ELECTROMAGNETIC DISTURBANCE-RESISTANT CONTROLLER BASED ON THE MODIFIED INTEGRAL CONTROL ALGORITHM

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Abstract
The paper presents a feedback controller based on the modified integral control algorithm, which allows achieving higher resistance to electromagnetic disturbances compared to cases when proportional-integral-derivative, proportional-integral and classical integral control algorithms are used. Also the proposed controller guaranties shorter response time of the control system as compared to the classical integral controller. Distinctive feature of the developed controller is that the integral constant changes discretely the value at a certain threshold value of the control error. The control system with the modified integral control algorithm based controller is investigated using the Matlab/Simulink simulation program.
Key words: Feedback control system, electromagnetic disturbances, integral control algorithm, variable integral constant.

Introduction

Actual automatic feedback control systems used in industry are often exposed by the electromagnetic disturbances (Narasimman, 2016: 1167–1176; Ning, 2021: 1686–1693). These disturbances are radiated by various electrical devices used in technological processes, such as electric motors, switches, relays, etc. Noise signals generated by electromagnetic disturbances are usually induced in the feedback signal line of the control system connecting the sensor that measures the controlled parameter with the controller input. The noise signal, when entering the controller input, can cause fluctuations in the parameters of the controlled plant or even cause the instability of control system operation. The vast majority of feedback controllers used in industry are PID (proportional-integral-derivative) controllers, based on the combination of proportional integral and derivative control algorithms (Yuliawan, 2021: 96–102; Zhang, 2022: 105–109). The derivative term of the controller is the most sensitive to noise signals, therefore it is often disconnected in actual applications (Bielskis, 2020: 1–18). The integral term of the controller is the least sensitive to noise signal, because of this a controller with only an integral term is the most resistant to noise signals. However, a control system implemented using a controller with only an integral term is slow, i.e. it responds slowly to changes in operating conditions. Therefore, the response time of the control system, which is the main dynamic parameter, is much longer in a control system based on integral controller as compared to the case when PID or PI (proportional-integral) controllers are used.

This paper presents a feedback controller based on the modified integral control algorithm, which allows achieving faster control system response compared to the classical integral algorithm. Also, the control system with the modified integral controller is characterized by higher resistance to noise signals caused by electromagnetic disturbances compared to cases when PID, PI and I (integral) controllers are used.

The control system with the proposed modified integral controller is investigated using the Matlab/Simulink simulation program. The first section of the paper describes the proposed control algorithm and presents the structure of the analysed control system. The second section presents the simulation results of the control system based on the proposed controller, comparing them with cases when PID, PI and I controllers are used. At the end of the article, based on the obtained research results, the conclusions of the work are presented.

Modified integral control algorithm

Distinctive feature of the proposed modified I controller as compared to classical I controller is that the proposed controller is implemented using the modified integral control algorithm, in which the integral constant in fact is variable because it changes discretely its value at a certain threshold value of the control error. The proposed I controller with the discrete variable constant (vI controller) guaranties shorter response time of the control system than when using the classical I controller.

The algorithm of the vI controller is described by the following equation:

$$U(t) = K_{\mathrm{I}} \int_{t_0}^{t} e(t)\,\mathrm{d}t, \qquad (1)$$

$$K_{\mathrm{I}} = K_{\mathrm{I1}}, \quad |e(t)| > e_{\mathrm{tr}},$$

$$K_{\mathrm{I}} = K_{\mathrm{I2}}, \quad |e(t)| \le e_{\mathrm{tr}},$$

where $U(t)$ is the output signal of the controller, using which the process or plant is controlled, $e(t)$ is the control error, which is calculated as the difference between the desired value of the controlled parameter of the plant $Y_d(t)$ and the actual value of the controlled parameter $Y_a(t)$, K_{I1} and K_{I2} are discrete values of the controller integral constant K_I, e_{tr} is control error threshold value, at which the integral constant value is switched, t is time and t_0 is initial time moment, at which the controller starts to operate. The discrete values of integral constant have to be chosen so that they satisfy the condition $K_{I1} >> K_{I2}$.

