Power Supply for Light-Rail and Rapid Transit Systems in Germany

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The purpose of this paper is to define the present state of the art in the design of the power supply for light-rail and rapid transit systems in Germany. The scope includes the incoming alternating-current switchgear, rectifier direct-current switchgear, catenary, and third-rail systems, as well as the breaker on the light-rail vehicle. Attention is paid to the problems of coordinating the various components of standard design and of dealing with corrosion due to the leakage of current from the power supply. Experiences with various catenary designs and their interconnections in Germany are also described. This paper is limited to experiences in Germany, and the underlying design criteria are based on German electrical regulations. Since the implementation and reliability of power supply for light-rail and rapid transit systems in Germany are considered to be highly successful, the data, views, and experience presented in this paper should be of interest in North America.

The long years of development in light-rail transit (LRT) and rapid transit systems have led to definite and proven system parameters. This paper covers the latest power-supply system concepts in Germany.

LRT systems generally use 600-V or 750-V direct current, although in the development of more modern, attractive, and powerful systems, there is a trend toward using 750-V direct current. The allowable voltage tolerances according to the German regulations for electrical transportation (VDE 0115) are 70 to 120 percent of the rated voltage. In order to allow as high a voltage drop on the catenary system as possible (to permit the maximum distance between rectifier stations), the full-load terminal voltage rating of the rectifier should be 10 percent higher than the rated voltage of the vehicle.

The transformation of the three-phase high voltages of the utility network is carried out by rectifier substations equipped with specially designed modern silicon rectifiers. These are strategically located along the LRT line; the intervals are based on energy distribution criteria and economic calculations. The electrical connection between the rectifier substations and the light-rail vehicle (LRV) is made through a catenary system.

SHORT-CIRCUIT PROTECTION

Short-circuit protection of each section of the line is provided by properly dimensioned direct-current high-speed breakers located in each of the rectifier substations.

Catenary Systems Energized From One End Only

If such technical parameters as the power demand, speed limits, and substation intervals permit, single overhead wires are used, even in today's densely populated areas. These wires have, in most cases, a maximum cross section of 120 mm² in order to keep the architectural environmental pollution to a minimum. The actual resistance of the overhead wire is usually reduced through parallel connections for both directions of travel on double track. Interconnections at regular intervals along the line serve to provide equal current distribution in both overhead wires. Both of these overhead wires can then be switched and protected by only one direct-current high-speed breaker. The simplicity of this electrical constellation is, however, coupled with the disadvantage that the two directions are interconnected, which necessitates their total isolation in cases of short circuits or other interference. If a sufficient cross-sectional area per direction can be provided by an additional wire, as in a compound catenary, or if the third rail, which has a relatively large cross-sectional area can be used, both directions can be electrically separated, so that in cases of disturbance, such as a short circuit, only one direction is affected.

Short-circuit protection is relatively simple to accomplish on catenary systems that are energized from one end only. If a voltage drop of 70 percent of the rated voltage occurs under the rated LRV load at the most distant point on the line from the rectifier substation (where the terminal voltage is set at 1.1 times the rated voltage), then the short-circuit current at the end of the line would be 2.75 times the normal operating current. Even if this factor is not reached because of the characteristic impedance of the power supply, a trip-current setting on the breaker can be set to trip at a current approximately 20 percent higher than the maximum operating current, which would still lie well below the lowest short-circuit current.

Catenary Systems Energized From Both Ends

To improve the voltage stability along the line, especially when high traction power is required, double-ended energization may be installed. In this case, the line catenary between two rectifier substations is simultaneously energized from both substations, which are connected by one high-speed breaker at each station. If, for example, the cross-sectional area of the catenary wire and the substation intervals are the same as those for a catenary system that has single-end feed, double-ended energization both reduces the voltage drop along the line and diminishes the catenary power losses. Furthermore, it permits equalized loading of the rectifier substation.

