Synthesis of ADRC and its Application to an Electrical Power System

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Abstract:
As the power system becomes smarter, the difficulty of control is also increasing. Since, load frequency and voltage stability is an important power quality index in power system, any sudden load disturbance will cause the system load frequency and voltage deviation, and as the power system becomes more complex. However, the stability and reliability of the smart power grid are facing great challenges caused by the intermittency and randomness of renewable energies. Nowadays, it is necessary to find a more appropriate control strategy and techniques. Due to the superior anti-interference and anti-coupling ability of the active disturbance rejection control (ADRC), novel applications of this control technique have been developed in smart system. This paper presents firstly a synthesis of ADRC and then it discusses some important applications of ADRC in this field.

Keywords: ADRC, Power Grid, AVR, Active Distribution Network.

1. INTRODUCTION

Load frequency and voltage stability is an important power quality index in power system, any sudden load disturbance will cause the system load frequency deviation, and as the power system becomes more complex, the difficulty of control is also increasing, it is necessary to find a more appropriate control techniques such as Active disturbance rejection control (ADRC), which has the superior anti-interference and anti-coupling ability of the active disturbance rejection control (ADRC).

Active disturbance rejection control (ADRC) can be summarized as follows: it inherits from proportional–integral– derivative (PID) the quality that makes it such a success: the error driven, rather than model-based, control law; it takes from modern control theory its best offering: the state observer; it embraces the power of nonlinear feedback and puts it to full use; it is a useful digital control technology developed out of an experimental platform rooted in computer simulations. ADRC is made possible only when control is taken as an experimental science, instead of a mathematical one. It is motivated by the ever-increasing demands from industry that requires the control technology to move beyond PID, which has dominated the practice for over 80 years. Specifically, there are four areas of weakness in PID that we strive to address: 1) the error computation; 2) noise degradation in the derivative control; 3) oversimplification and the loss of performance in the control law in the form of a linear weighted sum; and 4) complications brought by the integral control. Correspondingly, we propose four distinct measures: 1) a simple differential equation as a transient trajectory generator; 2) a noise-tolerant tracking differentiator; 3) the nonlinear control laws; and finally, 4) the concept and method of total disturbance estimation and rejection. All together, they form a new set of tools and a new way of control design. Times and again in experiments and on factory floors, ADRC proves to be a capable replacement of PID with unmistakable advantage in performance and practicality, providing solutions to pressing engineering problems of today. With the new outlook and possibilities that ADRC represents, we further believe that control engineering may very well break the hold of classical PID and enter a new era, an era that brings back the spirit of innovations.

ADRC has been a work in progress for almost two decades [1, 2], with its ideas and applications appearing in the English literature, amid some questions and confusions, sporadically only in recent years; see, for example [3, 4]. In ADRC, we see a paradigmatic change in feedback control that was first systematically introduced in English in 2001 [3]. The conception of active disturbance rejection was s further elaborated in [5]. However, even though much success has been achieved in practical applications of ADRC, it appears that this new paradigm has not been well understood and there is a need for a paper that provides a full account of ADRC to the English audience [6]. Such need is unmistakable in the recently proposed terminologies such as equivalent input disturbance [4] and disturbance input decoupling [7], all of which can be seen as a special case of ADRC where only the external disturbance was considered. It is primarily for this reason that this paper is written [8].

2. DESCRIPTION AND PRINCIPLE OF ADRC TECHNIQUE

Active disturbance rejection control (ADRC) is a new generation of digital control solutions, which may replace the efficient conventional controller PID in the 21st century, keeping the same advantages, but trying to reduce its disadvantages [8].
ADRC has been proposed by J. Han [8] and simplified by Z. Gao [3, 5]. In order to understand the idea behind this control law, it is necessary to follow the reasoning of J. Han. [8] (Han, 2009) who noticed that the right idea is to understand the two characteristics of PID and its faced challenges. For this reason, all most innovative control methods that have been developed such as adaptive and robust control, aim to have better control performance even with uncertainties. In this mind, J. Han began the process that ultimately led to the ADRC [9, 10].
In fact, to replace PID control, a control method should have the following properties: 1) a fixed control structure, and the structure should be easy to be implemented in practice; 2) few tuning parameters, and the parameters are directly related to the performance of the closed-loop system, and the tuning is easy to understand by control engineers; 3) can predict or estimate the error between the output and the set-point in real time so that better control performance can be achieved. It is clear that few control methods possess these properties in the development of advanced control theory; this is why PID control is still dominant [11].
Mathematical modeling causes obvious gaps which leads to smart implementation and terrible performance. Academic research, so active in automation, sometimes called "modern" for more than fifty years, finds much of its motivation there [12].
Many systems face disturbance phenomena that reduce the precision, the quality of service or even the age of the processes. Control laws that may be developed must take into account the need to improve the performance of new components, machines or complex systems such as energy systems and hence the reduction of the effect on the environment.
This research work aims to improve the precision and robustness of processes in energy production by trying to cancel the influence of disturbances on the behavior of the complete system by designing a controller / observer, using an integrated approach [13].

During the period 1980-1990, Jingquin Han published several papers on a new unconventional control method (Han, 1988, 1995a, b, 2009, 1989) [10].
The central idea is to treat the internal uncertainties and external disturbances as a “generalized disturbance,” and try to estimate in real time by an extended state observer (ESO), and then it can be used in the feedback with the aim to compensate the disturbance quickly. ADRC configuration is shown in Figure 5.1, where b contains the gain information of the controlled plant; TD is a tracking differentiator that is used to get the desired response for the reference; ESO is the extended state observer that is used to estimate the generalized disturbance and the plant output (including its derivatives of various order); NLSEF is a nonlinear state error feedback that utilizes the error and its derivatives of various order in a nonlinear fashion to achieve good control performance. An important character of ADRC is that the estimated disturbance ˆf is combined with the nonlinear state error feedback so that the final control u can reject the disturbance. The structure is not hard to implement with the modern digital computer technology and is shown to be able to achieve good control performance. However, the structure is still complex and needs to tune a bunch of parameters, which makes it difficult to use in practice. To overcome the difficulty, [14] and [5] consider the “linear” version of ADRC (LADRC), where liner ESO and linear state feedback are used. Furthermore, the number of parameters for the LADRC is reduced to two, the controller bandwidth ωc, and the observer bandwidth ωo, and these two parameters are closely related to the performance of the closed-loop system, thus LADRC possesses all the properties listed above for replacing PID [11].

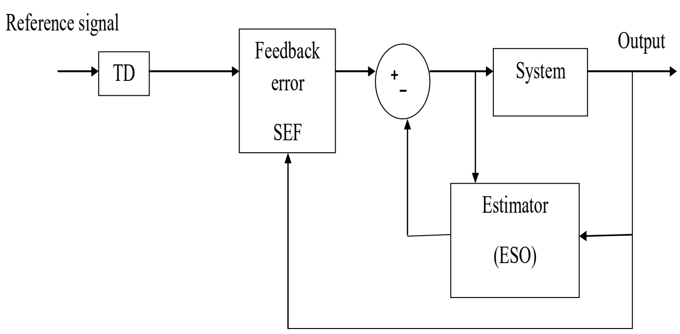


Fig.1 ADRC functional block diagram.

