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Published in:
2023 25th European Conference on Power Electronics and Applications, EPE 2023 ECCE Europe

DOI (link to publication from Publisher):
10.23919/EPE23ECCEEurope58414.2023.10264455

Publication date:
2023

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Abubakr, H., Lashab, A., Golestan, S., M. Abusorrah, A., J. H. Rawa, M., Yaqoob, M., Vasquez, J. C., & Guerrero, J. M. (2023). Adaptive Control as a Hierarchical System. In *2023 25th European Conference on Power Electronics and Applications, EPE 2023 ECCE Europe* (pp. 1-9). Article 0264455 IEEE. https://doi.org/10.23919/EPE23ECCEEurope58414.2023.10264455

Adaptive Control as a Hierarchical System

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Acknowledgments

Hussein Abubakr is funded by the Ministry of Higher Education of the Arab Republic of Egypt. This work is also supported by VILLUM FONDEN under the VILLUM Grant (no. 25920): Center for Research on Microgrids (CROM).

Keywords

«Adaptive control system», «Hierarchical control system», «Conventional feedback control system», «Automatic voltage regulator», «Stability analysis ».

Abstract

An adaptive control system is a system that can cope with variations in a plant where it plays a major role in smart controllers needed for sophisticated systems. In this study, the adaptive control system is represented as a hierarchical control structure consisting of primary, secondary, and supervisory levels to monitor the system performance and adjust controller parameters for system regulation and stability. To validate the adaptive control concept, a basic automatic voltage regulator model is employed as an example. System performance is assessed against the conventional feedback control system under different step perturbations. The results demonstrate the effectiveness of the proposed adaptation mechanism, acting as a secondary control loop, in achieving superior performance and stability compared to the conventional one.

Introduction

According to Webster's dictionary, adaptation refers to changing one's behavior to conform to new or altered circumstances. The term adaptive control has been utilized since the early 1950s [1]. An adaptive regulator can intuitively change its behavior against variations in process dynamics and perturbations. Since regular feedback serves the same objective, the query of the distinction between adaptive and feedback control increments promptly. A precise definition of adaptive control that enables monitoring and determination of its adaptiveness is still lacking [1, 2].

Early surveys on adaptive control were conducted by researchers from the 1950s to the 1980s [3-6]. In the 1960s, crucial contributions to control theory were discussed that were necessary for the expansion of adaptive control, where theories of stability and state-space were presented. Notably, substantial findings were also made in stochastic control theory. Bellman introduced dynamic programming [3], while Feldbaum contributed to the understanding of adaptive processes through dual control theory [4]. Moreover, Tsipkin demonstrated the mutual framework of various adaptive learning schemes using stochastic approximation equations [5]. Furthermore, Åström and Eykhoff made significant progress in parameter estimation and system identification [6].

A brief review of several approaches based on adaptive control has been presented, including theoretical and machine learning-based approaches in [7]. Furthermore, three main schemes were discussed before in detail such as self-tuning regulators, model reference control, and gain scheduling. The principles underlying those adaptation schemes that now finding their path into products and applications were described early on [1]. The adaptation framework has been developed starting from [8] until now using self-optimizing controls. This type of adaptation way has recently been modernized and applied based on heuristics and metaheuristics optimizers in a direct adaptive control manner for many power system applications [9-12].

Over time, many challenges and failures of adaptive control emerged. It consists of three groups: The first incorporates challenges encountered in developing the subject including obstacles commitment to the bursting, MIT rule, Rohr’s counterexample, and unplanned instability in iterative identification and control. The second one is general issues; This constitutes a list of difficulties in almost all the adaptive control issues that algorithms need to overcome including impractical control targets, handling an abruptly unsteady closed-loop, transient instability, and problems with changing experimental conditions. For example, if a plant is unknown, and a control target is set, the target may be unachievable in practice, and any adaptive control algorithm needs to handle this possibility. The third group includes some problems of great interest to researchers at present, including model-free design and multi-model adaptive control, which are further elaborated in [13, 14].

The history of the HCS starts from [15] then J. Albus [16] who introduced the theory and practice of the hierarchical control concept, through T. Moor and J. Davoren, who developed a hierarchical control synthesis framework in collaboration with the Max Planck Institute that was sufficient to cover both continuous and discrete levels. Josep Guerrero [17] applied the concept of HCS to AC and DC microgrid systems. Further knowledge about the concept and theory of the HCS is provided in the following section.

