# ELECTRIFICATION AND CONTROL SYSTEMS FOR LIGHT RAIL SYSTEMS

R. D. Touton, Jr., Louis T. Klauder and Associates

This paper provides a broad overview of available electrification and control system technologies for new light rail systems. It is intended for groups with widely diverse backgrounds ranging from city planners to economists and consequently does not deal with detailed, specific, technical design parameters. The portion on electrification is subdivided into sections on power generation, distribution, and collection on the light rail vehicle. The portion on control systems is broader and is divided first into propulsion control on the vehicle and then into systemwide operational control features that are further subdivided into sections on control on the vehicle, control among a number of vehicles, control at a central status reporting area, and automation. The paper concludes with general recommendations for a typical light rail system but recognizes that conditions might require additional or fewer optional features. This is done to emphasize the flexibility and adaptability of light rail systems.

The principles of electrification and control are equally applicable to all modes of rail transport from main-line railroad commuter service to full-scale rapid transit to light rail transit (LRT). Fortunately, as these principles are scaled down to LRT requirements, the cost and complexity also can be scaled down without any serious degradation of the ability to transport passengers effectively and comfortably.

We will concern ourselves first with the basic means by which electrical power is generated, distributed over the system, and finally collected on the vehicles under the term electrification. The term control systems then will be used first to cover propulsion control on the vehicle and then systemwide operational control on the vehicle, control among a number of vehicles, control at a central status reporting area, and automation relationships.

It is important to recognize that LRT is a "here-and-now" technology. It is evolutionary and not revolutionary. Worthwhile designs and even apparatus developed in the past can and should be used where the technology is either still appropriate or has room for growth. On the other hand, dramatic improvements also can be achieved by using current technologies or even by making provisions for using advanced technologies. The key here is selection: selection of the proper design or equipment to do the job. "Old" is not necessarily best but neither is "new" necessarily better. A careful appraisal of the goals and the risks must be made. Technology for the sake of technology must not be part of that appraisal.

Electrification begins at the substation or powerhouse where the appropriate type of electricity is converted or generated for use on the vehicle. Direct current is provided for distribution to the vehicles on line even though, in most cases, alternating current has first been generated and subsequently rectified. Perhaps some of you are aware that a few personal rapid transit (PRT) systems are using alternating-current power. However, in these cases the 3-phase alternating current is collected by 3 power collectors and rectified on board each vehicle for use by the direct-current traction motors.

Direct current was chosen because it was the most easily generated at the turn of the century, but it was soon determined that direct current had another major advantage; that is, it is easily controlled so that motors can be operated at various speeds quite readily. This, of course, is what all electric transit vehicles must do and is especially true of light rail vehicles (LRVs), which must start and stop more frequently than full-scale rapid transit systems or main-line railroads.

However, the use of low, 600 Vdc suffers from high transmission losses over long distances and, unlike high-voltage alternating current, transformers cannot be used to step voltages back up to usable values. These losses stem from the resistance in the distribution lines, and consequently either substations must be provided at very frequent intervals or many additional distribution lines called feeders must be provided. Traditionally these feeders have been heavy insulated wires supported in the air by lineside poles and often have appeared unsightly.

Developments have occurred in recent years that can reduce both the losses and the unpleasant visual impact. For example, new solid-state substations are so small that they can be unobtrusively and economically placed in small underground vaults in city areas or inside small attractively landscaped enclosures in outlying areas. The substations may use convenient local sources of high-voltage alternating-current power, and in many cities these alternating-current sources already have been placed underground.

Now let us consider exactly what type of electrical energy is being carried by the distribution system. For example, in mining operations, 250-Vdc systems are used because of the close proximity of open wires to personnel and structures, but, to reduce losses, extremely large overhead wires are used. At the other end of the scale, older electric interurban systems used 1,200- or even 1,500-Vdc systems because of their need for improved transmission characteristics over long distances. The new Bay Area Rapid Transit (BART) system has selected 1,000 Vdc as being optimum, but the vast majority of existing and proposed rapid transit systems still remain in the 600- to 750-Vdc range. The streetcar predecessors of LRVs also operated at the 600-Vdc level, and this still appears to be a good level in terms of safety, current-carrying capacity, and minimum installation cost. In any case, a great deal can be gained by picking a single standard for future development to maximize interchangeability of parts and reduce production costs as well as use an existing technology based on the extremely modern mining substation designs without significant developmental risks.