The significant difference between the ADRC and other control methods is that the ADRC not only estimates plant uncertainties and external disturbances in the ESO, but also actively compensates for them in the SEF. Therefore, the ADRC becomes a potential candidate for controlling dynamic systems with plant uncertainties and external disturbances [15].

Many ADRC applications have been reported in the literature, e.g., gyroscopes [16], load frequency control [17], gasified [18], two-mass drive [19], tank gun control [20], robotic-enhanced limb rehabilitation trainings [21], under-actuated systems [22], diesel engines [23], and flywheel energy storage system [24]. To advance the study on ADRC, two special issues were published in ISA Transactions in 2014 and Control Theory & Applications in 2013, which greatly propagates the ADRC idea. Though ADRC has made much progress, it has not attracted much attention in the control area, partly because few theoretical results are available to verify the method, among which the most important are frequency analysis for LADRC [25], stability analysis of LADRC [26], verification and performance analysis of ESO [27], frequency analysis of nonlinear ADRC by describing function method [28], convergence of nonlinear ADRC [29], singular perturbation analysis of ADRC [30], adaptive Lyapunov methods for ADRC [31]. Interested readers may refer to [32] for a recent survey on ADRC. It is noted that ADRC only needs to know the relative order of the process and the corresponding gain. This is the advantage of the method, but it is also the target of criticism:

1) Is such little information enough for a good control?

2) If more plant information is available, can such information be used to improve control performance?

3) How can extra information be incorporated in ADRC [11]?

However, owing to the usage of nonlinear functions in all three parts of the ADRC, the complicated controller structure and a large number of tuning parameters pose challenges in practical applications. To simplify the structure of the ADRC, a linear ADRC was proposed in, where the TD is removed and the nonlinear functions used in the ESO and SEF are replaced by linear functions. To date, the application of the linear ADRC has been widely extended to many different fields.

3. STABILITY ANALYSIS OF ADRC SYSTEM

Generally, when a closed-loop control system is linear, the stability can be easily analyzed by determining the Eigen values of the control system. All the Eigen values that have negative real parts indicate that the control system is stable. When the control system is nonlinear, Lyapunov second method is the most general method to study the stability. In [32], the stabilities of the nonlinear ESO and the ADRC system were analyzed based on Lyapunov second method. It was shown that: 1) there exist appropriate observer gains, the estimation errors between the ESO and the system states are convergent; 2) there exist proper gains of the SEF, the ADRC system is stable, i.e., the estimation errors between the transient profiles and the system outputs are convergent. Similarly, the stability analyses of the linear ESO and the ADRC system based on Lyapunov's second method were presented in [16, 26]. It was shown that there exist appropriate gains of the linear ESO and the linear weighted sum, the linear ESO and the ADRC system are stable, and the estimation errors are bounded. The aforementioned stability analyses based on Lyapunov's second method are the generalized justifications of the convergences of the ADRC systems, where the models of the controlled systems are not required. However, for a specific controlled system, these generalized justifications are unable to determine whether a set of gains of the ADRC controller can stabilize the controlled system. The main reason why there is no stability justification of the ADRC for a specific, controlled system can be attributed to the fact that constructing the Lyapunov functions for nonlinear and complex dynamic systems is very challenging, because no constructive rule exists in the Lyapunov stability theory. Therefore, to address this challenge, an alternative means to study the stability of the ADRC system is desirable. In this thesis, the concept of Lyapunov exponents, as a powerful tool for the stability analyses of complicated and nonlinear dynamic systems, is introduced to investigate the stability of the ADRC system consisting of a nonlinear vehicle model. The Lyapunov exponents describe the long-term evolution of a dynamic system with an initial condition [33]. The signs of the Lyapunov exponents describe the stability property of the dynamic system [34]. Compared to Lyapunov's second method, the methods for calculating the Lyapunov exponents are constructive either based on a model of the dynamic system or a time series. The concept of Lyapunov exponents has been applied to the stability analyses of the PD control for a biped [35, 36] and a nonlinear vehicle model in plane motion [37].

4. TUNING OF ADRC

The linearization of the nonlinear ADRC generates a simple control structure and reduces the number of tuning parameters. Within the framework of the linear ADRC, the number of tuning parameters nt is proportional to the order of the dynamic system n: nt=2n+1 [11]. That is, for a second-order dynamic system, the number of tuning parameters is five. To further facilitate the tuning process, a bandwidth tuning method was proposed to reduce the number of tuning parameters to two, i.e., the observer bandwidth and the controller bandwidth [14]. This is realized by expressing all parameters of the linear ESO as functions of the observer bandwidth and expressing all parameters of the linear weighted sum as functions of the controller bandwidth. Most applications of the ADRC mentioned above were based on this tuning method. The bandwidth tuning method ensures the stability of the ADRC system and works well for tuning the ADRC for controlled systems described by first- and second-order mathematical models [14]. However, it is found to be conservative in tuning the ADRC for controlling hydraulic actuators described by fourth- and fifth-order systems, because a large number of tuning parameters determined by only two bandwidths cannot meet the desired tracking performance [11]. There has been little research on tuning the ADRC. In [11], a tuning method similar to the bandwidth tuning method was proposed. In [11], a method was proposed by incorporating the known system dynamics into the ADRC. This method works for systems for which accurate models are available but not for complicated systems with plant uncertainties and faults [15].

A. State representation of Model

Consider a system of n order written in the standard form proposed by Han;

$$y^{(n)}(t) = bu(t) + f(t) \qquad (1)$$

Its output quantity is y (t), the control quantity u (t) and f (t) the quantity defining the total disturbances which will be estimated and rejected after that.

The perturbation rejection is done according to the ADRC as follows:

$$u(t) = \frac{1}{b}(-f_0(t) + u_0(t)) \qquad (2)$$

Where, $f_0(t)$ is estimate of the total disturbance $f(t)$,$u_0(t)$ is the new control input that will be used to reach the objective.

Substituting equation (1) in equation (2), we obtain:

$$y^{(n)}(t) = b[\frac{1}{b}(-f_0(t) + u_0(t))] + f(t) \qquad (3)$$

If $f(t)$ is well estimated by$f_0(t)$, we will have$f_0(t) = f(t)$, then, equation (5.3) can be simplified to:

$$y^{(n)}(t) = u_0(t) \qquad (4)$$

It can be concluded that if the total disturbance is well estimated, the ADRC control does not require knowledge of any system parameters (without model) to follow the reference value.

This estimation of the total disturbance $f(t)$is provided by the extended state observer (ESO).

The equation (5) summarizes the mathematical model of a linear system in state representation

$$\begin{cases} \dot{x}(t) = A\,x(t) + Bu(t) + Eq(t) \\ y(t) = Cx(t) + Du(t) \end{cases} \qquad (5)$$

Where: $x(t)$ is the state vector with the matrix A which characterizes the internal dynamics of states, $u(t)$ is the control inputs vector with the matrix B which characterizes the way in which the control inputs modify the states of the system, $q(t)$ is the disturbance vector with the matrix E characterizes.