In this work, a new conceptual idea of the adaptive control system as a hierarchical control system (HCS) is presented. The utilization of hierarchical structure has gained significant appeal in various control system applications. The primary objective is to measure the system performance after adding an adaptation loop at the secondary level alongside the primary one, comparing it to the conventional feedback control system in terms of maximum overshoot/undershoot, settling time, and steady-state error. Thus, the key features and importance of this study lie in introducing the application of a hierarchical control structure in the context of adaptive control systems, highlighting the benefits and effectiveness of this incorporation, performance comparison with conventional feedback systems, and focus on adaptation to changing disturbances. These aspects contribute to advancing the understanding and practical implementation of adaptive control systems.

Hierarchical Control System: Theory and Concept

The HCS can be explicated as an endeavor to address complex problems by breaking them down into smaller sub-problems and gathering their solutions into a hierarchical shape. The HCS is a form of a control system in which a set of tasks is arranged at each level with possibly different periods of planning and execution time in a hierarchical tree. The general control system structure of an HCS is depicted in Fig. 1.

The HCS is subdivided into several levels, as follows:

- Level 0 is the lowest layer of the HCS called the inner control loop or the instrumentation layer. It contains field devices (i.e., transmitters and sensors) and control elements (actuators) such as

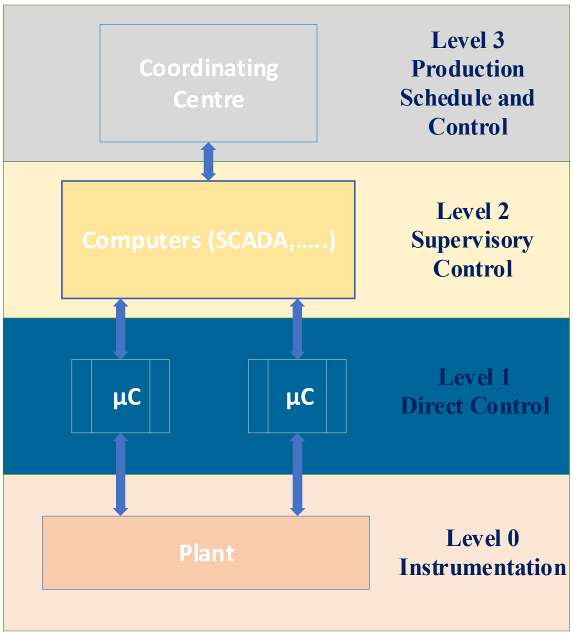


Fig. 1: Basic control process levels.

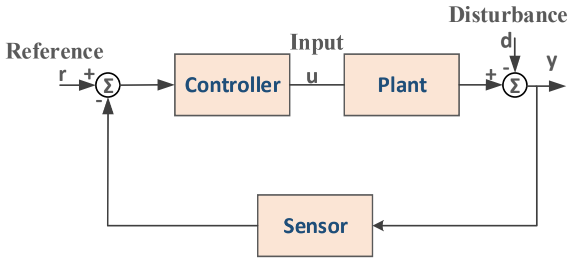


Fig. 2: Conventional feedback control loop.

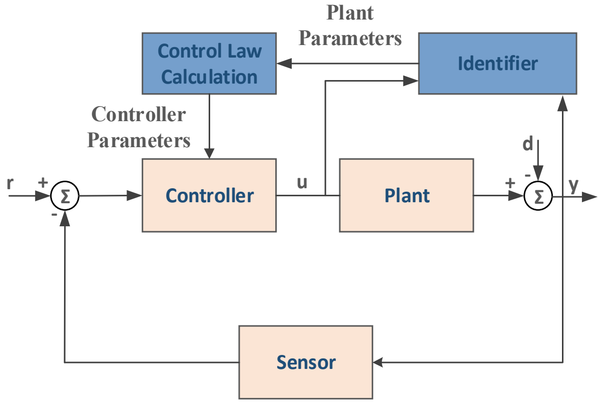


Fig. 3: High-level architecture of adaptive control [14].

pumps and control valves. The purpose of this layer is to provide information to the upper control layer about the final status of the plant (direct control).

