TRACTION POWER SUPPLY SYSTEM FOR CALIFORNIA HIGH-SPEED TRAIN PROJECT

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ABSTRACT

The Phase I of California High-Speed Train Project (CHSTP) to be implemented between San Francisco and Anaheim will be a 520 route-miles long state-of-the-art rail system providing intercity travel with modern high-speed trains running at speeds up to 220 miles per hour. The traction power supply system (TPS) for this project will be a 2x25kV ac autotransformer feed system, and is being designed to provide traction power for safe, efficient, and reliable operation of trains per the operations plan. The TPS design is based on the European Union’s Technical Specifications for Interoperability (TSI) relating to the ‘Energy’ and other related subsystems, and conforms to North American standards (AREMA, NESC, IEEE, NFPA, CEC, etc) and relevant International and European standards (EN, IEC).

The TPS will have, in general, traction power substations (SS) spaced approximately 30 miles apart, located close to HV utility transmission network/grid substations, switching stations (SWS) located midway between adjacent SS, and paralleling stations (PS) located at approximately 5-mile spacing between SS and SWS. The capacity of the main transformers and autotransformers has been arrived at based on the train operations plans, rolling stock parameters, track alignment, and spacing of these facilities. The TPS configuration has been verified by running traction power supply load flow analyses over representative sections of the project.

This paper describes the main features of the traction power system design for CHSTP including system configuration, reliability, system protection, interface options with HV power supply utility networks, and other related aspects.

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1. PROJECT OVERVIEW

1.1 General

The California High-Speed Rail Authority proposes to construct, operate, and maintain an electric-powered high-speed train (HST) system in California. The California High-Speed Train Project (CHSTP) consists of new rail alignment, entirely within California, grade-separated from road vehicle traffic and freight trains, with a top design speed of 250 mph and operational speeds of up to 220 mph, reducing travel time from downtown Los Angeles to downtown San Francisco to less than 2 hours and 40 minutes. On portions of the route where track capacity permits, the system is being designed to accommodate shared use of tracks with compatible conventional rail passenger services. The top design speed of HST on the shared-use corridors will be 125 mph. When completed, the nearly 800-mile train system will provide new passenger rail service to California’s metropolitan areas and through the counties that are home to 93% of the state’s population.

The HST will operate primarily on exclusive (dedicated) track with portions of the route shared with other existing passenger rail operations. The route (alignment) will be constructed either at-grade, in an open trench, in a tunnel, or on an elevated guideway, depending on the terrain, physical constraints, environmental impacts and community input along each section. The system will predominately be within, or adjacent to, existing rail or highway right-of-way to reduce potential environmental impacts and minimize land acquisition.

The CHSTP will be implemented in phases. Phase 1 includes the proposed route between San Francisco and Anaheim via the Central Valley (approximately 520 miles long), depicted in Figure 1. Subsequent phases are planned for a southern extension from Los Angeles to San Diego via the Inland Empire and an extension from Merced north to Sacramento.

Proven train technologies similar to those used in other countries with established high-speed train systems (for example: Japan, France, Germany, Great Britain, Spain, Korea and China) will be used. This technology includes steel-wheel-on-steel-rail, entirely electric power, state-of-the-art safety and signaling systems, and automated train control.
1.2 Project Delivery System

The CHSTP is a large project, and has been split into ‘regions’ of lengths from 50 to 150 miles for effective management. The Core Systems, including Traction Power Supply System (TPS), are however, being developed centrally to ensure that a cohesive system results across the regional boundaries. Consistent with the regional approach, the TPS system parameters are then transferred to the regional teams for local applications and site specific design. The HST design is being carried upto 30% level and thereafter ‘Design and Build’ procurement method will be adopted for implementation.

The HST is being designed following the European Union’s Technical Specifications for Interoperability (TSI), and conforms to North American standards (ANSI, IEEE, NESC, NFPA, NEMA, AREMA, CEC, CPUC, etc.) and relevant International and European standards (IEC and EN).
1.3 Energy Implications of the Project

Introduction of the CHSTP, like any high-speed train system, is expected to bring about reduction in energy consumption and emissions (1). The transportation sector at 38% is the largest source of energy consumption in California (2). Based on traction power load flow simulations for the HST alignment the specific energy consumption (with regenerative braking) is expected to be around 108 Wh / train-seat mile. The HST when fully operational is expected to consume around 8 GWh of electrical energy per day in the year 2035 for the expected ridership. With the implementation of the CHSTP it is expected that a portion of the passenger travel will shift from road vehicles and airlines to the HST. It is estimated that in the year 2035, this shift will involve about 17 million road vehicle-miles per day and 200 airline flights per day. This is expected to bring about a net energy saving of roughly 69,000 MMBtus/day by the year 2035.

2. TRACTION POWER SUPPLY SYSTEM (TPS)

2.1 General

The traction power supply system (TPS) is the railway electrical distribution network used to provide energy to high-speed electric trains, which comprises three types of traction power facilities (TPF) - traction power substations (SS), switching stations (SWS), and paralleling stations (PS) in addition to connections to the overhead contact system or catenary (OCS) and to the traction return and grounding system.

The traction electrification system (TES) is the combination of the TPS, OCS and the associated supervisory control and data acquisition (SCADA) system.