The way in which measurable disturbances act on the system states; where $y(t)$ is the output vector. Matrix C characterizes the evolution of outputs as a function of the states of the system; it is called the output matrix.

The matrix D characterizes the direct influence of the control quantities on the system outputs; it is a direct connection matrix. When the system is causal the matrix D is null. The function $h(t)$ is set at an unknown function which represents the derivative of the function $f(t)$. This function exists because $f(t)$depends on the unmodeled dynamics of the system, so it accepts a dynamic that is necessarily differentiable.

Moreover, the function $h(t)$ is introduced just for the needs of state representation; it will not be used in the further development.

The equation (5) becomes:

$$\begin{cases} \dot{x}(t) = A\,x(t) + Bu(t) + Eh(t) \\ y(t) = Cx(t) \end{cases} \qquad (6)$$

Where, $A = \begin{bmatrix} 0 & 1 & 0 & 0 & \dots & 0 \\ 0 & 0 & 1 & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \dots & \vdots \\ 0 & 0 & 0 & 0 & \dots & 1 \\ 0 & 0 & 0 & 0 & \dots & 0 \end{bmatrix}$,

$B = [0 \quad 0 \quad \dots \quad b \quad 0]^T$,

$C = [1 \quad 0 \quad \dots \quad 0 \quad 0]$,

$E = [0 \quad 0 \quad \dots \quad 0 \quad 1]^T$.

It can be concluded that only the term b added by the designer takes place in the control structure [11]. The disturbance rejection control is based on the idea of formulating a robust control strategy. It aims to compensate for dynamics and disturbances in real time. This approach accurately and quickly estimates disturbances using an extended and compensated non-linear state observer (ESO) during each sampling period to meet the performance requirements of these systems and improve their efficiency [8].

B. Extended State Observer

Knowing that the inputs to ESO are the system output y and the control signal u, and the output of ESO provides the important information about F. Now we move to the structuring of the observer.

We have chosen one of the most famous observers in the state feedback controls is the Luenberger observer. It allows reconstructing the state of the system under observation when all or part of the state vector cannot be measured. It can also estimate the variable or unknown parameters of a system.
A full order Luenberger state-observer can be designed as follows:

$$\begin{cases} \dot{\hat{x}}(t) = A\,\hat{x}(t) + Bu(t) + L(y(t) - \hat{y}(t)) \\ \hat{y}(t) = C\hat{x}(t) \end{cases} \quad (7)$$

$\hat{x}(t)$ and $\hat{y}(t)$ respectively the dynamics and the output of ESO, L Correction gain matrix or the observer.
It must emphasize on the term $L(y(t) - \hat{y}(t))$ which defines the error between the real system and that given by the observer. It can be noted that the good choice of the matrix L makes it possible to modify the dynamics of the observer which helps us to cancel the error and to converge estimating system to the real one.

C. Sizing of the observer gain L

A well-dimensioned estimator gives a zero error between real system and observable, these results in:

$$(y(t) - \hat{y}(t) = 0 \equiv C(\,x(t) - \hat{x}(t)) = 0 \quad (8)$$

The error $\varepsilon(t)$ is the difference between the internal states of the system and the estimated ones,

$$\varepsilon(t) = x(t) - \hat{x}(t) \quad (9)$$

The derivation of this error gives the difference between the two dynamics describing the two systems:

$$\dot{\varepsilon}(t) = \dot{x}(t) - \dot{\hat{x}}(t) \quad (10)$$

The substitution of equations (5.6) and (5.7) in (10), gives:

$$\dot{\varepsilon}(t) = A(x(t) - \hat{x}(t)) - L(y(t) - \hat{y}(t)) \quad (11)$$

Using equations (8) and (9) in (11), we obtain:

$$\dot{\varepsilon}(t) = (A - LC)\varepsilon(t) \quad (12)$$

Hence, the error is given by the following expression:

$$\varepsilon(t) = e^{(A-LC)t} \quad (13)$$

In order the estimation error tends towards 0 when t increases, it is necessary to choose L so that the Eigen values of the matrix $(A - LC)$ have strictly negative real parts.

$$VP(A - LC) = (p + \omega_0)^{n+1} \quad (14)$$

Where, ω_0 is the observer's bandwidth.
And,

$$H(s) = \frac{K_r}{1+sT_r} \quad (15)$$

Determination of the matrix L helps to find out the observer poles.

All elements of the matrix L depend on a single parameterω_0. Therefore, the adjustment of the observer is conditioned by the choice of its own pulsation $\omega_0$with$(\omega_0 > 0)$.
The combination of this observer with the control law leads to this final structure of the ADRC control [38].

5. ILLUSTRATION OF THE LADRC ON A NONLINEAR SYSTEM

The aim of this section is to present the linear example of ADRC in a stand-alone manner[14, 39],

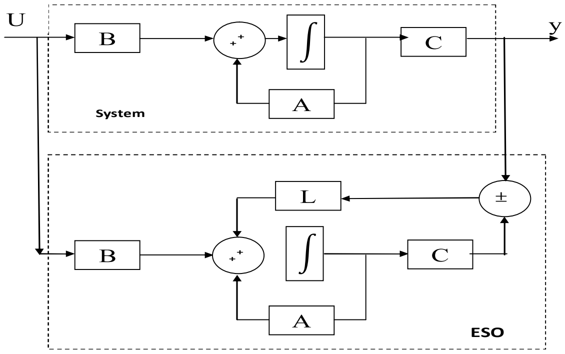


Fig.2 ADRC control structure

Due to the important practice, the first-order case will be treated first and explicitly, even though the fact that there are numerous systems - although technically they are all first-order. Nonlinear and higher-order, in which, at least at some operating points, exhibit first-order-like dominant behavior.
The justification for the second-order order will be established later (case of power system application).

A. First-Order ADRC

Consider a simple first-order process, P(s), with a DC gain, K, and a time constant, T:

$$p(s) = \frac{y(s)}{u(s)} = \frac{K}{Ts+1} \rightarrow T.\dot{y}(t) + y(t) = Ku(t) \quad (16)$$

We add an input disturbance, d(t), to the process, abbreviate b = K/ T and rearrange:

$$\dot{y}(t) = -\frac{1}{T}.y(t) + \frac{1}{T}d(t) + \frac{K}{T}.u(t) = -\frac{1}{T}.y(t) + \frac{1}{T}d(t) + b.u(t) \quad (17)$$

As our last modelling step, we substitute $b = b_0 + \Delta b$, where b0 shall represent the known part of $b = \frac{K}{T}$ and Δb, an (unknown) modeling error, and, finally, obtain Equation (18). We will see soon that all that we need to know about our first-order process to design an ADRC is b0 ≈ b, i.e., an approximate value of $\frac{K}{T}$. Modeling errors or varying process parameters are represented by Δb and will be handled internally.

$$\dot{y}(t) = \left(-\frac{1}{T}.y(t) + \frac{1}{T}d(t) + b.u(t)\right) + b_0 u(t) = f(t) + b_0 u(t) \quad (18)$$

