Traction Power Supply for the Portland Interstate MAX Light Rail Extension

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Interstate MAX is a 5.8-mi extension of the 39-mi MAX light rail system serving Portland, Oregon. The line will connect downtown Portland to neighborhoods and other major destinations in North Portland. Ten passenger stations are provided and located approximately every half-mile. Trains will provide direct service from Expo Center through downtown and back. The project is currently under construction and scheduled for revenue operation in May 2004.

A general description of the traction power supply system is presented. Primary power is provided by the local utility companies at 13.2 kV and 11 kV and rectified by six mainline traction power substations to deliver DC power to the light rail vehicles. The major items discussed are computer loadflow simulation, regeneration studies and the selection of 825 Vdc versus 750 Vdc as traction voltage, built-in place substations, substation PLC controls, grounding, way-side electrical distribution, testing, and energization.

INTRODUCTION TO TRIMET'S MAX LINE

TriMet's Metropolitan Area Express (MAX) is a 39-mi light rail system connecting the cities of Portland, Gresham, Beaverton, and Hillsboro. The first 15-mi Banfield Eastside MAX Line opened on September 5, 1986. The 18-mi Westside and Hillsboro MAX extension opened on September 12, 1998. The 6-mi Portland International Airport extension opened on September 10, 2001. The 5.8-mi Interstate MAX extension to the Portland Expo Center is scheduled to open in May 2004.

The MAX line now features 50 stations, 16 park-and-ride lots which provide spaces for 6900 cars, and 78 cars, including ultimately 52 new, air conditioned, low-floor cars. The Washington Park (Zoo) Station is the only stop in the dual-bore, 3-mi tunnel. At 260 ft underground, it is the deepest transit station in North America.

The low floor cars for the Westside Light Rail are the first of their kind in North America (*1*). They make boarding easier, especially for people who use mobility devices. Each 92-ft low floor car is capable of speeds up to 55 mph carrying 166 passengers, and costs $3.1 million each.

Average weekday ridership of the MAX system is expected to exceed 90,000 passengers by the year 2004.

TRACTION POWER SYSTEM

Overview

The Interstate MAX extension is powered by six built-in-place substations located along the system route spaced approximately one mile apart. The nominal (full-load) voltage is 825 Vdc. The nominal voltage was chosen to be the same as the Eastside Banfield Line in order to minimize voltage drop, maximize the vehicle propulsion system performance, and still maintain the benefits of train regeneration. Each substation is rated at 1MW and is connected to a three-phase nominal 12.47–13.2 kV distribution circuit from Portland General Electric, except the Graham traction power substation is connected to a 11kV distribution circuit from Pacific Power.

The overhead contact system (OCS) is similar in conductor sizes to the existing line with the 500 kcmil underground supplementary parallel feeder in the Rose Quarter area to sustain voltage levels at the east end of the line with the Rose Quarter substation out of service. The substations are designed to comply with National Electrical Code wherever possible, except for the DC portion of the substation equipment. The substations were built-in-place, and the equipment was installed by licensed electricians. Each substation building is required to be inspected by the State of Oregon electrical inspectors.

Equipment Arrangement

The equipment arrangement of the Interstate Max line substations is similar to the Westside substations, except that the traction power transformer was placed in the equipment line up between the AC switchgear and the rectifier and the building width dimension was increased to allow for rear access to the utility incoming cubicle, AC and DC switchgear equipment.

AC Switchgear

The AC switchgear assemblies are indoor, metal clad vacuum circuit type breaker. The switchgear is rated at 15 kV, 500 MVA. The following relaying protections are provided with the AC switchgear:

- Phase overcurrent protection (50/51);
- Ground overcurrent protection (50/51N);
- Negative sequence voltage relay (47);
- Rectifier overload relay (51A); and
- AC lock-out relay (86).

Siemens SIPROTEC 4 7SJ61 digital multifunction relay is used for overcurrent protection. Siemens 4700 AC meter is used for power monitoring.

