EVALUATION OF TRANSFORMER INRUSH-INDUCED VOLTAGE DIPS

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ABSTRACT

Transformer energization can cause significant inrush currents that lead to perceivable voltage dips. This paper evaluates a voltage dip event that occurred in a transmission system and was detected and reported by the connected distribution utilities. A simulation model of the system concerned was built in ATP and validated against field measurement results. The effect of sympathetic interaction between transformers has been investigated and an estimation of the worst-case voltage dip scenario has been made. Using thresholds derived from standards and grid codes, the largest dip magnitude is 14%, with the dip to 90% for duration of 0.23 s or the dip to 97% for duration of 2.85 s.

INTRODUCTION

Power quality variation is of growing concern for power system operators because of the increasing prevalence of sensitive loads, such as variable speed drives and microprocessors [1-2]. One of the main power quality issues is voltage dips (sags) which can be triggered by short-circuit faults, motor starting or transformer energization. Both voltage dips caused by short circuits and transient voltage variations due to motor starting were thoroughly evaluated in [3-4] and [5].

On the other hand, it is until recent years that the voltage dips induced by transformer energization have been explored [6-12]. Systematic methods were provided in [6] for processing measured voltage dips due to transformer saturation. The impact of energizing generator step-up transformers from a 138kV transmission network was addressed in [7]. Energization of MV wind turbine transformers was studied to ensure compliance with Engineering Recommendation P28 (ER-P28) [8-10]. Similar voltage dip cases can also be found in offshore oil and gas systems and ship systems [11-12].

To address this type of voltage dip, a 'back-of-the-envelope' method was proposed for estimating the maximum magnitude of voltage dip [7] and a rule of thumb was suggested for determining whether a transformer energization is likely to exceed the 3% voltage step change limit suggested by ER-P28 [9]. For a more detailed assessment, an EMTP (Electromagnetic Transient Program) type simulation, which can contain consideration of transformer saturation and network characteristics, is preferable.

In this paper, transformer inrush-induced voltage dips that appeared during the simultaneous energization of two Generator Step-Up (GSU) transformers via a long-distance transmission network are reported. An ATP simulation is set up and the circuit model is validated with field measurement results. The uniqueness of this event is the sympathetic interaction between the already and to-be energized transformers. Sensitivity study is performed and quantification approach developed to determine the worst voltage dip scenario.

TRANSFORMER INRUSH

Transformer inrush can appear during transformer energizing or reclosing actions after a fault clearance. Both operations can cause temporary over-fluxing of transformer core, introduce an abrupt increase of transformer magnetizing current and bring a sudden change of voltage.

In the case of transformer energization, the outcome of inrush is largely dependent on following factors [12]:

- ✓ The point on wave at which the transformer is energized;
- ✓ Remnant flux;
- ✓ Core saturation characteristic;
- ✓ Impedance of the supply circuit;

Specifically, the first peak of inrush current is associated with the switching instant, remnant flux and the core saturation characteristic. Its decay is determined by system losses. However, if there are transformers already connected at the same bus to the adjacent transformer being switched in, the decay can be further prolonged due to the so-called sympathetic inrush phenomenon [13-14]. The build up of sympathetic inrush is influenced by the resistance of the supply circuit and its decay is largely dependent on transformer losses.

VOLTAGE DIP EVENTS

A generating plant needs to be connected to the grid. As the plant requires external power supply to support auxiliary loads before the generator can start operation, energization of the GSU transformers from the main grid is required.

The transmission line between the source and the transformers is quite long so the system impedance is relatively high. In addition, the substation was designed using one circuit breaker for two transformers meaning that they have to be energised simultaneously. The relatively weak (low fault level) system combined with this aggregated energization mode made the subsequent voltage dips more severe to the point where they could be measured and reported by the distribution utility. Field measurements were made to investigate the severity and likelihood of the voltage dips.