- Level 1 contains the industrialized Input/Output (I/O) modules.
- Level 2 includes the supervision computers that collect data from the direct control level and provide the operator control screens.
- Level 3 is the production schedule and the level of control, which is responsible for monitoring the production and targets. This level might be also divided into stages (level 3 for controlling the production and level 4 for scheduling it).

These levels depend on the applications and may start from levels 0-5 as discussed in [18], which include an inner loop, unit /cell, area/line, building/production, campus/plant, and enterprise levels. On the other hand, they can be primary, secondary, tertiary, and supervisory levels as suggested by Josep Guerrero in [16] for micro/mini-grid applications.

Adaptation Control Scheme

To understand the conceptual idea of adaptive control, the distinction between adaptive control and conventional feedback control system must be clarified first. Let's start with the main reason for applying it to keep the performance of the control system at a high level. Nevertheless, in practice anonymous and boundless variations of process parameters negatively affect the overall performance of the proposed control system. One of the key reasons for variations is disturbances as shown in Fig. 2, which describes the closed-loop control system. The controller is determined using knowledge of the plant along with a list of specifications for the closed-loop performance: the specifications may compose the requirement to reduce a particular performance index.

In conventional control systems, feedback (in practice sensors) is used mainly to decline the effect of disturbances on the controlled variables and to return them to the desired values considering a given performance index. To fulfill this, the controlled variables are first measured, then the measurements are compared to the desired (reference) ones and the difference is added to the controller which will create a suitable control signal for the plant.

The first thing that differs in the context of adaptive control is that the plant is initially unknown, only partially known, or may change slowly. Since in many cases, the conventional controller is not able to deliver a satisfactory result for any potential plant, it is necessary to incorporate some learning capability in the controller [14].

In this regard, a high-level architecture for the adaptive control is shown in Fig. 3. A typical non-adaptive controller plots the error signal $(r-y)$ in Fig. 2. into the plant input u in a causal time-invariant manner [14]:

$$\left.\begin{aligned}\dot{x}_c &= A_c x_c + b_c(r-y)\\ u &= c_c + x_c\end{aligned}\right\} \qquad (1).$$

where A_c, b_c, c_c mean constant matrices, and x_c is the controller state vector which is adjusted adaptively.

The function of the identifier is to determine what the plant is or to estimate the plant. The control law calculator does online what a designer can do before presenting the controller with a traditional control issue where the plant is known.

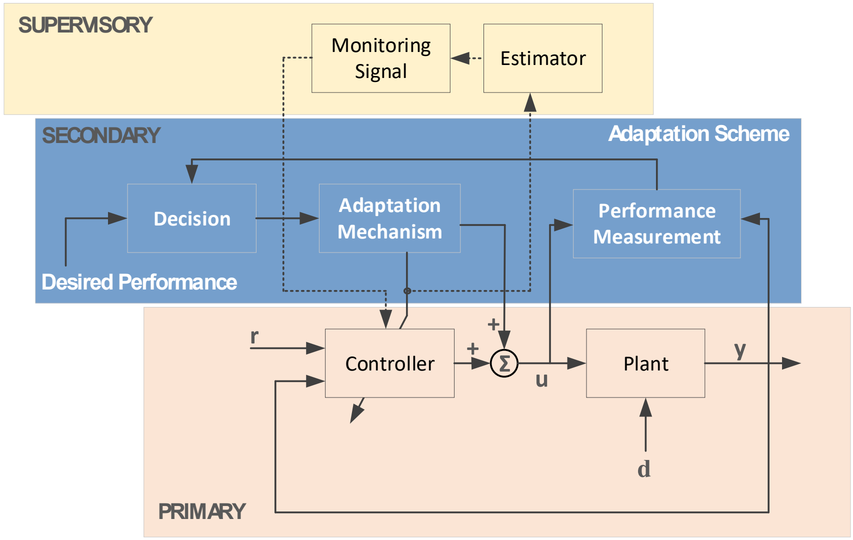


Fig. 4: Proposed hierarchical system-based adaptive controller.