The TPS is an important component of the CHSTP high-speed rail network. Its planning and development are fundamental steps to the successful implementation and operation of the HST in California. The design of the TPS and associated site works is being coordinated with:

1. The requirements of the power supply utility companies (both investor owned and municipal utility companies) providing electrical power to the CHSTP system

2. The requirements of the state and local jurisdictions in which the traction power facilities (TPF) are located

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3. The technical and operational parameters and requirements of the HST (e.g., track work, overhead contact system, rolling stock, operations, maintenance, train control system, communications system, electromagnetic compatibility)

2.2 Choice of Feed Configuration for the Traction Electrification System (TES)

After careful consideration a 2x25kV autotransformer feed configuration has been chosen for the traction electrification system for the main lines because:

1. Although 1x25kV traction power supply systems have been used successfully for electrified main line railroads for many years, 2x25kV autotransformer feed systems have become the modern 'Standard' for main line electrification, especially for high-speed lines. The 2x25kV configuration utilizes autotransformers to supply (+)25kV to the catenary wires and (-)25kV to the negative feeders (NF), essentially providing a 'boost' to the voltage on the OCS and extending the reach of the substations.

2. In total there are more traction power facilities required for a 2x25kV autotransformer feed system than for a 1x25kV system, but there are fewer substations, with their associated HV utility circuits, HV transformers and HV switchgear – this is a major advantage (See Figure 2).

3. A further benefit of the 2x25kV system is that the electromagnetic interference (EMI) emitted due to the load current in the OCS and running rails is considerably reduced. Autotransformers inherently attempt to equalize the current flowing in the two sections of the transformer windings. For autotransformers that are supplying a heavy OCS load current the net effect is that traction return current in the running rails is drawn through the autotransformer’s (-)25kV winding and into the NF in order to create the required balance (See Figure 3). Due to this autotransformer effect the current in the running rails is much reduced between the train and the remote autotransformer feeding the electrical section, and very much reduced in the adjacent electrical sections closer to the substation. Since the EMI caused by the supply and return current loop is proportional to the field created by the magnitude of the current in the loop and the size of the loop then reducing either will reduce the level of EMI generated.
4. Because of the fact that in 2x25kV system the return current flowing in the rails in the sections close to the substation is much less than the corresponding figure for the simple single-phase system, the rail potential in these sections is reduced. Therefore, it is a safer system.

The traction electrification system for the rolling stock maintenance facility yards will, however, be 1x25kV ac system.
2.3 Traction Power Supply System (TPS) Performance Requirements

The TPS, in conjunction with the overhead contact system (OCS) is being designed as a state-of-the-art system to meet the operational and performance requirements of the HST, specifically the following:

1. The design peak frequency of trains, which will be 12 trains per hour in each direction with nine trains consisting of two train-sets (400 m) and three trains consisting of one train-set (200 m)

2. The line speed for both the sections of the CHSTP dedicated to very high speed where the maximum operating speed is 220 mph and the maximum design speed is 250 mph, and also the shared use corridors where the maximum operating (and design) speed is 125 mph
3. No degradation of train performance in case of single contingency conditions, that is, isolation of any one incoming HV supply circuit or one power transformer in a substation, one autotransformer in a paralleling station/switching station or of negative feeder (NF) for any one electrical section

4. There must be no stranding of trains in case of double contingency conditions, that is, simultaneous occurrence of more than one single contingency condition in any electrical section though there might be a degradation of service

5. The system will support the maximum train current, the tractive effort and braking effort available/permissible at different speeds, the train acceleration/deceleration/adhesion characteristics, and other relevant parameters of a typical modern high-speed train system.

2.4 Design Facets of TPS

Some important facets of TPS design for the CHSTP are described in the Sections 3 to 7.

3. SYSTEM CONFIGURATION

3.1 General

The proposed TPS configuration utilizes traction power substations (SS) with main transformers, and switching stations (SWS) and paralleling stations (PS), both with autotransformers, which provide 25kV (nominal) voltage to the catenary with respect to remote ground and also 25kV to along-track negative feeders (NF) with respect to remote ground. Both of these voltages are 180° out-of-phase with each other, and hence, the catenary is at 50kV with respect to the NF.

Electrical power will be supplied to the trains from wayside traction power facilities (TPF) through the catenary, which distributes the power to the train pantographs. The pantographs, mounted on the roof of the rolling stock, collect the electrical power from the catenary through mechanical contact by running / sliding under the contact wire. The electrical circuit is completed back to the source SS via multiple return paths, including running rails, static wires, ground, and the NF. From the SS – which transforms two phases of the high-voltage (HV), 3-phase, utility power to the 2x25kV single-phase power of the autotransformer feed system – the power for the trains will be distributed along the tracks by the OCS. There will be one NF

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per mainline track, attached to the catenary structures with brackets and insulators. The catenary will consist of a messenger wire and a contact wire. The contact wire will be suspended from the messenger wire by the means of hangers, and tied electrically to the messenger wire by means of jumper wires.

Autotransformers will be provided periodically along the line, interconnecting catenary, NF and rails. The autotransformer turns ratio will be 2:1 of primary (catenary-to-NF) to secondary (catenary-to-Rails) windings, in order to step down the 50kV distribution voltage between catenary and NF, to 25kV nominal between catenary and rails, suitable for the trains.

