HIGH-PERFORMANCE ELEVATOR CONTROL SYSTEM

Optically character-recognized copy of original in Elevator World, Nov., 1984. Minor corrections made.

by C.A. Skalski, Senior Member, IEEE, United Technologies/Otis Elevator Company

INTRODUCTION

During the past five years two basic types of elevator motion controls were developed and placed into service. These are for high-speed, high-rise gearless elevators using SCR and MG motor drives. Control achieved is swift, precise, and smooth. Flight times are usually within 0.3 sec of ideal. Leveling accuracy is typically within several millimeters. Vertical vibrations are insignificant and one type of control can work directly into hoistway resonances without the need for tuned compensators.

The systems make extensive use of closed-loop techniques. The velocity and position controls rely on this. Additionally, these techniques were applied to pre-torquing, motor field weakening, and brake lifting.

The velocity controls are the heart of these systems. These can now be designed quickly, in a highly structured manner. Details related to hoistway resonances need be considered only in a general way. The basis for this is the Hoistway Theorem, which is explained after a consideration of elevator control system requirements.

ELEVATOR CONTROL SYSTEM REQUIREMENTS

The basic form of the control systems is shown in Fig. 1. There is a dispatcher which controls a group of elevators. This acts with the operational control to provide a destination command that is caused to be executed by the profile-generator/position-reference system. The output of that system is a velocity command. This in turn results in a controlled force on the drive sheave. When combined with a lifting of the brake, car motion occurs. This is sensed continuously with a primary position transducer (PPT). Velocity of the drive sheave is sensed with an encoder called the PVT (primary velocity transducer). Load information is obtained by transducers under the cab and is used for pre-torquing and operational control. The system is safe-guarded by use of both mechanical and electrical braking, speed governors, safety jaws to grip the rails, hoistway switches, buffers, and interlocks. Also, PPT and PVT information is used for safety purposes. Most of the system logical functions are performed by processors. A portion of the velocity control is also implemented in a processor.

A typical machine-room arrangement is depicted in Fig. 2. The mounting of the PPT is shown. This device uses two encoders coupled by precision gearing. It is connected to the car by means of a steel (selector) tape. A detailed view of the PPT [1] is shown in Fig. 3.