System Limitations

HCSs offer advantages in managing complex control problems, but they also have certain limitations, which include:

- As the complexity of a control system increases, it becomes more challenging to manage the interactions and coordination among different levels.
- Effective communication between different levels is essential for HCSs. Delays or failures in communication can degrade system performance or even lead to instability.
- HCSs can include robustness limitations due to failure in adjusting the control parameters at specific levels. Therefore, robustness-based adaptation mechanisms can enhance the system's robustness by dynamically adapting the control strategy to maintain performance and stability in the presence of uncertainties.
- HCs may face scalability issues when the number of levels and interactions grows significantly.

Moreover, there are limitations associated with robustness-based adaptive control including adaptation rate, modeling uncertainties, control saturation, convergence, and stability. This study introduces the concept of adaptive control's ability to redesign as an HCS. However, in practical systems, these limitations must be considered when designing and implementing adaptive control strategies.

Relation between Adaptive Control System and Hierarchical Control System

To determine the desired performance, the damping factor is assumed to be the performance index to be measured for the closed-loop plant shown in Fig. 1. This state of measurement will be compared to the input (reference) as the desired index. The resulting values will be fed into the adaptation mechanism if the difference is not acceptable. In the latter case, the adaptation mechanism will attempt to tune the controller gain parameters to modify the overall system performance by generating an auxiliary control to keep the damping index within the set of given ones. The basic configuration of the adaptive control system is shown in Fig. 4. In addition, [19] provides a general definition of the adaptive control system, which involves measuring a specific performance index using known inputs, outputs, states, and disturbances.

It is clear from Fig. 4, that there are three control loops defined as primary, secondary, and supervisory levels:

The primary level is a conventional feedback control that monitors the controlled variables that are affected by disturbances. At this level of control, the performance of the control system is varied, which means that it is not monitored.

The secondary level is the adaptation loop which contains a supplementary loop next to the conventional one (primary loop) for adjusting the controller parameters. In addition, it will monitor the system performance in case of parameter perturbations.

Finally, the supervisory level is practically presented as a monitoring level by computerized systems such as (SCADA…. etc.). It aims to create an online strategy for stating whether or not the determinations are satisfied and fulfilled for a valid process according to the adaptation loop to attain the best performance given the current state and system inputs. It is composed of two essential blocks: (i) the multi-estimator; and (ii) the monitoring signal generator; The estimator is a dynamical system that monitors the tuned output signal and generates a set of estimator errors. Then, the monitoring signal generator processes the estimation errors to create appropriate signals of supervision that will be utilized for decision-making to help the measured signal match the desired one.

Adaptation Mechanism and Stability Validation

In this study, a soft optimizer named Harris Hawks is proposed with the adaptation mechanism for adjusting the controller parameters. The basic principle of the optimizer is inspired by the hunting behavior of the hawks in some steps such as tracing, encircling, closeness, and finally attacking, as detailed in [20]. This method offers several benefits, including simplicity of coding, less computational time, and ease to use. Moreover. It can be used to solve discrete, constrained, and unconstrained optimization problems. Thus, the performance of this method is remarkable, powerful, and unaffected by issues related to the wide dimensions. The effectiveness of the optimizer is demonstrated in [21].

For robustness and stability validation of the proposed scheme:

The system with the proposed control scheme can be visually represented by a block diagram, as depicted in Fig. 5. The adaptive mechanism attempts to make the plant output (y_p) match the nominal transfer function (y_m). The adaptation loop is responsible for tunning the regulator parameters in such a way as to minimize the error between e_o to zero [22]. Where,

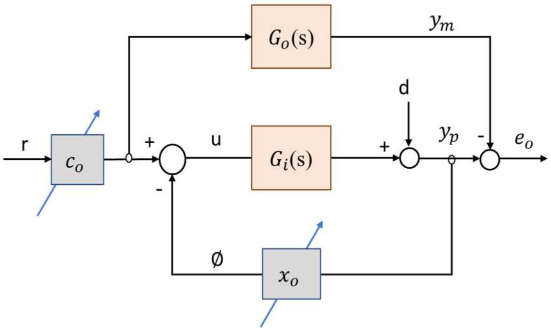


Fig. 5: Proposed hierarchical system-based adaptive controller.

$$\left.\begin{aligned} u &= c_o r + x_o y_p \\ e_o &= y_p - y_m \end{aligned}\right\} \quad (2).$$

where c_o and x_o are the nominal values of the controller parameters. Let the vector Ø contain the adjustable controller parameters. The idea is to reduce the $e_o$by adjusting Ø:

$$\frac{d\emptyset}{dt} = -a\frac{\partial}{\partial(\emptyset)}\left(e_o^2(\emptyset)\right) = -2ae_o(\emptyset)\frac{\partial}{\partial(\emptyset)}\left(y_p(\emptyset)\right) \quad (3).$$

where (a) is the adaptation gain.