Entirely adequate 600-V light rail substations with typical capacities of 2,000 to 4,000 kW are available and can be placed at 2-mile (3.2-km) intervals on the outer portions of any light rail line. Each will operate unattended, turn itself on and off as needed, and, in the event of an overload or failure, will even bypass itself so that adjacent similar substations on either side can temporarily carry the loads. They also are virtually maintenance free, have an almost infinite service life potential, are extremely efficient, and are environmentally sound.

These same self-contained substations can be used on the inner portions of light rail lines, but, if 2 or more lines converge, it may be even more efficient to use larger size units. For example, the San Francisco Muni-Metro will have the capacity to run up to four 4-car trains simultaneously in each power block with an 8000-kW capacity in the downtown subway sections. Fortunately, these, too, are available off the shelf from other industrial applications and have all of the virtues of their smaller brothers.

However, it must be clearly understood that light rail systems do not necessarily guarantee the use of smaller substations than are used with full-scale rapid transit. The required capacity is tied to the number of vehicles that will be in operation, not only the type of vehicle.

There is 1 additional source of power that must not be overlooked and that is the vehicle itself. Of course, the vehicle uses power as it accelerates, but it also can generate power as it decelerates. This characteristic has been known for years, but, in the cheap energy era, it was never developed on any significant scale for transit applications after an initial flurry in the early trolley car days. Luckily, the necessary technology is available, and it is only a matter of developing a business climate to justify going into production of the necessary hardware. One point deserves clarification. Estimates on energy savings by use of vehicle generation of power range from

0 to 50 percent or more but only 20 to 30 percent savings have been demonstrated to date. This saving is a worthwhile goal, though.

With the appropriate source of direct-current power available at suitable intervals along the line, we may now consider how these fixed sources are best delivered to moving LRVs. In the current state of the art, an overhead wire system is used for main-line electrified railroad operations and city streetcars, and a third-rail system is used on full-scale rapid transit systems. A few cities including Paris, London, New York, and Washington, D. C., previously used a plow-and-conduit system in which an arm reached down from under the car into a slot in the surface of the street. Beneath the slot, a pair of conductors were arranged to make contact with the arm as the car moved. Although visually better because no overhead wires were used, the conduit system was incredibly complex and costly to maintain, particularly in later years when streets were salted in the winter and severe corrosion was caused.

The third-rail system can carry high currents effectively as required by trains of relatively high-powered transit cars, but the structure and on-car collection devices are such that speeds must be limited to about 85 mph (136 km/h) for new systems. The Long Island Railroad will eventually operate at speeds around 100 mph (160 km/h) by modifying their present third-rail system, but this exception is based on a cost-benefit analysis that showed that installing a wholly new overhead system was better than long-term maintenance of the third rail.

Although the third rail is covered by insulating material, primarily to safeguard the operating and maintenance staff, the casual unauthorized intruder can receive a lethal shock if any part of his or her body comes in contact with the third rail. Thus virtually all modern rapid transit systems are totally grade separated and often are completely fenced in to protect against this intrusion. Because light rail systems may operate on some sections of city streets and very likely will not be fully grade separated or fenced on their outer extremities, it is not usually appropriate to consider third-rail power distribution.

An overhead system, usually of catenary design, is used on main-line railroads because of its capability to collect power at speeds up to 200 mph (320 km/h). The catenary is the free hanging curve of a line or cable suspended between 2 points. A contact wire is hung from this catenary in precise vertical and horizontal alignment over the track. This arrangement serves 2 purposes. The 2 wires add to the current-carrying capability (a form of feeder), and the precise alignment allows the collector on the vehicle to attain the desired high speeds.

In light rail applications, the overhead contact wire is the best choice in the interest of safety of persons on the ground, but, contrary to a popular misconception, an elaborate catenary system is not always required. This is true because precise alignment is not essential at lower speeds that seldom exceed 65 mph (104 km/h) and because current capacities of main-line railroad character are not needed. Instead, a simple single wire suspended at 100- to 125-ft (30- to 38-m) intervals usually will suffice. This suspension can be a supporting cross-span wire between 2 poles or buildings in city areas or a bracket arm mounted on a single pole adjacent to the track in outlying areas. Those of you who remember streetcars may recall that some people considered this single wire and the related poles to be ugly. However, since those days, myriad other poles, some towering, have sprouted up to carry complex automotive traffic signals and high-intensity street lighting. Very often, installation of a light rail system can provide the impetus to bring order out of this chaos. A single attractively designed pole can be arranged to carry the street lights, traffic signals, and the light rail overhead wire in an aesthetically pleasing and effective manner.

