QUALITY OF SUPPLY ISSUES ARISING FROM DC TRACTION LOADS ON A METRO SYSTEM

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ABSTRACT

DC traction loads connected to AC transmission and distribution networks give rise to quality of supply problems such as voltage fluctuations and harmonic voltage distortions on the AC network. These problems in quality of supply are influenced to some extent by the impedance of the power intake transformers. This paper uses a case study to explore the optimisation of the requirements for the transformer impedance against the requirements for quality of supply. The paper also explores a possible conflict between these impedance requirements, the requirement for a low loss transformer and the asymmetric break rating of the switchgear.

INTRODUCTION

The connection of DC metro systems to AC transmission and distribution networks gives rise to a number of power supply quality issues at the Point of Common Coupling (PCC). DC traction loads fed through AC/DC rectifiers generate non-linear voltages and currents on the AC system resulting in the harmonic voltage distortion of the power supply system. The Distribution Network Operator (DNO) requires that the voltage harmonic emission of connected loads comply with relevant standards to ensure that the performance of electrical equipment connected to the system is not impaired.

Another characteristic of traction loads that gives rise to quality of supply problems is the random starting, stopping, and acceleration of trains which subjects the power supply system to load swings and consequently voltage fluctuations and flicker. The DNO again requires the voltage fluctuations to comply with Engineering Recommendations and relevant standards.

The careful design of transformer parameters and other primary equipment may improve the system performance in terms of voltage fluctuations and harmonic voltage distortions and in some instances ensure that the electromagnetic compatibility immunity levels and the power rating of existing equipment is not breached. This may avoid the upgrading or replacement of existing downstream equipment.

This paper uses a case study to examine the voltage fluctuations and harmonic distortion of a power supply system and to assess issues surrounding the optimum design of power transformers with respect to power quality issues. Potential constraints in the design optimization process are considered. For example, the need to specify high transformer impedances in order to limit fault levels conflicts with the requirement to limit voltage fluctuations and to maintain acceptable voltage profiles. Further, the higher the impedance of the transformer, the greater the shift of harmonic resonances to lower frequencies. In addition, the need to install low energy loss transformers can conflict with the need to maintain an X/R ratio which is consistent with the asymmetric break rating capability of the switchgear.

BACKGROUND

The network under consideration is an 11kV system which consists of about 20 transformer rectifier stations which feed the metro system. In addition, there are a number of 11/0.4kV transformers which supply the lighting load of the metro stations. This discrete 11kV network is supplied via 2 x 45 MVA 132/11kV grid transformers. The grid transformers are connected to the 132kV PCC by two 7 km long 132kV cables. Each of the grid transformers has two secondary windings with each winding connected to its own section of busbars on a four section switchboard as shown in Figure 1.

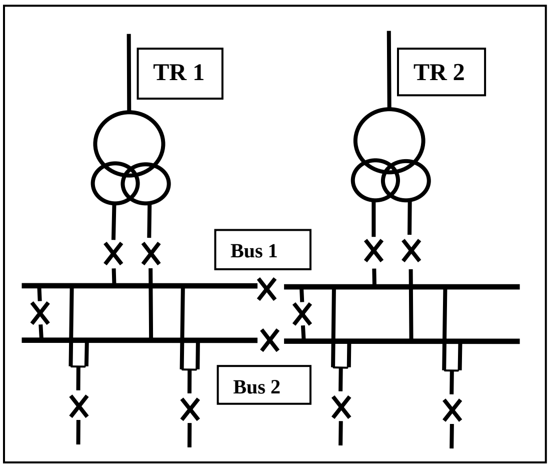

Figure 1: Power Intake Single Line Diagram

The switchboard arrangement together with the two secondary winding arrangements of the grid transformers provides an enhanced level of reliability for busbar faults. The reliability of the system is further enhanced by operating all four secondary windings in parallel. However, this operating arrangement results in increased fault levels and the impact on existing switchgear ratings needs to be assessed. Further, a fault that causes an outage of one secondary winding on a transformer may result in an unacceptable voltage rise on the open circuit winding depending on the selected transformer impedance.

PLANNING AND DESIGN REQUIREMENTS

The main requirement for the design of such a power intake which supplies a metro system is to provide a reliable and secure infeed which complies with power quality standards such as the IEC Electromagnetic Compatibility Standards [1], [2], the Planning levels for harmonic voltage distortion set by the Electricity Networks Association Engineering Recommendations G5/4 [3], [4], the Planning limits for voltage fluctuations stipulated in Engineering Recommendation P28, [5] and other relevant standards and codes of practice.

The harmonic distortion levels and voltage fluctuation limits set in the above standards and Engineering Recommendations are mandatory at the PCC but not on the internal 11kV system. Where the current performance of the internal system is considered acceptable, the applicable requirement would be for the system to be no worse than the prevailing conditions although it would be good practice to comply with relevant standards.