Generalized disturbance f(t)

By combining $-\frac{1}{T}.y(t)$, the disturbance $d(t)$, and the unknown part Δb·u(t) to a so-called generalized disturbance, f (t), the model for our process changed from a first-order low-pass type to an integrator. The fundamental idea of ADRC is to implement an extended state observer (ESO) that provides an estimate, $\hat{f}(t)$, such that we can compensate the impact of f(t) on our process (model) by means of disturbance rejection. All that remains to be handled by the actual controller will then be a process with approximately integrating behavior, which can easily be done, e.g. by means of a simple proportional controller. In order to derive the estimator, a state space description of the disturbed process in Equation (18) is necessary:

$$\begin{pmatrix}\dot{x}_1(t)\\ \dot{x}_2(t)\end{pmatrix} = \begin{pmatrix}0 & 1\\ 0 & 0\end{pmatrix}.\begin{pmatrix}x_1(t)\\ x_2(t)\end{pmatrix} + \begin{pmatrix}b_0\\ 0\end{pmatrix} u(t) + \begin{pmatrix}0\\ 1\end{pmatrix}\dot{f}(t) \quad (19)$$

$$y(t) = \begin{pmatrix}1 & 0\end{pmatrix}.\begin{pmatrix}x_1(t)\\ x_2(t)\end{pmatrix}$$

Since the "virtual" input, $\dot{f}(t)$, cannot be measured, a state observer for this kind of process can, of course, only be built using the input, u(t), and output, y(t), of the process. An estimated state, $\dot{x_2}(t)$, however, will provide an approximate value of f (t), i.e., $\hat{f}(t)$, if the actual generalized disturbance, f(t), can be considered piecewise constant. The equations for the extended state observer (integrator process extended by a generalized disturbance) are given in Equation (20). Note that for linear ADRC, a Luenberger observer is being used, while in the original case of ADRC, a nonlinear observer was employed [122].

$$\begin{pmatrix}\dot{\hat{x}}_1(t)\\ \dot{\hat{x}}_2(t)\end{pmatrix} = \begin{pmatrix}0 & 1\\ 0 & 0\end{pmatrix}.\begin{pmatrix}\hat{x}_1(t)\\ \hat{x}_2(t)\end{pmatrix} + \begin{pmatrix}b_0\\ 0\end{pmatrix} u(t) + \begin{pmatrix}l_1\\ l_2\end{pmatrix}.\left(y(t) - \hat{x}_1(t)\right)$$

$$= \begin{pmatrix}-l_1 & 1\\ -l_2 & 0\end{pmatrix}.\begin{pmatrix}\hat{x}_1(t)\\ \hat{x}_2(t)\end{pmatrix} + \begin{pmatrix}b_0\\ 0\end{pmatrix} u(t) + \begin{pmatrix}l_1\\ l_2\end{pmatrix}.y(t) \quad (20)$$

One can now use the estimated variables, $\hat{x}_1(t) = \hat{y}(t)$ and $\hat{x}_2(t) = \hat{f}(t)$, to implement the disturbance rejection and the actual controller.

$$u(t) = \frac{u_0(t) - \hat{f}(t)}{b_0} \quad (21)$$

with $u_0(t) = K_p.(r(t) - \hat{y}(t)$

According the structure of the control loop, it is presented in Figure 3. Since KP acts on $\hat{y}(t)$, rather than the actual output y(t), we can have a estimation-based state feedback controller, but the resemblance to a classical proportional controller is striking to practitioners. In equation (21), $u_0(t)$represents the output of a linear proportional Controller.

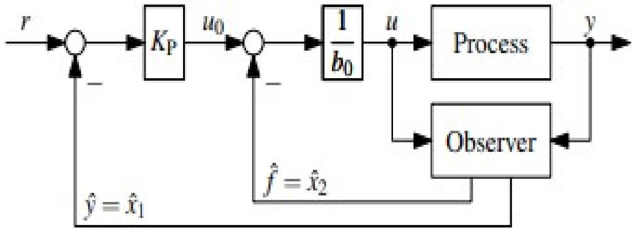


Fig.3 Control loop structure with ADRC for a first-order process.

The remainder of the control law in u(t) is chosen such that the linear controller acts on a normalized integrator process if $\hat{f}(t) \approx f(t)$ holds. The effect can be seen by putting Equation (21) in Equation (18):

$$\dot{y}(t) = f(t) + b_0.\frac{u_0(t) - \hat{f}(t)}{b_0} = \left(f(t) - \hat{f}(t)\right) + u_0(t) \approx u_0(t) = K_p.(r(t) - \hat{y}(t))$$

If $\hat{y}(t) \approx y(t)$ holds, we obtain a first-order closed loop behavior with a pole, $s^{CL} = -K_p$:

$$\frac{1}{K_p}\dot{y}(t) + \hat{y}(t) \approx \frac{1}{K_p}\dot{y}(t) + y(t) \approx r(t)$$

If the state estimator and disturbance rejection work properly, one has to design a proportional controller only one single time to obtain the same closed loop behavior, regardless of the parameters of the actual process. For example, one can calculate K_p from a desired first-order system with 2%-settling time:

$$K_p \approx \frac{4}{T_{settle}} \quad (22)$$

In order to work properly, observer parameters, l_1 and l_2, in Equation (4) still have to be determined. Since the observer dynamics must be fast enough, the observer poles, $s_{1/2}^{ESO}$, must be placed left of the closed loop pole, s^{CL}. A simple rule of thumb suggests for both poles:

$$S_{\frac{1}{2}}^{ESO} = s^{ESO} \approx (3 \ldots 10).s^{CL} \quad (23)$$

with $s^{CL} = -K_p \approx -\frac{4}{T_{settle}}$

Placing all observer poles at one location is also known as "bandwidth parameterization" [130]. Since the matrix (A − LC) determines the error dynamics of the observer, we can compute the necessary observer gains for the common pole location, s^{ESO}, from its characteristic polynomial:

$$\det\left(sI - (A - LC)\right) = s^2 + l_1.s + l_2 = (s - s^{ESO})^2 = s^2 - 2s^{ESO}.s(s^{ESO})^2 \quad (24)$$

From equation (5.24), the solutions for l_1 and l_2 can immediately be read off:

$$l_1 = -2\ s^{ESO} \text{ and } l_2 = (s^{ESO})^2 \quad (25)$$

To summarize, in order to implement a linear ADRC for a first-order system, four steps are necessary:

1. Modeling: For a process with (dominating) first-order behavior, $p(s) = \frac{K}{Ts+1}$, all that needs to be known is an estimate $b_0 \approx \frac{K}{T}$.
2. Control structure: Implement a proportional controller with disturbance rejection and an extended state observer, as given in equations (20) and (21):

$$\begin{pmatrix} \dot{\hat{x}}_1(t) \\ \dot{\hat{x}}_2(t) \end{pmatrix} = \begin{pmatrix} -l_1 & 1 \\ -l_2 & 0 \end{pmatrix} . \begin{pmatrix} \hat{x}_1(t) \\ \hat{x}_2(t) \end{pmatrix} + \begin{pmatrix} b_0 \\ 0 \end{pmatrix} u(t) + \begin{pmatrix} l_1 \\ l_2 \end{pmatrix} . y(t)$$

$$u(t) = \frac{K_p.\left(r(t) - \hat{y}(t)\right) - \hat{f}(t)}{b_0} = \frac{K_p.\left(r(t) - \hat{x}_1(t)\right) - \hat{x}_2(t)}{b_0}$$

