Adaptive Control Strategy for Conveyor Drive Systems

EMIL POP*, COSMIN COVACIU**, ADRIAN AVRAM**, FELICIA NEGHINA**

*System Control, Applied Informatics and Computer Engineering Department, University of Petrosani, Romania, emilpop@upet.ro
**Ph.D. student at the University of Petrosani, Romania

Abstract: In this paper the adaptive control strategy for conveyor systems is presented. Based on the block diagram of the drive system used in conveyor transport process, the appropriate adaptive control strategy is determined. The strategy consists of two steps. First the real drive load is identified, second is regulated so that the necessary torque and power are reached. For the identification the gradient algorithm with MIT rules is used. In order to estimate the unknown parameters of the transport process, the un-phase angle $\phi$ between current and voltage is measured. The adaptive control strategy is modeled and simulated in MatLab-Simulink to certify the feasibility of the proposed method. The models and simulation results are used for designing and implementing adaptive control software in Visual Basic environment. There are done laboratory experiments and based on these the implementation in an open pit conveyor system is proposed.

Keywords: adaptive control, gradient algorithm, identification, simulation, conveyor

1 Introduction

The electric drive conveyors work with time variation and shock loads; have low efficiency and frequent electro-mechanical breakdowns. In order to reduce the power losses and electro-mechanical breakdowns as much as possible, a good solution should be the adaptation of drive to the necessary load. That means: Change the power so that there will be assured the maximum efficiency and minimum breakdowns. In this form the demand cannot be physically implemented. There is a possibility to achieve the above request as follows: adapting the motor parameters very close to static power load, using the above strategy.

For this reason, it is necessary to use as inputs the voltage and frequency to control the speed, torque and power consumption and a solution to minimize the power losses. The unknown parameter is time variation load which is difficult to measure, because many times it is non observable. For this reason the load can be estimated by un-phase angle between current and voltage as intermediate parameter. From this angle it is possible to identify the load and by this: the voltage and frequency necessary to control the speed. To achieve the above demands, an adaptive control system will be designed and implemented.

The strategy consists of developing and identifier for the motor drive load and adjusting the adaptive controller by U/f scalar method for a necessary speed and appropriate power consumption.

In fig.1 is presented a belt conveyor (T), having a drive system (A), programmable controller (AP), identification and adaptation block (BIA), voltage and frequency converter (C). The adaptive control principle presented above consists of identifying the conveyor load control $q_r$ by angle $\phi$ and according to this it will be chosen the motor speed $\omega$ so that the power will be the one requested by the load, the motor running on the mechanical U/f characteristic near the nominal point.

![Fig.1. Adaptive control strategy block diagram](image-url)
The main economic effects are: power save and efficiency increasing; sensor-less control and monitoring; software oriented control and virtual measurement.

2 Problem Formulation

2.1 The adaptive control strategy

The adaptive control strategy consists of identifying the unphased angle between current and voltage and from this it will be estimated the load, torque, voltage, frequency, speed and power losses. The speed will be reduced according to the load so that the motor works near the nominal point with maximum efficiency and power factor.

The adaptive control algorithm consists of online identification of unphased angle $\hat{\phi}$ using gradient adaptive method with MIT rule. Based on this it will be calculated the needed torque ($M_{sx}$) in order to ensure a certain transport flow ($q_x$).

So, the motor is controlled with such a voltage and frequency $U/f$ that the report $\lambda_N = \frac{M_{kn}}{M_N}$ is maintained constant and the motor torque is equal to its estimated value ($\hat{M}_{ss} = M_{sx}$).

The identifier will determine the necessary voltage and frequency in order to get the needed torque ($N_{sx}$), using the following equation:

$$\frac{U_x}{f_x} = \frac{U_N}{f_N} \cdot \sqrt{\frac{M_{sx}}{M_N}}$$

(1)

where $U_x$ and $f_x$ are the needed voltage and frequency, $U_N$ and $f_N$ are the nominal voltage and frequency and $M_{sx}$ and $M_N$ are the estimated and nominal motor torque.

In this way the motor runs closed to a nominal point on the $U/f$ mechanical characteristic generated by the identifier.

By this strategy the torque, speed and power vary, efficiency is increase and power losses are decrease. Identification is made periodically at an appropriate rate according to the conveyor speed.

In the case on load-free running, the conveyor will run at a minimum speed during a specified time period, after this it stops. This time period can be established according to the process particular conditions.

2.2 Modeling and simulation

The mathematical model in steady state regime is based on the following data: $P_N$ [kW] – nominal power of the drive motor; $P_0$ [kW] – absorbed power at conveyor load-free running; $U_N$ [V] – motor nominal voltage; $f_N$ [Hz] – nominal frequency; $n_N$ [r/min] – nominal speed; $n_0$ [r/min] – synchronism speed; $q_N$ [kg/s] – conveyor nominal mass flow; $s_N$ – nominal slip; $\lambda_N$ – nominal torque overload.