_Traction power load flow studies_ for the representative sections of the CHSTP were conducted to assess the spacing of the traction power facilities (SS, SWS, and PS) and the ratings of transformers so as to meet the performance requirements of train frequencies, track alignment and rolling stock parameters during normal operations and also under contingency situations. Based on the results of these studies the following configuration was arrived at:

1. Traction power substations (SS) spaced approximately 30 miles apart, each having two 60-MVA transformers. The SS locations have been determined in consideration of the results of the load flow simulation analysis, proximity to high-voltage transmission facilities and feasibility of drawing HV power, and availability of real estate

2. Switching stations (SWS) located midway between two adjoining SS will each have two autotransformers of 20 MVA

3. Paralleling stations (PS) located five miles apart between SS and SWS will each have one 20-MVA capacity autotransformer. (The sequence of the facilities will be SS – PS – PS – SWS – PS.)

### 3.2 Traction Power Substations (SS)

At each SS two separate 3-phase HV circuits will be drawn from the power utility network. These circuits should be originating from different utility substations, at least from different bus systems. These may however, be carried on the same transmission towers. Each SS will have two equally sized HV traction power transformers, each transformer supplied from a separate incoming circuit. Both transformers will be energized under normal TES configuration, with one of them supplying power to the feed section north of the SS, the other to the section to the south, with the two feed sections separated by a phase-break (neutral
section) at the SS. Both the HV power transformers will be individually capable of supplying the full normal load of the SS.

The HV transformers will be single-phase, with their primary windings connected to two phases of the utility HV 3-phase system. The secondary winding of the HV transformer will be either a single winding with a grounded midpoint connected also to the running rails, or comprise two separate counter-phase secondary windings connected in series, with the common point grounded and connected to the running rails. The HV transformers will be outdoor type, mineral oil insulated, self cooled, with 60 MVA ONAN rating, with a provision for installing cooling fans and pumps etc. for ONAF rating at a subsequent date. Each HV transformer will have a no-load tap changer on the primary side and on-load tap changer on the secondary side.

The traction power substation’s single line diagram and re-configuration capabilities will be such that in the event of a power loss to one of the incoming HV feeder lines, or temporary outage of one of the transformers, or transformer-related equipment, or outage of a 25kV bus section, the remaining transformer will be able to supply power both north and south feed sections of the SS (See Figure 4).

The ‘positive’ bus of the SS (the bus supplying power to the catenary) will be split into two sections interconnected via normally open (N.O.) motorized tie circuit breaker, with each bus section supplied by a different transformer under normal conditions. Each section of the positive bus will feed two different catenary electrical sections in normal TES configuration for two main line tracks. The ‘negative’ bus of the SS (the bus supplying power to the along-track NF) will be sectionalized likewise. Tie-breakers of both the catenary and the NF buses will be interlocked with each other so that they open and close together.

The outer terminals of the secondary winding of each HV transformer will be connected to the positive and negative buses (the bus sections corresponding to the particular transformer) through a two-pole circuit breaker. The positive and negative buses in turn will be connected to the catenary and NF, respectively, through single-pole circuit breakers and in-series connected no-load motorized disconnect switches.

Jumper type motorized, N.O., load-break disconnect switches will also be provided, connected between each pair of in-phase, same-side, single-pole circuits to allow for one 25kV circuit to feed both tracks sections under emergency conditions of feed extension because of complete failure of any SS.
Furthermore, N.O. trackside, motorized, load-break switches will be installed at the substation’s phase break, to provide for electrical continuity in emergency conditions between the catenary and NF, respectively, on either side of the phase break. The flexibility and re-configuration capability of the single line diagram of the SS on the 50/25kV side will be such that a loss of one single-pole circuit breaker, or disconnect switch, or interconnecting cable will still allow the SS to feed the whole feed zone of the SS without having to de-energize one of the HV transformers.

3.3 Switching Stations (SWS)

The SWS is a facility interfacing the feeding sections of adjacent SS. This is an installation at which electrical energy can be supplied to an adjacent, but normally separated electrical section during
contingency power supply conditions (An **electrical section** may be defined as the entire section of the OCS which, during normal system operation, is powered from a circuit breaker of the traction substation).

Because the ac voltages on either side of any SWS will be of different phases (or even if of the same phase sequence, the angular displacement may be different) the SWS will include a phase break. In normal operations the phase break will be open, isolating the two feed sections. Autotransformers (AT) will be connected on either side of the phase break, one AT per side, serving as the last AT of the respective feed section.

The catenary and NF buses will be connected in turn to the primary winding terminals of the AT via a two-pole circuit breaker. The AT winding center tap will be connected to a neutral bus, which will be locally grounded and connected also to the running rails of both tracks (through impedance bonds as required) and to the static wires (**See Figure 5**).

The SWS equipment will include switchgear (25kV circuit breakers) and motorized disconnect and bypass switches in a configuration that allows isolation of an AT in case of problems, and as required for maintenance. The SWS design will provide for electrical continuity across the phase break in contingency operations, in the event the SS on one side is out-of-service. In such eventuality, the SS on the other side of the SWS will be used to provide power to the sections normally served by the out-of-service SS. This will be achieved by interconnecting the catenary and NF on both sides of the SWS, by closing N.O. circuit breakers. Furthermore, N.O. trackside, motorized, load-break disconnect switches will be installed at the SWS phase break, to provide for electrical continuity in emergency conditions between the OCS and NF, respectively, on either side of the phase break.