Two energization scenarios exist in this generating plant. Scenario I is to close the circuit breaker (CB2) to simultaneously energize two GSU transformers (T2&T3) with the third adjacent GSU transformer (T1) already connected. Scenario II is to close the circuit breaker (CB1) to energize GSU transformer (T1) with the other two adjacent GSU transformers (T2&T3) already connected. Two sets of measurement results are selected to show here; Figure 1 is the recorded voltage dips for energization scenario I and Figure 2 is the recorded voltage dips for energization scenario II. The observation point of the measurement is at a substation about 20 kilometres away from the generating plant. Results are represented by the variation of root-mean-square (rms) value derived from the measured instantaneous phase to ground voltages.

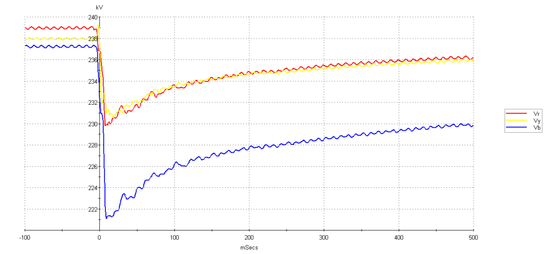

Figure 1 Measured phase to earth voltage dip of energization scenario I

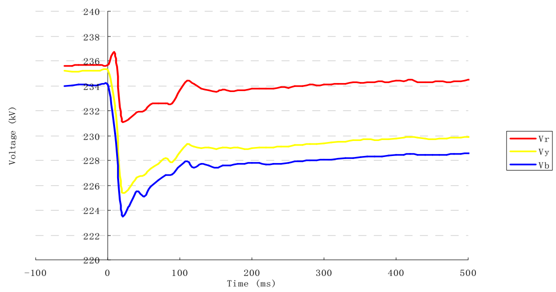

Figure 2 Measured phase to earth voltage dip of energization scenario II

It can be seen that the voltage dips caused by the transformer inrush is unsymmetrical and shallow in form. Although transformer energization is a planned operation, the uncertainties contributed by switching angle, remnant flux and system strength can still give rise to concerns about the magnitude of possible voltage dips and the consequent impacts. To estimate all the possible scenarios, a computer simulation exercise is used.

MODEL DESCRIPTION AND VALIDATION

The above-mentioned event suggests the necessity of evaluating the voltage dips caused by the energization of GSU transformers. This evaluation has been conducted in this paper based on the ATP/EMTP simulation platform. The following section shows the setup of the simulation circuit and its validation.

Model Description

The circuit under consideration is shown in Figure 3. The network beyond the supply source is represented by a Thevenin equivalent source. The transmission lines are represented here by using a constant parameter model. The loading conditions are also taken into account. The GSU transformers are modelled based on short-circuit test and open-circuit test results obtained from the transformer manufacturer’s test reports. Specifically, non-linear magnetizing curves have been estimated by curve fitting the open-circuit test data. The fitted curve is implemented into a type-96 nonlinear inductor which is capable of taking into account remnant flux.

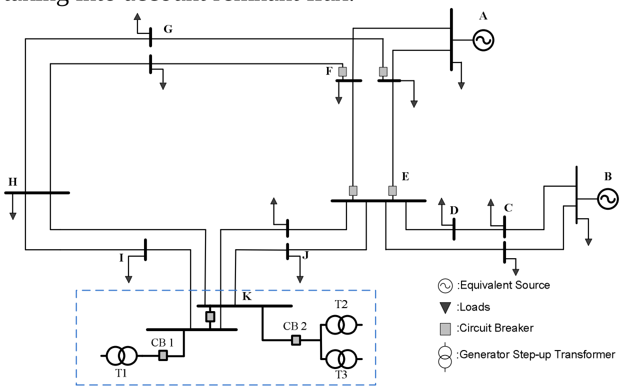

Figure 3 One line diagram of the system under study

Validation

Voltage dip events were simulated and the results were used for validating the simulation circuit by comparing with field test results. As mentioned before, the field test switching was conducted in energization scenario I where transformer T2 and T3 were energized together, with T1 already connected. This switching sequence was also followed by the simulation study. The comparison is based on the 3-phase rms voltage dips shown in Figure 4. It can be seen that the simulation circuit is capable to produce results very similar to the field measurement results, both in terms of voltage dip magnitude and the trend of voltage recovery.