The optimum design length for double-fed catenary is not determined by the maximum voltage drop that can be tolerated for an LRV's current load but rather by the short-circuit protection that is needed, as is shown in Figure 1. A symmetrical catenary with homogeneous line resistance between two stabilized rectifier substations that feed at a voltage 10 percent higher than the rated vehicle voltage is shown in a schematic diagram. The curve I₁₀ represents the short-circuit current fed from the left rectifier substation and limited by the line resistance. The trip setting of the direct-current high-speed breaker S₁ is set so that the level of the short-circuit current at the right end of the line is more than 20 percent over the set value; this will provide sufficient protection. If this maximum load is allowed by the breaker trip setting to move along the catenary, the partial current supplied through breaker S₁ is represented by the line I₁₁₀. The voltage drop due to this current load is depicted by the curve U. The lowest level in the middle of the line is 87 percent of the rated voltage. The limit of 70 percent of the rated voltage, allowable under
normal operation, has not been encroached on. A similar load relationship exists for the right rectifier substation.

**Tie-Breaker Application**

By applying a direct-current high-speed breaker as a tie breaker in the middle of the catenary system, a tighter layout with respect to short-circuit protection and stable voltage conditions can be achieved. Again, assuming a symmetrically designed network, a homogeneous line resistance, and a stabilized substation voltage of 110 percent of the LRV-rated voltage, the curves shown in Figure 2 would apply. With full use of the allowable voltage tolerances and double-ended catenary energization, the maximum allowable operating current \(I_{\text{max}}\) can be extracted at the midpoint. This current can be assumed to be a wandering load along the length of the complete catenary. The resulting partial current flowing through breaker S1 and the voltage drop caused by the load are represented by the straight line \(I_0\) and the curve \(U\). The overcurrent trip of the breaker S1 is set at the maximum permissible current \(I_{\text{max}}\) and the overcurrent trip of the tie breaker S2 is set at one-half this value. The curve \(I_1\) shows the short-circuit current flowing through the breaker S1; its location depends on the location of the short circuit. A comparison of the trip settings and the short-circuit current, which is situated at the critical short-circuit distances (catenary middle for S1 and catenary end for S2), shows that the final value of the short circuit still exceeds the tripping value by 37.5 percent. Short-circuit protection is therefore fully guaranteed even with allowances for the rectifier characteristics, the tolerances, and slight asymmetry. The same conditions apply for the high-speed breaker of the right substation.

**Cross-Tie Positions**

If the catenaries are separated with respect to direction and are fed from both ends, then ties for both cross connection and longitudinal connection can be located in the middle of the catenary system. Such complicated ties are usually made up of four direct-current high-speed breakers and one disconnect switch. Practical experience has shown, however, that there are more advantages to a simple network constellation that has good overview and reduced distances between substations rather than cross ties. The conditions shown in Figure 1 then prevail and result in lower transmission losses, better voltage stability, and reduced danger of leakage current than for tightly interconnected networks. A reduction in voltage drop for LRV operation can be accomplished by the use of chopper control with regenerative braking.

**REDUCTION OF CORROSION DUE TO LEAKAGE CURRENT**

The traction current of the LRV causes a voltage drop not only in the overhead wires but also in the rails being used as conductors for the return current. Although the relative voltage drops in the rails are considerably lower because of the cross-sectional area available, leakage currents and the danger of resultant corrosion nevertheless exist. Because of the negative direct-current polarity to the rails, leakage currents stray into the surrounding earth, buried metal pipes, and metal construction reinforcements, and they then return to the rails or the connecting conductors in the area of the rectifier substation. After years of operation, destructive corrosion may occur at the points of current discharge; the amount depends on the current's density and duration. Decades of effort on the part of authorities operating direct-current traction systems and corrosion-endangered utility systems and support from various research institutes and commissions led to the issuance in August 1975 of DIN regulation 57150 and VDE 0150. These regulations apply to all operations of direct-current systems that allow leakage or stray currents. In addition to this, the new regulation VDE 0115a on the reduction of danger caused by return currents in direct-current rail traction systems summarizes the protective requirements and regulations specified for rail systems. All technically and economically feasible protective steps and upper measurement values are listed; these are recognized as the maximum justifiable precautions that should be used to combat corrosion danger. Planning teams for new rail systems are required to carry out a preliminary calculation of the leakage current conditions. Guidelines for these calculations are published and are available for the planning engineers.