It is seen that in the proposed vI control algorithm (1) the value of integral constant is switched from K_{I1} to K_{I2} and vice versa at a certain threshold value of the control error e_{tr}. If the values of the integral constant are chosen so that they satisfy the condition $K_{I1} >> K_{I2}$, the vI controller guaranties shorter response time of the control system than when using the classical I control method. This is because in the vI controller the value of K_{I1} can be significantly higher than the K_I of the classical I controller.

The block diagram of the analysed feedback control system is given in Fig. 1. It consists of controller and controlled plant. $Y_d(t)$ is desired (set point) value and $Y_a(t)$ is actual value of the controlled parameter. $D(t)$ is the load disturbance and $N(t)$ is noise signal induced by the electromagnetic disturbances, which adds up with the feedback signal.

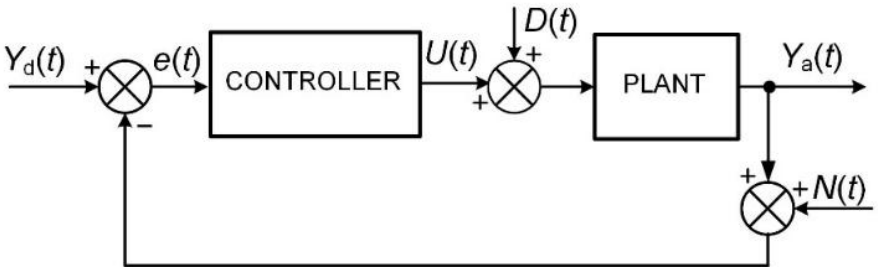

Fig. 1. Block diagram of the feedback control system *[Created by authors]*

Investigation results

The control system (Fig. 1) based on the proposed vI controller that implements algorithm (1) has been investigated using Matlab/Simulink software. The investigation was performed for the plant, dynamics of which is described by the second order transfer function with the delay $G_p(s) = e^{-Ts}/(\tau s+1)^2$, where T is plant response delay, τ is time constant. The investigation was performed for the plant with T =2 and τ =1. Additionally the control system was investigated for the cases when PID, PI and I controllers are used. The parameters of controllers are presented in Table 1.

Table 1

Parameters of controllers

PID	PI	I	vI
K_P=0.71 K_I=0.276 K_D=0.50	K_P=0.44 K_I=0.222	K_I=0.127	K_{I1}=0.235 K_{I2}=0.07 e_{tr}=0.90

Firstly, the control system set point $Y_d(t)$ unit step and load disturbance $D(t)$ positive and negative unit steps responses were simulated to evaluate the settling time of the control system. The obtained transients are presented in Fig. 2. The set point and load disturbance step responses settling times t_{SPS} and t_{LDS} of the control system for analysed controllers for ± 5% tolerance band of $Y_a(t)$ are given in Table 2. Since the t_{LDS} for positive and negative step load disturbance practically coincide (Fig. 2), there in Table 2, the t_{LDS} is presented just for negative step.

The obtained results (Table 2) show that proposed vI controller allows to speed up the control system response as compared to the case when classical I controller is used. On the other hand, the application of PI and PID controllers guaranties shorter response settling time as the vI controller provides. However, PI and especially PID controller are much more noise sensitive in comparison to integral control method-based controllers.

Table 2

Set point and load disturbance unit steps response settling time of control system

Controller	PID	PI	vI	I
t_{SPS}, sec	8.3	9.9	12.7	16.7
t_{LDS}, *sec*	11.5	11.6	18.6	25.0

