithm that uses the immune system's response to foreign substances, and the number of clones produced is given in equation (8).

$$ N_c = \sum_{i=1}^{n} round\left(\frac{N}{i}\right) \quad (8) $$

N_c: Number of clones produced from each antigen
N: Total population number
n: Number of antibodies selected

The basis of the wound healing algorithm is the principle of clonal selection [20]. The number of clones produced is calculated by equation (8). Wound healing algorithm was developed with the help of α (cloning) and f (cloning acceleration factor) parameters added to Equation 10. The final state obtained is shown in equation (9). With the help of the new parameters added, more optimized results were tried to be obtained. The flow chart of the developed wound healing algorithm is shown in Figure 1. After the initial population Pn is produced, the selection process kicks in and selects the antibodies with the best immune response (affinity) value to obtain the new Pn population. The basic rule during the selection process; is the affinity value of antibodies. Then, individuals in the population are cloned and new populations are created. The number of clones to be obtained varies according to the affinity value. At this stage, a new population is created by applying the hypermutation process to the clones. In the hypermutation process, a low mutation with a high affinity value is inversely proportional to its affinity value, and a high mutation rate with a low affinity value. Thus, antibodies far from the optimum solution are subjected to further mutation processes. Then, among the obtained clones, the ones with low similarity ratio are replaced with new ones. As a result, the optimum result is obtained with the help of cloning and mutation processes.

$$N_c = \sum_{i=1}^{n} round\left(\frac{\alpha * N_s * f}{i}\right) \quad (9)$$

α : Cloning factor ($0 < \alpha < 1$)
f: Cloning acceleration factor ($0.9 < f < 0.99$)
N_s: 2. Adımda seçilen en iyi antikor sayısı

4. Optimal Fractional Order PID (FOPID) Controller Design
4.1 Automatic Voltage Regulator

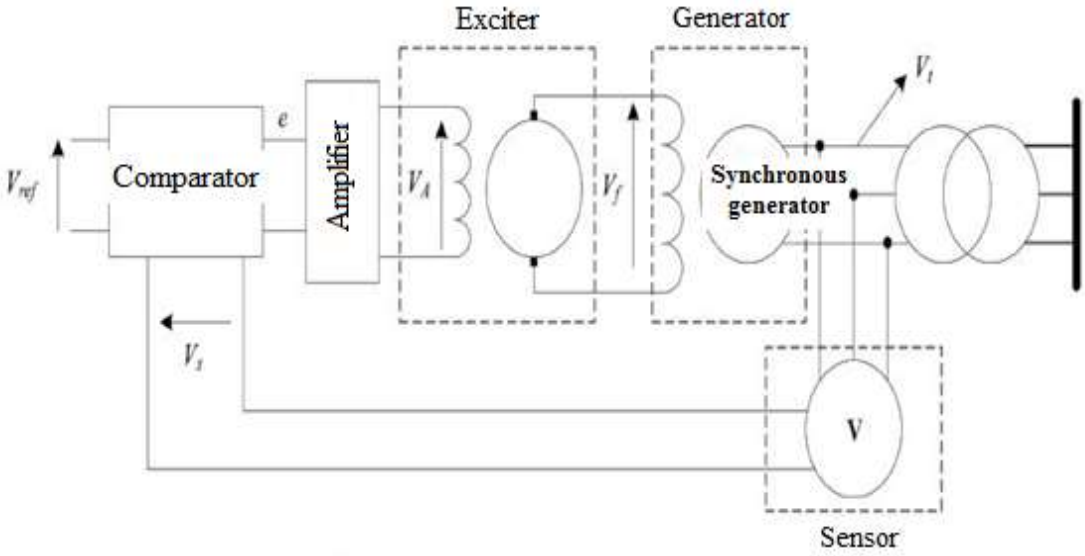

Figure 2: A simple AVR system with no controller

A simple controllerless OGR system consists of amplifier, exciter, generator and sensor as shown in Figure 2. The sensor is used to continuously measure the terminal voltage of the stator of the synchronous generator. In practice, this sensor is a voltage transformer, so three voltage transformers are used for all phases. Then the error signal is generated in the comparator, representing the difference between the desired voltage value (reference input) and the voltage measured by the sensor. Since the power of the error signal is very low, it must pass through an amplifier to increase its power. The amplified signal is used to control the exciter, which is usually realized as a controllable voltage source or a DC generator. That is, the V_A signal is applied as a control signal to the controllable voltage source or as a field voltage to the DC generator to define the appropriate field voltage V_f level. The field voltage indicating the output of an exciter is the voltage applied to the synchronous generator field winding located on the rotor and therefore defines the level of the terminal stator voltage of the synchronous generator. This system can vary in power range, complexity, response speed, etc. Researchers interested in the AVR system linearize each component. In other words, all the mentioned components are represented by a simplified first-order transfer function consisting of the corresponding time constant and gains.

