Experimental prototype of an electric elevator

M Gaiceanu\textsuperscript{1}, S Epure\textsuperscript{1}, and S Ciuta\textsuperscript{2}
\textsuperscript{1}Dunarea de Jos University of Galati-Romania, Department of Automation and Electrical Engineering, Domneasca Street, No. 47, 800008, Galati, Romania, \textsuperscript{2}SC Galfinband SA, Smardan 2A, Galati, Romania

E-mail: Marian.Gaiceanu@ugal.ro

Abstract. The main objective is to achieve an elevator prototype powered by a three-phase voltage system via a bidirectional static power converter ac-ac with regenerating capability. In order to diminish the power size of the electric motor up to 1/3 of rated power, the elevator contains two carriages of the same weight, one serving as the payload, and the other as counterweight. Before proper operation of the static power converter, the capacitor must be charged at rated voltage via a precharge circuit. At the moment of stabilizing the DC voltage at nominal value, the AC-AC power converter can operates in the proper limits. The functions of the control structure are: the load control task, speed and torque controls. System includes transducers for current measuring, voltage sensors and encoder. As reserve power sources the hybrid battery-photovoltaic panels are used. The control voltage is modulated by implementing four types of pulse width modulations: sinusoidal, with reduced commutation, third order harmonic insertion, and the space vector modulation. Therefore, the prototype could operates with an increased efficiency, in spite of the existing ones. The experimental results confirm the well design of the chosen solution. The control solution assures bidirectional power flow control, precharge control, and load control and it is implemented on a digital signal processor. The elevator capacity is between 300-450 kg, and it is driven by using a 1.5 kW three-phase asynchronous machine.

1. Introduction

The Archimedes of Syracuse, Sicily-Magna Graecia (c. 287 BC – c. 212 BC) was the father of the elevator in 236 BC, pulled by animals or by hand [1]. Around 1000, in Al Andalus, in order to destroy a fortress by raising a battering ram, a lifting appliance has been used [2]. The designed elevator in 1405 by the German engineer Konrad Kyeser (28 August 1366 – after 1405) [3] consists of a pulley system powered by hands [3]. The first elevator (the flying chair) was built in the period of Louis XV of France at Versailles in 1743 [4]. In 1853, Elisha Graves Otis exhibited at Crystal Palace in New York the first elevator for carrying persons and equipped with a special safety system in case of the breakage traction cable [5]. On 23 March 1857 at the Haughwout & Co. store from New York, USA operates the first elevator dedicated exclusively to people transport. The elevator was powered by a steam engine and had a speed of 0.2 m/s, accomplished by the inventor Elisha Graves Otis, founder of Otis Elevator company [6]. In 1846, Sir William Armstrong introduced the hydraulic crane [7]. The steam powered hydraulic elevator, exposed firstly at the Universal Exhibition in Paris, was invented by French engineer León-Francois Édoux in 1867 [8]. German inventor Ernst Werner von Siemens invented the electric elevator in 1880 [9]. Around 1883, at the Peles Castle, a Viennese company mounted the first electric elevator in Romania [10].
Regarding the vertical transportation systems, there are four types of them: hydraulic, electric, pneumatic, and rack& pinion (climbing) elevators. The types of the modern electric elevators are: with machine rooms (geared, gearless) and Machine-Room-Less (MRL) elevators.

The authors of this paper proposed an electric elevator system with a backup power system consisting of both solar and battery energy sources.

2. The regenerative drive

At the Romanian level there are only a few companies that produced electric drive systems and power converters for power quality: one of them is SC Electrotehnica Echipamente Electrice SRL, but the reversible AC-AC, DC/AC, AC/DC, DC/DC electrical drive systems are based on the thyristors (natural commutated power converters) [11]. A major problem in the adjustable electrical drives systems, produced by power converters themselves, is the generation of the harmonics. Due to their negative effects and of the EMC issues, there are specific standards which specifies the harmonic limits. Thus, the normative CEI-02.02.1000 (IEC 61000-2-2) specifies the maximum compatibility harmonic components ($I_h \leq 6\%I_{N_h}$), while the norm CEI-555-2 specifies the maximum contribution in the total harmonic content allowed by one source of disturbance, respectively $I_h \leq 0.85\%I_{N_h}$ (harmonic up to order 40). The electronics devices support distortions up to 8%. The case study - phenomena to mitigate electromagnetic interference (common mode and differential) of high frequency - highlighted the efficacy of the passive filters. Finally, as a corollary of the entire study conducted, it was recommended to use a passive filter for EMC issue. European Standard EN 61800-3, Electrical power drive systems with variable speed. Part 3: EMC requirements and specific test methods, specifies the requirements for PDS (power drive systems) containing the power converters supplied by the alternating line voltage up to 35 kV rms. Electric drives covered by this standard are installed both in industrial environments and residential.