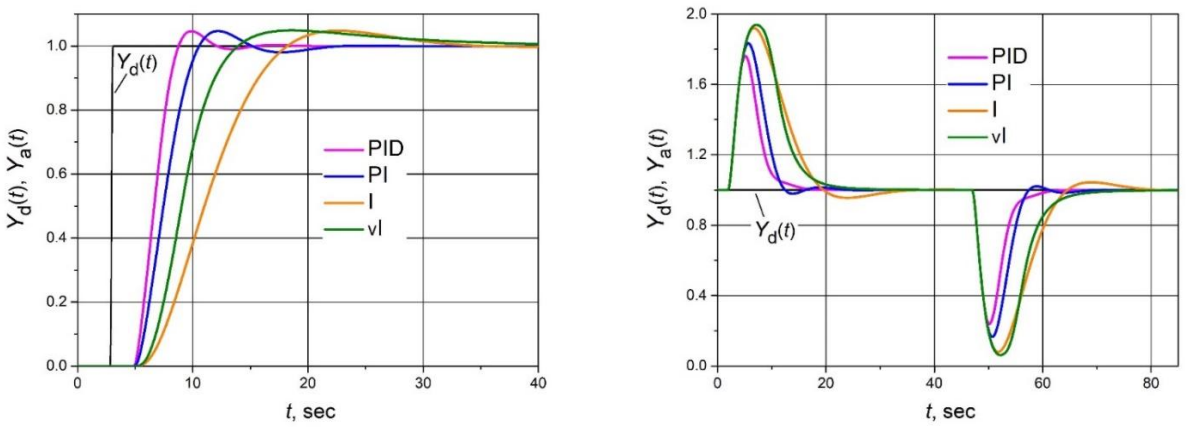

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Fig. 2. The set point unit step response (a) and load disturbance positive and negative unit steps responses (b) of the control system based on PID, PI, I and vI controllers *[Created by authors]*

The behaviour of control system based on the vI, I, PI and PID controllers in the situation when system is affected by noise signal $N(t)$ that ads up with the feedback signal of controller was investigated. The analysis was provided when $N(t)$ is band-limited white noise with sampling time t=1 sec, seed [23231]. The obtained set point step responses are given in Fig. 3. It is seen that the lowest fluctuations of the controlled parameter caused by the noise signal has the control system based on the proposed vI controller, i.e. the application of vI controller guaranties highest control system resistance to noise signal in comparison to the I, PI and PID controllers.