3. Closed loop dynamics: Choose K_p, e.g. according to a desired settling time equation (22):

$$K_p \approx \frac{4}{T_{settle}}$$

4. Observer dynamics: Place the observer poles left of the closed loop pole via equations (23) and (25):

$l_1 = -2\ s^{ESO}$, $l_2 = (s^{ESO})^2$ with $s^{ESO} \approx (3 \ldots 10).s^{CL}$ and $s^{CL} = -K_p$

It should be noted that the same control structure can be applied to a first-order integrating process:

$$p(s) = \frac{y(s)}{u(s)} = \frac{K_I}{s} \rightarrow \dot{y}(t) = K_I u(t) \qquad (26)$$

With an input disturbance, $d(t)$, and a substitution, $K_I = b = b_0 + \Delta b$, with Δb representing the unknown part of K_I, we can model the process in an identical manner as equation (18), with all differences hidden in the generalized disturbance, $f(t)$:

$$\dot{y}(t) = \left(-\frac{1}{T}.y(t) + \frac{1}{T}d(t) + b.u(t)\right) + b_0 u(t) = f(t) + b_0 u(t) \qquad (27)$$

Generalized disturbance $f(t)$

Therefore, the design of the ADRC for a first-order integrating process can follow the same four design steps given previoudly, with the only distinction that b_0 must be set to $b_0 \approx K_I$ in step 1.

B. Second-Order ADRC

Following the previous section, we now consider a second-order process, $p(s)$, with a DC gain, K, damping factor, D, and a time constant, T.

$$p(s) = \frac{y(s)}{u(s)} = \frac{K}{T^2 s^2 + 2DTs + 1} \rightarrow$$

$$T^2 \ddot{y}(t) + 2DT\dot{y}(t) = Ku(t) \qquad (27)$$

As for the first-order case, we add an input disturbance, $d(t)$, abbreviate $b = \frac{K}{T^2}$ and split b into a known and unknown part, $b = b_0 + \Delta b$:

$$\ddot{y}(t) = \left(-\frac{2D}{T}.\dot{y}(t) - \frac{1}{T^2}d(t) + \Delta b.u(t)\right) + b_0.u(t) \qquad (28)$$

Generalized disturbance $f(t)$

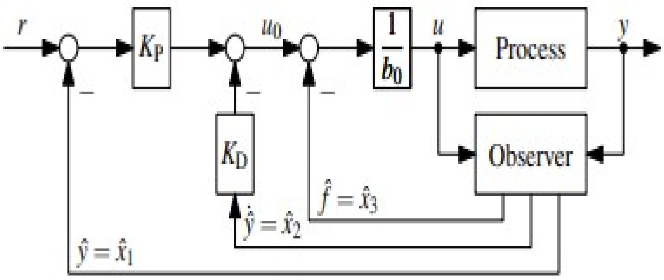
With everything else combined into the generalized disturbance $f(t)$, all that remains of the process model is a double integrator. The state space representation of the disturbed double integrator is:

$$\begin{pmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \\ \dot{x}_3(t) \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix} . \begin{pmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \end{pmatrix} + \begin{pmatrix} 0 \\ b_0 \\ 0 \end{pmatrix} . u(t) + \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} . \dot{f}(t) \qquad (30)$$

$$y(t) = \begin{pmatrix} 1 & 0 & 0 \end{pmatrix} . \begin{pmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \end{pmatrix}$$

In order to employ a control law similar to the first-order case, an extended state observer is needed to provide estimation, $\hat{x}_1(t) = \hat{y}(t)$, $\hat{x}_2(t) = \dot{y}(t)$ and $\hat{x}_3(t) = \hat{f}(t)$:

$$\begin{pmatrix} \dot{\hat{x}}_1(t) \\ \dot{\hat{x}}_2(t) \\ \dot{\hat{x}}_3(t) \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix} . \begin{pmatrix} \hat{x}_1(t) \\ \hat{x}_2(t) \\ \hat{x}_3(t) \end{pmatrix} + \begin{pmatrix} 0 \\ b_0 \\ 0 \end{pmatrix} . u(t) + \begin{pmatrix} l_1 \\ l_2 \\ l_3 \end{pmatrix} . (y(t) - \hat{x}_1(t)) = \begin{pmatrix} -l_1 & 1 & 0 \\ -l_2 & 0 & 1 \\ -l_3 & 0 & 0 \end{pmatrix} . \begin{pmatrix} \hat{x}_1(t) \\ \hat{x}_2(t) \\ \hat{x}_3(t) \end{pmatrix} + \begin{pmatrix} 0 \\ b_0 \\ 0 \end{pmatrix} . u(t) + \begin{pmatrix} l_1 \\ l_2 \\ l_3 \end{pmatrix} . (y(t) \qquad (31)$$



process.

Using the estimated variables, one can implement the disturbance rejection and a linear controller for the remaining double integrator behavior, as shown in Figure 4. A modified PD controller (without the derivative part for the reference value r(t)) will lead to a second-order closed loop behavior with adjustable dynamics. Again, this actually is an estimation-based state feedback controller.

$$u(t) = \frac{u_0(t) - \hat{f}(t)}{b_0} \text{ with } u_0(t) = K_p.\left(r(t) - \hat{y}(t)\right) - K_D.\hat{\dot{y}}(t) \qquad (32)$$

Provided the estimator delivers good estimates, $\widehat{x_1}(t) = \hat{y}(t) \approx y(t), \widehat{x_2}(t) = \dot{\hat{y}}(t) \approx \dot{y}(t)$ and $\widehat{x_3}(t) = \hat{f}(t) \approx f(t)$, one obtains after inserting Equation (31) into Equation (32):

$$\ddot{y}(t) = \left(f(t) - \hat{f}(t)\right) + u_0(t) \approx u_0(t) \approx K_p.\left(r(t) - y(t)\right) - K_D.\dot{y}(t) \qquad (33)$$

Under ideal conditions, this leads to:

$$\frac{1}{K_p}\ddot{y}(t) + \frac{K_D}{K_p}\dot{y}(t) + y(t) = r(t) \qquad (34)$$

