The Impact of Sympathetic Magnetization Transients on Harmonic Filters in Auto-Transformer Fed Railway Traction Applications

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Abstract— **The operation of mixed fleets of modern PWM rectifier and older thyristor locomotives and the tightening of harmonic emission standards globally will lead to more complex harmonic filter installations in railway applications. This paper shows that track switching operations in an auto-transformer fed system can generate sympathetic transformer magnetization currents that have very significant magnitudes, high harmonic content and last for some seconds. A sympathetic transient can occur when un-energized auto-transformers are switched into service and paralleled with energized transformers at the feeder station or in adjacent track sections. The harmonic loads imposed by these currents need to be considered in the design of the harmonic filter elements and protection.**

Keywords-railway; harmonic filter; sympahetic magnetization transient

I. Introduction

Railways, as a consequence of the very low rolling resistance offered by a steel wheel on steel rail, will remain the most energy efficient form of land transportation. Additionally electric railways avoid the use of liquid transport fuels. The expansion of rail operations, passenger and freight, is an inevitable response to limitations on oil supply and our global greenhouse challenges. Electric rail traction power supply presents some challenges. High speed passenger trains or minerals freight trains can draw real powers up to 15MW. The energy supply is single phase and re-balancing with static VAR compensators may be required. Given that power is generally supplied at the transmission system level extensive treatment with filters may be needed to reduce the total harmonic voltage distortion levels to typically one or two percent at the point of common coupling.

New feeder station designs must simultaneously deal with tighter harmonic disturbance limitations and locomotive traffic that might include a mix of older thyristor locomotives and modern PWM locomotives. Older feeder station filters, designed for thyristor locomotive traffic, might include one or two resonant links to selectively deal with the largest harmonics typically the third and the fifth. A modern feeder station filter might include three or four low order harmonic links and a high frequency link to deal with broad band emissions from a mixed locomotive fleet with thyristor and PWM locomotives. The more complex filters have more complex transient responses and higher sensitivity to power systems disturbances. This paper shows that the switching of auto-transformers within a rail network can produce large disturbances that can impact on the filter rating and protection.

II. Sympathetic Magnetisaton Transients

Transformers with saturable cores can produce a magnetization inrush transient. The core may saturate at energisation depending on the remnant flux and point switching within the mains cycle. If energized from and infinite bus, the currents will only be limited by the air-cored winding inductances and may easily reach peaks of 20 per unit. The currents have a strong DC component that produces voltage drops across the primary winding resistance that re-balances the core flux allowing the currents to decay over ten to twenty cycles.

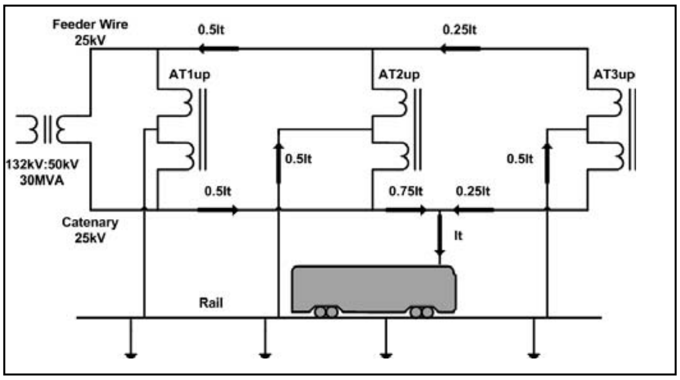

Figure 1. The 50:25kV Autotransformer Feeding Arrangement

If a transformer is energised from a weak bus the DC current produced by the magnetisaton transient produces a DC voltage at the point of connection. If other transformers are directly connected to this DC afflicted bus, the DC voltage can offset their core flux. These transformers saturate and draw an unbalanced magentising current. The DC component in this new sympathetic transient cancels the DC current produced by the original incoming transformers energisation. The transformers interact and generate mutually sustaining magnetization currents with cancelling DC components. These sympathetic transient persist for hundreds of cycles i.e. seconds. Sympathetic magnetization transients, [1-4], have been observed in general power systems but the phenomena has not been reported in the literature in regard to railway power supply systems. High levels of odd harmonics are produced and this has an implication for filter design and protection.