The main task of the automatic voltage regulator is to keep the output voltage of the synchronous generator constant under all conditions. Different disturbances in the system can cause voltage changes that negatively affect the stability of the power system. Therefore, the excitation system of the synchronous generator equipped with AVR has the task of correcting the deviations in the terminal voltage. The block diagram of AVR is shown in Figure 3. According to Figure 3; The terminal voltage of the generator V_g *(s)* is continuously controlled with the help of the sensor and compared with the desired reference voltage Vref (s). The difference between V_{ref} *(s)* and

V_g *(s)* is called the error voltage V_e *(s)*. $V_e(s)$ voltage is increased with the help of amplifier and the generator is stimulated with the help of exciter.

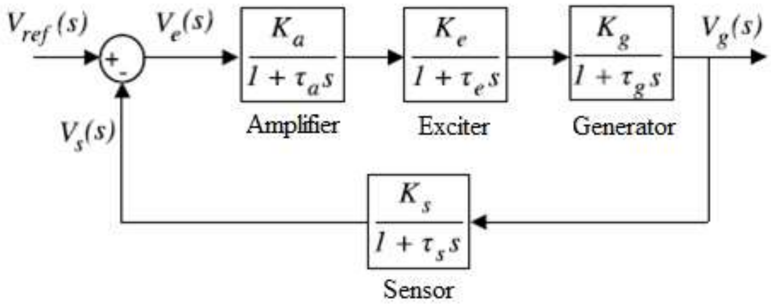

Figure 3: Block diagram of an AVR without using a controller

Table 1: Transfer functions of AVR system components

AVR components	Transfer Function	K gain value ranges	Time constant value ranges (τ)
Amplifier $G_a(s)$	$\frac{K_a}{\tau_a s+1}$	10 - 40	0.02 – 0,1
Exciter $G_e(s)$	$\frac{K_e}{1+\tau_e s}$	1 - 10	0.4 – 1
Generator $G_g(s)$	$\frac{K_g}{1+\tau_g s}$	0,7 - 1	1.0 – 2
Sensor $G_s(s)$	$\frac{K_s}{1+\tau_s s}$	0,9 – 1,1	0,001 – 0,06

In this study, K_a=10, τ_a=0.1, K_e=1, τ_e=0.4, K_g=, τ_g=1, K_s=1, τ_s= 0.01 among the values specified in Table 1 in the automatic voltage regulator system values were used [21, 22]. Using these values, the closed-loop transfer function of the AVR system is calculated as in equation 10.

$$G_{OGR}=\frac{V_g(s)}{V_{ref}(s)}=\frac{0{,}1s+10}{0.0004s^4+0{,}045s^3+0{,}555s^2+1{,}51s+11} \quad (10)$$

The step response of the AVR system in Equation 14 without using a controller is given in Figure 4. The G_{AVR} transfer function has zero at z= -100, 2 real poles at s_1= 99.96 and s_2= -12.5, and 2 complex poles at $s_{3,4}$ = -0.53 ± 4.66i.

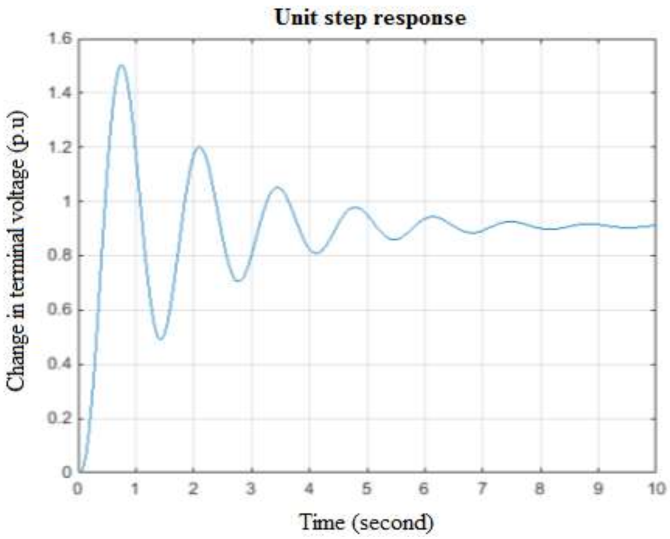

Figure 4: Step response of OGR system without using controller

When Figure 4 is analyzed, the maximum overshoot was calculated as 52.4%, settling time 6.97 seconds, rise time 0.261 seconds, steady state error 0.0099 in the uncontrolled AVR system, and the system has high overshoot time and oscillations.