Considering the nominal plant transfer function $G_o(s)$ as the base of the proposed adaptive controller, the system output will be defined as:

$$y^* = G_o(s).u \quad (4).$$

Now, the actual output is modeled as the output of the nominal plant combined with an additive uncertainty component represented by the abounded operator H_a, as follows:

$$y(t) = y^* + H_a.u(t) \quad (5).$$

where H_a represents the difference between the automated voltage regulation (AVR) real plant and the adaptation one.

$$H_a = G_i(s) - G_o(s) \quad (6).$$

The stability theory for an adaptive mechanism with parameter uncertainties is explained in [11], considering continuous trajectories over time (t). To guarantee stability, the following conditions are considered:

Assuming $c_0 = 1$, at any iteration (i), the impact of changes in system parameters can manifest in the value of the plant transfer function $G_i(s)$. The transfer function between the terminal voltage $V_t(s)$ to the reference $V_{ref}(s)$, as shown in Fig. 6, can be mathematically represented in (7).

$$G_{AVR}(s) = \frac{V_t(s)}{V_{ref}(s)} = \frac{G_i(s)}{1 - x_o G_i(s)} = \left(\frac{\left(K_P + \frac{K_I}{s} + K_D s\right) G_A(s) G_E(s) G_G(s)}{1 + \left(K_P + \frac{K_I}{s} + K_D s\right) G_A(s) G_E(s) G_G(s) G_f(s)}\right) \quad (7).$$

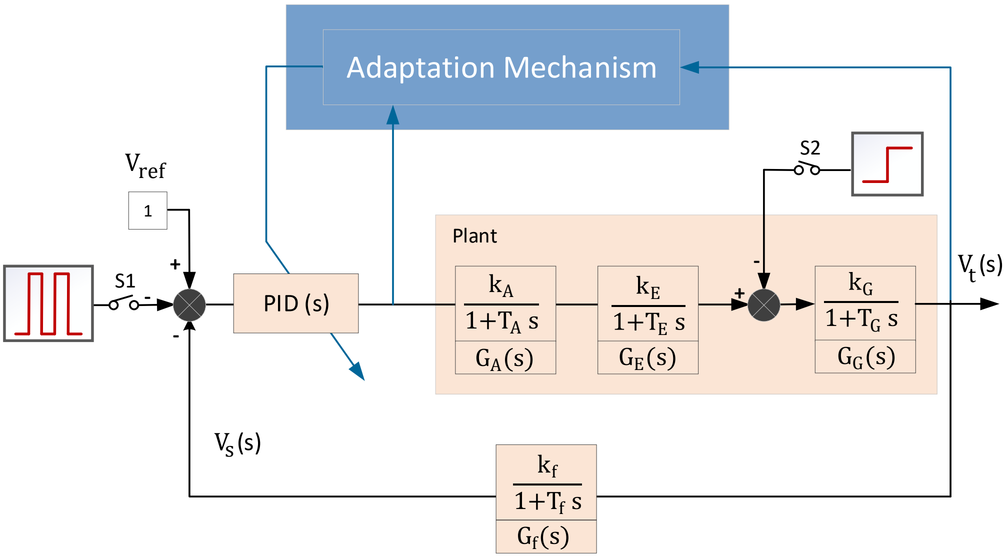


Fig. 6: A simplified AVR system block diagram.

For simplification, the MATLAB code is used to factorize the 4th order denominator in (7) into a 2nd order form, enabling the determination of the AVR system's poles and zeros, as follows:

$$sys = tf(Num\ /\ Den)_{G_{AVR}(s)}$$
$$poles = roots(cell2mat(sys, Den))$$
$$zeros = roots(cell2mat(sys, Num))$$

Table I: AVR system nominal parameters.