This paper examines a 30MVA 132kV:50kV feeder station that supplies two auto-transformer fed double-track sections, [5-6]. Each track section is 20km long and includes three 10MVA 50:25kV auto-transformers that provide 25kV catenary supplies for operating trains as shown in Figure 1. The auto-transformer AT_{1up} is adjacent to the feeder section, AT_{2up} is 10km distant and AT_{3up} is 20km from the feeder station. Figure 1 shows the connections for a single-track section. Indicative current flows are shown to indicate that adjacent auto-transformers will provide the bulk of the traction current. The exact sharing is determined by the overhead wiring and track impedances. The feeder station transformer 50kV winding is shown without a grounded centre-tap but it may be present in some installations, [6].

A double-track section facilitates train travel in both directions without the need for passing loops. It consists of an “up” and a “down” track. The adjacent parallel down track includes a further three auto-transformers designated At_{1down}, AT_{2down} and AT_{3down}. A 20km double-track section then includes six 10MVA auto-transformers.

A feeder station located in the centre sections of a rail corridor will normally supply two-double track sections using two separate supply phases. This results in a feeder station spacing of 40km in this example. In Australia, two single-phase transformers are used and the track sections appear as a single-phase line-to-line loads upon the transmission system. In other nations, [6], a three-phase to two-phase transformer conversion such as the Scott connection may be used to produced two single phase outputs with 90° displacement. In these situations if the two double-track sections are equally loaded, the feeder station appears as a balanced three phase load.

A normal operating switching sequence is to energise a track section while other track sections are in service. This brings a group of auto-transformers into service and parallels them with operating auto-transformers and the feeder station transformer. As a consequence sympathetic magnetizing transients may develop.

III. AUTOTRANSFORMER MODELLING

The saturation behavior of the auto-transformer depends on parameters that are not normally available on a type test certificate. These include:

- The air cored inductance – the inductance of the windings in the absence of a core, this is readily measured during manufacture;
- The saturation flux density for the core material;
- The knee point – the per unit terminal voltage at fundamental frequency at which the transformer core begins to saturate;
- The remnant flux density for the core material.

The determination of the exact values for a specific transformer will normally require the collaboration of the manufacturer. This paper uses the following parameter estimates:

- Saturation flux density - 1.7T;
- Remnant flux - 1.2T;
- Knee voltage - 1.15 per unit;
- Air cored inductance - 15% per unit.

The core material saturation flux density and remnant flux are estimated from materials properties presented in basic electrical machines texts, [7-8]. The knee point voltage is typically 5% to 15% higher than the operating voltage, [4]. Given that railway overhead systems are designed with higher voltage variations than experienced in a standard transmission system, the top end of this range is selected. The air-cored inductance is much less than 1.0 per unit and an estimate of twice the transformer leakage reactance has been previously proposed, [4]. For voltage regulation purposes the auto-transformers are designed with a low leakage reactance, [6]. Winding interleaving results in at least a four-fold reactance reduction. A better estimate for the air-cored inductance is twice the leakage reactance of a conventional two-winding 10MVA transformer. This would fall in the range of five to ten percent, [9]. On this basis a 15% reactance is proposed.

PSCAD in the modeling tool employed and it includes a saturable core transformer model with a piece-wise magnetic saturation model. Within this model the peak flux is 1.414 per unit when a 1.0 per unit fundamental voltage is applied. On this basis:

- The PSCAD knee voltage point is 1.15 per unit and this equates to 1.7T peak;
- At 1.0 per unit voltage peak flux is 1.478T or 1.414 per unit;
- The peak remnant flux 1.2T equates to 1.148 per unit.

The peak inrush current occurs for energisation at the voltage zero crossing, [10]. For a single-phase transformer with a piecewise linear saturation characteristic excited from a stiff source an expression for the peak transient inrush current is, [11]:

$$Ipk = \frac{\sqrt{2}U}{Xl}\left\{\frac{2Bn + Br - Bs}{Bn}\right\} \quad (1)$$

Where

U is the system RMS voltage
Xl is the air cored reactance
Bn is the normal rated flux (T)
Br is the remnant flux (T)
Bs is the saturation flux (T)

Substituting values for this case gives 3.13kA at 50kV. Figure 2 shows the current response for the saturable PSCAD auto-transformer model energized from a stiff 50kV bus with the following transformer per-unit parameters: magnetizing inductance current 1%; core loss 0.25%; full load copper loss 0.15%; leakage reactance 2%. The current peak is 3.17kA or 15.8p.u. on a 10MVA base.