4.2. Fractional Order PID (FOPID) Controller

Figure 5 shows the block diagram of the AVR using a fractional order controller (FOPID). The developed wound healing algorithm is used to optimize the parameters of the FOPID controller.

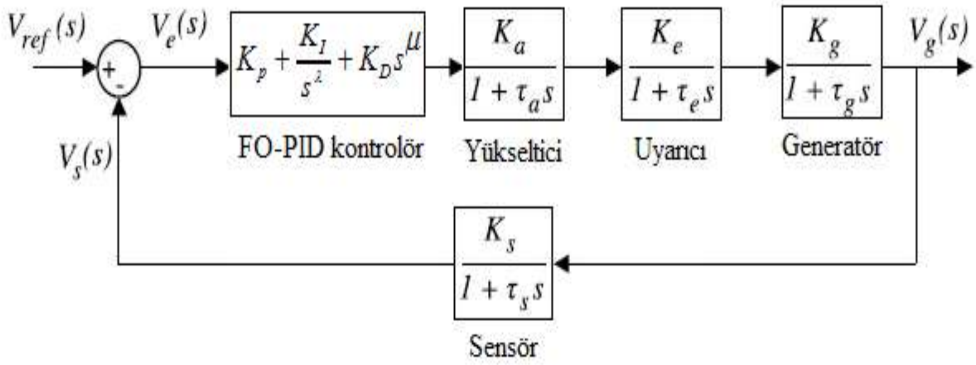

Figure 5: Block diagram of OGR with FOPID controller

4.3. Simulation Results and Discussions

The applications and analyzes of the fractional order controller (FOPID) proposed for the AVR system were carried out on a computer with a Core i5 processor, 2,8 GHz CPU and 16 GB RAM, in the Matlab/Simulink simulation environment and with a sampling period of 1 *ms*. The analyzes made in this study:

• Time domain analysis (step response)

• Frequency domain analysis (bode diagram).

4.3.1. Time domain analysis (Step response)

The fractional parameter values obtained as a result of the wound healing algorithm were calculated with the help of the developed program. Since the developed algorithm is a stochastic algorithm, it assigns the initial population values randomly. Therefore, in order to obtain the optimum result, the program was run 30 times and the optimum result values for the AVR system were selected from the obtained values at K_p=0,7745, K_I=0,5268, K_D=0,2219, λ=1,0529, μ=1,0921. With the help of the calculated FOPID parameter values, the simulation model of the AVR system in the Matlab Simulink environment is given in Figure 6.

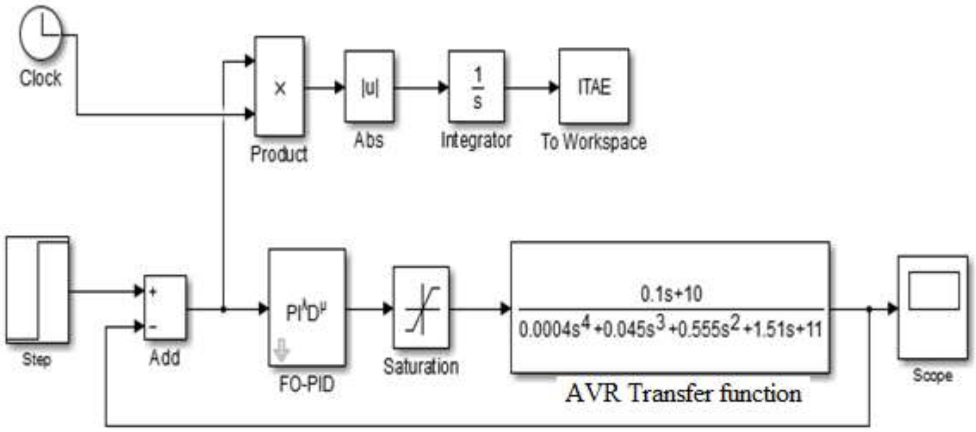

Figure 6: Matlab simulink model of OGR system (ITAE)

As seen in Figure 6, ITAE was used as the fitness function. The FOPID controller parameters obtained as a result of the wound healing algorithm were placed in the simulink model in Figure 6 and the step response of the system was obtained as in Figure 7.