Traction Power Transformer

The traction power transformers are vacuum pressure impregnated dry type. All transformers are rated 1110 kVA 65°C rise at 100% load, three phase, 60 Hz. The traction power transformers and the power rectifiers are matched assemblies capable of providing a twelve pulse, 825 Vdc output at rated 100% load using ANCI circuit no. 31. Primary windings are connected in delta and have six taps, except the Graham traction power transformer has two additional lower taps to accommodate the incoming voltage of 11,300 Vac. These taps are used to accommodate the utility's voltage variations and to provide limited control of the DC output voltage. The two secondary windings are connected in delta and wye with 30-degree phase shift to obtain 12-pulse rectification which reduces the harmonics in the utility power lines and the interference voltages due to residual ripple. The transformers are built in accordance with ANSI and NEMA standards for extra heavy-duty service. Transformer winding temperature devices furnished with the traction power transformers are used for annunciating or tripping upon pre-set high coil temperatures.

Power Rectifiers

The rectifiers are naturally ventilated silicon traction power rectifiers with silicon disc-type diodes. There are two three-phase bridges connected in parallel with two diodes per arm of one of the three-phase bridge. This configuration results in a total of 24 diodes per power rectifier. The two three phase bridges are connected in accordance with ANSI circuit 31 configuration. The nominal rated DC output is 825 Vdc. The rectifiers are rated at 1000 kW continuous load with the overload capabilities as specified in NEMA RI-9 for extra heavy-duty traction service.

DC Switchgear

The DC switchgear consists of a positive cubicle, which houses the motor operated disconnect switch connected to the positive bus, two DC feeder breakers and a negative cubicle. The negative cubicle includes a 2000A manual disconnect switch, keyed interlock with the positive switch, DC shunt current measurement, an interphase transformer, and a low resistance frame fault protection device with current and voltage tripping. Each feeder cubicle includes a 2000A high speed circuit breaker, solenoid operated with direct acting overcurrent trip device, 2000A/60mV Shunt and a Digital Protection Unit for incomplete sequence, over-current trip and rate-of-rise relays, reclosing, load measuring devices, and transfer trip protection.

Programmable Logic Controller

A Programmable Logic Controller (PLC) system was programmed to integrate and control all intercubicle functions and provide control, monitoring, and data logging at each substation. Auto-reclosing relays and logic, auxiliary relays, timers, and relaying logic were done through the PLC system. Considerable internal cubicle spacing was realized and interconnecting cabling between cubicles was virtually eliminated.

The PLC control system consists of the following components:

- Siemens "SIMATIC" S7-300, consisting of CPU, signal modules, and interface board; and
- Siemens SIMATIC Operator Panel OP3.

Station Service Cubicle Section

The station service cubicle includes a primary fused interrupter switch and a 25 kVA single phase, dry type, 115°C rise transformer. The transformer was built in accordance with ANSI C57.12 and was designed and tested in accordance with ANSI C57.12.91 inside the switchgear enclosure to determine maximum temperature rise. The transformer is mounted in the bottom rear of the compartment for easy access and maintenance. The access door to the rear transformer compartment is key interlocked with the fused interrupter switch to prevent access to the energized equipment.

Each substation is equipped with an AC and a DC distribution panelboard.

Grounding System

The substation grounding system is comprised of two separate ground mats referred to as the "AC" and "DC" mat, and one separate ground rod (*2*). The AC ground mat, designed to meet the requirements of IEEE 80 to limit step and touch potential to safe levels in the event of a fault on the AC system, is also used to ground the building metallic structure, conduits, and AC equipment, including switchgear. The AC ground mat is placed under the substation, and extends a minimum of 5 ft beyond the perimeter.

Another smaller ground mat called the "DC ground mat" is used exclusively for grounding of the DC equipment, including the negative bus through a diode for stray current monitoring or testing, and for grounding of the DC lightning arresters and protective relays.

A separation of 25 ft minimum between the AC and DC mat is used to reduce fault current contribution from the AC equipment to the DC equipment. It also provides for some reduction in DC stray current.

The 15 kV cable shields from the utility service 3 phase, 3 wire service conductors are isolated from the substation by termination on an isolated lug within the utility cubicle in the AC switchgear, and grounded to a single ground rod located a minimum of 25 ft from the AC and DC ground mat. This provides an effective grounding path through earth back to the utility supply in the event of a fault on the utility system, while significantly limiting the ground fault current contribution from the utility to the ground mats.