![Figure.1](image)

Figure.1 Comparative graph for power converters manufactures [14].

Traditional rectifiers widely used for supplying power voltage inverters continue to produce serious problems on harmonic content in the electrical network. By using modern power converters with forced commutation the harmonic content decreases, bidirectional power flowing and unity power factor could be obtained. The first power conversion approaches with PWM modulators were made by Ziogas [12], [13].
An analysis of competitors' product (Fig.1) made by an European company [14], shows that is is a lack of the power converter manufactures for the low power electric drive systems with, power quality abilities.

These product types will ensure a fastly high penetration in the regenerative drive systems. However, with an increasing demand for renewable energy systems, manufacturers reported an increasing trend of high power converters. The study conducted on a total of more than 40 companies producing static power converters, grid connected or standalone, shows that there is a wide price variation within manufactures, according to the used technology.

Table 1. Static power converters connected to the grid prices guide.

| Rated load power | < 1 kW  | 1-10 kW | 10-100 kW | > 100 kW |
|------------------|---------|---------|-----------|----------|
| Price (Euro / kW)| 1200-1800 | 600-1000 | 500-600 | 350-500 |

AC-AC power converters are divided into direct and indirect converters. The direct power converters have the advantage of reduced size of the reactive elements compared to the indirect ones. In order to increase the speed response of the DC voltage loop, the feed-forward load current component was introduced [15]. Control of power circulation is achieved by maintaining a constant DC voltage of the DC link. This feature is fully used for connecting multiple asynchronous machines [16]. By changing the current in the dc link, the power reversal of the entire system is obtained.

The AC-AC power converter with DC link is used in drives requiring power reversal capacity, such as lifts, cranes, wind turbines, etc [17-20]. The AC-AC power is used in the industrial AC drives that are needed to control the voltage and frequency of the AC machines.

The main objectives of the project are the design, development and testing of the AC-DC power converter system. In particular, the power converter system must have the following characteristics:

a) Controlling the phase input currents such that have to be sinusoidal and in phase with the supply phase voltages (unity power factor).
b) DC link voltage control at a constant value.
c) Input-output Power balance (output power converter system to be as the power input to the system).
d) Control of the circulation power, for regenerative operation.

The power control is based on a DC voltage control loop and of load power detection. The load power is used as the adequate feed-forward
current component as reference of the current loop. The output power is calculated either from the output of the DC link circuit or at the terminals of the AC power supply of the machine. Power feed-forward control allows to calculate the reference current based on the load power converter such that the power balance is satisfied.

3. The prototype
The prototype is an elevator which aims to raise variable loads counterbalanced by a trolley which sets counterweights (Fig.2). The main elements of the installation are:

A. vertical beam HEB 300 that provides a driveway for the 2 trolleys. This beam is assembled with a foot of the thick sheet through which the beam is fixed to the floor with four anchor bolt type screw. At the same time, on the beam at the top are placed two electric motors – Induction Machine (IM) with included brake, DC motor, and hydraulic motor to drive the trolleys, tachogenerator, joint gear, couplings related, joint chain transmission, cable drum lifting, the diverting pulleys, cable traction, and the two trolleys.

B. The designed electric drive system controls the movement of the trolleys. The AC drive consists of an AC motor with rated power \( P_n = 1.5 \text{ kW} \), and 1500 rev/min synchronous speed, flange mounted with included brake- FEA 2.5 type, supplied by a frequency converter to get the output variable speed control, the feedback speed being assured from the adequate tachometer mounted on a special bracket. The rated power of the DC motor is \( P_n = 4 \text{ kW} \) at 1500 rev/min. This DC motor is self ventilated and controlled in speed mode.