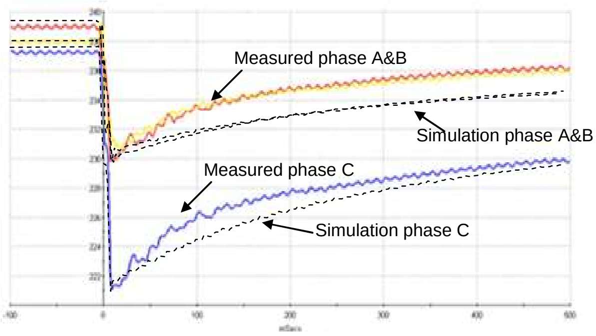

Figure 4 Comparison between tested and simulated results

EVALUATION OF VOLTAGE DIPS

In this section, the worst scenario voltage dip of the system under study is estimated, and based on this the thresholds were selected for quantifying the voltage dip duration according to the standards and grid codes.

Estimation of Worst Voltage Dip Scenario

From the perspective of the power system operator, the worst voltage dip scenario is the main concern. For a three-phase transformer, due to unsymmetrical saturation caused by different switching instants and remnant flux magnitudes, it is likely that only one phase can experience the biggest voltage dip. Referring to the circuit configuration shown in Figure 3, the worst scenario is estimated here by considering the impacts of aggregated energization of T2 and T3 with additional sympathetic interaction of T1. Under such condition, the voltage dip at the bus K is measured, with the largest voltage dip shown in Figure 5. The worst voltage dip scenario is found to occur when the switching instant is at voltage zero and the maximum remnant flux is in line with flux build-up. The worst scenario estimation gives the benchmark for the utility to determine whether additional measures should be applied to limit the voltage variation caused by transformer inrush.

Quantification of Voltage Dip

Benchmarking and comparison of voltage dips require pre-defined quantification criteria. A transformer inrush-induced voltage dip is typically quantified by dip magnitude and duration. Given a reference voltage, which is normally the nominal system voltage, the magnitude of the voltage dip can be measured explicitly. The duration of the voltage dip is closely related to the dip start and end threshold voltages. Normally, the value used for the end threshold is the same as the start threshold. However, differences between thresholds do exist in standards and in values suggested by utility companies. IEEE standard 1346-(1998) selects a 10% dip of reference voltage as the dip end and start thresholds for quantifying the dip duration. Yet the 10% dip threshold is somehow not in line with the requirements given by utility companies, for example the Grid Code applied to the transmission networks in Great Britain suggests that voltage excursions other than step changes may be allowed up to a level of 3%, and ER-P28 also recommends that the voltage step-change should be less than 3% after 30 ms of site energization.

Both thresholds are selected to assess the voltage dip duration: the first threshold is set at 90% of reference voltage and the second one is set at 97% of reference voltage, which are labelled in Figure 5 for quantifying the worst voltage dip scenario. The magnitude of the largest voltage dip is defined here as V_d; the duration measured based on threshold one is defined as d_1; the duration measured based on threshold two is defined as d_2. As can be seen, the largest dip magnitude is 14%, with the dip to 90% for duration of 0.23 s and the dip to 97% for duration of 2.85 s.