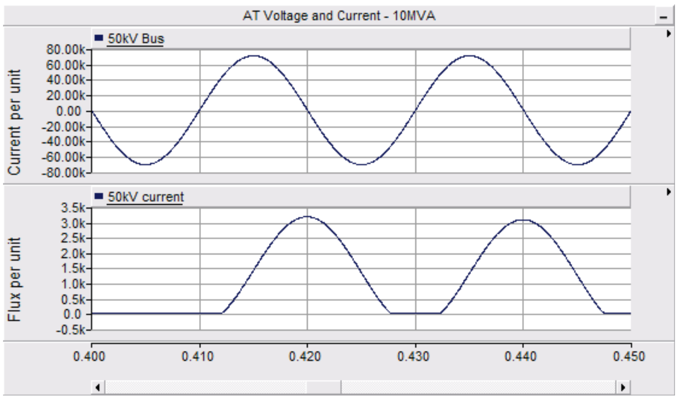

Figure 2. Auto-transformer Voltage and Current I_{pk} =3 125Ap

IV. SYMPATHETIC TRANSIENT SIMULATION

To illustrate the potential for sympathetic transients a feeder station and its harmonic filters were simulated using PSCAD. The key simulation parameters are:

- Point of common coupling: 132kV; symmetric fault level 5kA; X/R=5; Per phase series R+R//L model 2.99Ω+47.5mH//1200 Ω;
- Feeder station transformer: Single phase 132kV:50kV; 30MVA; magnetizing current 1%; core loss 0.5%; copper loss 0.3%; leakage reactance 8%; knee voltage 1.15; saturation flux density 1.7T; remnant flux 1.2T;
- Harmonic filter as shown in Figure 3:
  - Double tuned link, [12], third/fifth harmonic: 50kV; 120Arms, 6MVA fundamental current; impedance zeros 147Hz and 245Hz; anti-resonance frequency 189Hz; C_s=6.389μF; L_s=109.9mH; C_p=23.98μF; L_p=29.36mH;
  - Double tuned link seventh/ninth harmonic: 50kV; 60Arms, 3MVA fundamental current; impedance zeros 343Hz and 441Hz; anti-resonance frequency 389Hz; C_s=3.689μF; L_s=45.39mH; C_p=58.10μF; L_p=2.883mH;
  - High frequency damper: 50kV; 80Arms, 4MVA fundamental current; C=5.135μF; L=16.3mH; R=30Ω.
- Trackside arrangements – two 20km double track sections with three autotransformers per track section as per Figure 1; 12 autotransformers total
- Autotransformers: Single phase 50kV:25kV; 10MVA; magnetizing current 1%; core loss 0.25%; copper loss 0.15%; leakage reactance 2%; knee voltage 1.15; saturation flux density 1.7T; remnant flux 1.2T;
- Double track overhead wiring parameters: 1.33mH/km; 0.17Ω/km; 11nF/km, [3]