Ground mats are constructed from an assembly of driven rods and bare copper conductor. All joints are exothermically welded. The mats are typically located at a minimum of 3 ft below finished grade, and constructed before the substation building is built. The conductors are encased in native soil, which in most cases is clay with a resistivity between 50 and 100 ohm-meters, except at Delta Park substation where the soil resistivity is over 160 ohm-meters. At this particular substation location, four additional 50-ft ground rods encased in Bentonite material were used to achieve a lower value for the substation ground mat resistance. An insulating layer of 2 in. minus crushed rock, free of fines, is then placed over the ground mat, and a layer of "filter fabric" cloth is placed on top of the rock to prevent the contamination with the layers of soil surrounding it. The top layers may be comprised of asphalt, or soil, and this lends versatility to the design of the installation, since it permits planting, or landscaping.

Stray Current Monitoring

Each substation is equipped with provisions to monitor stray currents. Within the DC switchgear negative switch cubicle is a shunt and bolted bus link in series with the DC grounding conductor. By bolting the link in the closed position, the DC mat can be used to ground the negative return through a diode. In this position, the DC mat acts as a stray current collector and most stray currents will flow through the shunt. The shunt can be connected to a chart recorder or voltmeter to monitor and record stray currents over time.

An AstroDAQ data acquisition system is used for the monitoring, acquisition, storage, and review of real time data of the stray current monitoring system. The AstroDAQ utilizes a personal computer running the Windows operating system.

Emergency Shutdown

As a safety feature, each substation is equipped with two emergency shutdown stations. One button is recessed in a stainless steel enclosure mounted in an exterior wall and accessible by key only. The other button is readily accessible and located inside the substation by the access door. Actuation of either button will trip and lock out the 15 kV AC breaker of the substation, and transfer trip and lockout the DC breakers at the adjacent substations, thus completely isolating the fault or trouble.

Substation Field Acceptance and Commissioning Tests

In addition to factory tests, which include design verification and production tests for each type of major equipment, functional tests were performed to verify the correct installation of the equipment, and each protective device was tested and checked for correct settings.

The full voltage short circuit testing was performed after the functional testing has been completed. The purpose of the short circuit testing was to verify the correct operation of the substation protective relays and the fault-withstand capabilities of the substation equipment.

Two series of fault tests were performed at selected substations. The first test was to verify the successful interruption of maximum and minimum fault currents supplied by a substation. The second series of fault tests were carried on an OCS section fed by two substations to check for maximum energy fault and transfer tripping protection.

Computer Performance Simulation

The simulation was performed using the RR Model developed by LTK Engineering Services specifically to perform traction power simulation; the model is a comprehensive software tool used for the design and analysis of DC traction power system. The RR model consists of a group of programs capable of simulating the entire electrification system from the power utility interface point to the vehicles. The information used by the simulator includes track alignment and grades, traction power substation type and characteristics, DC distribution systems including the OCS, DC feeders, and return rails, and the power characteristics of the vehicles to be used on the system. The programs are written in C++ and is Microsoft Windows based with many user definable settings. These settings allow the user to quickly and accurately enter the vast amount of input data required.

The vehicles were simulated to operate on the network according to a fixed schedule taking into account route geometry, speed limits, and passenger station stops. The RR simulator accurately models the tractive effort and current curves for the desired vehicle and automatically adjusts these curves as the traction power voltage varies over the prescribed route. This is accomplished through the use of direct matrix inversion techniques and the ability to iterate to a steady state voltage condition.

The computer simulation was used to verify that the RMS power demand on each substation was within the allowable limits, that the voltage delivered to the vehicles was within acceptable limits, and that the current draw in the substation underground feeder cables and the overhead contact wire would not create an unacceptable increase in conductor and insulation temperature under the above criteria.

The voltage at the pantograph is designed to remain above the minimum 525 Vdc requirement at all locations during the sustained 3-min headways with all substations operating, and during peak operation using the 2005 revenue service schedule. The TES system is not designed to support 3- min headways with one substation out of service. Under these conditions, voltages below 525 Vdc will occur when two trains simultaneously accelerate out of a passenger station where the nearest substation is off line and the adjacent substations are approximately a mile away in either direction. The result of the line voltage dropping below 525 Vdc will be a propulsion cut-out on the affected vehicle. The cut-out will automatically reset without damage to the vehicle when the line voltage returns to a level above 525 Vdc. Line voltage will immediately return when one of the two vehicles drops propulsion. In general, in order to avoid these occurrences with one substation out of service during the peak schedule, train acceleration rates must be reduced by direction from Central Control in the vicinity where the substation is out of service.