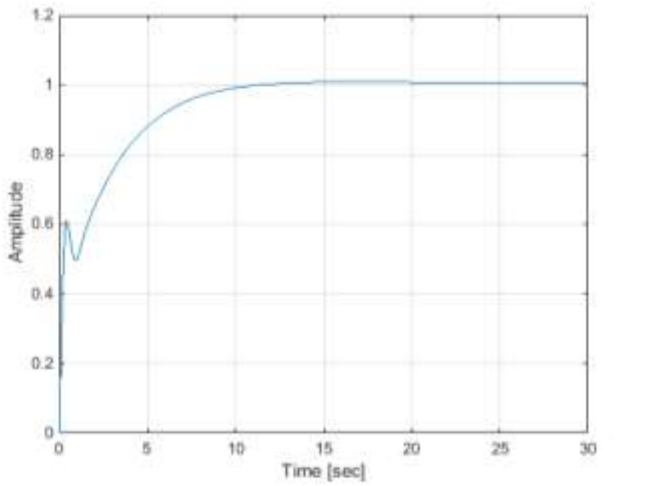

Figure 7: Step response of the designed FOPID controller

4.3.2. Frequency domain analysis (Bode Diyagram)

The Bode diagram of the designed FOPID controller is shown in Figure 8 and the Nyquist graph is shown in Figure 9.

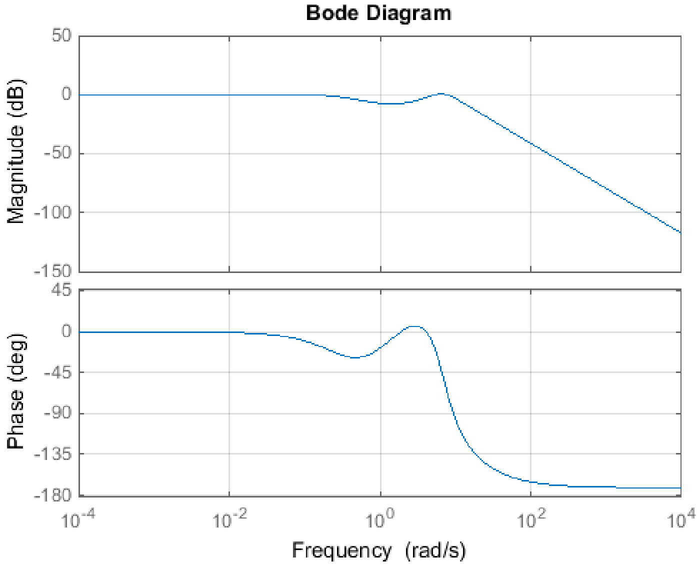

Figure 8: Bode diagram of the designed FOPID controller

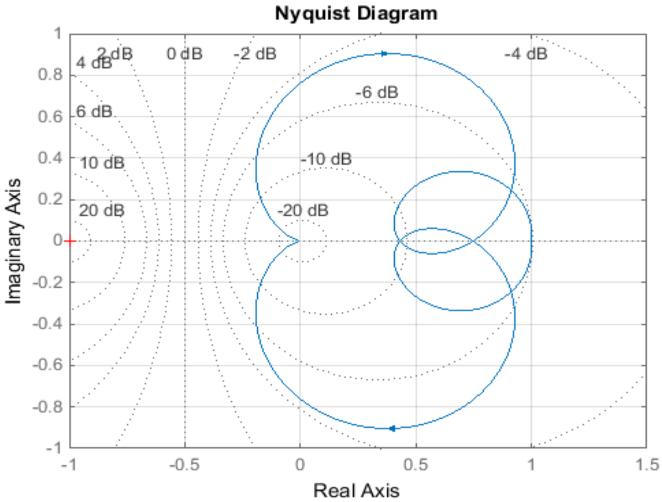

Figure 9: Nyquist diagram of the designed FOPID controller

5. Conclusions

In this study, a fractional order PID (FOPID) controller is proposed to improve the performance of a frequently used AVR system. During the design phase of the FOPID controller, the developed wound healing algorithm was used to optimally adjust the controller parameters (K_p, K_I, K_D, λ and μ). Time domain and frequency domain analysis of the designed controller were made and the results were compared with other meta-heuristic algorithms to show the efficiency and robustness of the proposed FOPID controller. Furthermore, the analyzed analyzes revealed that the proposed wound healing algorithm-based fractional order AVR controller provides the optimal design that is largely unaffected by a change in system parameters and thus is resistant to system parameter changes. Thanks to the excellent results of the present study, the proposed method can be extended to a range of power system applications such as power system stabilization, automatic generation control and speed regulation of various electric motors, together with the latest AI-based soft computing techniques.

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