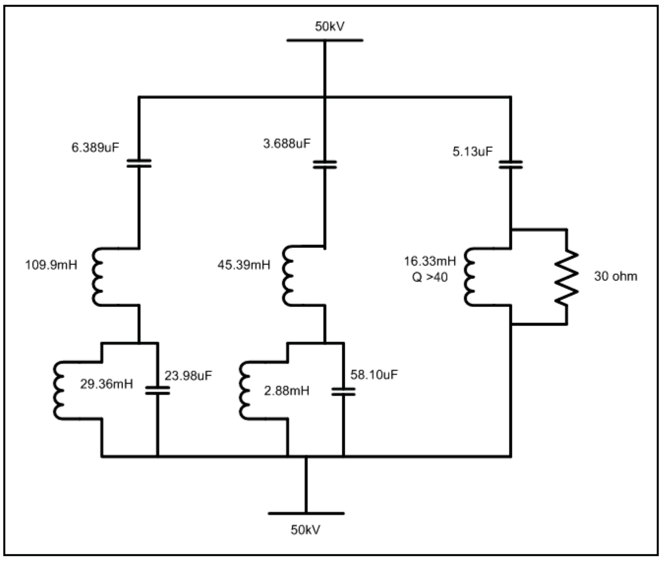

Figure 3. The 50:25kV Autotransformer Feeding Arrangement

The filter is based on double-tuned resonant links, [12]. Each link will be designed to sink two adjacent odd harmonics, for example, the third and fifth. Between these harmonics the filter has a parallel resonance. For a link tuned designed to sink the third and fifth harmonic this anti-resonance will fall close to the fouth harmonic. The size of the filter is specified in terms of the capacitive current drawn by the filter at the fundamental frequency. Four input parameters: the fundamental current, two impedance zeroes and one parallel resonance frequency uniquely determine the values of the two inductors and two capacitors, [12].

Figure 4 shows an abnormal operating condition where one phase of a feeder station is required to simultaneously supply two double-track sections. This may occur if alternate phase of the feeder station is unavailable due to faults or maintenance requirements. Initially circuit breakers “CB Up North” and “CB Down North” are closed. Figure 5 shows the 50kV bus voltage and the outgoing feeder station current resulting from the simultaneous closure of “CB Up South ” and “CB Down South ” to energise a double track section with six 10MVA auto-transformers. This is an extreme case that will be used to illustrate the possible consequences for the filters. The initial current peak is 5.6kA or 6.6pu relative to the feeder station rating.The intensity of the transient may be better understood when it is noted that this is 50% of the peak asymmetric bolted fault current of 11.1kA. The 50kV bus voltage is heavily distorted. It is clearly preferable to use a track switching protocol that introduces a single track section at a time, i.e. three auto-transformers, which results in much lower transients.

Figure 6 shows the response of the newly connected transformers AT_{4up} and AT_{4down}. These are adjacent to the feeder station. They have initial remnant fluxes of -1.2T which is established in the simulation by injecting a DC current into the transformers prior to their engergization. The switching occurs at 0.41s, the line-to-line voltage zero crossing, to maximumise the inrush. The peak current is 6.22pu or 1 240A for a 10MVA transformer. The more distant auto-transformers have smaller responses as the opverhead system wiring adds impedance.

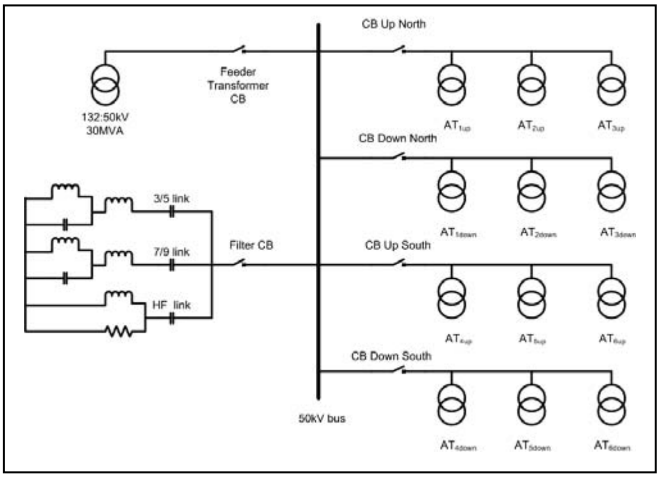

Figure 4. An Abnormal Feeding Arrangement

Figure 7 shows the disturbance to AT_{1up} and AT_{1down} which are previously energized auto-transformers adjacent to the feeder station. The currents drawn by the new auto-transformers produces DC votages that drives a flux offset and a peak negative magnetizing current of -2.77pu results. The new auto-transformers exchange hundreds of amperes of DC current with the previously energized auto-transformers. The auto-transformers largely supply each others DC current requirement. From Figure 4 it can be observed that they hold each other in the saturated state for dozens of cycles.