While any second-order dynamics can be set using K_p and K_D, one practical approach is to tune the closed loop to a critically damped behavior and a desired 2% settling time T_{settle}, i.e., choose K_p and K_D to get a negative-real double pole, $s_{1/2}^{CL} = s^{CL}$:

$$K_p = (s^{CL})^2 \text{ and } K_D = -2.s^{CL} \qquad (35)$$

with $s^{CL} \approx -\frac{6}{T_{settle}}$

Similar to the first order case, the placement of the observer poles can follow a common rule of thumb:

$$s_{1/2/3}^{ESO} = s^{ESO} \approx (3 \dots 10).s^{CL} \qquad (36)$$

with $s^{CL} \approx -\frac{6}{T_{settle}}$

Once the pole locations are chosen in this manner, the observer gains are computed from the characteristic polynomial of (A − LC):

$$\det\left(sI - (A - LC)\right) = s^3 + l_1.s^2 + l_2.s + l_3 = (s - s^{ESO})^3 = s^3 - 3s^{ESO}.s^2 + 3.(s^{ESO})^2.s - (s^{ESO})^3$$

The respective solutions for l_1, l_2 and l_3 are:

$$l_1 = -3s^{ESO},\ l_2 = 3.(s^{ESO})^2 \text{ and } l_3 = -(s^{ESO})^3 \qquad (37)$$

To summarize, ADRC for a second-order system is designed and implemented as follows:

Modeling: For a process with (dominating) second-order behavior, $p(s) = \frac{K}{T^2s^2+2DTs+1}$ one only needs to know an approximate value $b_0 \approx \frac{K}{T^2}$

Control structure: Implement a proportional controller with disturbance rejection and an extended state observer, as given in equations (30) and (35):

$$\begin{pmatrix} \dot{\widehat{x_1}}(t) \\ \dot{\widehat{x_2}}(t) \\ \dot{\widehat{x_3}}(t) \end{pmatrix} = \begin{pmatrix} -l_1 & 1 & 0 \\ -l_2 & 0 & 1 \\ -l_3 & 0 & 0 \end{pmatrix}.\begin{pmatrix} \widehat{x_1}(t) \\ \widehat{x_2}(t) \\ \widehat{x_3}(t) \end{pmatrix} + \begin{pmatrix} 0 \\ b_0 \\ 0 \end{pmatrix}.u(t) + \begin{pmatrix} l_1 \\ l_2 \\ l_3 \end{pmatrix}.(y(t) \qquad (38)$$

$$u(t) = \frac{K_p.(r(t) - \hat{y}(t)) - K_D.\dot{\hat{y}}(t) - \hat{f}(t)}{b_0} = \frac{(K_p.(r(t) - \widehat{x_1}(t)) - K_D.\widehat{x_2}(t)) - \widehat{x_3}(t)}{b_0} \qquad (39)$$

Closed loop dynamics: Choose (K_p and K_D, e.g. according to a desired settling time as given in equation (32):

$K_p = (s^{CL})^2$ and $K_D = -2.s^{CL}$ with $s^{CL} \approx -\frac{6}{T_{settle}}$

Observer dynamics: Place the observer poles left of the closed loop poles via Equations (33) and (34):

$l_1 = -3s^{ESO}$, $l_2 = 3.(s^{ESO})^2$ and $l_3 = -(s^{ESO})^3$ with $s^{ESO} \approx (3 \dots 10).s^{CL}$ [156].

C. LADRC Robustness

Since the nonlinear system is usually much more complex than the linear system, the linearization methods, which are invented based on the exact model information, cannot avoid the computation burden. More seriously, since uncertainties widely exist in practical systems, the model-based control design met great challenges in engineering practice, especially the problem of robustness.

The high level of robustness and the superior transient performance are the most valuable characteristics of ADRC to make it be an appealing solution in dealing with real world control problems. Next, the main results of [37, 41], which can explain these characteristics from the views of the frequency-domain and the time-domain, respectively.

In [158], the capability of LADRC for linear time-invariant SISO minimum-phase systems with unknown but bounded relative degrees, and unknown input disturbances, was analyzed. The result explains why one ADRC with fixed parameters can be applied to a group of plants of different orders, relative degrees, and parameters. In [36, 38], the analysis results in the frequency domain were shown. In [35], the loop gain frequency response was analyzed for a second-order linear time-invariant plant. The result showed that the LADRC based control system possesses a high level of robustness. The bandwidth and stability margins, in particular, are nearly unchanged as the plant parameters vary significantly; so is the sensitivity to the input disturbance. Such characteristics explain why LADRC is an appealing solution in dealing with real world control problems where uncertainties abound. Xue and Huang [38] further investigated the frequency properties of LADRC with the reduced-order LESO for a typical class of n-th order linear time-invariant uncertain system. It was shown that the phase margin and crossover frequency are almost unchanged in the presence of some uncertain parameters. And moreover, different kinds of uncertain parameters have various influences on the robustness of the ADRC based control system, t will be shown that the phase margin and crossover frequency are almost unchanged in the presence of some uncertain parameters. And moreover, different kinds of uncertain parameters have various influences on the robustness of the LADRC based control system [38, 42].

To make the system more robust without changing the set-point-tracking performance, two options are possible. 1) Increase the time constant λd of the disturbance-rejection filter (i.e., decrease the observer bandwidth ωo). 2) Increase the gain b.

The first option is natural since the robustness of the system is directly related to λd. The larger λd is, the more robust the system will be. The second option may seem strange. Deviating b from its nominal value introduces more model error in the system, which leads more difficulty in controller design. Nevertheless, if the controller design method can provide a controller with more robustness, then it is worth the risk of allowing more uncertainties in the model, as long as the nominal performance does not degrade. Moreover, the ESO of the LADRC can estimate the uncertainty and compensate it quickly, so for LADRC tuning, it is a good practice to increase b to achieve better robustness. That is why sometimes in some literature, LADRC has three tuning parameters instead of two, partly due to unknown information on b and partly due to robustness requirement [11].

In [11], to increase robustness of the system against uncertainty in the time delay, two sets of parameters are considered:

1) Decrease ωo,
2) Increase b.

The system becomes unstable for the first set of parameters, while it is still stable for the second. So increasing b may achieve better robustness than decreasing ωc for LADRC.

b is the high-frequency gain of the system. The exact value of b is not necessary for a satisfactory control of LADRC. Its effect can be compensated with choice of ωc and ωo. Choice of b influences the robustness of the closed-loop system. However, detuning of the control loop using parameter b may be a compensation for the poor choice of the closed-loop poles. If more plant information is incorporated, or different poles are chosen in LADRC design, then the parameter b should not be a tuning parameter. Instead, the gain Ko and Lo should be designed for LADRC.

6. APPLICATIONS

Load frequency and voltage stability is an important power quality index in power system, any sudden load disturbance will cause the system load frequency and voltage deviation, and as the power system becomes more complex, the difficulty of control is also increasing, it is necessary to find a more appropriate control techniques such as Active disturbance rejection control (ADRC), which has the superior anti-interference and anti-coupling ability of the active disturbance rejection control (ADRC).

A. Voltage Control using ADRC based AVR

The enhancement of the dynamic performance of large power systems as well as in micro-grids during disturbances can be ensured by the application of the ADRC to AVR [43, 44]. The structure of control loop is presented in Fig.6.