After completion of construction and commissioning, the potential differences that appeared to be critical in the calculations must be measured. If the actual values deviate too widely from the calculated values, the cause of deviation must be ascertained. The combination of preliminary calculations and actual measurement will reveal that, for example, if high discharge currents in the track network occur because the resistance of the track ballast is too low, only small differences in the potential will be measured. The regulations list 20 points, proposing a wide variety of corrective procedures and limi-
tions. A list of some of these regulations and recommendations follows.

1. The resistance of the track ballast (the quasi-isolating superstructure of clean ballast, wooden ties, isolating barriers, and so on) should be high.

2. The rails may not be directly connected to ground structures.

3. The rectifier substation intervals should be small.

4. All conductors and cables connected to the rails must be insulated for at least 0.6 kV.

5. The return-current busbars of the rectifier substations must be insulated against the ground.

6. If the negative polarity of the rectifier voltage is connected to the rails, the amount of corrosion protection may be reduced.

7. The portion of resistance caused by the rail bonds must not exceed 15 percent of the total resistance. The resistance of one bond may not exceed the resistance value of 5 m of track.

8. The use of salt or brines for treating snow and ice conditions should be avoided.

9. A distance of at least 1 m must be maintained between track and conductive civil works structures.

10. The longitudinal resistance of tunnel structures must be minimized and the track-bed resistance maximized so that the difference in potential within the tunnel structure is kept to a minimum. If the maximum operating current is flowing in the rails, a maximum difference in potential of 0.1 V is allowed throughout the complete tunnel length and the connection-point area.

Since these regulations have been in effect, all lines and tunnels have been planned and built accordingly. Such features as easily accessible track bonds at the tunnel entrances and multicore conductor cables to measure the potential are being included to facilitate measurement of current after periods of revenue service. The problem of corrosion from current leakage in rail systems cannot be declared solved; it is still undergoing progress and investigation. It is necessary to follow the continuing addenda to these regulations and recommendations to keep abreast of developments in this area.

CATENARY SYSTEMS

Various catenary systems have been designed to cope with different maximum speeds, current loads, and structural conditions.

Single Overhead Conductor

The use of a single overhead conductor for speeds up to 50 km/h has proven sufficient in most cases. The simplest design uses a simple catenary with drop-wire suspension approximately every 15 m; both ends are anchored. Temperature expansion leads to an increase in the sag of the conductor, which must be compensated for by the vertical travel range of the pantograph. A catenary system that uses fixed tensioning allows a longer distance between poles or structure supports. A network of this type of suspension provides an elastic overhead conductor suspension.

Under moderate traffic density, it is possible to use an automatically tensioned weight- and-pulley overhead conductor suspension for speeds of up to 70 km/h. Automatic tensioning guarantees a constant sag. The relative longitudinal movements of the conductor are not hindered in this design. The elasticity of the system is improved through the distribution of weight by angular drop wires. The horizontal positioning of the overhead

is carried out in a zigzag formation from support to support on straight stretches; it is positioned on curves by the addition of curve-tensioning guy wires as shown in Figure 3 to ensure even wear on the pantograph collector.

Compound Catenary Design

A compound catenary system (Figure 4) is installed on lines that have speeds of more than 70 km/h. The full-length messenger wire serves to support the actual overhead conductor, as well as to increase the electrical conductivity by offering a higher cross-sectional area. Vertical drop wires between the horizontal supporting catenary and the overhead conductor are placed at relatively short intervals—10 to 12 m—in order to practically eliminate sag of the contact conductor; this ensures good contact between pantograph and conductor even at high speeds.

It is possible to use two supporting catenary wires for higher current loads. If a heavy power demand is required by a stopped LRV (because of the needs of its heating or air-conditioning systems, for example), it is recommended that two overhead conductors be installed. The overhead conductors are normally automatically tensioned, whereas the supporting wires can be either fix anchored or automatically tensioned.

The compound catenary system offers the best capacity with respect to current-carrying capacity and dynamic transmission. It is preferred for heavily loaded lines that use high speeds and is recognized as today's standard equipment for modern urban and LRT systems.

