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DISTURBANCES EMITTED TO THE NETWORK AND ENVIRONMENT BY VARIABLE FREQUENCY ELEVATOR DRIVE APPLICATIONS

PhD Theses

by
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1. INTRODUCTION TO THE TOPIC

With the spread of urbanisation and the emergence of metropolitan areas multi-story buildings appeared and proliferated. This brought along the need for vertical transportation (freight, passenger). Today, the existence of multi-story buildings without elevators is unimaginable.

Due to advances in technology the elevator industry is capable of producing and operating high-speed, high capacity elevators providing a comfortable ride-experience. All this has been made possible by the advent of power electronics such as the emergence of technologically advanced semiconductor elements which, as a result of their decreasing costs, have seen widespread use. However, despite all their advantages, these new advances have also been the source of hitherto unconsidered problems. The alternating current choppers and frequency converters utilised in elevator drive systems act as high-power, so-called non-linear loads causing disturbances in the electric supply system. At the same time, the control systems of modern elevators are typically low-wattage and are quite sensitive to disturbances on the network.

Changes in elevator technology are a part of the considerable changes in building technologies. The following are affected: energetics, lighting technology, control and measurement systems, safety systems, communication technologies and environment protection. The use of information technology and electronics has become standard in these areas. Intelligent buildings are now in existence where high levels of energy are required for operation but low energy levels suffice for the control and management of systems. The same is true of modern-day elevator control and monitoring systems. These systems are sensitive to network interference; however, they themselves are quite often the source of such disturbances.

The following elevator systems are installed in Hungary:

- Elevators with a dual-speed, asynchronous machine-based drive system
- Elevators with AC chopper supplied, variable-frequency, asynchronous machine-based drive systems
- Frequency converter supplied asynchronous machine-based drive systems

Elevators with a single or dual speed, asynchronous machine-based drives do not meet the requirements for modern-day elevator systems either in terms of power transmission or passenger comfort [1], [3]. These systems may be considered as linear loads connected to the electric network. The current distortion factor is not significant. The electric network is exposed to disturbances only during starting and switch-over periods. The power factor depends on the load. Regarding radiated interference, the operation of the high-inductance mechanical braking mechanism has quite an adverse effect.

Elevators with AC chopper supplied asynchronous motor drive systems, known as phase-splitting inverters in professional jargon, have seen widespread use, are quite reliable and are suitable up to speeds of 2,5 m/s. The motor-side Park vector patterns show a hexagonal symmetry, as dictated by the presence of six semi-conductor elements, resulting in the typical and the largest disturbance which occurs in the 5^{th}, 7^{th}, 11^{th}, 13^{th} harmonics. Commutational reactive power demand depends on the angle of the ignition delay (maximum at $\alpha = 90°$) [2], [4], [9], [12], [13]. Current harmonics on the electric network are within acceptable tolerances and can be further reduced by choking reactors. The harmonic distortion factor is tolerable, because the inductance of the motor limits the fragmentation and the slope of the current. This type of drive mechanism doesn't generate major radiated interference; The high-inductance mechanical brake system is more of a factor in this regard.

Modern, frequency converter supplied, variable-speed drives have replaced other solutions in almost all areas of industrial application. They are replacing the previously ubiquitous motor-generator-based drives which were operated on the controlled - "phase-splitting" principle. Their rise is due to their efficient power transmission properties. The supply of asynchronous motors through frequency converters (inverters) ensures continuous and lossless governance of their revolutions by means of the simultaneous alteration of the supply voltage and frequency [6] [8] [16]. Inverters applied in the elevator industry are composed of IGBTs which are controlled by PWM [11]; their control is field-oriented [10], [12], [14], [16]. However, these favourable drive characteristics achieved through the use of modern technological solutions come at a price. Frequency converter supplied drives pollute the electric network to a greater extent than those operating on the phase-split principle.

2. OBJECTIVE

The goal of my research is a theoretical and metrological examination of electrical disturbances caused by elevator systems. On the basis of the domestic and international technical literature, as well as standard specifications, I will discuss elevator systems and the low and high-frequency disturbances and their effects on the quality of electric power and, indirectly, on our surroundings.

The relevance of the topic and the timing for this study can be explained firstly by the fact that elevator systems as a potential source of electrical interference as well as a factor influencing the quality of electrical power in electric networks haven't been subject to study. This topic has received scant coverage in the literature. Secondly, the proliferation of so-called non-linear loads, which include variable-speed drives, must force a change in attitude, as the prevalent design and operating practices are not feasible any longer [5]. Loads on the electric network have been regarded as linear ones, that is to say they assumed that equipment connected to a sinusoidal voltage form would draw sinusoidal current. Thirdly, there is a relatively new concept: Electrosmog, a part of which is the electromagnetic field [7], generated by elevators used in office and residential buildings. The concept and its effect on the human body enjoy widespread interest and should, therefore, be worthy of scientific study. This research aims to cover the gaps outlined above.