Fig. 2. Elevator System

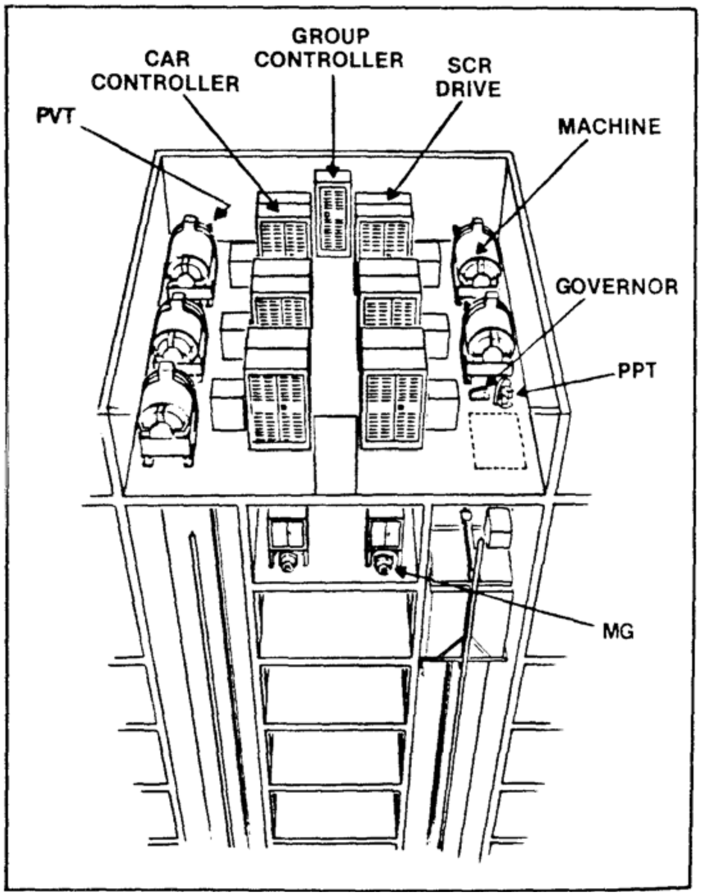


Fig. 1. Basic Elevator Control System

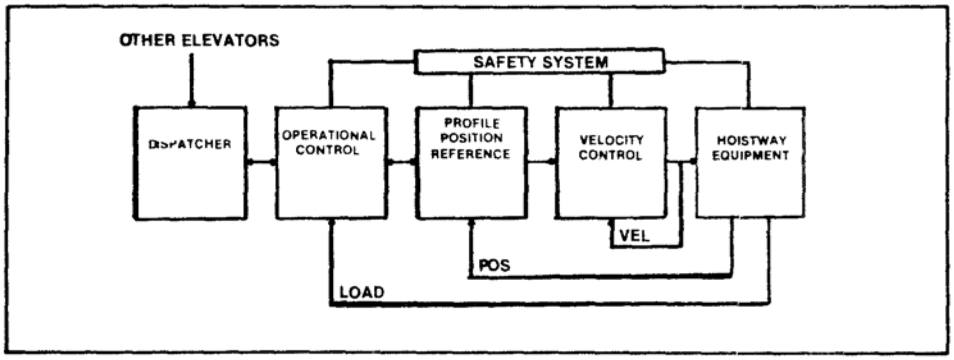
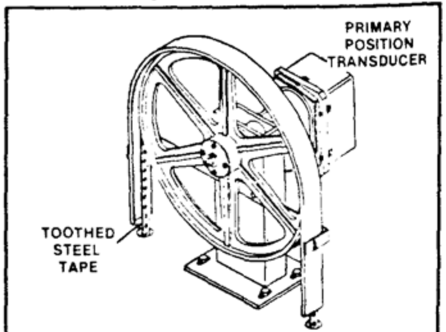


Fig. 3. Primary Position Transducer



Continued overleaf

Continued from overleaf

HIGH-PERFORMANCE ELEVATOR CONTROL SYSTEM

Elevator motion controls have requirements differing substantially from those for industrial drives and most horizontal transport systems. Velocity control operation at very low speeds must be swift to permit satisfactory leveling. At all speeds, vibration levels must be small for passenger comfort. This requires special control design to cope with ever-present, lightly-damped hoistway resonances.

Additionally, the controls need to have jolt-free starting for a wide range of loads. This requires having a pre-torquing system. To be economical, field weakening at high-speeds is important. Quiet operation in the cab and machine room sometimes requires use of a harmonic filter with SCR drives. Reliability and long-term stability of adjustment are additional considerations.

The designs presented here were made to meet these application conditions:

1. Contract speeds from 2.7 to 9.8 m/s with 2% accuracy
2. Load capacity range of 900 to 3600 kg.
3. Rise to 394 m.
4. Acceleration of 1/8 g and jerk of 1/4 g/sec.
5. Leveling accurate to 6 mm with 3 mm desirable.
6. Floor to floor time of 4.3 sec for 3.6 m (12 ft).

The acceleration and jerk requirements are imposed by comfort and hoistway equipment limitations. The one-floor flight time is based on the stated acceleration and jerk levels.

HOISTWAY THEOREM

The driven elements in an elevator system are mostly reactive. These are masses and springs which are lightly damped by hoistway friction and (wire) rope hysteresis. Modeling of the hoistway for velocity control design is done with the drive-sheave (mechanical) impedance. This relates drive-sheave velocity to applied force. The hoistway theorem states that the drive-sheave impedance function has a phase angle in the. range -90 to +90 deg. This can be proved using arguments based on energy conservation, noting that the hoistway is a passive system. It has also been proved in other contexts by Guillemin [2] and Foster [3]. Foster's reactance theorem states that the poles and zeros of a reactive impedance function determine the frequency characteristics of the impedance. Further, the poles and zeros must alternate. Each alternation causes a 180 deg phase shift such as - 90 to + 90 to - 90, etc.

The impedance functions for elevators are a function of car position in the hoistway. The amplitude peaks are resonances and the dips antiresonances. The phase shift approaches +90 deg just ahead of a resonance and -90 deg just past it.