In addition to the above design requirements, the power intake needs to fulfill the following requirements;

- Provide sufficient capacity for normal and abnormal feeding conditions.
- Provide reliable supplies under planned and unplanned outage conditions.
- Optimise the transformer energy losses.
- Maximise the use of existing equipment and avoid wholesale replacement or upgrading of downstream primary equipment and,
- Ensure operational flexibility through the paralleling of the grid transformers.

CHOICE OF GRID TRANSFORMER IMPEDANCE

The choice of grid transformer impedance is constrained by the source impedance at the PCC and the switchgear fault rating capability within the 11kV network. Within these constraints, there is an option of paralleling all four 11kV busbar sections i.e. paralleling all four transformer secondary windings or operating with a split 11kV busbar. A split busbar arrangement will facilitate the choice of lower transformer impedance compared to a solid busbar arrangement which will require higher grid transformer impedances in order to limit the fault levels within the set constraints.

The higher transformer impedance option and the solid busbar arrangement was selected following an iterative approach taking into account operational flexibility, harmonic resonances and voltage fluctuations. Further, the requirement for a low loss transformer in this particular case resulted in a system X/R ratio which was greater than 55 and consequently the asymmetric short circuit current exceeded the standard asymmetric break rating of a 25kA rated switchboard.

Options to address this asymmetric fault current break rating problem include reducing the X/R ratio by increasing the transformer winding resistance with a consequent increase in the transformer copper losses. Alternatively, the rating of the switchboard could be increased to about 31.5kA, even though the symmetric fault level is unlikely to exceed 20kA.

The higher loss transformer option was finally adopted after comparing the increase in capital costs of the higher rated switchboard against the increased cost of transformer losses over the life of the transformer and also the initial reduction in the capital cost of the transformer as a result of the reduction in copper. This analysis was undertaken with the aid of the standard model of optimizing distribution transformer losses [6].

ASSESSMENT OF VOLTAGE FLUCTUATIONS

Engineering Recommendation P28 sets a voltage fluctuation limit of 1% at the PCC. There is however no obligation to comply with this limit within the internal 11kV network. A figure of 4% was chosen as the limit for the 11kV busbars at the power intake based on voltage fluctuation measurements of the existing system and the P28 short term severity (P_{st}) figure of 3% for voltage fluctuations.

Voltage fluctuations on the metro system under consideration are caused by the random movement of trains which in turn cause power swings on the network. The magnitude of power swings do not increase with increasing load demand since the larger number of trains creates a smoothing effect. A combination of measurements and both deterministic and probabilistic analysis techniques were used to quantify the power swings and hence the voltage fluctuations. Figure 2 shows some power swing curves derived from a probabilistic analysis of multi-train simulation studies (MTS).

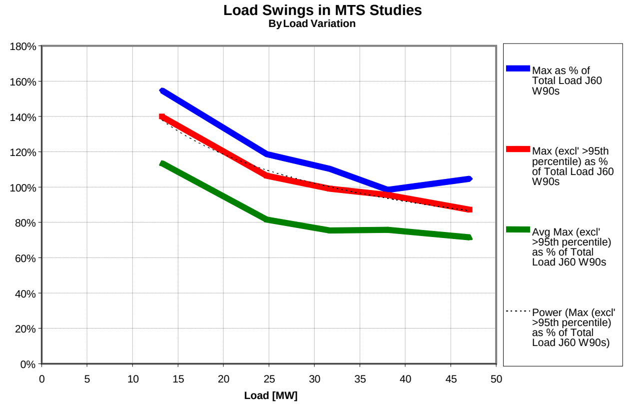

Figure 2: Power Swing Curves

Calculations of voltage fluctuations were made for both the high and low impedance transformers and it was noted that in both cases, the introduction of the new grid intake improved voltage fluctuations and steady state voltage profiles on the 11kV network. However under abnormal feeding conditions or in the case of an outage of one grid transformer, the voltage fluctuations for the higher impedance transformer exceeded the set limits on the 11kV network. In all cases, the voltage fluctuations at the PCC remained within the P28 limits.

It was therefore concluded that static var compensation (SVC) equipment would be required to control voltage fluctuations on the 11kV network under contingency conditions. The SVC would not strictly be required under normal operating conditions but it was recommended that these be kept in service whenever they were available as this is considered to be good practice.

ASSESSMENT OF HARMONIC VOLTAGE DISTORTION

Engineering Recommendation G5/4 specifies the harmonic limits at the PCC but the available headroom for harmonic emission depends on the background harmonic levels and the calculated gain factors between the PCC and the DNO's lower voltage substations. The gain factors are calculated by injecting 1 p.u. current at the PCC and then comparing each of the calculated voltages at the other busbars to the PCC voltage distortion. For each of the relevant DNO lower voltage busbars, the calculated gain factors did not significantly exceed 1.5 and the available headroom at the PCC was therefore simply calculated as the difference between the harmonic order G5/4 limit and the measured background harmonic order.