TRACTION POWER SUBSTATION BUILDINGS

The substation buildings, including low voltage substation AC auxiliary electrical system and facility electrical equipment such as AC panelboards, heating and ventilation systems, transformer partitions, all embedded conduit work, utility instrument enclosure, door intrusion switches, lighting, and substation ground mats were built in the “Civil” contracts in advance of the Traction Electrification contract.

The medium voltage electrical systems, traction electrification, and communications equipment were installed later in the follow-on TES/Communications contracts. Included in the Traction Electrification contract were cable trays, conduit systems, and cable for traction power, electrically insulated floor coating under the DC switchgear, AC and DC switchgear, traction power transformers, and the substation alarm panel. The Remote Transmitter Unit connected to the Supervisory Control and Data Acquisition system (SCADA) was installed by the Signals/Communications Contract.

Refer to Hastings et al. (*3*) for additional information on TriMet built-in-place traction power substation buildings.

OVERHEAD CONTACT SYSTEMS

Single Contact Wire Auto Tensioned

The Single Contact Wire Auto Tensioned (SCWAT) is installed from the existing MAX route at Rose Quarter Half Grand Union to the Interstate MAX Rose Quarter Station. The SCWAT system is auto-tensioned by using balance weight assemblies to maintain constant tension despite temperature variations. The SCWAT consists of a single contact wire (300 MCM) connected in parallel with an underground 500 MCM supplementary parallel feeder cable. The SCWAT system is supported by single-track cantilever, cross-spans by rollers and bridles mounted on steel poles. Two levels of electrical insulation are provided between the contact wire and a grounded pole or other grounded structure.

Simple Catenary Auto Tensioned

The Simple Catenary Auto Tensioned (SCAT) system is installed from the Rose Quarter Station to the Expo Center. The SCAT system consists of a single contact wire (300 MCM) suspended from a 500 MCM messenger wire. The SCAT is auto-tensioned by using balance weight assemblies so that the tension remains constant despite temperature variations. The SCAT support structure consists of either single-track cantilever, or headspan arrangements mounted on steel poles located between the two tracks. Two levels of electrical insulation are provided between the contact wire and a grounded pole or other grounded structure.

OCS Support Systems

Wide flange or tapered multifaceted tubular poles and all cantilever structures are made of galvanized steel. Cantilevers are mounted back to back on a common center pole located between the tracks. Where the clearance between tracks is not sufficient, side poles with head/cross span arrangements are used. At overlap sections and at turnouts where two cantilevers are required, both cantilevers are installed on the same poles for aesthetic appearance improvements.

Balanced Weight Anchor Assembly

The tensions for the contact wire and messenger wire are 3000 lb and 4500 lb at 60^{o}F respectively. Both the contact and messenger wires are combined tension and the forces are maintained by counterweight wheel with a ratio of 3:1 between wires and counterweight. The maximum distance between two tensioning points is about a mile and depending on the amount of curves and the individual track configuration, the distance would need to be reduced to ensure the auto tensioning effect of the wheel assembly. A mid-point anchor is installed approximately at the mid-distance between the weight assemblies to reduce the along-track movement of the OCS equipment and minimize the work in case of a conductor breakage.

Sectionalizing

OCS is sectionalized to provide isolation of the OCS section at each substation. Insulated overlaps are used for sectionalizing. Section insulators are installed at the crossover locations. To maintain electrical continuity, jumpers are used at overlaps and at crossover locations.

OCS Disconnect Switches

OCS Disconnect switches are of outdoor type, single-pole, single throw, non-load break, non-fusible, manual air–insulated switches.

CONCLUSION

The Interstate MAX light rail extension was designed and implemented to be safe, reliable, cost-effective, easily maintained and efficient. The TriMet MAX system has been in operation for over 16 years, the system has functioned quite well, and ridership has been increasing steadily and additional extensions of the system to Clackamas, Milwaukie, and to Clark County are imminent.

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