Two successful types of vehicle current collectors remain in use today. The first and oldest is the trolley pole in which a U-shaped shoe slides along the wire to collect power. With carbon as a shoe material, currents of 400 to 500 amperes (399.92 to 499.9 A) (typical of a PCC car) can be collected. With bronze, the current can be increased to 700 or 800 amperes (699.86 to 799.84 A); with steel, it can be increased to 1,000 to 1,200 amperes (999.8 to 1199.76 A), but then the wire must be lubricated. None of these is adequate for the new LRVs because they will require 1,000 amperes (999.8 A) per car and the cost and complexity of wire lubrication would be excessive.

Fortunately, suppliers are working on the problem and new copper-carbon shoes capable of 1,200 amperes (1199.76 A) are being tested in Boston and San Francisco. The trolley pole is inexpensive ($750), simple, and lightweight, and is free to track any wire irregularity in any combinations of horizontal and vertical deflections. However, if the LRV is of bidirectional design, then 2 poles are needed, 1 for each direction.

The second collector is the pantograph in which a long, flat, bar-shaped carbon shoe that is affixed to the top of the wire also slides along under the wire. Contact shoes are available for current capacities ranging up to several thousand amperes. The pantograph is costlier ($2,500), more complex, and heavier than a trolley pole and is free to move only up and down. Horizontal wire misalignment is accommodated by having the longest dimension of the shoe arranged transverse to the wire so that the shoe and wire can slide from side to side. Several forms of this device exist, but the functions are the same. At LRV speeds only 1 pantograph per car is required, and it will work equally well in either direction. However, at main-line railroad speeds, most railroads require separate pantographs for each direction.

Current European practice almost universally uses pantographs. In certain applications, however, the trolley pole should not be discounted. It is interesting to note that the first 20 new LRVs for Boston and San Francisco will carry both poles and pantographs and the proposed Canadian standard light rail vehicle will offer either option without degradation of performance.

Now that we have considered the methods by which electrical power is generated, distributed over the system, and collected on the vehicle, we can proceed to investigate the equally important area of control systems. It should be noted that control criteria for LRVs are no different from those for a full-scale rapid transit vehicle. The only basic variable is the degree of automation that is desired.

The control system must permit the car to remain at rest, accelerate smoothly, run at speed, decelerate smoothly, and stop safely. A way must be provided to vary the energy to the motors and this takes the form of a variable resistor (or its more modern equivalents) that varies the voltage from 0 to maximum while limiting the current to reasonable values so that the system is not overloaded.

As the car is started a high resistance is inserted into the propulsion system and this is gradually reduced to allow the car to accelerate. At full speed this resistance is cut out entirely. Further speed increases can be achieved by altering the electrical characteristics of the motors themselves, such as field weakening.

In the past, the operator of the first electric vehicles varied resistors manually by turning a handle connected to a moveable contact running over the surface of the resistor in the 600-Vdc circuit. This was not an optimum electrical arrangement. Also the early wooden cars tended to short circuit in wet weather and the operator often became the variable resistor. Low-voltage control devices became almost universally used by the 1920s, and this circumvented the problem. In this situation, the operator moved a controller through a series of switch contacts that connected various combinations of safer 32-V circuits, and these, in turn, activated relays that selected appropriate portions of the 600-V resistors.

Quite logically, it was obvious that these relays could be operated automatically in a more effective predetermined pattern (now we would call it programmed) than that provided by the operator's judgment. In moving the controller handle, the operator, with this system, could select a suitable rate of acceleration or desired running speed (depending on the type of control installed on the car). Then, a series of interlocked electrical relays or pneumatic contactors opened or closed automatically as needed, or a mechanical motor-driven cam advanced automatically and opened or closed appropriate switches. In another form, this latter device was called accelerator control. It has been used on over 6,000 Presidents' Conference Committee streetcars built in the United States and is still used on many new LRV cars in Europe.