The hydraulic motor is driven by an own hydraulic station composed of hydraulic oil tank, pump, pressure control and command equipment, and hoses connection.

C. Common transmission with double chain, 10A type, with role of forward movement from the electric and hydraulic motors to the common gearbox.

D. Common 2-stage mechanical gearbox with transmission ratio \( i = 50.4 \),

**Figure 3.** Dynamic sizing of the electrical machine.
E. The reel for the traction cable, diverting pulleys, and the cable traction.  
F. Platform support gearbox, cable drum and diverting rolls, platform support for electric motors, hydraulic motor and tachogenerator.  
G. Trolley for the variable load, trolley for the counterweights  
H. Electric Drives cabinet

4. Selection of the electric motors  
The electric motors have been selected based on the dynamic procedure (Fig.3). Weight cabin and half payload are balanced by counterweight, which is guided in its movement runner. In this manner, the necessary power of the electric motor is decreased by 3 times. The counterweight conduct to a reduction 3:1 of the necessary electromagnetic torque, leading to significant energy decreasing. In order to control the load (the cabin and the rated mass) based on the imposed tahogram (fig.3), the regenerative AC drive system have been considered.

5. Numerical simulation results  
In the Fig.4 the control system of the regenerative power converter with solar backup power is shown. The numerical simulation results are obtained based on the developed Matlab/Simulink regenerative power converter of $S_n=22kVA$ (Fig.5) [21]. The parameters of the input inductance are $L_{in}=2.1mH$, $R_{in}=0.001\Omega$, and the dc-link capacitor of $C=1565uF$ is chosen. The electric motor type is squirrel cage asynchronous motor with rated power $P_n=1.5$ [kW], $n_N=1420$ [rpm] under the rated load torque $T_L=10$ [Nm]. By using this topology for the prototype the braking energy is recovered into national grid. The solar backup system is capable to support a voltage outage up to 280 minutes. Taking into account the above mentioned constraints, a photovoltaic panel of 1000W and a 12V, 92Ah battery pack are inserted.

Figure 4. Block diagram of the complete control system of the quasi sinusoidal AC-AC converter.  

Through the numerical simulation results, the quality of the entire control is shown: for a proper speed cycle (Figure 6) under a load torque (at $t=0.2s$) of 7 Nm (Fig.7), by taking into consideration that the initial state begins from 0 (fig.6), the reactive current control is shown in the fig.8, the active power control efficiency in fig. 9, and the dc link voltage control in Fig.10. Moreover, during the imposed speed cycle, the unity power factor (Fig.11) is shown both in inverter and regenerating modes of operation (Fig.12). In the fig. 6 the speed control high performances could be found.
**Figure 5.** Simulink model of the ac-ac power converter with PV back-up power system.

**Figure 6.** Speed control performances.

**Figure 7.** Comparative results: the load torque and the electromagnetic torque.
Figure 8. Reactive current control performances.

Figure 9. Active current control performances.

Figure 10. The dc link voltage loop control performances.

Figure 11. Unity power factor in any operating conditions.
6. Functional tests on the power side

Functional tests were performed and on the power side. It described the procedure for making experiments. Also they were measured DC link voltage and current, four strategies in real-time modulation (sinusoidal, inserting third order harmonic, phasor and optimized) have been developed and implemented. For high output voltages the use of a precharge circuit is required. The precharge circuit (Fig.13) consists of three-phase rectifier and it is designed in order to charge the dc link capacitor under a limited dc current (Fig.14).

The implementation has been done both on dSpace platform, the control board and the signal processor. The sinusoidal modulation has been involved firstly (fig.15). The V/f scalar control of the three-phase induction motors has been implemented on the dSpace platform (Fig.16-18).

Figure 12. Relationship between grid current and grid voltage showing unity power factor operation.

Figure 13. The experimental precharge circuit.

Figure 14. The precharge voltage and the corresponding current.

Figure 15. Duty cycles generation based on the sinusoidal modulation.
7. Conclusions
An experimental elevator prototype has been presented in this paper. Firstly, the mechanical side is described, followed by the experimental platform consisting of power electronics and control implementation. The speed control has been performed. The sinusoidal modulation has been implemented by using both dSpace platform and the autonomously 16-bit digital processor (Digital Signal Processor), specially designed to control AC motors.

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