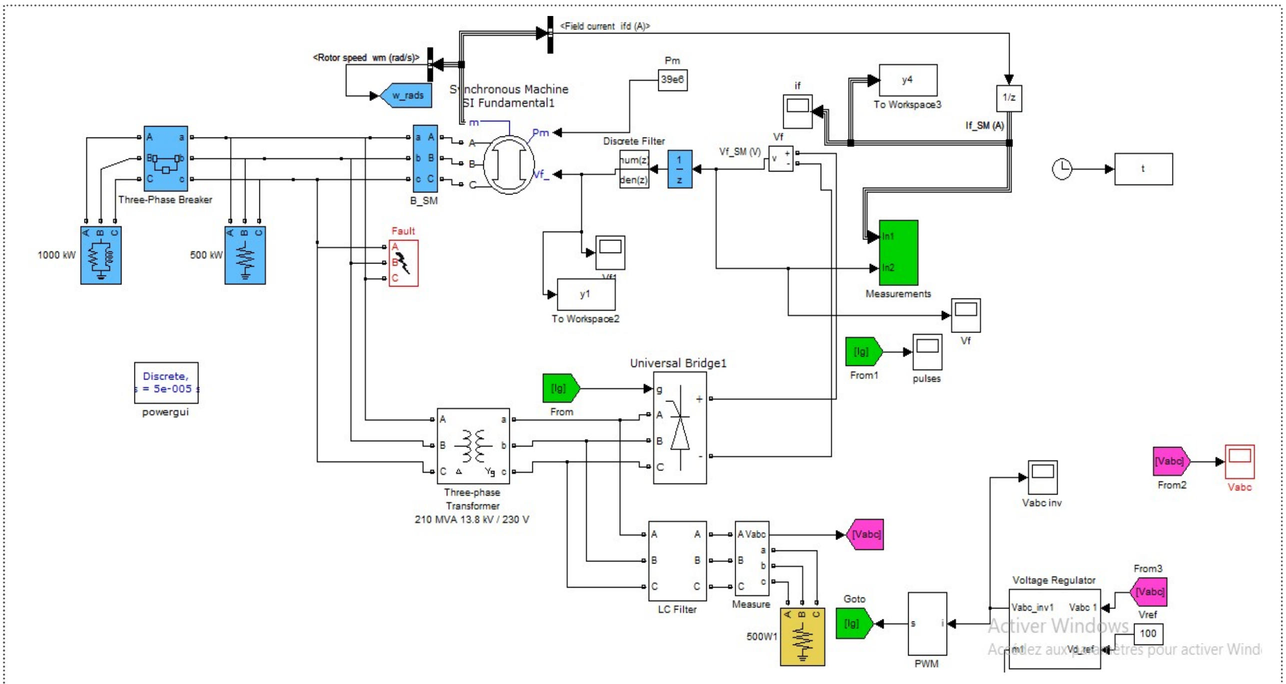


Fig. 6 Schematic diagram of the ADRC function block.

To show the performance of the proposed controller, a MATLAB/Simulink model has been established.

The performance of the proposed controller is investigated under the following two cases: a) ideal condition; b) load disturbance

The voltage regulator block shown in the figure 7 contains the hierarchical control.

The general-purpose ADRC implementation was designed as a building block that was easily accessible and used in a standard way. It encapsulates all process-independent calculations, as well as additional functionality. Its simplified schematic with its input-output specification defined to allow easy parameterization is shown in Figure 6. This block also provides error information when errors occur during operation. The ESO calculates the estimation variables and the control law calculates the manipulated variable applied to the process.

For experimental validation, the proposed command structure is implemented and executed. A MATLAB simulation model is built to test the control design, as shown in Fig 6.

```
%
clear all
clc

%% Modèle d'état de l'observateur à 3 états
   omega0 =5; % pulsation permettant de calculer le gain de l'observateur
   b0 = 12; % instable pour b0 =

   Ao = [0 1 0
         0 0 1
         0 0 0];
   Bo = [0
         b0
         0];
   Co = [1 0 0];

% Observer gain design
 polesobs = [-omega0 -omega0 -omega0];

  L = Acker(Ao',Co',polesobs)';


% Set-point tracking controller design
  omegac =0.1 ; %4.5;
  zz = 0.01;
Kp = omegac^2;
%          0         omegac^2];
  Kd = 2*zz*omegac;
```

Fig.8 ADRC program

The controller and observer bandwidths are set from Figure 8. For comparison a PI controller is tuned with a proportional gain and an integral gain. The parameters were tuned to achieve the best stable response.