### 3.4 Paralleling Stations (PS)

The (PS) is a facility featuring an AT and associated switchgear and disconnect switches. The PS helps boost the OCS voltage and reduce the running rail return current by means of the autotransformer feed configuration. The AT installed along the line in the PS steps down the 50kV nominal voltage between catenary and NF to the 25kV level between catenary and running rails. Similar to the SS, the number and locations of the PS have been determined based on the results of a traction power study, and by taking into account environmental and real estate considerations.
One AT of 20 MVA rating serving all tracks will be installed at each PS, along with a line-up of medium voltage switchgear containing separate buses for connections to the catenary and NF circuits. The switchgear will include single-pole 25kV catenary circuit breakers and NF circuit breakers, and double-pole 50kV AT circuit breaker. The catenary and NF conductors will be connected to the switchgear buses via no-load type motorized disconnect switches and the switchgear. The catenary and NF buses will be connected in turn to the primary winding terminals of the AT via a two-pole circuit breaker. The AT winding center tap will be connected to a neutral bus, which will be locally grounded and connected also to the running rails of both tracks (through impedance bonds as required) and to the static wires (See Figure 6).

The PS will provide a booster connection to the OCS, without OCS sectionalizing gap. There will be no sectionalizing of the catenary and NF circuits at the PS. The catenary of each mainline track will be connected via single-pole circuit breaker to the catenary bus of the PS. Likewise, the NF wire of each track will be connected via tap connection and single-pole circuit breaker to the NF bus.
3.5 Modifications to Spacing of TPF

TPF for HST are preferably, spaced uniformly along the alignment. However, it is not feasible to provide uniform spacing of TPF at all locations because the track alignment passes through different types of terrain including level ground and stretches of mild to steep gradients. In other sections, wetlands, parks and densely populated areas present difficulties in finding suitable sites for the TPF. Additionally, HV utility feeding points are not available at uniform distances along the alignment. This necessitates non-uniform spacing of these facilities. At the time of carrying out the preliminary design, this flexibility in spacing/configuration of TPF was quantitatively ascertained on the basis of load flow studies for different ‘what-if’ scenarios of track alignment. Based on the results of these studies the following empirical rules were developed as guidelines for locating TPF under these constraints:

1. The basic TPS configuration is satisfactory and will support train operations on continuously graded sections as well as on longer feed sections, i.e., 16~17 miles long.
2. Under exceptional circumstances 6-mile spacing of TPF may be acceptable.

3. For feed sections 18 miles long, it may be preferable to provide an additional PS so as to bring inter-TPF spacing to 5 miles or less.

3.6 Sectionalizing of Main Line Tracks

On main tracks of the HST, the catenary will be sectionalized both between the tracks and longitudinally on the same track along the route, in order to limit the extent of an outage zone due to faults or maintenance. Longitudinal sectionalizing of the catenary will be provided at the SS, SWS, and at all track interlockings and track turnouts. The sectionalizing at the SS and SWS will be of the phase break type; elsewhere it will be a regular sectioning gap.

At TPF, the sectionalizing gaps will be provided with normally-open (N.O.) motorized disconnect switches, that can be closed during contingency operations if the catenary on both sides of the sectionalizing gap needs to be electrically continuous.

At track interlockings, the longitudinal sectionalizing gaps will be provided with normally-closed (N.C.) circuit breakers and no-load type motorized disconnect switches, which can be opened during contingency operations to isolate a smaller segment of one track between adjacent interlockings (contained within an electrical section) or within an interlocking and the adjacent SS or SWS (contained within an electrical section), and permit single-track operations on the other track. At back-to-back crossovers, the sectionalizing arrangement will be such that the catenary of any track on either side of the interlocking can be isolated selectively.

Concerning the negative phase, two parallel along-track NF will be provided along the route (one per mainline track) regardless of the number of parallel tracks at a given location. Longitudinally, the NF system will be sectionalized at the SS and SWS.

3.7 Additional Location Requirements

Some site-specific design requirements for location of traction power facilities are enumerated below:

1. If the TPF has to be located in the proximity of or beneath high-speed train tracks located on aerial guideways, it will be ensured that that the main power transformers and autotransformers are
located in an open area (not be located underneath structures), and that proper clearances are available for the main gantry.

2. Access to the track for service and maintenance vehicles will be provided at each TPF location.

3. There will be a strain gantry located within the railroad right-of-way (ROW) parallel to and on the opposite side of the track away from the TPF, with footprints exactly equal to that of the main gantry.

4. If the TPF is located away from the track, the main gantry will also be located within the railroad ROW, parallel to and towards TPF side of the track. In this case duct banks and manholes for laying power cables from the TPF to the main gantry will be laid on the strip of land provided for this purpose.

5. At locations where track alignment is on viaducts, the TPF will be located on ground, and power cables will be routed from the TPF to the gantries located on the viaducts through duct banks and manholes and then onto the vertical columns of the viaducts.

6. At locations where track alignment is in trenches, the TPF will be located on ground, and power cables will be routed from the TPF to the motorized disconnect switch (MOD) assemblies located adjacent to the trench alignment through duct banks and manholes and then onto the OCS. If the TPF is located adjacent to the trench alignment, the MODs will be located within the TPF fence.

7. Phase-breaks will not be located in tunnels, and in the vicinity of stop signals at passenger stations and wayside interlockings.

8. If an AT connection to the OCS is inescapable in a tunnel, the respective PS will be located at the entrance of the tunnel, and feeder cables will be carried along the walls of the tunnel to provide connection to the OCS.