The equipment such as network analysers suitable for accurate measurements, and the elevator systems of various principles which formed the technological background for the research were provided at the Institute of Information Technology and Electrical Engineering of the Pollack Mihály Faculty of Information Technology and Engineering at the University of Pécs and by its industrial partners.

3. RESEARCH METHODOLOGY

The nature of this topic called for a deductive research strategy. This served as a framework for the examination of conducted and radiated disturbances in the supply network emitted by AC chopper and frequency converter fed asynchronous motor drives for elevators which were examined in an unloaded state while travelling upwards (EU – Empty cabin Upwards) and downwards (ED – Empty cabin Downwards) respectively.

When selecting the right machinery to be involved in the research, I took care in the interest of comparability that the technical parameters (payload, weight, lifting height, speed) of the elevators should not differ significantly. In addition, I wanted to ensure that among the dual-wound asynchronous motor-driven systems there should be one capable of dual-speed operation. The dual-speed, asynchronous motor drives are connected directly to the mains and receive a supply of sinusoidal power and act as linear loads on the mains. This way, the same machinery can be used to compare the effects of a linear and a non-linear load provided the machinery is fed either through a frequency converter or directly by the mains.

I carried out the examination of conducted disturbances transmitted along electrical lines using a HIOKI 3196 network analyser capable of measuring, recording and evaluating the quality of low-voltage, industry-grade electricity. I measured and recorded the features listed below which are suitable for illustrating the electrical disturbances caused by non-linear loads:

- During the complete journey by an empty cabin travelling upwards and downwards respectively:
  - active power over time,
  - the rms value of the phase current as a function of time,
  - the rms value of the phase voltage as a function of time,
  - the positive peak value of phase current as a function of time,
  - the phase current distortion factor as a function of time,
  - phase voltage distortion factor as a function of time.
- At the start of an empty cabin moving downwards:
  - the shape of three-phase voltage,
  - the shape of the three-phase current,
  - the three-phase voltage value,
  - the three phase voltage peak,

- the value of the three phase voltage distortion factor,
- the value of the three phase current distortion factor,
- the value of each harmonic current component up to the 50^{th} harmonic,
- Fourier spectrum of voltage,
- Fourier spectrum of current.

The special attention devoted to the start period of motion is warranted because this period places the heaviest strain on the drive as well as on the electric network.

The ESM-100 measuring device manufactured by Maschek was used for the measurement of radiated disturbances. This device utilises a patented method which allows the isotropic measurement of electric and magnetic fields simultaneously.

Two consecutive measurement cycles were performed in the case of all tested elevators.

- The first measurement was taken while the empty cabin was moving downwards at reduced inspection speed in order to determine the spatial location of maximum radiated emissions. I recorded and measured the *E* electric field strength and *B* magnetic flux density values on an elevation plane 0.5 meters above the drive shaft with the measurements arranged in a matrix at intervals of 0,25 meters. The instrument determined the electric and magnetic field vector components in all three spatial directions (X, Y, Z) - in 5 Hz - 400 kHz frequency range - and calculated the resulting vector in 3D. The X axis was parallel to the drive shaft while the Y axis was perpendicular to it. Using the Graph ESH-100 application I determined the point of maximum value on the basis of the three dimensional measurements.
- During the second part of the radiated disturbance measurement process I measured the changes in electric field strength and magnetic flux density over time in the locations described above. The elevator was in the same load state as during testing for conducted disturbances transmitted along electrical lines: That is to say, I examined the full path described by an empty cabin travelling downwards (ED) and upwards (EU) respectively.

The curves yielded provide information on the effects exerted by the drive motor during the period of starting, at constant revolutions and when braking.

4. SCIENTIFICAL RESULTS

THESIS I.

Based on a comparison of phase current distortion factors of alternating current elevator drives I have found that, dual-speed asynchronous machine-based drive systems providing low ride-comfort emit disturbances of low levels and thus can be considered as linear loads. Phase current distortion factors caused by asynchronous machine-based, variable speed elevator drives fed by frequency converters or alternating current choppers significantly exceed the reference values of dual-speed asynchronous machine-based drive systems measured in motor and generator mode.