It is neither practical nor necessary to use the exact impedance function for control system design. The phase shift around a velocity control can go to 180 deg before a potentially unstable condition exists. Allowing 90 deg for the hoistway, up to 90 deg of phase lag is permitted for the rest of the control. Usually, it is desirable to try to limit this additional amount to 45 deg to achieve a robust design. Phase shifts in the drive system and processor are of primary concern.

VELOCITY CONTROL WITH SCR DRIVE

The basic, normalized form of the control is shown in Fig. 4a. This model is valid for frequencies below the hoistway resonances. It is later extended to include these resonances.

There is a proportional-integral (PI) controller. The drive/motor/load combination is represented by an integrator 1/s. The primary feedback is to the dictation input. A secondary feedback goes to a point after the controller. GR is the integral loop gain and R is usually close to unity. Names given to G and R are GAIN and RESPONSE, respectively.

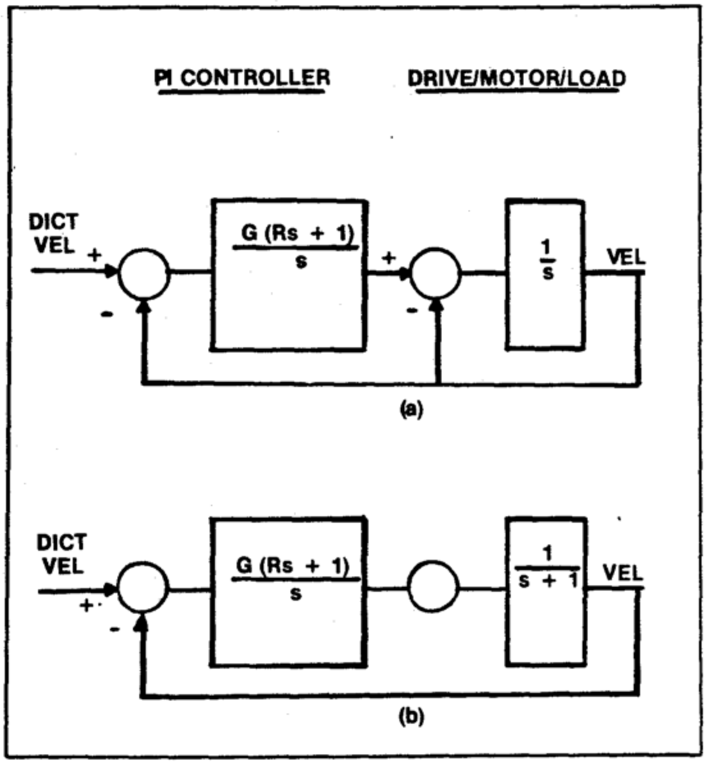


Fig. 4. Basic Form of SCR Velocity Control

The theory of control operation is now discussed using well-known control concepts [4]. First, a reduced block diagram (Fig. 4) is prepared. This shows that the low-frequency phase shift of the controller is compensated by the secondary feedback loop. The resulting approximate open-loop transfer function = G/s. The closed-loop transfer function = G/(s+G). This function reveals no speed error for constant dictation. For a ramp input, an analysis shows that the output lags the input by 1/G sec. This is the tracking delay. G is on the order of 10.

The basic control is now extended to include hoistway resonances by substituting the hoistway impedance for the 1/s block in Fig. 4a. Also, the control loop is considered for frequencies above 2 Hz, since hoistway resonances are