3.8 Regenerative Braking

The TPS and the associated OCS will be designed to permit the use of regenerative braking as a service brake and also as an emergency brake.
The following steps are being considered for facilitating use of regenerative braking:

1. Transfer of braking energy back into the OCS for use of another train(s) that is (are) drawing power from the OCS and is (are) located in the same electrical section as the braking train,

2. Transfer of braking energy back to the power supply utility company’s network in case trains in the same electrical section do not draw the full regenerated power,

3. Provision of rheostatic braking resistors or other electrical energy absorbing units on-board the trains, and

4. Provision of automatic assured receptivity unit (AARU) braking resistors within traction power supply substations.

The SS control and protection devices will be configured to allow regenerative braking.

4. INTERCONNECTION WITH HV UTILITIES

4.1 Impact of HST TPS on the HV Utility Grid

The load imposed by the railway's traction power supply system on the electric utility 3-phase, HV system will be single-phase, nonlinear and rapidly variable over time. Since each HV transformer will draw power from only two phases of a three-phase system, this will inevitably cause some current and voltage unbalances in the HV supply grid. Of the current and voltage unbalances, the voltage unbalance is of greater concern, as it affects the power quality of other utility customers. Other impacts of railway load are (a) voltage flicker, caused by the highly variable nature of the load, and (b) harmonic distortion, produced by the power convertors on the trains.

In order to mitigate the effects of the unbalanced loading, the single-phase connections of the HV transformers will be alternated from one pair of phases feeding one transformer to a different pair of phases feeding the other transformer at the same SS; and the phase connections will be changed between substations. This will tend to partially balance the load between the three phases regionally.
At each interconnection point redundant 115kV or 230kV transmission line connections would be required to ensure the capacity and reliability of the network could support the operational demands of the high speed rail system.

4.2 HV Utility Interfaces

The substations will be located 30 miles apart, and therefore, it is necessary to identify suitable HV power sources nearby. The utility power grid in California is divided into territories, and Phase I of the CHSTP passes through the territories of four utility companies with the appropriate 115kV or 230kV transmission networks, (a) Pacific Gas and Electric (PG&E) in the northern part of the state, (b) Southern California Edison (SCE) in the south, (c) Los Angeles Department of Water and Power (LADWP) serving greater Los Angeles County, and (d) Anaheim Public Utilities (Anaheim) serving customers within its city boundary (3).

Therefore, the TPS planning for the 520 miles of phase I of the CHSTP requires coordination with all four utilities. Based on the 30-mile spacing, there will be a total of 18 traction power substations, and based on the 5-mile paralleling station spacing there will be approximately 100 other facilities (SWS and PS). There will be three additional traction substations for the rolling stock maintenance facilities (one SS for each rolling stock facility located in San Francisco area, Los Angeles area and in the Central Valley).

4.3 Utility Study Coordination Process

The HV interconnection planning work was initiated by plotting the HV transmission network of the power supply utilities and the alternative HST track alignment options on the same map to identify potential candidate HV interconnection points. This preliminary work is being further refined by more detailed discussion with the power supply utilities on case by case basis. This process involves (a) execution of a Non-Disclosure or Confidentiality Agreement with each utility, (b) putting in place a Feasibility Study Agreement with each utility to enable each utility to examine the feasibility for each interconnection point, and (c) execution of Impact Analysis Study Agreement with each utility. In this study, a radius of 5-10 miles around the intended interconnection point will be analyzed for potential harmful effects on the network or other customers by the future railway load. If any significant impacts are determined, the mitigations will be included in the interconnection designs (3).

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5. SYSTEM VOLTAGE


The system voltage (U) will be the potential at the train’s current collector or elsewhere on the catenary, measured between the catenary and the rail return circuit. It will be the rms value of the fundamental ac voltage and its values will be as following (See Figure 7):

1. The nominal voltage (U_{\text{n}}), that is, the designated value for the system voltage, will be 25kV.

2. The highest permanent voltage (U_{\text{max1}}), that is, the maximum value of the voltage likely to be present indefinitely, will be 27.5kV.

3. The highest non-permanent voltage (U_{\text{max2}}) that is, the maximum value voltage likely to be present for a limited period of time (as defined below), will be 29.0kV.

4. The lowest permanent voltage (U_{\text{min1}}), that is, the minimum value of voltage likely to be present for a long period, will be 19.0kV.

5. The lowest non permanent voltage (U_{\text{min2}}) that is, the minimum value of voltage likely to be present for a limited period of time (as defined below), will be 17.5kV.

The system design will ensure fulfilling of following voltage related requirements:

1. The duration of voltages between U_{\text{min1}} and U_{\text{min2}} will not exceed 2 minutes.

2. The duration of voltages between U_{\text{max1}} and U_{\text{max2}} will not exceed 5 minutes. (If voltage between U_{\text{max1}} and U_{\text{max2}} is reached, it will be followed by a level below or equal to U_{\text{max1}} for an unspecified period). Voltages between U_{\text{max1}} and U_{\text{max2}} will only be reached for non permanent conditions such as regenerative braking.

3. The voltage at the busbar of the substation at no-load conditions will be less than or equal to U_{\text{max1}}.
4. Under normal operating conditions (including single contingency situation), voltages will lie within the range \( U_{\text{min1}} \leq U \leq U_{\text{max2}} \).