At the current state of development the cam and accelerator control still have considerable merit because they are relatively simple, rugged, and easy to maintain by current shop forces. However, a new form of all-electronic solid-state control called the chopper has arrived as a result of developments in the past 5 years. The chopper

control holds promise for reduction of energy losses and improved reliability because some mechanical devices are eliminated. The same function as that performed by resistors is obtained electronically by "chopping" the 600-Vdc propulsion current into small energy blocks of various sizes through use of solid-state devices called thyristors.

The existing BART full-scale rapid transit cars and the forthcoming San Francisco and Boston LRVs are chopper equipped and will be watched with great interest by the rail transit community.

Choppers, however, are not the final answer. All devices have some inherent limitation, and something will probably come along in 5 to 10 years to replace the chopper. The chopper system retains direct-current traction motors, which, although rugged and reliable, require frequent routine maintenance. Thus, the next step likely will be a fully integrated system making use of other chopper-like concepts such as pulse-width-modulation propulsion, which incorporates a more forgiving and maintenance-free alternating-current traction motor yet retains the desirable direct-current performance characteristics.

Finally, it is also important to note that virtually any propulsion-control system, from electromechanical cams to solid-state choppers, can be designed or retrofitted to provide the energy-saving regeneration features previously mentioned, and any of them can provide the same acceleration capabilities with adequate smoothness.

Short of coasting down a hill, using the motors is the only way to accelerate the car. Deceleration or stopping, on the other hand, can be accomplished in 2 ways. First are various friction braking combinations in which a pad or shoe is caused to rub against the wheels, against disks attached to the wheels, or directly against the rail head itself. Second are the unique characteristics of motors that permit them to be used as generators. The kinetic energy of the moving vehicle is used to turn the motors, which then apply a retarding force by virtue of having to do work to generate power. But, unlike an internal combustion engine, which spews out useless exhaust gases, some of the power generated can be put back into the overhead line for use by other LRVs on the system. If this energy is reused, the system is called regenerative braking; if the energy is not put back in the line and is dissipated on the car, the system is called dynamic or rheostatic braking. To achieve higher braking rates and added reliability through redundancy, the friction braking and the dynamic/regenerative braking can be combined to supplement each other; this arrangement is called blended braking. These systems must simultaneously move the car safely and simply, must be economical in usage of power, must operate smoothly, and must be reliable and capable of easy maintenance.

So far we have considered only 1 LRV operating by itself, but, if full advantage is to be taken of the light rail scheme, vehicles should be capable of being coupled together in trains and operated from a single control point. Thus, the control system is called on to relay commands to all cars. This concept is called multiple-unit or, simply, MU operation.

Automatic control allows the operator to select an appropriate value of acceleration or running speed or both; the desired performance will be achieved without further intervention by the operator. However, he or she still must bear the responsibility for determining whether the way ahead is clear of other cars, whether the speed selected is appropriate to conditions of curves or grades, and whether the desired headway is maintained with respect to other cars on the line. As service speeds and traffic densities have increased over the years, the operator may not be able to make the best choices to control all of the variables. Consequently, it is often desirable to introduce additional automation concepts to relieve him of some or all of these burdens, but these installations must be based on sound economic, passenger-capacity, and safety judgments.

Many techniques described by many different names have evolved over the years, but in the simplest terms they are all forms of signaling systems in that they "signal" the operator to do something or "signal" the control equipment to take automatic action. This information can be provided visually by wayside signal lights (or even just wayside signs) or by coded energy fed through the running rails. These can be used

singly or in combination if the traffic density warrants.

Wayside signals require that the operator (or a wayside device called a "track trip") initiate a desired action but this can be done only when the car arrives at the next signal location.

Coded energy rail systems are in the general category of cab signals; they can be arranged to alert the operator to take action, or they can directly trigger the control system on the car. In either case, they give an instantaneous picture of conditions ahead as they change. Thus the operator (or the car itself) can immediately increase speed to take advantage of improved conditions rather than plod along until the car gets to a wayside signal with a higher speed aspect. This feature alone maximizes capacity of the rail line and reduces minimum headways.

In addition to their basic function, either the wayside or the cab-signal system can be arranged to determine track, curve, and grade conditions without operator intervention for safety, maximum speed, and minimum headways, or they can be arranged to operate automatically from a central reporting area to maximize operation of all cars on all parts of the system.