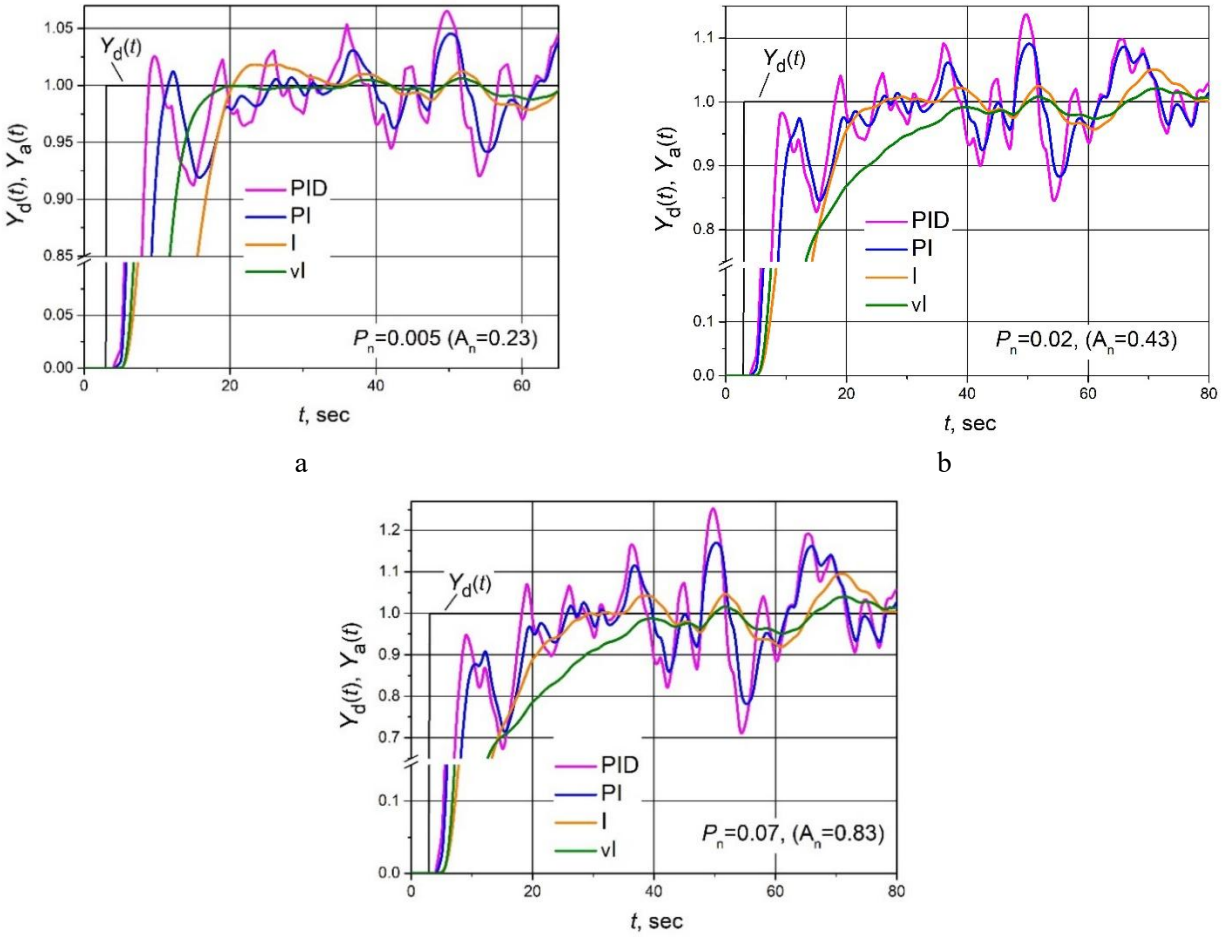

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Fig. 3. The set point unit step response of the control system based on PID, PI, I and vI controllers when controller is affected by the band-limited white noise with sampling time t=1 sec and seed [23231] at various noise power P_n (amplitude A_n) *[Created by authors]*

The maximal amplitudes of fluctuations caused by the noise signal for all analysed controllers are presented in Table 3. It is seen that the amplitudes of the $Y_a(t)$ fluctuations using vI controller is approximately 2 times lower as compared to the case when I controller is used and 6–9 times lower in comparison when PI and PID controllers are employed.

Table 3

Maximal amplitudes of $Y_a(t)$ fluctuations caused by the noise signal

Controller type \ Noise power (Noise amplitude)	0.005 (0.23)	0.02 (0.43)	0.07 (0.83)
vI	0.01	0.02	0.05
I	0.02	0.05	0.10
PI	0.08	0.15	0.29
PID	0.09	0.17	0.32

Important parameter of control system is robustness, which demonstrates the ability to operate stably when dynamic parameters of the controlled plant change. The analysed control system based on the proposed vI controller was investigated when response delay time T and time constant τ of the plant change by values ΔT and $\Delta\tau$ and controller parameters remain not changed and are adjusted for the case when ΔT, $\Delta\tau$=0. The results of investigation are presented in Fig. 4. They show that control system operates stably even when ΔT and $\Delta\tau$ increase by 100%, just the response transient settling time increases.