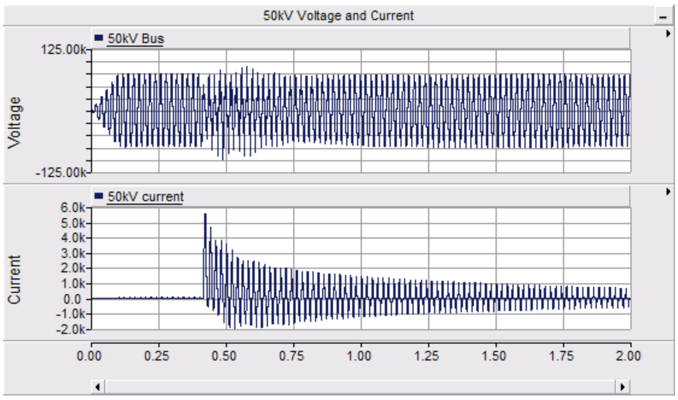

Figure 5. Combined Track Section Voltage and Current - 100kVp 5.6kAp

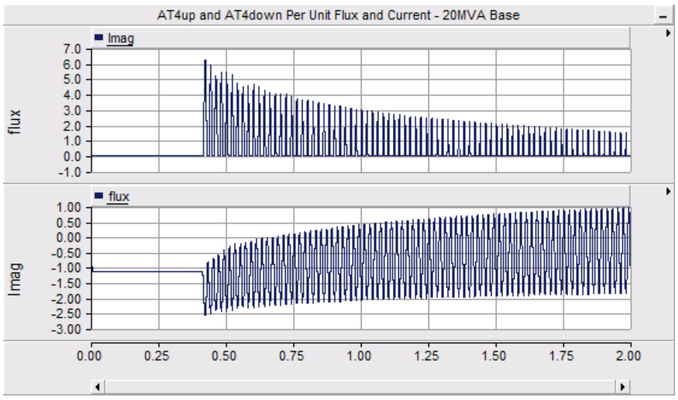

Figure 6. Newly Energised Auto-transformer Response – Ip = 6.22pu

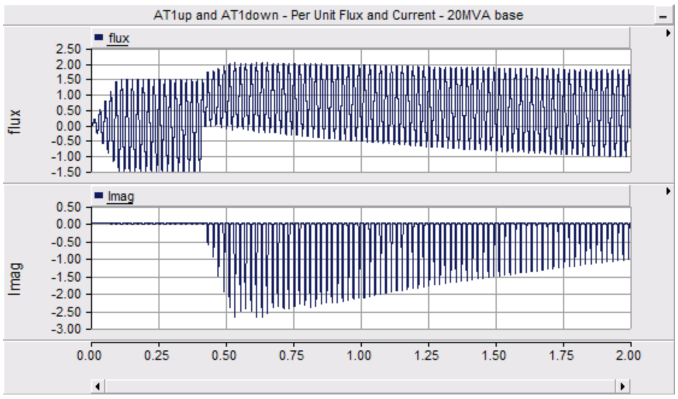

Figure 7. Previously Energised Auto-transformer Flux and Current Response – Ip = -2.71p.u.

The 30MVA feeder station bulk supply transformer is similarly affected but that result is not shown here. The sympathetic magnetization currents are a rich source of harmonics. Figures 8 to 10 shows the RMS current in each filter link averaged over a 20ms period. The filter ratings will depend on the traction load. Thyristor locomotives will have a THD of twenty to thirty percent. At thirty percent THD the total harmonic load current would be 180A.

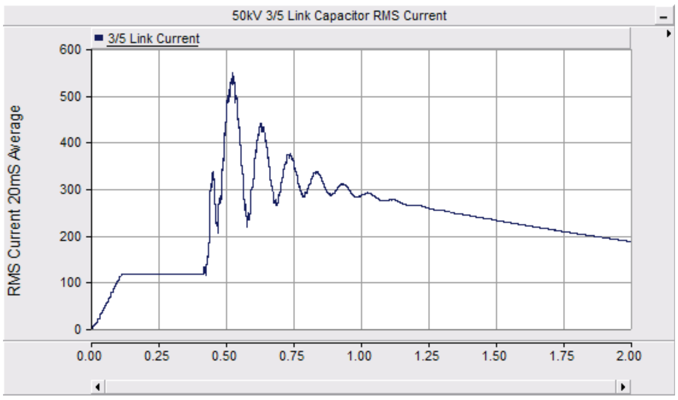

Figure 8. Third/Fifth Filter RMS Current Response – 549Arms maximum, 20mS Average.

