HV CONNECTION OPTIONS WHEN INTRODUCING REGENERATIVE BRAKING ON HS TRAINS

Vukan POLIMAC
Polimac Ltd, UK
vukan@polimac.net

Jelica POLIMAC
Polimac Ltd, UK
jelica@polimac.net

ABSTRACT

The paper addresses power quality issues, namely consideration of negative phase sequence (NPS) requirement, at the point of common coupling (PCC) between Transmission System Operator (TSO) and Railway Infrastructure Company (RIC). The issue is often raised when RIC is subsequently introducing regenerative braking on the trains close to TSO connection points that are not particularly strong to cope with power quality disturbances. Trains operating in the regenerative mode act as generators and mostly provide power to other trains in the same section but would also supply surplus of power to the grid.
The paper suggests mitigation measures in order to enable the trains to run in regenerative breaking mode without the operational constrains.

INTRODUCTION

Trains operating in regenerative braking mode provide an opportunity to reduce the overall power consumption at the supply point which reduces the cost of energy to the traction power system. When employing regenerative braking the electrical power output produced by a train is generally utilized by other trains in the same traction electrical section. When these trains are not available the power is exported to the supply system.

The effect of regenerative braking within the electric traction distribution system and also at the supply point must be reviewed to ensure continued safe and reliable operation of the railway and the electricity transmission system.

The analyzed railway traction system in Figure 1, chosen as typical for supply of modern high speed railway, is supplied via three electricity supply points FS (Feeder Stations) namly Substation 1, Substation 2 and Substation 3. For normal feeding arrangement these FS operate independently and supply only the traction sections between their respective overhead line neutral sections (NS). Under planned or unplanned outage events at the FS the feeding sections can be extended to provide continuous resilient traction power supplies.

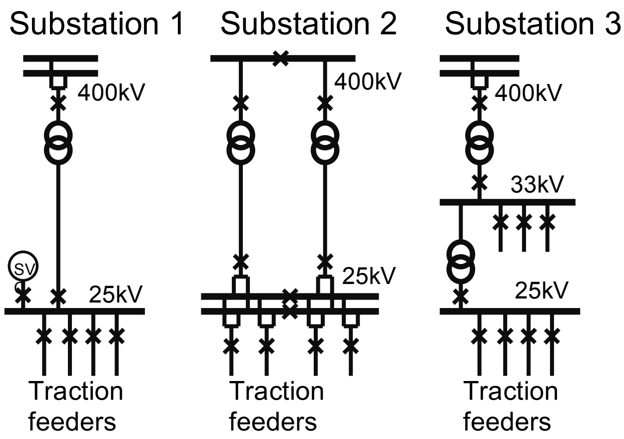

Figure 1

Each FS is connected to the HV Transmission System under certain Terms of Connection Agreement (TCA). This agreement provides requirements for operation of the FS while connected to the transmission system and for compliance with the TSO Grid Code. The Grid Code states the requirements for connection to the TSO as well as for managing the interface between connections.

The railway traction power demand is a single-phase demand that presents an unbalanced voltage at the Point of Connection (POC) to the transmission system. The general limits of unbalance in UK are given in the Energy Networks Association (ENA) documents [1] and [2].

These ENA recommendations are related essentially to the effect of voltage unbalance, or the resultant negative phase sequence (NPS) voltage, on the torque and losses in three phase electric motors such as traction motors. This voltage unbalance is dependent upon the impedance of the supply or prospective fault current available. However, where power control devices are employed such as semiconductor converters, the effect of unbalance on their performance is more significant. Assuming that the supply impedance of the 400 kV network at Substation 3 is such that the prospective fault current is not as high perhaps as other locations on the 400 kV transmission system. For this reason and also if complex connections such as nuclear plants and DC links are present the FS connection agreement may include tighter constraints on the permissible limit of NPS voltage at 400 kV.

Usual way to mitigate the unbalance in traction systems is load balancer to ensure that the unbalance at 400 kV due to the single phase traction power demand is within the constraints of the Connection Agreement. Those balancers were previously designed only for feeding arrangements from TSO to the traction. Once regenerative breaking is subsequently introduced the balancers would need to be redesigned for the scenario when traction is exporting power to the TSO network.

When considering regenerative braking, the railway FS is a single phase source or generator for the short periods of braking power export to the transmission system. The effect of the reverse power flow is to cause an unbalance at 400 kV. The existing load balancer design and operating range does not allow for adequate compensation under the reverse power condition.