Based on a comparison of measurements obtained on the same asynchronous machine during, on the one hand, frequency converter fed operation and, on the other hand, during dual-speed operation, it can be concluded that network disturbances caused by a frequency converter fed drive are an order of magnitude higher than those arising from a dual-speed drive. The maximum value of the total harmonic current distortion factor with an empty cabin moving downwards (ED) came to $THCD_{fr2EDmax} = 145.9\%$ during regulated operation, while during dual-speed operation $THCD_{2spEDmax} = 25.5\%$. The maximum value of total harmonic voltage distortion during variable speed operation $THVD_{fr2EDmax} = 4.09\%$, whereas during dual-speed operation $THVD_{2spEDmax} = 3.51\%$.
In case of an empty cabin moving upwards (EU) in generator break mode of the asynchronous motor the total harmonic current distortion factor $THCD_{2spEUmax} = 26.11\%$, significantly lower than that in case of frequency converter mode of $THCD_{FCEUmax} = 148.43\%$. This significant difference does not appear in the voltage distortion factors of $THVD_{2spEUmax} = 3.14\%$ and $THVD_{FCEUmax} = 3.38\%$ respectively thank to the well dimensioned supply cable. As far as constant speed operation ($THCD_{2sp} = 8\%$) of the drive is concerned, it is apparent that there is practically no disturbance emitted to the electric network.

It can be said that dual-speed drives, albeit offering low-levels of ride-comfort are the best from the point of view of causing the least amount of conducted interference and therefore, to all intents and purposes, can be considered as linear consumers.

THESIS II.

Through determining the phase current distortion factors, the current harmonics and phase voltage distortion factors I have demonstrated that, frequency converter supplied induction motor-based, variable speed elevator drives (without filter circuits, or reactors) although possessing favourable power transmission characteristics emit more disturbances to the electric network than those drives operating on the "split- phase" principle.

The maximum current distortion factor values in the case of frequency converter supplied, variable speed asynchronous drives significantly exceed (137, 134.56, 145.94, 148.43%) the corresponding values for split-phase controlled elevator drives (64.95 to 94.79%) both in cases of the empty cab travelling in an upward or a downward direction.

Table 1: Current distortion factor maximum values

Elevator equipment		$ITHD_{max}$ [%]	
No.	Operating Principle	ED	EU
1.	Frequency converter	137	134,56
2.a.	Frequency converter	145,94	148,43
2.b.	Dual-speed	25,5	26,11
3.	Split-phase	74,61	73,69
4.	Split-phase	64,95	94,79
5.	Split-phase	69,45	105,68
6.	Split-phase	85,75	93,5
7.	Split-phase	81,29	88,4

It should be noted that the variation is even larger when the phase current distortion factors were measured at constant speed operation. The current is periodic, but not sinusoidal with both types of variable speed drive systems.

Due to the capacitor charging current, pulse peaks are created in frequency converter elevator drives while with "split-phase" drives intermittent pulses are created. The dominant current harmonics are the 5^{th}, 7^{th}, 11^{th}, 13^{th}, 17^{th}. Owing to the differences in operating principles in the two drive arts, the percentile values of the current harmonics show significant deviation relative to the baseline frequency values. In the case of variable speed drives, the value, for example, of the 5^{th} harmonic is 79.5% and 76.3%, of the 7^{th} harmonic is 71.4% and 67.8%. In comparison, for an AC chopper-fed elevator these values are much lower (15.4%, 9.4%, 15.8%, 11.8% and 13.5 % and 7.1%, 5.1%, 7.0%, 6.7% and 7.4%).

THESIS III.

The significant current distortion emitted by frequency converter-fed elevator drives does not affect the characteristics of the power supplied to these drives. The phase voltage distortion factors and the voltage values at the connection points in all load states are within the prescribed ranges, since with a correctly dimensioned power cable (with a suitable cross-section) and a none too distant transformer, the harmonic currents only cause a minimal voltage drop on the impedance depending also on the frequency apart from the length, cross-section and structure of the cable.

Based on measurement data, the following can be deduced concerning the power supply voltage characteristics of the elevator systems under study:

- In all cases, the values for the total phase voltage distortion factor are below the 8% threshold set out by specifications (EN 50160:2011),
- Neither the minima nor the maxima of the rms phase voltage values reach the required 207 V < U_n < 253 V threshold values.

The current, including harmonics flowing through frequency converters and other non-linear loads, can create a voltage drop which also carries the harmonic components. The extent of the voltage drop is proportional to the impedance of the supplying network measured at the connection point and to the current harmonics. Since the supplying network has usually an inductive nature, its impedance increases with increasing frequency. This voltage drop distorts the mains voltage; in other words, it degrades the quality characteristics of electricity on the network not only on non-linear consumer terminals, but at all other terminals of loads connected in parallel to the same transformer.

The voltage drop is not significant provided power lines are correctly dimensioned (with suitable cross-sections) and the transformer is not remotely placed. In these cases, as verified by measurements, despite a relatively high current distortion factor value, the voltage distortion factor will still be within acceptable limits.