5. Under double contingency conditions, the voltage in the range \( U_{\text{min2}} \leq U \leq U_{\text{min1}} \) will not cause any damage or failure, and will permit continuing vehicle operation with some degradation. Rated vehicle power and performance will not be available but reduced operation will be possible assuming on-board logic will automatically degrade the performance of the traction system (rolling stock) and auxiliaries.

6. The setting of under-voltage relays in fixed installations or on board rolling stock should be from 85% to 95% of \( U_{\text{min2}} \).

7. Both the following acceptance criteria for ‘Quality Index of Power Supply’ for ac 2x25kV autotransformer feed configuration will be satisfied:

   a. \( U_{\text{m}} = > 22.5 \text{kV} \)

   b. \( U_i \Rightarrow 19 \text{kV} (U_{\text{min1}} – \text{Lowest permanent voltage}) \)

Where, the Mean Useful Voltage \( (U_{\text{m}}) \) is the mean value of all rms voltages analyzed in the system simulation study, and gives an indication of the quality of the power supply for the entire system during the peak traffic period in the timetable, and

\[
U_{\text{m}} = \frac{\Sigma U_i}{N}
\]

where \( U_i \) is the rms ac voltage over the \( i^{th} \) second during the peak period for all trains in the system, and \( N \) is the total number of observations.
6. ELECTRIC PROTECTION SCHEME

6.1 General

The relay protection system for the TPS is being designed to:

1. Protect the TPF equipment and the catenary and NF against short-circuit faults, overloading, and
subcomponent failures

2. Include fault location and discrimination capabilities, including automatic circuit breaker reclosing for catenary and NF circuits, as well as manual local and remote re-closure management.

3. Provide proper coordination and selectivity for rapid fault clearance to the affected area of the system only, preventing as much as possible the loss of power to the healthy sections of the TES.

4. Adequately discriminate between short-term high loads and fault conditions.

High-voltage relay protection equipment on the primary side of the traction power substations will be coordinated with respective utility company as applicable.

Catenary and NF circuit breakers will be provided with electronic, microprocessor-based protective relays and devices to protect against short-circuits and conductor overloading conditions. The number and type of protective devices for a particular circuit breaker will be based on the overall relay protection scheme for the TES.

6.2 Electrical Protection Coordination between TPS and Rolling Stock

The protection system for the TES will be designed for a maximum catenary – rails short-circuit fault current of 15 kA.

Compatibility of protective systems between rolling stock (RS) and TPS will be verified for the following:

1. When any internal fault occurs within the RS, both the SS feeder circuit breaker and the RS circuit breaker may trip immediately. However, as far as possible, the RS circuit breaker should trip in order to avoid the substation circuit breaker tripping.

2. After the substation circuit breakers have tripped these will be capable of being reclosed either automatically or manually only after a lapse of at least three seconds.

3. The RS circuit breakers will trip automatically within three seconds after loss of line voltage.

4. On re-energization, the RS circuit breaker will not reclose within three seconds of the line being re-energized.
6.3 Safety Related Protective Provisions of TES

The TES design of CHSTP envisages running rails electrically insulated from ground, but connected to ground at intervals, at least at TPF locations, through the neutral points of impedance bonds. A part of the return current will flow through the running rails because they are part of the traction return system. Because of the impedance of the rails this return current flow will cause a voltage with respect to the ground especially at locations away from the ground connections.

Electrical safety of the TPS will be achieved by the following means:

1. The installations will be designed and tested such that the permissible touch/accessible voltages caused by the traction system under fault conditions or in operating conditions will not exceed values specified in Section 7 of European Standard EN 50122-1:1997, “Railway Applications – Fixed Installations – Part 1: Protective Provisions Relating to Electrical Safety and Earthing”.

2. A direct connection will be made between the return circuit and the grounding system of the TPF (SS, SWS and PS).

3. Each TPF will be connected to the running rails and the aerial ground wire by at least two return cables. Each return cable will be of sufficient size to carry the maximum load current, thereby allowing for the failure of one return cable. The connection to the running rails will be through impedance bonds.

4. All TFP will be grounded as specified in IEEE 80-2000, “IEEE Guide for Safety in AC Substation grounding”.

The rated impulse voltage $U_{Ni}$, minimum clearance in air (in mm), and the short-duration power-frequency (ac) test level voltage $U_A$ (kV rms) will be as given in the Tables A.2, A.3, and B.1 of European standard EN 50124-1:2001, “Railway Applications – Insulation Coordination – Part 1: Basic Requirements – Clearances and Creepage Distances for all Electrical and Electronic Equipment”.

All traction power facilities will be fenced against unauthorized access.

The grounding of TPF will be integrated into the general grounding system along the route to comply with the requirements for mitigating electric shock as specified above.
6.4 Harmonic Distortion Limits

The harmonic distortion limits for individual and total harmonic distortion of voltage and current will be followed per Tables 11-1, 10-3 and 10-4 of IEEE Std 519, “IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems,” unless the limits imposed by the concerned power supply utility are more strict.