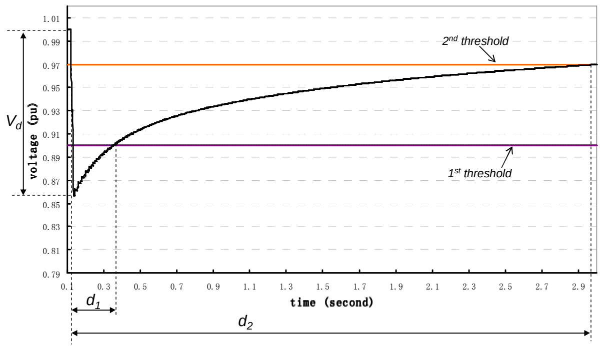

Figure. 5 Estimation of worst voltage dip scenario

Sympathetic Interaction

The worst scenario voltage dip is that shown in Figure 5 which contains the impact of sympathetic inrush due to the engagement of transformer T1. To show the signature of this sympathetic interaction, the case without sympathetic interaction is also estimated by simulating energization of T2 and T3 with the same setting used in the worst scenario estimation but without transformer T1. Both the voltage dip results with and without sympathetic interaction are shown in Figure 6. As can be seen for both cases, the dip magnitudes are the same, which indicates the sympathetic interaction has no impact on the dip magnitude; the duration of voltage dip, however, is further prolonged when sympathetic interaction is involved. Specifically, the prolonged duration $\triangle d_1$ is about 0.05 s and $\triangle d_2$ is about 1.34 s. If the duration of the scenario without sympathetic interaction is chosen as the base, it can then be further calculated that d_1 has been prolonged by 30% and the duration d_2 has been prolonged by 81% due to the sympathetic inrush. This shows that the prolonging effect of sympathetic interaction on dip duration can be very significant, especially when the smaller percentage dip threshold is chosen.

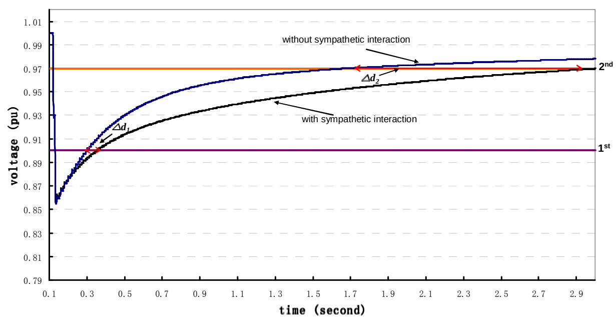

Figure. 6 Signature of sympathetic interaction

Impact of Numbers of already Energized Transformers

The case above considers only one adjacent already energized transformer. However, there are cases where more than one adjacent transformer can be engaged in sympathetic interaction. A particular case can be found in a wind farm grid connection where a branch of wind turbine transformers is energized with other branches of wind turbine transformers already energized.

Simulation studies were carried out to consider such a scenario based on the circuit shown in Figure 3. The worst voltage dip scenario estimated above is chosen as the base case, where the numbers of transformer T1 are varied from zero to five. The comparison of results is shown in Figure 7. It is intuitive to know that increasing the number of transformers can significantly prolong the duration of voltage dips, due to the increased sympathetic interaction. However, the largest voltage dip is always staying the same.

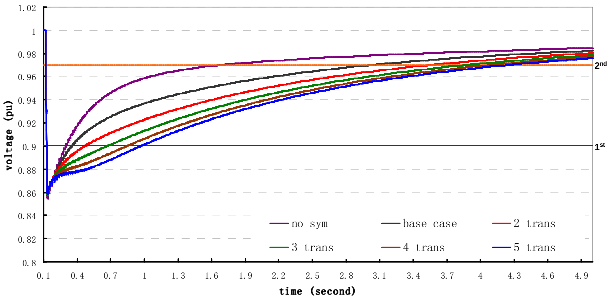

Figure 7 Impacts of numbers of already energized transformers on the magnitude and recovery of voltage dips

CONCLUSIONS

This paper presents voltage dip events caused by the energization of generator step-up transformers from the main grid. This voltage dip event occurred in a transmission system and was detected and reported by the connected distribution utilities. Field measurement results are used to verify the simulation model developed in ATP to enable detailed evaluation of the worst case scenario.

It shows that a weak (low short-circuit fault level) system is not only vulnerable to significant voltage dips but can also present conditions favourable to initiating sympathetic inrush when there are previously energized transformers adjacent to the transformer being switched in. Impacts of such a sympathetic interaction are studied and the voltage dip is quantified using thresholds derived from standards and grid codes.

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