The model equations are the followings:

$$M_s = \frac{2 \cdot M_{sx} \cdot (\omega_{0s} - \omega_s) \cdot s_{sx} \cdot \omega_{0s}}{(\omega_{0s} - \omega_s)^2 + s_{sx}^2 \cdot \omega_{0s}^2}$$

(2)

Kloss formula for mechanical characteristics

$$M_N = \frac{P_N}{\omega_N}$$

(3)

nominal torque

$$M_{kn} = \frac{P_N \cdot \lambda_N}{\omega_N}$$

(4)

maximum torque

$$s_N = \frac{\omega_{0N} - \omega_N}{\omega_{0N}}$$

(5)

nominal slip

$$s_{sx} = s_N \left( \lambda_N + \sqrt{\lambda_N^2 - 1} \right)$$

(6)

nominal critic slip

$$M_0 = \frac{P_0}{q_N}$$

(7)

constant parameter

$$k_N = \frac{M_N - M_0}{q_N}$$

(8)

constant parameter

$$M_{sx} = M_0 + k_N \cdot q_x$$

(9)

static torque for load $q_x$

$$f_x = f_N \cdot \frac{M_{sx}}{M_N}$$

(10)

control strategy frequency

$$U_x = f_x \cdot \frac{U_N}{f_N} \cdot \sqrt{\frac{M_{sx}}{M_N}}$$

(11)

control strategy voltage

$$\omega_{0s} = \frac{2 \cdot \pi \cdot f_s}{p}$$

(12)

motor speed

$$p=2$$

(13)

drive poles number

$$M_{ks} = M_{kn} \cdot \left( \frac{U_x}{U_N} \right)^2 \cdot \left( \frac{\omega_{0N}}{\omega_{0s}} \right)^2$$

(14)

maximum torque for mechanical characteristic

In fig.2 are presented the strategy model and the simulation results, consisting of the mechanical characteristics on which the drive motor runs in this adaptive control strategy.
Passing from a speed to another can be done continuously or in speed steps. Usually the five speed steps are the following: maximum, higher, medium, minimum, zero.

In the model presented above, the load $q_x$ is considered known, but in reality it is not. It is necessary to estimate it by an adaptive control algorithm.

The adaptive identification algorithm is done as follows:

- Is estimated identified unphased angle between $U$ and $I$ ($\hat{\phi}$)
- Is estimated the necessary torque to drive the conveyor ($M_{ss}$)
- Is estimated transported flow ($\hat{q}_x$)
- Is estimated the necessary voltage and frequency for the inverter ($\hat{U}, \hat{f}_x$)
- The adaptive controller is set by estimated parameters
- Results the motor speed ($n_x$)
- Are determined the real power factor ($\cos \phi_{\text{real}}$) and the real efficiency ($\eta_{\text{real}}$)
- Is estimated the power save ($\Delta \hat{P}$)
- The steps above are repeated with a suitable rate cycle.

### 3 Problem Solution

#### 3.1 Adaptive control solution

In order to achieve the adaptive control there are necessary data and then it will be determined the mathematical model for estimation and identification.

Are necessary the additional data from the above section:

- $\eta_N \text{ [-]}$ – nominal efficiency;
- $\eta_0 \text{ [-]}$ – minimum efficiency;
- $\cos \phi_N \text{ [-]}$ – nominal power factor;
- $\cos \phi_0 \text{ [-]}$ – load-free running power factor;

The adaptive identifier will estimate the following values:

- $\hat{\phi} \text{ [grades]}$ – unphase angle between $U$ and $I$;
- $\hat{q}_x \text{ [kg/s]}$ – conveyor estimated flow;
- $\hat{P}_{sx} \text{ [kW]}$ – estimated necessary power.
- $\hat{\eta}_{\text{real}} \text{ [-]}$ – real efficiency;
- $\cos \hat{\phi}_{\text{real}} \text{ [-]}$ – real power factor;
- $\Delta \hat{P} \text{ [kW]}$ – achieved power savings.

Based on these there will be determined and transmitted to the controller the values:

- $U_x \text{ [V]}$ – motor necessary voltage;
- $f_x \text{ [Hz]}$ – necessary frequency;

*The supplementary equations for drive are:*

$$\eta_{\text{real}} = \eta_0 + \frac{(P_{sx} - P_0) \cdot (\eta_N - \eta_0)}{P_N - P_0} \quad (15)$$

by interpolation;

$$\cos \phi_{\text{real}} = \cos \phi_0 + \frac{(P_{sx} - P_0) \cdot (\cos \phi_N - \cos \phi_0)}{P_N - P_0} \quad (16)$$

by interpolation;

$$n_x = \frac{\hat{U}_x}{U_N} \cdot n_N \quad (17)$$

where $\hat{U}_x$ is the estimated voltage

$$\hat{P}_{sx} = P_0 + \frac{(\cos \hat{\phi}_x - \cos \phi_0) \cdot (P_N - P_0)}{\cos \phi_N - \cos \phi_0} \quad (18)$$
\[ \Delta \hat{\rho} = \left( \eta_N + \cos \varphi_N - \eta_{real} - \cos \varphi_{real} \right) \cdot P_{sx} \tag{19} \]