7. CONCLUSIONS

The CHSTP is the first HST system being implemented in USA that would operate trains at 220 mph. At present no specific codes / standard for HST are available in USA. This system is being designed utilizing the knowledge of other countries (France, Germany, Spain, UK, Japan, South Korea, Taiwan, and China) that have experience of HST. Some important design facets of traction power supply system of CHSTP have been presented in the preceding sections.
ACKNOWLEDGEMENT

In this paper a large amount of unpublished data and information developed for the California High-Speed Train Project has been used. The author expresses gratitude to the California High-Speed Rail Authority for use of the unpublished data.
REFERENCES

1. UIC (High Speed Committee), High Speed, Energy Consumption and Emissions; November 2010; ISBN 978 2 7461 1900 0.

2. US Energy Information Administration 2008, Table S1

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Traction Power Supply System for Cal Hi-Speed Train Project

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Traction Power Supply System for CHSTP

Scheme of Presentation

- System Description
- System Verification
- Interface with Power Supply Utilities
- System Voltage Limits
- Present Status
2011 ANNUAL CONFERENCE

September 18-21, 2011 | Minneapolis, MN

Definition of High-Speed Rail (HSR)

1. Outside of USA, HSR implies speed > 150mph (240kph)

2. Per EU, HSR is:
   - For new lines, speed > 155mph (250kph)
   - For upgraded line, speed > 124mph (200kph)

3. FRA’s 2010 guidelines for HSR services:
   - Core Express Corridors, speeds 125~250mph
   - Regional Corridors, speeds 90~125mph
   - Emerging/feeder routes, speeds ≤ 90mph

California High-Speed Train Project (CHSTP) will be a Core Express Corridor with a maximum operating speed of 220mph.
Traction Power Supply System for CHSTP

The CHSTP

- 520-mile system (Phase 1 from San Francisco to LA/Anaheim)
- Up to 800 miles (with Phase 2 extensions to San Diego and Sacramento)
- Speeds: Infrastructure designed for 250 mph; operates up to 220 mph on dedicated high-speed track; 90-125 mph in shared track areas
- 100% clean electric power
- Safety: Grade-separated
Train Operations Plan

1. 12 trains in each direction during peak hour with:
   - 9 trains 400m long (each consisting of 2 coupled train sets), &
   - 3 trains 200m long (each consisting of one train set)

2. No degradation of train performance during Single Contingency Power Supply Conditions (the loss of a single utility supply circuit, or a single Item of equipment, or a single negative feeder, or a single rail return circuit)

3. No stranding of trains during Second Contingency Power Supply Conditions (the concurrent loss of any two of the above, in any combination)
Traction Power Supply System for CHSTP

Basis of TPS Design

1. Provide traction power for safe, efficient, and reliable operation of trains per the train operations plan

2. Based on Technical Specifications for Interoperability (TSI) relating to ‘Energy’ and other related subsystems, issued by the EU

3. A number of ‘System Requirements’ developed & forwarded to FRA for review and development of ‘Rules for Particular Applicability’

4. The system conforms to North American standards and codes (AREMA, IEEE, NFPA, CEC, CPUC etc) and International and European standards (EN, IEC)

5. 2x25 kV AC Autotransformer Feed System for the main-line operation.
**Traction Power Supply System for CHSTP**

**2x25kV Autotransformer Feed System**

**Pros:**
- Requires less number of substations vis-à-vis conventional 1x25 kV AC system
- HV utility circuits
- HV transformers and switchgear
- Relatively less EMI generated
- The modern ‘standard’ for HS Lines

**Cons:**
- Requires more number of traction power facilities
- Requires along-track negative feeder

**Decision:** Decided to go in for 2X25 kV AC autotransformer feed system
Traction Power Supply System for CHSTP

2x25kV Autotransformer Feed System
1. In general, traction power substations (SS) spaced 30 miles apart, close to 115 kV (or 230 kV) HV utility network/grid substation

2. Switching stations (SWS) midway between adjacent SS

3. Paralleling stations (PS) located at approximately 5-mile spacing between SS and SWS

4. The sequence of location of traction power facilities: SS-PS-PS-SWS-PS-PS-SS-PS and so on

5. With a view to preventing stalling of trains at the phase-breaks, the SS and SWS should preferably, not be located within a 2-mile distance from the nearest end of any railway station, wayside crossover, or tunnel portal
Traction Power Substation (SS)

- Draws HV power from utility grid, steps down to 2X25 kV and feeds OCS conductors
- Located adjacent to railroad ROW
- Two main transformers, each of 60 MVA capacity
Traction Power Supply System for CHSTP

System Configuration - Continued

1. Switching Station (SWS)
   - Facilitates supply of electrical energy to an adjacent, but normally separated electrical section during contingency power supply conditions
   - Has two 20 MVA autotransformers
   - Also acts as a PS

2. Paralleling Station (PS)
   - Helps boost the OCS voltage and reduce the running rail return current
   - Has one 20 MVA autotransformer
## Facility Footprints

<table>
<thead>
<tr>
<th>Facility Type</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substation with 2 HV transformers</td>
<td>200’ x 160’</td>
</tr>
<tr>
<td>Substation with 3 HV transformers</td>
<td>200’ x 210’</td>
</tr>
<tr>
<td>Switching Station</td>
<td>160’ x 90’</td>
</tr>
<tr>
<td>Paralleling Station</td>
<td>120’ x 80’</td>
</tr>
</tbody>
</table>
Traction Power Supply System for CHSTP

115kV utility supply transformed to 2x25 kV for railroad use (AMTRAK)
Traction Power Supply System for CHSTP

Wayside Power Control Cubicles (WPC)