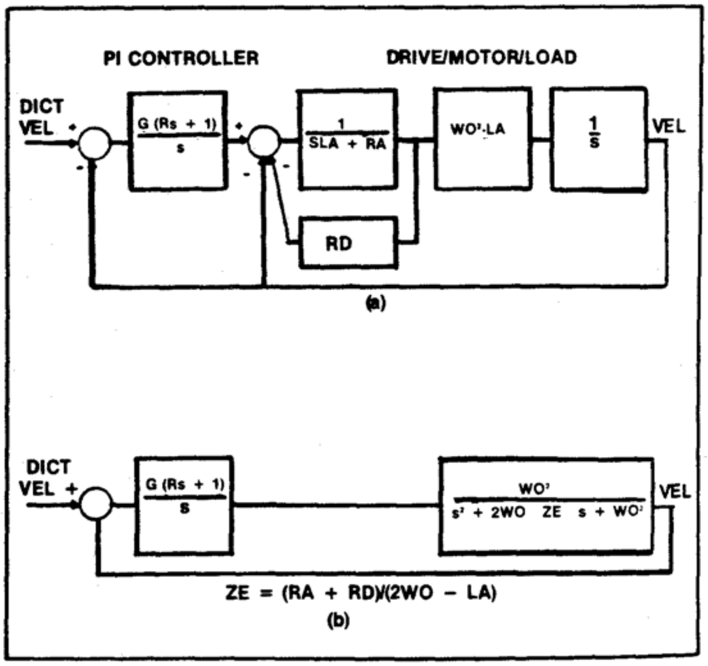


Fig. 5. Basic Form of MG Velocity Control

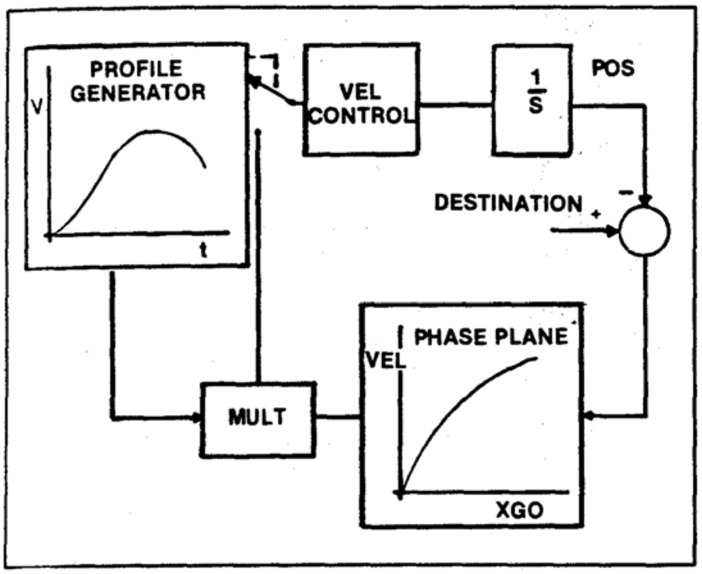


Fig. 6. Position Control System

usually in the band 2-10 Hz. This leads to the conclusion that the open-loop transfer function is proportional to the hoistway impedance for all frequencies. The Hoistway Theorem states that the phase must lie between -90 to 90 deg This phase condition assures a stable control, irrespective of gain. Also, it assures that the magnitude of the closed-loop transfer function cannot exceed unity. Thus the velocity output cannot exceed the dictation, irrespective of the frequency and damping of the resonances. This bound on spurious response is adequate for an elevator system.

VELOCITY CONTROL WITH MOTOR-GENERATOR DRIVE

Controls using MG sets (Ward-Leonard) are configured differently from those with SCR drives. This is done to avoid having to implement a high-performance armature current regulator. These controls can usually work into hoistway resonances without the use of additional compensation.

The basic form of the control together with a reduced block diagram are shown in Figs. 5a and 5b. There is a PI controller, as in the SCR-drive system. The drive/motor/load is represented in normalized form such that the armature inductance LA and resistance RA stand out. The inner-most feedback loop represents armature-current feedback. The next feedback loop relates to counter-EMF generation in the motor. Finally, the outer loop is the one used to control velocity.

The natural frequency WO is determined by. the hoistway inertia, armature inductance, and the field strength. It is a fundamental system characteristic, having a value on the order of 5 rad/sec. The associated damping ratio ZE can-be controlled by varying RD, the gain of a feedback loop. ZE must be made sufficiently large to obtain satisfactory leveling performance. Some tradeoff exists between adjustment of the response R and the damping.