Identifier input equations
\[ u_1 = \sin(2 \cdot \pi \cdot f_N \cdot t) = \sin(\omega \cdot t) \]
\[ u_2 = \cos(2 \cdot \pi \cdot f_N \cdot t) = \cos(\omega \cdot t) \tag{20} \]
\[ A_1 = \frac{U_N}{10} \cdot \cos(\varphi_{real}) \]
\[ A_2 = \frac{U_N}{10} \cdot \sin(\varphi_{real}) \tag{21} \]

Adaptive identifier equations
\[ y = A \cdot \sin(\omega \cdot t + \varphi) \tag{22} \]
measured voltage equation
\[ A = \frac{U_N}{10} \tag{23} \]
measured voltage amplitude reduced by 10 times, where \( \varphi \) is the unphase angle between voltage and current.

\[ \theta^T = \begin{bmatrix} A_1 & A_2 \end{bmatrix} \cdot u = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} ; \quad \theta^T = \begin{bmatrix} \hat{A}_1 \\ \hat{A}_2 \end{bmatrix} \tag{24} \]
\[ y = A_1 \cdot \sin(\omega \cdot t) + A_2 \cdot \cos(\omega \cdot t) \tag{25} \]
\[ y = \theta^T \cdot u = A_1 \cdot u_1 + A_2 \cdot u_2 \tag{26} \]
\[ \hat{y} = \theta^T \cdot u = \hat{A}_1 \cdot u_1 + \hat{A}_2 \cdot u_2 ; \quad \varepsilon = y - \hat{y} \tag{27} \]
\[ \dot{\hat{A}}_1 = \gamma \cdot \varepsilon \cdot u_1 \quad \dot{\hat{A}}_2 = \gamma \cdot \varepsilon \cdot u_2 \tag{28} \]
\[ \gamma = (1..100) - \text{is chosen} \tag{29} \]
\[ \dot{\hat{\varphi}} = \arctan \frac{\hat{A}_2}{\hat{A}_1} \tag{30} \]

Based on these equations, the adaptive identifier is modeled as shown in fig.3.
Adaptive control model and the simulation results are presented in fig.4.

Fig.3. Adaptive identifier model

Fig.4. Adaptive control: a) model; b) simulation results
3.2 Experimental results
For experimenting there was used a squirrel-cage 1kW induction motor supplied from a 3kVA U/f inverter. The inverter was controlled directly from MatLab-Simulink by use of dSpace equipment.

Below are presented several running examples for the adaptive control algorithm for 5 different types of loads: \( q_x = 0; q_x = 0.25*q_N; q_x = 0.5*q_N; q_x = 0.75*q_N; q_x = q_N \). The results are in the following table:

<table>
<thead>
<tr>
<th>NO.</th>
<th>REAL DATA</th>
<th>ESTIMATED DATA</th>
<th>CONTROL DATA</th>
<th>SAVINGS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( q_x )</td>
<td>( P_{sx} )</td>
<td>( \varphi_{real} )</td>
<td>( \eta_{real} )</td>
</tr>
<tr>
<td>1.</td>
<td>0</td>
<td>10</td>
<td>63.26</td>
<td>0.6</td>
</tr>
<tr>
<td>2.</td>
<td>12.5</td>
<td>35</td>
<td>57.49</td>
<td>0.66</td>
</tr>
<tr>
<td>3.</td>
<td>25</td>
<td>60</td>
<td>51.32</td>
<td>0.725</td>
</tr>
<tr>
<td>4.</td>
<td>37.5</td>
<td>85</td>
<td>44.56</td>
<td>0.78</td>
</tr>
<tr>
<td>5.</td>
<td>50</td>
<td>110</td>
<td>36.87</td>
<td>0.85</td>
</tr>
</tbody>
</table>

As application for the adaptive control strategy was considered the case of open pits six conveyors system. There was designed a program in Visual Basic and tested in laboratory conditions. In fig.5 is presented the program windows during runtime.

4 Conclusions
Adaptive control is suitable to be used for conveyor systems.
Adaptive control requires the presence of minimum hardware.
The adaptive control solves the problems using sophisticated mathematical algorithms with good results.
Generally, the adaptive control ensures power savings of up to 10% of the real power used in case of non-adaptive control.
There can be used a simplified solution, which is to work with only 4 speeds: maximum, medium, minimum and zero. This simplifies the control algorithm and can be combined with fuzzy logic control.

References
Automatic Control, Modeling and Simulation (ACMOS’09), ISSN 1790-5117, pg.128-133, Istanbul, Turkey, 2009.