OVERHEAD CONDUCTOR IN TUNNELS

Overhead conductors were designed for use in tunnels where the available height made it impossible to use a catenary system such as those previously discussed. The design shown in Figure 5 can be applied in tunnels and under bridge girders, for example. The design of the elastic cantilever support shown in Figure 6 allows automatic tensioning through the cantilever arm's capability for horizontal movement. The height of the overhead conductor can be adjusted at the base of the arm. A pretensioned cylindrical rubber insert absorbs the forces exerted by the conductor and also offers the required elasticity. If additional current-carrying capacity is required, further parallel conductors can be mounted on the tunnel roof or wall and cross-connected every 30 to 50 m.

THIRD RAIL

The third-rail is usually selected to supply the current for the heavy power demand of subways (Figure 7). Its cross section is much larger than that of an overhead conductor. Its design is simple, robust, and dependable in operation. The third rail is located adjacent to the rails (Figure 8) and is supported approximately every 6 m. The LRV current collector can operate on any face of the third rail, but in Germany collection from the bottom surface is preferred. A cover of polyvinyl chloride is installed in order to provide protection against accidental contact.

The standard steel third rail (according to DIN regulation 43156) has a current-carrying capacity of up to 300 A, and a cross-sectional area of 5100 mm². The higher power demand of future rail vehicles will require the use of alloys (steel and copper or steel and aluminum) in rail manufacture to improve the conductivity. The third rail is manufactured in sections 180 m and 90 m long and welded together on site. Separations and transitions are required at switches and crossovers. Expan-
sion joints (to compensate for temperature changes) are incorporated at appropriate intervals along the rail. Isolating insertions permit electrical sectioning. The length of the isolating pieces depends on the dimensions of the LRV collector.

The cable from the substation is connected to the

Figure 3. Simple catenary with two messenger wires and fiberglass cantilevers.

Figure 4. Automatically tensioned trolley wire with bridle and pulley.

Figure 5. Overhead current supply in a tunnel.

Figure 6. Elastic cantilever support.

Figure 7. Third-rail power supply system with polyvinyl chloride protection.

Figure 8. Third-rail systems with top contact, side contact, and bottom contact respectively.

Figure 9. Basic circuit diagram of a rectifier substation.
rail by a bushing, which divides into several many-strand copper cables. This is necessary to avoid cable breakage because of vibration and oscillation. The same method of connection should be used for the connection of the return-current cable.

DIRECT-CURRENT RECTIFIER SUBSTATIONS

The rectifier substations, which are situated along the rail line, are either enclosed in their own housings or integrated with other facilities. When they are located in tunnels, it has proven advantageous to use the space available at the end of the passenger loading platforms. If the stations are located on the surface, the utilities may use prefabricated station housings. Space requirements, accessibility, ease of maintenance, operating safety, and the safety of personnel should be taken into account in the design of stations. The basic design of a standard rectifier substation is shown in Figure 9. The principal electrical components can be grouped as follows:

1. Incoming high-voltage alternating-current switchgear;
2. The rectifier unit, consisting of a rectifier transformer and the rectifier;
3. Load-side switchgear with direct-current high-speed breakers to provide direct-current short-circuit protection;
4. An auxiliary station supply, backed by an emergency battery supply for underground stations; and
5. High-voltage switchgear to supply station equipment.

RECTIFIER UNIT

The heart of the direct-current power supply system is the rectifier transformer and the rectifier, which together constitute the rectifier unit (1). Each unit is switched by a high-voltage breaker equipped with an overload time delay and a bimetal relay to protect the rectifier against short circuits in the network. Several rectifiers can be located side by side and connected in parallel should the power demand require this. Three-phase bridge connections like that shown in Figure 10 are most commonly used. Modern diodes, which have peak inverse voltages of 4 kV, permit rectifiers designed to handle up to 1.8 kV direct current with only one diode in the reverse direction. The diodes are connected in parallel and their quantity is determined by the individual current ratings and class. For rail operation, classes for up to 10 kA are used. A fuse is connected in front of each diode so that, in case of dielectric breakdown, only the faulty diode is disconnected and the total operation is not interrupted. Reverse current transformers register the current flowing up to the point at which the fuse melts; this provides a record of the breakdown of a diode. The rectifiers are protected against high-frequency overvoltages by means of a resistance-capacitance filter on the direct-current load side.