An enclosure for power supply equipment for operation of motorized disconnect switches and associated SCADA equipment located on the wayside. Footprint – 10’X8’

Located at railway stations, wayside crossovers, maintenance facility yards, tunnel portals, and in long tunnels.
Traction Power Supply System for CHSTP

Typical at-grade OCS feeding gantry system in a TPF (AMTRAK)
Traction Power Supply System for CHSTP

Switching station gantry on a viaduct (THSR)
System Verification

1. Traction load flow analysis of two representative busy sections, ‘Los Angeles Union Station – Anaheim’ and ‘San Francisco – San Jose’ done using standard application software

2. Section Characteristics:
   - 12 high-speed trains per hour in each direction during peak hour, 9 trains of 16-car (2 train-sets) consist and 3 of 8-car (single train-set) consist
   - In SF-SJ section 10 commuter trains in each direction also modeled on separate dedicated tracks
   - Auxiliary loads of trains standing at LA & Anaheim stations, and San Francisco 4th and King’s Street stations during peak hour with raised pantographs awaiting departure modeled as point loads
   - Train movements to/from maintenance yard/storage depot modeled as empty train movements

3. Not only normal peak operations but also single contingency and double contingency operations (with different combinations) were also modeled to assess impact on system parameters:
   - train voltage,
   - loading on main and autotransformers, and
   - OCS conductor ampacities
The load flow analysis showed that:

1. 60-MVA main transformers & 20-MVA autotransformers were OK
2. 5-mile spacing of PS and 15-mile long electrical sections generally acceptable
3. OCS conductors had adequate ampacities
4. The system voltages remained above the minimum prescribed limit (‘Quality Index of Power’ was satisfied – EN 50388) in all the cases

\[
\text{Quality Index of Power: } U_{\text{mean useful}} \geq 22.5 \text{ kV},
\]

\[
\text{where } U_{\text{mean useful}} = \frac{\sum U_i}{N},
\]

\[U_i = \text{instantaneous 1 sec voltage reading },
\]

\[N \text{ is the number of readings, and } U_i \geq 19 \text{ kV}\]
System Verification - continued

Further two real-life situations simulated where:

1. The alignment continuously along a gradient for a whole ‘electrical section – from an SS to adjacent SWS’, i.e. the base case was run with different scenarios of alignment having continuous 0%, 1%, 2%, 3% and 3.5% gradients.

2. The inter-TPF spacing is not uniform and the ‘electrical section’ is longer than 15 miles, even as long as 18 miles

Results:

1. The basic TES configuration is satisfactory and will support planned train services on:
   1. Continuously graded ‘electrical sections’
   2. Longer ‘electrical sections’ i.e. 16~17 miles long

2. Under exceptional circumstances 6-mile spacing of TPF may be acceptable

1. For 18-mile long ‘electrical section’ it would be advisable to provide one additional PS to keep inter-TPF spacing within 5 miles.
Interface with Power Supply Utilities

HV power at 115 kV/230 kV to be drawn at 21 locations

Four power supply utilities involved in the Phase 1 of the Project:

1. Investor Owned Utilities (IOU)
   - Pacific Gas and Electric (PG&E) – 13 substations
   - Southern California Edison (SCE) – 5 substations

2. Municipalities
   - Los Angeles Department of Water and Power (LADWP) – 2 substations
   - City of Anaheim Public Utilities – 1 substation
Traction Power Supply System for CHSTP

Interface with Power Supply Utilities – Steps Involved

• Broad Identification of HV Interconnection Points
• Execution of Non-Disclosure Agreement
• Feasibility Study/Method-of-Service Study by the Utility
• Impact Analysis Study
• As-Required Strengthening of the Utility’s Network
• Execution of Service Agreement
Traction Power Supply System for CHSTP

System Voltages

\[ (U_{\text{max}2}) \text{ Highest Non-permanent Voltage, only possible during regeneration} \]

\[ (U_{\text{max}1}) \text{ Highest Permanent Voltage, likely to remain indefinitely} \]

\[ (U_n) \text{ Nominal or designated Voltage} \]

\[ (U_{\text{min}1}) \text{ Lowest Permanent Voltage, likely to remain indefinitely} \]

\[ (U_{\text{min}2}) \text{ Lowest Non-permanent Voltage, likely to remain for a limited period of time} \]

SYSTEM VOLTAGES IN KILOVOLTS – FIGURE 7
Traction Power Supply System for CHSTP

Energy Implications of the Project

Transportation sector (38%) the largest source of energy consumption in California

Load flow analysis shows specific energy consumption figures for CHSTP:
  • 126 Wh/seat-mile without regeneration, and
  • 108 Wh/seat-mile with regeneration

Estimated traction energy consumption/day in year 2035 = 8.32 GWh/day

HST expected to bring a net energy saving of roughly 70,000 MMBtus/day in 2035
Traction Power Supply System for CHSTP

Present Status of the Project

Undergoing NEPA/CEQA review in all project sections
- Central Valley sections (Merced-Fresno, Fresno-Bakersfield) are completing scoping and the analysis of alternative alignments
- On track to secure environmental clearance by early 2012.
- All seven Phase 1 sections continue to do environmental analyses.
- Receiving public input on all alignments

Building toward construction
- RFPs for Initial Construction Segments in early 2012
- Begin awarding construction contracts in the second half of 2012
Traction Power Supply System for CHSTP

THANK YOU