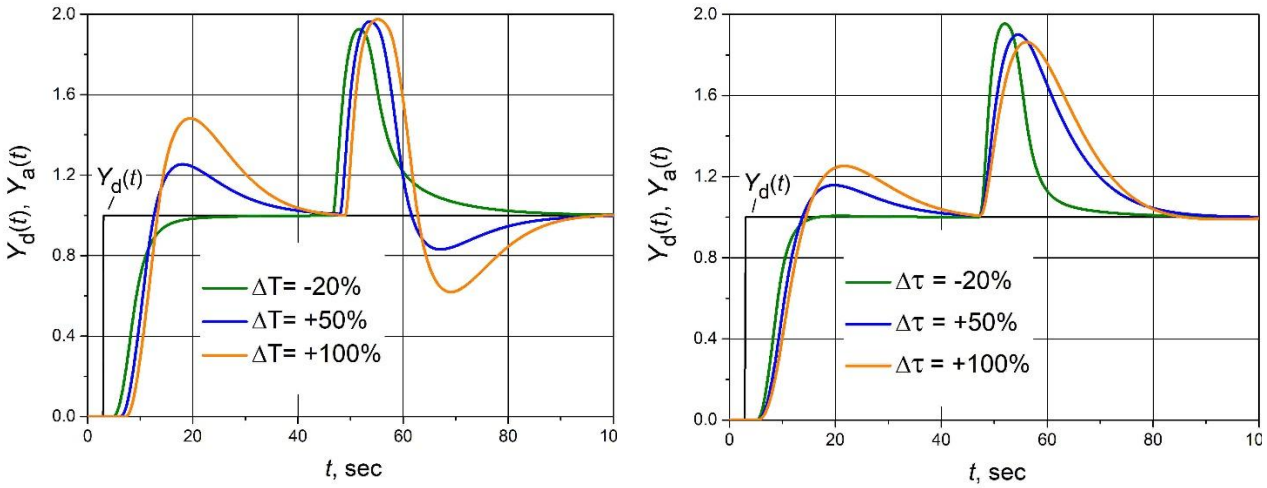

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Fig. 4. The set point and load disturbance unit step responses of the control system based on the vI controller when the value of plant response delay changes by ΔT and the value of the time constant – by $\Delta\tau$ *[Created by authors]*

Conclusions

1. The application of the proposed vI controller with the discrete variable integral constant allows to speed up the control system response as compared to the case when classical I controller is used. The unit step set point and load disturbance response settling times of the control system with the second order plant with the delay using the vI controller was 12.7 and 18.6 seconds, accordingly. Meanwhile, the same settling times using the classical I controller were 16.7 and 25 seconds, respectively.

2. In the case when band-limited white noise with sampling time t=1 sec, seed [23231] affects the control system and adds up with the feedback signal the application of vI controller guaranties highest control system resistance to noise signal in comparison to the I, PI and PID controllers. The maximal amplitudes of the $Y_a(t)$ fluctuations caused by the noise signal using vI controller are approximately 2 times lower as compared to the case when I controller is used and 6–9 times lower in comparison when PI and PID controllers are employed.

3. The investigation of control system robustness when dynamic parameters of the controlled plant change show that control system operates stably even when the plant response delay and time constant increase by 100%. Just the response transient settling time increases in such a case.

4. The disadvantage of the proposed vI controller is that the control system based on this controller has a longer response settling time as compared with the case when PI and PID controllers are used. However, a control system based on the PI and especially PID controller is much more noise sensitive as compared to control system based on the vI controller.

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ELEKTROMAGNETINIAMS TRIKDŽIAMAS ATSPARUS VALDIKLIS PAGRĮSTAS MODIFIKUOTU INTEGRINIU VALDYMO ALGORITMU

SANTRAUKA

Straipsnyje pateikiamas modifikuotu integriniu valdymo algoritmu pagrįstas grįžtamojo ryšio valdiklis, leidžiantis pasiekti didesnio valdymo sistemos atsparumo elektromagnetinių trikdžių sukeliamiems triukšmo signalams, lyginant su atvejais, kai naudojami proporcinis-integrinis-diferencinis, proporcinis-integrinis ir klasikinis integrinis valdikliai. Taip pat siūlomas valdiklis garantuoja trumpesnį valdymo sistemos atsako laiką, lyginant su klasikiniu integraliniu valdikliu. Skiriamasis siūlomo valdiklio bruožas yra tas, kad jame integrinė konstanta diskretiškai keičia savo vertę, esant tam tikrai valdymo paklaidos vertei. Valdymo sistema su pasiūlytu modifikuotu integriniu valdikliu ištirta naudojant Matlab/Simulink modeliavimo programą.

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