The design of a self-cooled rectifier (Figure 11) should incorporate only a few supporting insulators to provide ease of maintenance, dependability, and lack of sensitivity to dirt. A standard sheet-metal enclosure is recommended to protect operating personnel from making accidental contact with parts that are carrying current. The specially designed heat sinks for these self-cooled rectifiers are made out of diagonally cut extruded aluminum. The 45° diagonal cut of the cooling ribs, as shown in Figure 11, provides an excellent chimney effect and proper channeling of the cooling air. The stacked rectifiers all belong to one branch of the rectifier arm, which is connected in parallel to the vertical busbar. In the illustrated rectifier cubicle, the alternating-current connections are at the top and the direct-current connections at the bottom.

Figure 12 shows the rectifier cubicle for the Munich subway, which is rated at 3 kA. The vertical buses, which have diode fuses, are recognized very easily. The measurements of this cubicle are width = 900 mm, depth = 800 mm, and height = 2200 mm. The rectifier transformers in the substation should be specially designed to ensure long life. There is a tendency to use dry resin transformers for up to 3 MVA. These do not require a drip pan and are especially preferred in underground installations because they are inflammable and self-extinguishing. In addition, they are no noisier than liquid-insulated transformers. The rectifier units are designed to withstand a short circuit on the direct-current load side without the diode fuses blowing or the transformer or rectifier being damaged until the alternating-current breaker switches the power off. Overcurrent protection and a bimetal relay are connected in the alternating-current circuit and provide continuous protection, as is shown in Figure 13. The bimetal relay provides tripping in the range of minutes, whereas the overcurrent relay provides tripping in the range of seconds in its delayed function and in the range of milliseconds in its instantaneous function.

Rectifier circuits exert reactive effects on the energizing alternating-current power supply. The intensity of the coupling is reduced as there is an increase in the harmonic frequency. The three-phase rectifier bridge in a six-pulse connection has a reactive effect on the alternating-current network that feeds the substation, especially with respect to the fifth and seventh harmonic, which is 420 Hz in 60-Hz networks. Past investigations have shown that these reactive effects are tolerable as long as the rectifier's power capacity is lower than 20 percent of the network's capacity, as is the case in all LRT installations in Germany. If the rectifier rating is higher than 20 percent, the fifth and seventh harmonic can be avoided if a 12-pulse connection is used. A reduction in the harmonic content can be achieved if the secondary windings of the transformers of every second rectifier unit are shifted 30 electrical degrees. The rectifier units as a whole then react under heavy power demand as they would in a 12-pulse connection. The alternating-current switchgear is of standard design; it is preferred that it be withdrawable and have short-circuit switching capacities of up to 50 kA.

DIRECT-CURRENT SWITCHGEAR

The short-circuit protection of the catenary system is provided by the direct-current high-speed breaker, which is directly coupled to the direct-current busbar system. Siemens, for example, manufactures direct-current breakers that have current ratings of 2 kA, 3.15 kA, 4 kA, and 6.3 kA. These breakers have an overload capacity of 1.5 times the rated current for 1 min and 4 to 5 times the rated current for 20 s, which can easily accommodate load peaks and rapid changes of direct-current traction systems. The inherent response time of only 3 ms between the moment the tripping value is reached and the contact opening of the breaker classifies it as a high-speed breaker. It ensures that the short-circuit current is tripped before it reaches its peak. This speed permits practically unlimited short-circuit capacities. The breaker is equipped with a magnetic overcurrent trip that is directly coupled to the switching linkage. The trip functions independent of current
direction and rate of rise when the current reaches the set value.