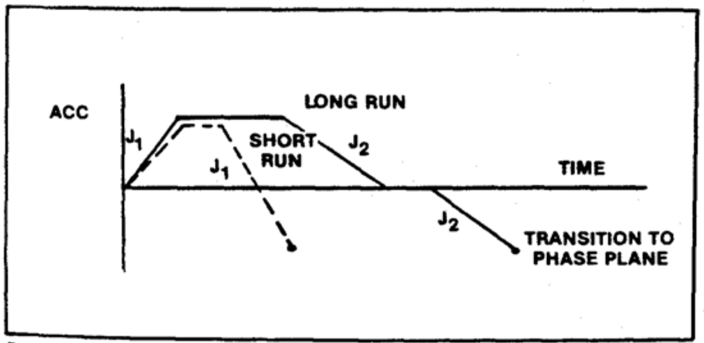


Fig. 7. Timed Acceleration Profile

The loop phase shift at high frequencies with the idealized SCR control is 90 deg lagging. The hoistway theorem was used to extrapolate from this to a more general situation, showing that the control is satisfactory without added compensation. The idealized MG control has a high-frequency phase shift of 180 lagging. As opposed to the SCR control, this control is significantly affected by the damping of the hoistway resonances. Insufficient damping may lead to intolerable spurious response close to the resonant frequencies. Helping to prevent this is roll-off of loop gain with frequency squared. In practice, most MG controls have been implemented without need for additional compensation. If needed, this is placed just after the PI controller.

The GAIN and RESPONSE for these controls are adjusted to have values similar to those used with SCR controls. The tracking delay for ramp input is usually held to approximately 0.2 sec, slightly more than most SCR controls.

POSITION CONTROL

The position control system (Fig. 6) acts on the velocity control to bring the elevator up to speed and to land it precisely (leveling). All runs begin with a timed velocity profile. The car position is compared to the destination position to obtain the distance-to-go XGO. At the appropriate moment, control shifts from a timed velocity to one based on XGO (phase-plane control). A multiplier is used at the transition to assure no discontinuity in dictated velocity.

The velocity profile is adaptive, capable of being altered after the start of a run. It is more easily understood by study of the acceleration profile shown in Fig. 7. Actually, the velocity profile is generated by a double integration of jerk. The magnitudes of these jerk rates are marked on the acceleration profile. The jerk J2 is less than J1 to prevent excessive power demands. The region of zero acceleration corresponds to elevator operation at full (contract) speed. Short runs are those for *which contract* speed is not attained. These are made as a subset of a long-run profile. The transition from the timed profile to the phase plane is made at constant jerk.

The phase-plane function used to decelerate and land the car is basically related to the square root of XGO. This gives a constant deceleration. For XGO small there is deviation from the square-root function to provide jerk control and moderate the position loop gain. This is necessary to achieve smooth, well-damped leveling.

The performance of the velocity control during the timed dictation is not critical. However, during deceleration and leveling the dynamics of the velocity control must be properly matched to the rest of the system. This is done by varying the GAIN and RESPONSE adjustments until satisfactory leveling is achieved.

ADDITIONAL CONTROL FEATURES

Additional closed-loop control is used for pre-torquing, motor-field weakening, and brake operation. Pre-torquing initializes the armature current. Field weakening is used to permit economies in the size of the drive components. It also increases energy efficiency. Closed-loop control of the brake is economically achieved in a computer-implemented system. It permits considerable operational flexibility and minimizes brake power requirements.

Pre-torquing is referenced to cab load. For SCR drive systems the armature current is set directly. MG drive systems, however, are plagued by residual magnetism and are basically armature-voltage controls. These difficulties are overcome by use of a special pre-torquing current-regulating loop.

IMPLEMENTATION

The electronic systems are implemented in 16-bit processors, digital circuits, low-level analog circuits, and an SCR drive or generator-field power amplifier (GFPA).

The basic SCR velocity control design permits working into all hoistway resonances, irrespective of frequency and damping. Practical limitations are imposed, however, by cycle time

Continued overleaf

Continued from overleaf

HIGH-PERFORMANCE ELEVATOR CONTROL SYSTEM

of the velocity-loop processor and performance of the current regulator in the SCR drive. The digital implementation of part of the velocity control results in good stability with respect to time and environment. This is important in obtaining consistently high leveling accuracy.