Any combination of automation devices can be considered under the broad term automatic train operation (ATO). These may include automatic speed control (ASC), automatic train protection (ATP), and automatic train control (ATC).

Automatic speed control quickly brings the vehicle to a stop if it exceeds any of a predetermined series of speed commands appropriate to the curves and grades. The operator can prevent such emergency stops only by keeping car speed within the prescribed limits and properly acknowledging any reduction in speed commands. In other words, automation enforces the speed limits, but the operator still runs the train.

Automatic train protection establishes signal blocks of appropriate length to provide adequate stopping distance for cars entering each of these blocks at maximum speed. Car occupancies of all blocks also are compared continuously. This results in an arrangement in which a car will be stopped before it gets too close to the car ahead. In this case, automation enforces train separation, and the operator limits the speed and runs the train.

Automatic train control establishes a local operational pattern on a given line so that all cars are accelerated, run at speed, braked, and stopped automatically in accordance with curve and grade conditions, block occupancy, required station stops, and desired headways. This can be expanded to an operational pattern for all lines in a system under the manual direction of a single person at a central reporting area or under automatic direction of a computer system. If desired, even the opening and closing of a car's doors at station stops can be included. This means that automation performs all functions, and the operator may have so little to do that he or she might become bored and inattentive.

All of these features can be provided on an LRV system, but full automation usually is not needed (at least not initially). If full automation seems necessary, then full-scale rapid transit would probably be a better choice than a light rail system. Nevertheless, the fact must not be overlooked that a light rail system can be started economically with minimal automation, and various features can be added without obsolescence to all or part of it as traffic increases over a period of years.

The new San Francisco Muni Metro includes 6 miles (9.6 km) of dense, close headway tunnel and subway operation into which 5 light rail lines will operate with trains of up to 4 cars. This section will be equipped with a wayside signal system at junctions (interlockings). It also will be equipped with a 100-Hz, continuously coded, cab-signal system permitting speeds of 10, 27, and 50 mph (16, 43, and 80 km/h) as an ASC function and providing block occupancy protection as an ATP function. Full ATC is not provided. However, on the surface portions, where each route runs on its own separate track, no signaling is provided and cars will be operated on a manual, line-of-sight control basis. The system is further designed so that failure of 1 or more functions still allows safe operation with relatively little service degradation. If the cab-signal system (ASC/ATP) fails, the cars still can be run manually by observing the wayside interlocking signals. If the wayside signals fail, the cars can be manually dispatched by radio from central control. Under no circumstances should any light rail system be designed

to rely on 1 automation control system whose partial failure will stop all service.

So far, we have considered only how propulsion and signal-control systems directly affect normal movement of car. But there are other system interfaces. The control system must be arranged so that a car cannot start if any of its doors is still open, that the doors cannot be opened while the car is moving, that the wheels do not slip and spin if the rail conditions are slippery, and that a car does not proceed into an area where a rail has broken. These and many other functions can be achieved at little additional cost or complexity.

Fortunately, the selection of the proper ingredients is not as difficult as it might seem, and we can close with a brief summary and a recommendation for an initial starting point for a light rail system.

Commercial high-voltage alternating current could be purchased and delivered at key property owned substations where the voltage would be reduced and rectified to 600 Vdc by small solid-state units. This power could be fed to a single overhead wire every 1,000 ft (305 m) and collected by a trolley pole or pantograph on the vehicle as appropriate. The arrangement could be bidirectional so that power could be delivered to the car in acceleration or back to the substation from the car in deceleration for reuse by other cars under the regeneration option. The LRV would have either an electromechanical or an electronic solid-state propulsion-control system selected on the basis of local conditions and cost considerations. Finally, ATO signal-control options would be installed on the vehicle and the wayside to the extent necessary as established by readily identifiable passenger-capacity, policy-headway, and safety criteria.

In short, the light rail concept makes use of vehicles that are constructed by using proved, but modern, technologies that will be appropriate for at least the design life of the vehicle. The system can be built now and will be fully operational now on a reasonable, cost-effective basis.

With the support of the properties in accepting standardized hardware, the support of industry in taking normal business risks to provide this hardware, and the continued generous support of government in providing funds and research facilities, light rail transit will become an even more valuable addition to the catalog of available and appropriate transit vehicles of all kinds.