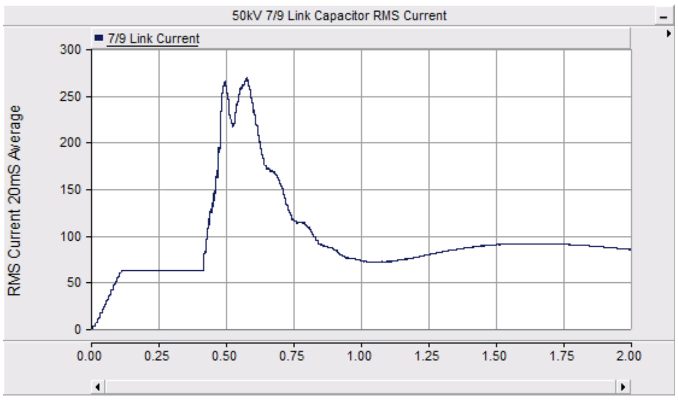

Figure 9. Seventh/Ninth RMS Current Response – 269Arms maximum, 20mS Average.

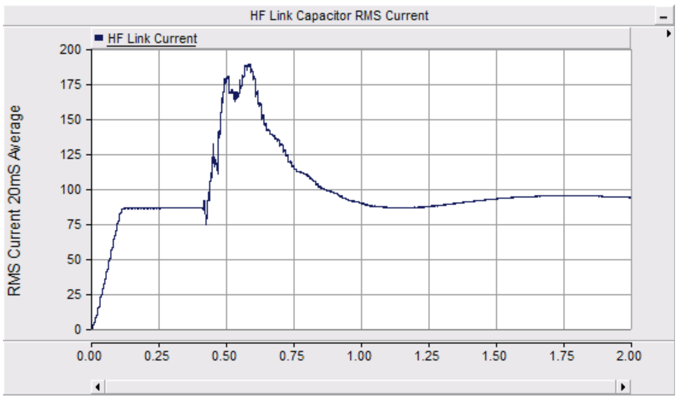

Figure 10. High FrequencyLink RMS Current Response – 189Arms maximum, 20mS Average

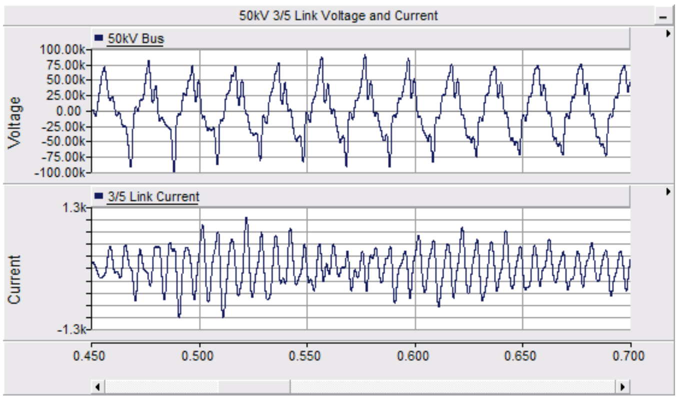

Figure 11. Third/Fifth Filter RMS Voltage and Current Response at the Peak Loading Period.

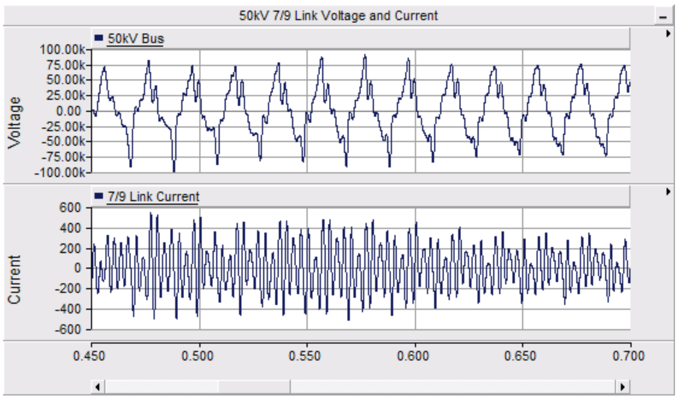

Figure 12. Seventh/Ninth RMS Voltage and Current Response at the Peak Loading Period.