By using an electronic rate-of-rise current trip in addition, a short circuit can be recognized before the magnetic trip is activated, and the short circuit can be switched off in less than 3 ms. Calibrated potentiometers of the electronic monitor can select tripping values for near and distant short circuits; this optimizes the protection for the catenary system and the LRVs, reduces the short-circuit damage, and also more adequately protects the power supply system. High-voltage switching peaks also represent danger to the catenary system and the LRVs. Alteration of the arc chamber design criteria makes it possible to limit the arc voltage during switching to a relatively low voltage, e.g., 750 V plus 20 percent for the switchgear limits the switching peak to approximately 1.5 kV. Current designs do not require blow-out coils; this in turn allows the switching of low-value direct currents, which normally poses a problem. Since the breaker is mechanically latched, continuous energization of the holding coil is not necessary.

Figure 10. Traction rectifier in three-phase bridge connection.

![Diagram](image)

Figure 11. Design of a self-cooled rectifier.

![Diagram](image)

Figure 12. Rectifier cubicle for the Munich underground railway.

![Image](image)

Figure 13. Means of protection of the rectifier.

![Diagram](image)

Figure 14. Cross section of a high-speed direct-current circuit breaker.

![Diagram](image)

Figure 15. Switchgear cubicle with withdrawable breaker.

![Image](image)
Figure 14 shows a cross-sectional view of a high-speed breaker with a 750-V arc chute. The main current path is illustrated. Its fixed and movable contacts show: on the left, the mechanical linkage; on the right, the magnetic overcurrent trip mechanism; and, on the far left, the motor drive. The main connections are on the side, which aids in making it withdrawable. The direct-current high-speed breakers, in their switching function, govern separate line sections and are located in individual cells—either fixed and mounted or, preferably, withdrawable. Withdrawability provides a visible and positive means of disconnection, which avoids the cost of an additional disconnect and provides quick exchangeability and a high level of safety for operation and maintenance personnel. An interlocking between the breaker and the operation of the withdrawal mechanism removes any danger of malfunction.

The switchgear cubicles also provide a place for mounting the necessary auxiliary controls and protection equipment, such as the rate-of-current-rise monitor and test and reclosing controls. These electronic testing and reclosing controls make remote and automatic operation of the line power supply possible. After a trip of the breaker, the electronic circuiting will check, by sending out limited current according to a timed program, whether an actual short circuit still exists. If, for example, no short circuit is registered after a flashover or if the breaker on the LRV has tripped, the direct-current high-speed breaker will automatically switch back on. The adjustable test circuit can differentiate between test current flowing from auxiliary equipment on the LRV and test current flowing because of a line short circuit. If a preselected number of tests are unsuccessful during the total test period, a continuous short-circuit condition will be registered, and the high-speed breaker will be electrically interlocked in the off position. A line inspection would then be necessary to locate the fault.

Switchgear cubicles that have withdrawable breakers are available in widths of 1250 mm and 800 mm or even 500 mm (compact design). Figure 15 shows an 800-mm cubicle with a withdrawable breaker. Good overview of each component is provided, even with an inserted breaker. Only the breaker itself is mounted on the withdrawable frame. Figure 16 shows a compact 500-mm cubicle on which the auxiliary and monitoring equipment are mounted on the withdrawable frame; good overview and accessibility are available only when the truck is out.

In addition to the direct-current high-speed breakers for each line section, an additional bypass breaker is often installed. This breaker, which consists of a busbar and a changeover disconnect (often remote controlled), can be switched in to replace any line breaker, thereby making maintenance easier and reducing downtime.

A combination of no-load or load disconnects is usually inserted between the direct-current switchgear and the line in order to facilitate coupling, disconnecting, or changeover of the various catenary sections.

GROUND PROTECTION OF EQUIPMENT

To protect a substation against damage from faulty currents flowing through the metal frame of the system, ground protection for equipment should be incorporated into the design. The cells must be set on insulation pads, and the cell frames should be connected by a low-ohm current relay to the protective ground of the substation. Relatively low faulty currents will be picked up by this current relay and evaluated; this will lead to the tripping of the alternating-current and direct-current breakers. The current relay is laid out to handle current up to the tripping level of the breakers without being damaged. In addition, a voltage relay can be inserted between the equipment ground and the rail ground in order to monitor voltages of more than 90 V and to initiate the trip.