Component	Parameter	Value
PID	$[K_P, K_I, K_D]$	[1, 0.25, 0.28]
Amplifier	k_A	10
	T_A	0.1
Exciter	k_E	1
	T_E	0.4
Generator	k_G	1
	T_G	1
Sensor	k_f	1
	T_f	0.05

So, it will be easier to determine the parameters indices using the standard formula, as follows:

$$T.F = \frac{\omega_n^2}{s^2 + 2\eta\omega_n s + x_o\omega_n^2} \quad (8).$$

Therefore, to maintain system stability, x_0 should be $\leq 2\eta\omega_n$. where x_0 *is* the K_{PID}.

Example: Discussion

A simple example is presented to highlight the importance of adding an adaptation loop to the conventional feedback control for achieving the desired damping in various operating conditions.

The example focuses on developing an adaptive PID controller to improve the performance of an AVR in a synchronous generator. The controller is designed based on the mathematical model of the system mentioned in [21, 23]. The AVR system consists of multiple first-order models, namely amplifier, generator, exciter, and sensor to measure the output terminal voltage as shown in Fig. 6 and is examined under different operating conditions. The nominal parameters of the AVR system are given in Table I.

For normal operation, switches S1 and S2 are open, as shown in Fig. 6. It is observed from Fig. 7 that the AVR system-based conventional control (primary loop) exhibits high overshoot around + 0.29 pu and undershoot by -0.183 pu, with a long stabilization time (t= 9.6 s) which leads to a large steady-state error. Therefore, the objective is to mimic this damping initially by adding an adaptation control loop (acting as a secondary loop) to adjust the parameters of the PID controller and assist the conventional feedback loop in regulating the terminal voltage. It is clear from Fig. 7 that the addition of the adaptation loop improved the performance indices of the proposed AVR system by reducing overshoot (+0.01 pu), eliminating undershoot (0 pu), stabilizing faster (1.5 s), and decreasing the steady-state error compared to the primary loop.

Disturbances have a negative impact on the controlled variables and restoring them to the desired values requires target damping, assuming the initial parameter values of the plant are known. The damping response varies when sudden changes occur in the plant due to these perturbations, as shown in Fig. 6.

The test is performed in different stages: first, close switch (S1) and open switch (S2), a sudden sequence of changes occurs at t=15 s with a variation of -10% and increments again at t=30 s by +20% and then decrements by 10 % at t= 45 s during the whole simulation time of 1 minute as shown in Fig. 8a. From Fig. 8b, the terminal voltage response with the conventional control loop still has high oscillations during the switching period. At switching t=0, the overshoot, undershoot, and settling time is equal to 1.29 pu, 0.829 pu, and 9.6 s, respectively. At t= 15s, the performance indices are 0.87 pu for undershoot and begin to stabilize at t=17 s. At t= 30 s, the overshoot is 1.29 pu and stabilizes at t=33 s. Finally, at switching t=45 s, the undershoot is around 0.94 pu and stabilizes again at t= 48 s. On the other hand, with the existence of the secondary/adaptation control loop, it is seen that the terminal voltage is boosted in terms of over/undershoot, settling time, and steady-state error for all abrupts changes at t=0, 15, 30, and 45 s as compared to the conventional feedback one. Moreover, the measured output signal-based secondary controller roughly corresponds to the input disturbance signal (it means that the nominal performance is recovered).
Second, opening switch (S1) and closing switch (S2), a sudden step change happened at t=30 s with a perturbation of 3% as shown in Fig. 9a. From Fig. 9b, it is found that a significant drop occurred in the terminal voltage by a 0.28 pu resulting in excitation loss and typically lead to an Undervoltage and Overcurrent trip if not controlled. For this reason, we added a secondary control loop-based adaptation mechanism to mimic the drop in the terminal voltage and make the system stable during this abrupt disturbance. The drop in the terminal voltage using the secondary level is about 0.064 pu. Therefore, the studied AVR system with the availability of the suggested adaptation mechanism provides a fast and stable response compared to the conventional feedback control loop (primary level).

Here in this example, there is no need to add a supervisory control loop because the system is fully recovered by the secondary adaptation loop. Therefore, the supervisory loop will look to the secondary one and monitor the difference between the measured and desired performance index and decide according to the received data from the secondary level.