DESCRIPTION OF THE ISSUE

Unbalance in the TSO 400kV network is created by tapping into two out of three phases to feed the railway network, as it is shown in the feeding arrangement on Figure 1 at each of the three substations. The unbalance in the 400kV system is limited by percentage of negative phase sequence where 1% discrepancy measured at the POC is being generally acceptable. Particular problem is assumed to arise at the infeed Substation 3 where 400kV system cannot receive full available regenerative power from the railway company. This is because Substation 3 is assumed to be located in the weak part of the system with significantly low short circuit value at 400kV for certain configuration scenarios. This constrain is quantified through the reduced limits of NPS specified at this particular POC which is much lower than prescribed in the standard. The analytic analysis showed that under most scenarios studied for implementation of regenerative braking, the calculated values of NPS at that substation were above the prescribed level and regenerative braking mode would not be allowed by TSO.

ANALYSIS AND DEVELOPING OPTIONS

The problem was addressed from different angles considering options to modify equipment at the Railway Company 400kV POC substation as well as assess the flexibility of relaxing the NPS limits prescribed by TSO. The equipment that was considered to be modified or new equipment added in is related to power quality performance. Modification of existing Static VAr Compensator (SVC) or addition of a new one would incur additional costs which must be assessed in the overall whole life cost (WLC) analysis in order to be accepted as a viable option. On the other hand the analysis of the TSO system may indicate that the worst scenario for which the NPS was specified occurs under a double HV circuit outage in specific configuration of the network, which may be considered as a remote event albeit associated with high negative consequences and with high safety risk.

Technical background

The railway traction supply at Substation 3 is assumed to be a three phase 400 kV supply connected to the 400 kV busbars. This TSO substation would be connected to two overhead lines between further two substations. The 400 kV supply to the FS can be selected between lines via the busbar selector and the bus section circuit breaker.

It is assumed that the three phase minimum fault level (minimum prospective fault current) at the 400 kV busbar at Substation 3 is as low as 6 GVA (8.7 kA).

The FS arrangement comprises three phase 70 MVA, 400 kV/33 kV transformer to supply a 33kV busbar. The single-phase 33 kV/25-0-25 kV traction supply transformer is then supplied from this busbar together with the three-phase load balancer and internal harmonic filter.

Power Quality issues

The Connection Agreement for a POC with low fault level such as Substation 3 could state that the harmonic voltage distortion limits may be as low as 0.1 % for all odd order harmonics up 25 together with the NPS limit of 0.1 % unbalance at the Point of Common Coupling (PCC). There is potential further constrains of the unbalance to the used phases, for example Blue – Red phases. The NPS percentage in this case is assessed as the ratio of single phase apparent power (MVA) with three phase short circuit capacity (MVA).

The NPS value is presented as an absolute value and is measured by TSO at the 400 kV busbars. ENA document P24 [1] recommends the maximum value of NPS averaged over any half hour period and assumes a zero background NPS level. However, the ENA recommendation is ultimately to make provision to co-ordinate with motor protection relay characteristics. The TSO's 400 kV busbars include connections to a high number of high power converter and semi-conductor power control equipment. Poor quality, as unbalanced supply voltage, significantly affects the control and output of this equipment.

A review of the power quality constraints may be requested in compliance with the Grid Code, by a modification to Connection Application. Any revision of the power quality constraint would necessarily require a review of all other connections and the associated constraints to assure continued Grid Code compliance for these and suitability of all power conditioning and mitigation.

It is assumed that the fault level at 400 kV Substation 3 busbars and associated transmission lines is not forecasted to provide a significantly higher prospective fault current in the next ten years.

Re-generative Braking modeling

Modeling was carried out for the rolling stock to apply the regenerative braking. While a major part of the regenerated energy available is used by other rolling stock there are periods of where up to 20 MVA is to be exported at Substation 3. This value of exported energy varies for each FS under normal feeding as the electrical overhead line sections are not equal and the service pattern is modified by the location of passenger stations. Analysis of train simulation model output data indicates that this export power will present a voltage unbalance at the 400 kV busbars (PCC) of approximately 0.4 %, which exceeds the set limit of 0.1% at Substation 3.

The modeling and analysis provides an indication of magnitude, feeding section and approximate period for the power export. Further investigation of perturbations within the timetable and abnormal feeding arrangements would be needed to complete the exercise to quantify the full regeneration capability. If however, any export of power to the transmission system operator (TSO) presents a non-compliant power quality at the PCC then disabling regeneration for that FS or time period could be considered. This would require co-ordination between the train, the signaling area and the feeding section; including extended feeding conditions and assuming the trains will be supplied with dual braking systems.

Load Balancer Operation

Typical solution to mitigate NPS is a load balancer connected at the three phase 33 kV busbars. It would provide capacitive reactive power support and harmonic voltage mitigation to ensure the three phase voltage is balanced for all traction power demand conditions within the power factor range 0.8 to 0.9 lagging. The balancer would control the busbar voltage at the set point within the range 0.94pu to 1.03pu.

The control parameters of this typical balancer have lack of inductive reactance within the balancer, which means that this balancer cannot provide adequate voltage support during the periods of regeneration export. Effectively, it is not operating for the export conditions.