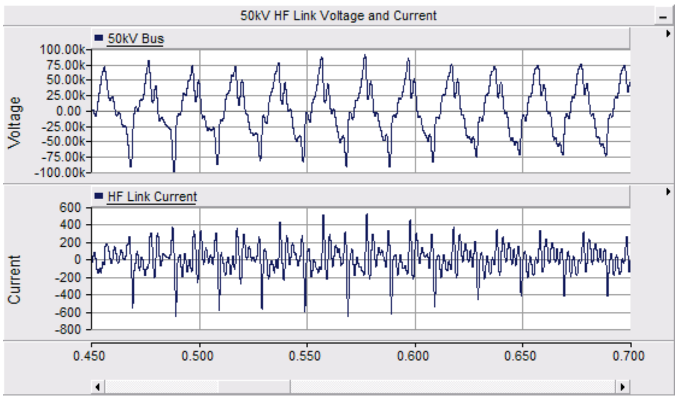

Figure 13. High FrequencyLink Voltage and Current Response at the Peak Loading Period.

This is further increased by harmonic inflows from the mains side. A further allowance will be made for the filter switch-on transient and curent amplification due to shifts in the power system frequency during system disturbances. Once the filter tuning frequencies are set the filter size is adjusted using the remaining free design variable, the fundamental current rating. As a guideline the RMS current rating of a filter link will be in the range 1.5 times to twice the fundamental current rating.

For example, the third/fifth link has a fundamental current of 120Arms or 6MVA at 50kV. If the filter rating is twice the fundamental rating, i.e. 240Arms total, the peak observed current during this transient, 549Arms, is 2.3 per unit. On this basis the seventh/ninth filter link rating could be 120Arms and the peak current is again 2.3pu. The high frequency link rating would be 160Arms and the transient magnitude is 1.2pu. This transient is large enough to have consequences for both the filter design and protection settings. Figures 11 to 13 show the harmonic current flows between 0.45s and 0.70s, the period over which the largest RMS currents occur. In each case the link voltage is the 50kV bus voltage which is intensely distorted.

The magnetisation transients will produce odd and even harmonics. The filter does not provide a path for even harmonics and as a consequence the 50kV bus will show even harmonic votage distrotion. An inspection of the voltage waveforms shows half-cycle asymmetery which confirms the the presence of even harmonic distortion that makes a significant contribution to the voltage peaks. The resulting voltages could have an effect on protective elements such as lightning arrestors.

V. CONCLUSIONS

As more stringent voltage harmonic limitations are imposed on railway installations more complex filters will be required to deal with the broad band attenuation requirements of thryristor and PWM locomotive fleets. These filters will have complex transient responses and potentially a sensitivity to power systems disturbances. Track section switching brings auto-transformers into service and parallels these with transformers that are already energized. The railway power system is economically designed for traction loadings rather than continuous current and has relatively higher system resistances. All of the conditions are in place to generate sympathetic magnetization transients that have significant magnitudes, are rich in harmonics and have durations of seconds.

A railway system will operate with many auto-transformers especially during abnormal feeding or extended feeding operations. The practice of bring many auto-transformers into service simultaneously can generate transients that are much larger than the feeder station rating. This paper examined a case where a 30MVA feeder station faced the demands of energizing 60MVA of new auto-transformer load paralleling these with 60MVA of operating auto-transformers. The inrush transients reached 50% of the asymmetric bolted fault current. The resulting filter currents were shown to exceed normal traction current harmonics. It is probable that these overloads could cause filter protection relays to trip. These effects should be considered during the design of the track section switching protocols and during the filter element and protection design. The possible modifications to switching protocols may include switching auto-transformers with the filters disconnected or connecting auto-transformers in the smallest groupings that the track switching arrangements allow.

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