The SCR drives are proven designs that have been adapted for elevator service. Rather than being stand-alone voltage or velocity controls, these units are high-performance armature-current regulators having some armature-voltage feedback below 1.0 Hz. The bandwidth of the current regulators exceeds 20 Hz. The drives have good performance in terms of speed of current reversal and dead zone. This is important for smooth transitions from acceleration to deceleration and during conditions of steady running with balanced load.

The GFPA is a small current-reversing SCR unit used to control the generator field current. This translates almost directly into control of armature voltage - a major difference between MG and SCR drives. The performance of the GFPA is comparable to that of the current regulator in the SCR drives. Performance of the GFPA affects velocity-loop performance in much the same way as an SCR drive.

Fast, simple operation of the processor is demanded for the velocity control. The position control operates more slowly. The operations performed are complex and would be impractical without the processor. It allows not only sophisticated basic operation but also the addition of almost unlimited design features by means of software.

FIELD EXPERIENCE AND PERFORMANCE DATA

The controls are part of Otis' Elevonic 101® and Elevonic 401™ elevators. Over 500 of these are now operating. Performance of the controls is consistent. This permits a description in general terms. Data are then presented for an SCR drive system and an MG drive system.

Two characteristics provide an accurate way of judging the dynamic performance of an elevator control. One is flight time for 3.6 m (12 ft); the other is leveling accuracy. Flight time for an ideal control is 4.0 sec when acceleration is limited to 1/8g and jerk is limited to 1/4 g/sec. The flight time for a practical control is defined from the time dictation starts to the time the car is within 6 mm of its destination. This is meaningless without a concurrent statement about the leveling accuracy. A poor control can, for example, make a one-floor run quickly by rapidly passing through the destination point. Its leveling accuracy, however, would be poor.

Elevonic 101® and Elevonic 401™ elevators generally make one-floor runs in under 4.3 sec. The leveling accuracy is usually better than 3 mm and almost always within 6 mm. The tracking delay on the SCR-drive controls is on the order of 0.15 sec, being slightly greater for MG-drive systems. The flight time is comprised primarily of the ideal flight time, the tracking delay, and the delay (or hesitation) in making the final approach to the destination. The tracking delay is directly related to the bandwidth of the velocity control. Too high a bandwidth subjects the control to potential vibration problems and is costly.

The primary instrument used to monitor system dynamics is a two-channel strip-chart recorder. By recording drives-sheave velocity (VDS given in car velocity units) and dictation, the tracking delay can be found easily. The most important set of traces are those of VDS and armature current (IA). Use of a highly expanded scale for VDS permits close examination of the motion at the start and finish of a run and for determining flight time. The trace of IA is useful for checking for hoistway vibrations, acceleration, and jerk.

A typical set of VDS and IA traces for an SCR-drive system are shown in Fig. 8. The flight time is close to 4.3 sec, although some motion is evident for 4.9 sec. A highly expanded VDS scale is used and the area of each block represents a distance of 10 mm. On this basis the arrival into the destination zone is determined and marked on the trace. The travel time in this zone is approximately 0.6 sec. Subtracting this from the total motion time yields the flight time. Measurement of so-called motion to motion flight time with a stop watch would give a result close to 4.3 sec. The most accurate measurements of flight time are made with a logic-state analyzer connected to the main processor.

Performance of MG controls has been close to that of SCR controls. These can be more difficult to implement, especially as the size of the hoistway equipment increases. Significant compared to older controls, the present controls are quite insensitive to generator compounding, brush alignment, hysteresis, and saturation. Data obtained at a large building are given. The rise is over 200 m, the duty load is 1800 Kg, and the contract speed 7 m/s. The one-floor flight times as determined with a logic state analyzer are given in Table 1. All times are close to the targeted value of 4.3 sec except the 4.6 sec for full-load-up operation. This operation makes the heaviest demands for motor torque and it appears that some limiting of torque took place.

CONCLUSIONS

All design objectives for the control systems were met and many are in service. Flight times and leveling accuracies are achieved on a consistent, long-term basis. This has become possible by extensive use of closed-loop control, microprocessors, and the development of a high-performance position transducing system. Design flexibility and performance enhancement have resulted from the use of SCR drives having high-performance current regulators.