For single phase export power compensation the balancer control and protection would need to be re-designed to be biased across a range of capacitive to inductive reactance and suitable inductance added to the existing thyristor controlled capacitors. Practically, this would require the layout of the typical outdoor equipment to be revised.

The power quality constraint relates to the TSO system minimum fault level. This system condition prevails for a period of time during the summer months. If the prospective fault current is planned to be much higher outside this period, then regenerative braking export NPS would be assessed to be lower than the limit set in the connection agreement. During the period at the lower prospective fault current the traction supply feeding sections could be extended from the alternative FS where the NPS limit is significantly higher.

Design Amendment for Substation 3

As the assumption was that the original design did not cater for the regenerative braking mode, further electrical traction system studies ware required to assess it. The studies would also be required as part of the overall Railway Safety Case which should cover power, signaling and co-ordination of electromagnetic interference and compatibility. For the power system the studies will provide modeling output data for normal and abnormal operating conditions with extended feeding and timetable perturbations. This output data will confirm the rating of the traction supply equipment. Associated regenerative braking export capability will also be further assessed for the feeding conditions.

Further to the supply of real power to the TSO system, at different times during any 24 hours there may be a benefit to export reactive power for the TSO operational purposes and to save further additional equipment to be connected to the 400 kV busbars. This embedded reactive power generation should be considered within the scope for the load balancer design and operation. This output would be metered at 400 kV and controlled through the interface with the railway traction control room.

ANALYSIS OF OPTIONS

Relaxation of Connection Agreement NPS Limits

The process of relaxation of the limits imposed at the

POC would require significant additional studies associated with several risks. Mitigation measures of risks associated with the parameters such as configuration at which the limits could be relaxed and scenarios when NPS are jeopardized would need to be agreed by TSO.

Assuming a number of modern equipment such as non-linear and semi-conductor equipment connected at the 400 kV busbar together with the long term plans to retain the low fault capacity at Substation 3, it would be impracticable to increase the NPS limit.

Traction Power Operating Restrictions

There could be an opportunity to take advantage of a higher prospective fault capacity outside the TSO summer minimum period should that be the case. TSO would need to confirm the fault capacity at the sufficient level to reduce the apparent NPS. For the duration of the summer TSO minimum fault capacity condition, the traction supply system could be configured to extend the feeding with Substation 3 being off line. The export power would be dissipated through the other feeder stations. This would need to be acceptable for the overhead line system operation and maintenance and would require a further Reliability, Availability, Maintainability and Safety (RAMS) review to ensure continued safe and reliable railway operation. The ability of the alternative feeding arrangements to support the railway operation should be confirmed if this option were to be considered further than this review.

Alternatively, to restrict the opportunity for export power to the TSO system, the regenerative braking may be disabled at the trains for the overhead line section fed from Substation 3. This can be deployed through the signaling system assuming the signaling sections are in line with the traction power feeding sections.

Load Balancer Design and Operation

To comply with the power quality constraint of 0.1% NPS assumed in the Connection Agreement at Substation 3, the load balancer could be re-designed and re-commissioned for power flow in both demand and export conditions. Further studies of all operating scenarios including timetable perturbations and FS outages would confirm the required rating and operating ranges.

At the same time with the procedure to submit an application to TSO to modify the connection at Substation 3, the operation of the load balancer to provide reactive power export could be considered. At times of low traction power demand the balancer may be able to export reactive power, metered at 400 kV, to support the TSO system. The scope, range and operating arrangements would be part of the Modification Application and the consequential revised Connection Agreement.

Summary of the options

The analysis resulted in a number of options for the Railway Company to pursue in order to assess the optimum solution. The main options are elaborated in the paper:

- Adding a new SVC in Substation 3 which would be of sufficient capacity for all future scenarios of new rolling stock and ultimate timetable. This is associated with significant capital cost. However, this cost could be offset if Railway Company provides compensation to TSO during the engineering hours, which would significantly reduce the whole life cost of the balancer.
- Develop a switching sequence between the 400kV PCC triggered by the low NPS requirement which would switch Substation 3 off and transfer all RC load to the Substations 1 and 2. The scheme application risk is considered high due to the complexity and high consequence risk.

CONCLUSION

In this example there is little opportunity to revise the NPS constraint at the points of common coupling with TSO. The ability to export the power produced at the FS would be therefore constrained and alternative mitigation will be required for the introduction of regenerative braking.
Installation of the load balancer is considered as the most practical and feasible option, which would not only provide unconstrained regenerative braking in future but also reduce the cost if used for voltage support to TSO network during the engineering hours.

REFERENCES

[1] Engineering Recommendation P24: 1984 AC Traction Supplies to British Rail
[2] Engineering Recommendation P29: 1990 Planning Limits for Voltage Unbalance in the UK