THESIS IV.

I have proved through the spatial mapping of radiated disturbance emitted by asynchronous motor elevator drives that, spatial distribution of magnetic flux density and maximum flux density values are not affected by the working principles of elevator drives. These parameters are jointly determined by the type and power of the elevator motor, by the structure of stator and rotor windings and insulation, by the type of the brake magnet and by the load condition.

Recorded data of radiated disturbances by asynchronous motor-based variable speed drives show widespread variation, but it was concluded through the 3D measurements that maximum flux density was invariably located over the axis of each drive. Values decrease with increasing distance down to environmental values occurring 50-70 cm from the point of maximum value. The three-dimensional representation of the data set shows components such as the brake magnet or the transformer for the controls as having high radiation. It wasn't considered practical to compare magnetic flux density values measured in the various elevators since these machines were manufactured by different vendors (LOHER, ASTOR, LANCOR), and even when the manufacturer was the same, as is the case with the LOHER elevators, they were of different models with different dimensions and structural design.

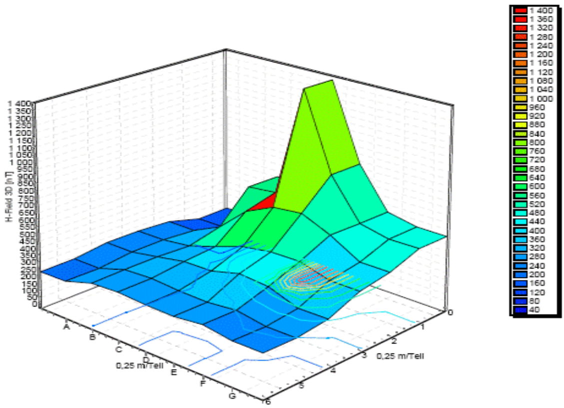

Figure 1. Magnetic flux density values in a three-dimensional magnetic layout measured on a plane 0.5 m above the motor drive.

THESIS V.

I have shown that of the spatial components of the disturbance radiated by asynchronous motor drives, the electrical component being constant in time, and independent of the load condition as well as the magnetic component depending on the parameters and load condition of the drive motor meet the prescriptions. State of the art frequency converter fed and alternating current chopper fed elevators emit no disturbances harmful to the health.

In practice, field strength depends on the surface area, distance from the surface and on the voltage level compared to ground potential. The test results supported these conclusions since, although I recorded different values, I measured values which were constant in time irrespective of the load. The measured values varied considerably; however, they conformed to standards.

Magnetic field component is generated in the environment of the equipment under power if current flows through it. This is reflected in measured and recorded values of magnetic flux density as a function of time.

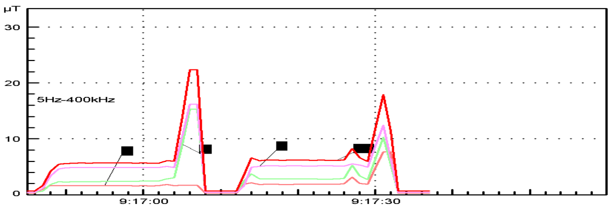

Figure 2: Changes in the flux density of the magnetic field over time in case of the frequency converter-fed elevator drive travelling upwards (EU) and downwards (ED) with empty cabin

Based on the evaluation of the diagram, the following conclusions can be reached:

- During the period of the motor drive starting, the flux density increases over the environmental value with the degree of the increase depending on the type of drive-motor used,
- Values obtained with the various elevators show a large variation (2.85 to 25.5 μT) depending on the type of the motor

drive and design; however, these values all comply with relevant standards,

- Of the two load states, downward motion of an empty cab usually produces greater maxima which can be explained by the higher currents associated with this operating state,
- The peak values of the curves signal the starting and the stopping of the motor associated with a start-up surge, and another current surge which is the result of braking (brake magnet operation).

Measured maximum values do not exceed the health limit values for electric field strength and magnetic flux density stipulated by prescriptions of different sources, like the European Union, Germany, Sweden, Russia, Hungary. Values of the field components decrease with increasing distance from the elevator machine, therefore it can be stated that, radiation harmful to the health are present neither in the machine room, nor in the cabin used by the passengers.

5. USE OF RESULTS

The test results showed the non-linear nature of AC chopper and frequency converter-fed asynchronous motor drives being installed partly as replacements of dual-speed asynchronous motor drives applied previously by the elevator industry and acting as linear loads. As demonstrated by these tests, the impact of these loads on the quality characteristics of electric networks should be taken into consideration during design and operation.

For instance:

- when dimensioning the supply cable,
- when selecting the drive control.,
- when selecting the driving machine,
- When assessing the possibility of reducing adverse effects on the network.

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