The control principles described here have been verified both in practice and by simulation studies. Application to SCR-drive systems is possible without need to know detailed hoistway characteristics. Necessary are such parameters as total system mass, contract speed, and torque/power characteristics of the drive and motor. MG-drive systems can be designed much the same way, but the possibility exists that supplementary compensation will have to be used.

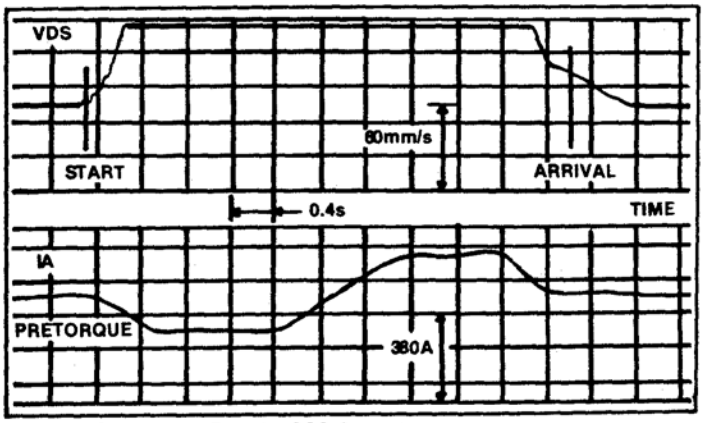


Fig. 8. VDS and IA vs. Time for SCR Control

Position	Bottom		Middle		Top	
Load \ Dir	Up	Down	Up	Down	Up	Down
Empty	4.3	4.3	4.25	4.25	4.2	4.16
Balanced	4.3	4.15	4.26	4.16	4.13	4.16
Full	4.6	4.1	4.2	4.1	4.1	4.13

Fig. 9. Flight times (sec) for MG Control

The velocity control performance achieved is close to the theoretical limit, and further refinement of the control strategies seems unwarranted. Refinements in application techniques will occur, however, in a continuing effort to produce controls that are as economical and reliable as possible.

The velocity control technique using SCR drives relies on a strong regulation of torque in a DC motor. This same idea is applicable to AC and other types of drive systems as well. The bandwidth of the torque control in these systems should be substantially greater than the band of typically encountered hoistway resonances.

REFERENCES

1. M. Masel, R.J. Meehan, J. Schroeder, "High Resolution and Wide Range Shaft Position Transducer System," U.S. Patent 4,384,275, May 17, 1983.
2. E.A. Guillemin, Theory of Linear Physical Systems, p. 224-226, 232-236, Wiley, New York, 1963.
3. W.L. Everitt, Communications Engineering, 2nd. ed., p. 88-92, McGraw-Hill, New York, 1937.
4. B.C. Kuo, Automatic Control Systems, 3rd ed., Prentice-Hall, Englewood Cliffs, N.J. 1975.

ACKNOWLEDGEMENT

The work reported here was part of a substantial development effort at United Technologies Corporation. It was influenced by many of the program participants. Isabel Blanco and Vlad Zaharia of Otis were deeply involved in the development and test of the motion controls, especially the first successful demonstrations. Much of the control hardware was developed at Hamilton Standard, based on inputs from many Otis engineers. The United Technologies Research Center provided backup with large-scale computer studies and information on material properties.

1983 IEEE. Reprinted with permission from 1983 CONFERENCE RECORD INDUSTRY APPLICATIONS SOCIETY, IEEE-IAS-ANNUAL MEETING, October 3-6,1983, Mexico City.)

The responsibilities of Clement A. Skalski at Otis Elevator Company's R & D Center in Farmington Connecticut relate primarily to elevator control systems. Previous to joining the manufacturer, Mr. Skalski did transportation systems engineering at Mitre Corporation. He holds degrees through PhD in Electrical Engineering from Rensselaer Polytechnic Institute and Cornell, Columbia and Northwestern Universities. Mr. Skalski is a senior member of the Institute of Electrical and Electronic Engineers (IEEE).

Skalski