The analysis and quantification of harmonic voltage distortion is more complex than that of voltage fluctuations since the latter only involves analysis of the fundamental frequency as opposed to several harmonic order frequencies. The methodology adopted in this case study involved injecting harmonic currents at each rectifier. The injected current at each rectifier was based on the loading of that rectifier and the characteristic harmonic spectrum of a typical rectifier. The rectifier load was calculated by simply spreading the system load proportionately, based on the individual rating of each rectifier. This method of injecting harmonic currents ignores the diversity introduced by specific train operating patterns. Further, the harmonic currents were applied at the same phase angle resulting in a pessimistic combination.

A proprietary model of the system was used to calculate the propagation transfer function of the harmonics when propagating through the network. Impedance profiles were used to assess the system sensitivity and resonances. The impedance profiles of the higher impedance transformer option showed a greater shift of harmonic resonances to lower frequencies compared to the lower transformer impedance option, see Figure 3 and Figure 4. As a consequence, the total harmonic distortion (THD) on the 11kV network for the higher transformer impedance option was much higher at about 11% compared to about 4% for the lower impedance option. However the THD at the PCC was found to be within acceptable limits. Mitigation in the form of harmonic filters was therefore recommended on the 11kV network since the THD exceeded both planning and compatibility limits.

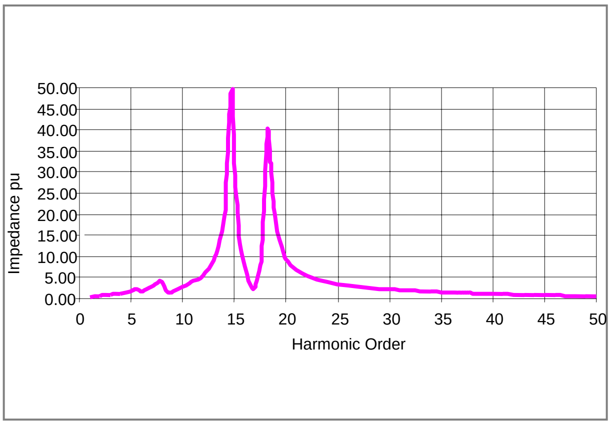

Figure 3: Impedance Profile for Low Impedance Transformer

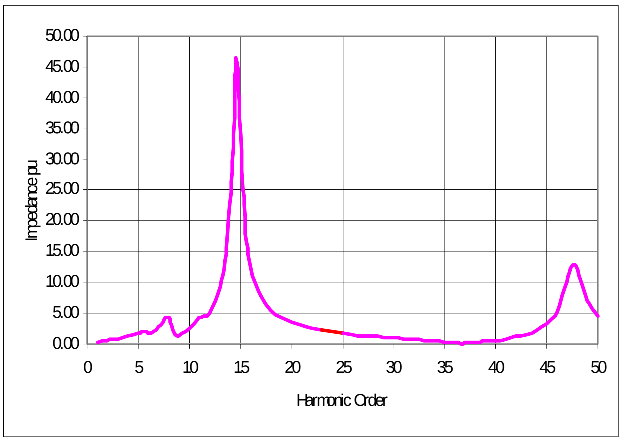

Figure 4: Impedance Profile for High Impedance Transformer

CONCLUSIONS

The quality of supply issues arising from DC traction loads on a metro system have been presented. The paper shows that through a careful optimization of the design of primary equipment, it is possible to improve the system performance of a metro system network in terms of voltage fluctuations and harmonic voltage distortion levels. However, constraints on fault level requirements may dictate the need for static var compensation equipment and harmonic filters in order to comply with limits set in the applicable power quality standards.

The paper has presented an iterative approach to determining the parameters of primary equipment in order to optimize the power quality performance of the system. The key issues considered include:

- The reliability and security of supply,
- The impact of grid transformer impedance on the quality of supply.
- Quantification and assessment of power swings, voltage fluctuations, and voltage profiles,
- Quantification and assessment of harmonic voltage distortion levels,
- Optimization of transformer losses,
- Assessment of asymmetric fault levels and the required asymmetric break rating of switchgear.

The main findings from the case study are that,

- The need to control fault levels through higher grid transformer impedance needs to balanced against the requirements for voltage fluctuations,
- Higher grid transformer impedances shift harmonic resonances to lower frequencies and consequently increase the total harmonic distortion.
- A low loss transformer with higher impedance can result in asymmetric fault currents which exceed the standard asymmetric break rating of switchgear.

Other issues that need to be considered but are beyond the scope of this paper include operational issues and the associated operational risks depending on the complexity of the scheme.

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