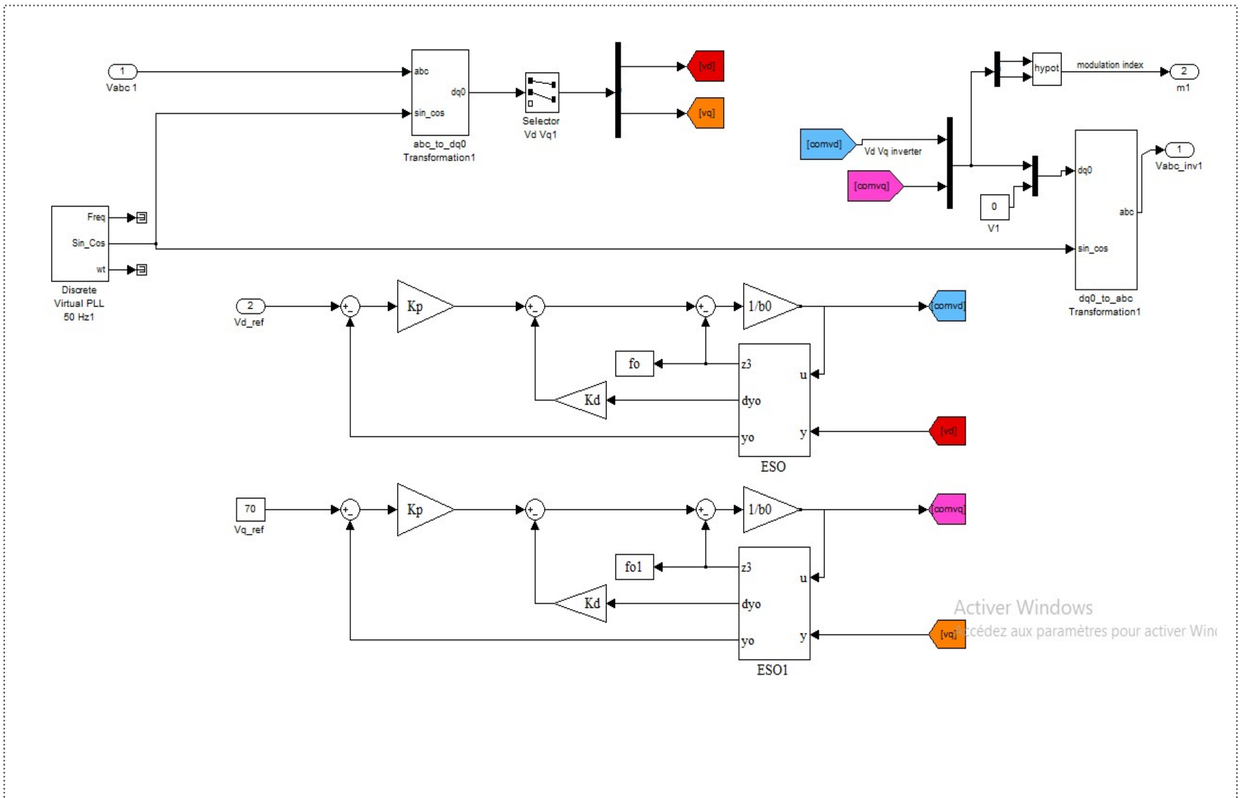


Fig.7 Voltage regulator bloc diagram

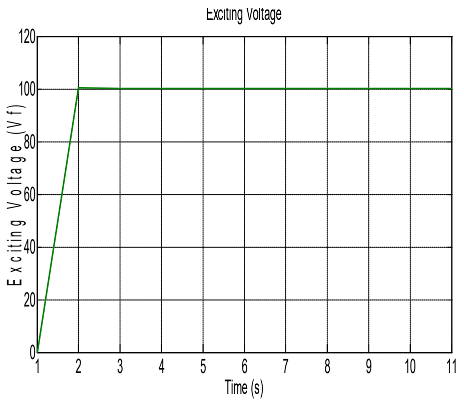


Fig.9 Excitation voltage V_f (V) with ADRC

The same values were used for simulations and measurements. Figure 9 represents the layout of the excitation voltage .We observe that the response stabilize after three second. The response is faster, which confirms the reliability of the ADRC methods.

An earthling resistance R = 1 * 10-1 ohms is applied at t=11 Sec.

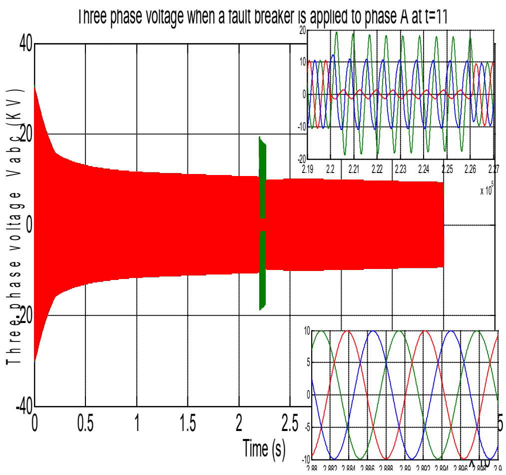


Fig.10 Three phase voltage when a fault breaker is applied to phase A at t=11.

Fig. 11 Three phase current when a fault breaker is applied to phase A at t=11

It can be noticed that ADRC controller responds quickly when a fault is applied and it offers better performance (see figures 10, 11), and therefore the requirement of voltage regulation is satisfied. The performance of the proposed controller is investigated under the following two cases: a) ideal condition; b) load disturbance Figure 12.

➢ *Simulation Results Discussion*

The Simulation results verify the efficiency of the ADRC which drives the voltage to its nominal value despite the presence of various disturbances. They also demonstrate that ADRC has better set point tracking and robust performance than PID-PSO.

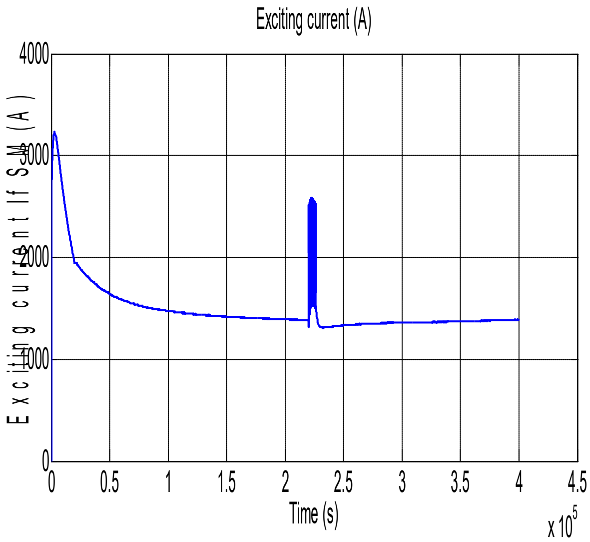


Fig. 12 Exciting current.

The good follow of the reference and the speeds of the dynamics which are ensured by the ADRC controller, compared to the PI regulator can be shown in figures 10 and 11.

B. Load Frequency Control using ADRC

For multivariable systems with weak coupling or approximate decoupling, the paper [45] designs the ADRC controller for each loop based on the diagonal model. Because the coupling between loops is not considered in this method, the parameters of the decentralized controller need to be adjusted repeatedly to obtain good control effect, and the design process is tedious and the workload is large. Vu and Lee [46] first proposed the concept of effective open-loop transfer function (EOTF) to design of multi-loop PI/PID controllers. EOTF is an approximated model, can't completely describe the cross coupling between loops, so the decoupling performance of multi-loop PI/PID controllers based on EOTF method is possible to be improved. LFC system as a typical model of multivariable coupling system, in order to solve the above problems, a novel method of ADRC controller design is introduced. This method is based on ADRC excellent tracking ability to resist disturbance, combined with EOTF concept to guide the design of decentralized ADRC controller, coupling information can be included, and can make use of ESO estimate ability to fully offset the additional error of equivalent process. Therefore, the design process can be greatly simplified. The proposed method is applied to the LFC model, and the simulation results verify the effectiveness of the developed method.

7. CONCLUSION

ADRC uses two laws to control the system the first to provide regulation by compensating for the generalized disturbance previously estimated by ESO. The second is a control by a state feedback which makes it possible to ensure stability and closed-loop set point tracking.

The advantage of the ADRC method over other simple methods is to provide a quick way to estimate performance and robustness by playing on the synthesis parameters. This is an important advantage makes it possible to meet specific regulator objectives.
This method has been proven to be used for reducing overshoot. The fast response can be obtained after adjusting the voltage as well as the frequency.

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Appendix

187M VA SG parameters.[matlab bloc parameters]

Nominal power	P_n	$187*10^6 VA$
Nominal rms line-to-neutral voltage	U_n	*13800 v*
Frequency	*f*	*60 Hz*
Stator resistance	R_s	$2.9*10^{-3}\ \Omega$
Rotor resistance	R_f	$5.9*10^{-4}\ \Omega$
Stator leakage inductance	*Ll*	$3.089*10^{-4}\ H$
Direct-axis synchronous magnetizing inductance	*Lmd*	$3.21*10^{-3}\ H$
Quadrature-axis synchronous magnetizing inductance	*Lmq*	$9.71*10^{-4}\ H$
Field leakage inductance referred to the stator	*Llfd'*	$3.0712*10^{-4}\ H$
Direct-axis damper resistance	*RKd'*	$1.019\ 10^{-2}\ \Omega$
Direct-axis damper leakage inductance	*LlKd'*	$4.91*10^{-4}\ H$
Quadrature-axis damper resistance	*RKq1'*	$2.008\ 10^{-2}\ \Omega$
Quadrature-axis damper leakage inductance	*LlKq1'*	$1.03*10^{-3}\ H$
inertia	*J*	$3.89*10^6 Kg.m^2$
Pole pair	*p*	*20*