The size of an LRT network increases the operational problems and responsibility. In order to solve these problems and, at the same time, to rationalize and improve the operational dependability, centralization is
becoming more and more popular for controlling and monitoring the power supply system. Remote control and measurement are carried out by using standard, proven telemetering components. By adding specific components, the problem of the automatization of the traction power supply can be solved. Integrated circuits provide a high level of dependability, high transmission speed, simple expansion, and simple programming. The signals, commands, and measurements to be transmitted are coded into impulses that are transmitted over a single pair of wires. The receiver then decodes these impulses.

The central control can be simplified by using mosaic block systems in which the push buttons, control switches, pilot lights, and so on are inserted. Mosaic boards have the advantage that future changes of the network can be incorporated very easily. Although the mosaic technique maximizes the number of control functions that can fit in a small space, some regional control centers require a control board that would be too long for efficient operation. Large control rooms and long control panels debase the overview and reaction time. Such large regional control centers have selective graphic displays and use computers. The network is represented on the mosaic display board to give a general overview. The illumination of the mosaic board, which depicts the actual switching conditions, is governed by a process computer. The complete and detailed display of stations or network sections (as selected by the operator) is shown on the graphic display board (Figures 17 and 18). The switch to be operated is located on the graphic display and can then be switched by a single push button. If a faulty operational signal has been given, the process computer will so indicate in written form, giving the correct operating instructions. All signals and operations will be recorded; this permits accurate reconstruction of the situation in case this is needed.

REFERENCE


Technology and Economics of Regeneration for Light-Rail Applications

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Regeneration is one method of recycling a vehicle's surplus kinetic energy during braking. Regeneration is recuperative braking in which the recycled energy goes back to the vehicles' power supply system for use by other vehicles. Several propulsion systems that use regenerative braking have been applied and operated on direct-current electrified rail systems. The fundamental limitations on effectiveness that are beyond the propulsion designer's control are considered. The performance of an alternating-current induction motor system with an inverter and a direct-current series motor system with a chopper are explored to illustrate the present state of technology. Comparison is made with two other types of recuperative braking—flywheel energy storage and height changes in the route profile. The inefficiency of the former and the difficulty of construction of the latter are noted. The industry's present interest in regeneration is questioned since it would have minimal economic impact but require complex propulsion hardware and extra maintenance costs.

Regenerative braking is one method of recycling a vehicle's surplus kinetic energy during deceleration. It is recuperative braking in which the recycled energy goes back to the supply system for use by other vehicles. In transit operation, acceleration and deceleration are the predominant vehicle activities. Because of this, the duty cycle that determines the required rating of a vehicle's propulsion system and brake system equipment depends primarily on the acceleration and deceleration needs for that vehicle. For example, on the Norristown Line of the Southeastern Pennsylvania Transportation Authority (SEPTA) local cars go through 21 acceleration-deceleration cycles in a 26-min run that covers 20.9 km (13 miles). That averages out to just more than 74 s/cycle. Of this, approximately 50 to 55 s are spent accelerating and decelerating, which leaves from 19 to 24 s for coasting and station dwells.

The propulsion and brake equipment on these cars is from an era when the virtues of simplicity and serviceability were considered as well as the costs of power. The motors and motor controls have only one task, i.e., accelerating the car. The friction brake has only one task, i.e., decelerating the car. When these cars were built in the early 1930s, it was not practical to usefully recover the energy wasted in braking. Energy costs were important then, as is indicated by the aerodynamic body shape and the attention given to light weight in the vehicle design. For an interesting history of these cars, one may refer to Chapter 7 of The Red Arrow (1). Some trolley coaches were equipped with special compound field motors that provided limited regenerative braking at higher speeds by means of motor field control (2).

Subsequent developments in motors and motor controls have produced vehicles that have dynamic braking (properly called rheostatic braking) that lessens the duty and wear on the friction brake system. In dynamic or rheostatic braking, the drive motors function as generators during deceleration, but all the resulting electrical braking energy is wasted as heat in the braking resistors. The use of rheostatic braking does not provide any savings in the vehicle's energy consumption.

DEVELOPMENT OF REGENERATIVE BRAKING

Although there is a long history of attempts to develop