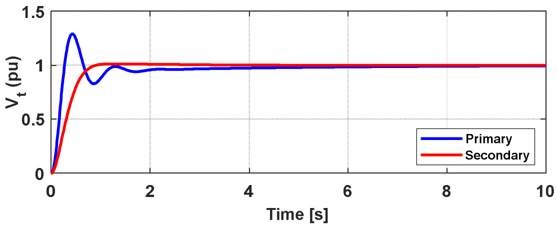
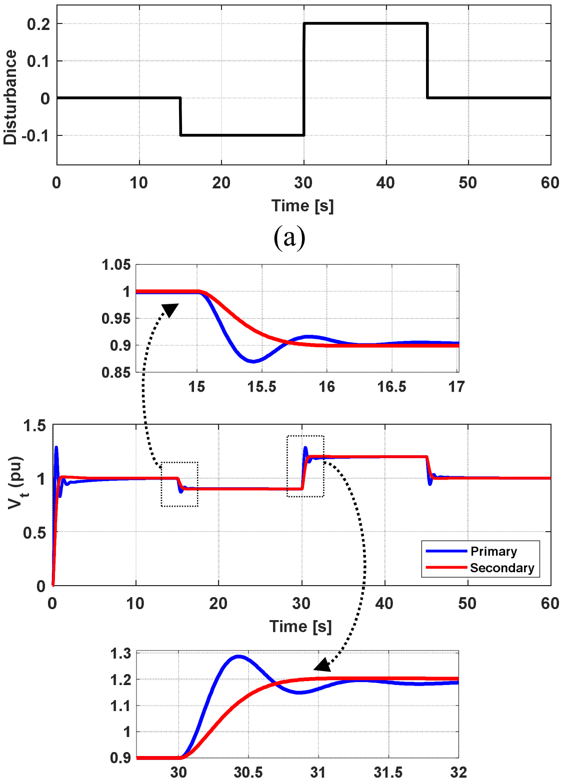


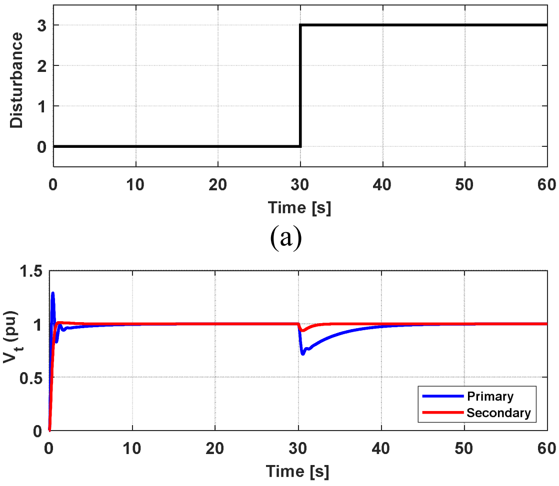
Fig. 7: AVR system response with (secondary) and without (primary) the adaptation mechanism.



(a)

(b)

Fig. 8: AVR system response under different sequence perturbations: (a) disturbance signal and (b) primary and secondary control loops.



(a)

(b)

Fig. 9: AVR system response under a 3% sudden step change.

Conclusion

When the nature of the disturbances is changing, the system performance will be adversely affected. Therefore, it is beneficial to be able to estimate a model that can adapt to these variations in the plant. In this work, the conceptual idea of the adaptive control system and how it can be represented in a form of a control system that contains a set of tasks arranged for each level in a hierarchical tree is highlighted. The main objective is to provide automatic adjustment of the controllers to keep the desired level of the control system performance and monitor it when the parameters of the plant model are unknown and/or change in time. The above discussion clarifies the need to initiate an adaptive control strategy to deal with critical problems in classical control systems caused by a sudden change in plant parameters compared to a conventional feedback control system. Therefore, Auto tuning is very widely used, especially for PID controllers where the technologies can be grouped in such a way that the systems are very user-friendly.

A simple AVR system model is demonstrated in this work to prove the superiority of the proposed adaptation control loop which acts as a secondary control loop over a conventional feedback loop. The suggested AVR system is validated under an abrupt step and repeating sequences changes as disturbances. The final finding supports the concept of adaptive control and gives the potential to act as a hierarchical control system, in which there is a limited steady-state error, settling time, and overshoot found compared to the conventional feedback control loop that acts as a primary level.

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