On Assessing the Risk of SSR Related Torque Amplification in Series Compensated Networks

P. Vuorenpää, T. Rauhala, P. Järventausta, E. Acha

***Abstract*—It has been observed that, in general, disturbance in series compensated network may result in torsional stresses, which exceed the level of stresses resulting in case of similar disturbance in uncompensated network. A case in point is torque amplifications induced by the so-called Subsynchronous resonance related Torque amplification (SSR TA) phenomenon. Owing to the transient nature of the phenomenon, EMT analysis is the main tool to assess the level of torque amplification in detail. Also, frequency scanning techniques has been shown to be useful in providing indication of the most critical SSR TA conditions.**

This paper evaluates the feasibility of frequency scanning technique to assess the risk of SSR TA in meshed series compensated networks by comparing its results with results of EMT analysis. The comparison has been carried out by studying the SSR TA in a meshed series compensated transmission network model that has been developed to highlight the challenges that such network presents to traditional SSR analysis methods. The paper identifies and discusses the areas requiring development in frequency scanning technique so that it will provide more comprehensive overview of the severity of the SSR TA phenomenon also if meshed series compensated networks are studied.

***Keywords*: Electromagnetic transient analysis, frequency scanning analysis, series compensation, Subsynchronous resonance, Torque amplification.**

I. Introduction

In general, a disturbance in series compensated network may excite the sub-synchronous oscillation modes of the electrical system. If any complement of the frequencies of these modes coincides with the frequency of the torsional oscillation mode, the induced subsynchronous current components are expected to result in amplification of the torsional stresses experienced by the turbine-generator unit. This is commonly referred to as SSR Torque amplification (TA) phenomenon. In worst case scenarios, transient torques relating to the phenomenon may increase significantly fatigue of the mechanical parts of the turbine-generator unit resulting during and after transmission network faults. [1]

Due to the transient nature of the events leading to high levels of torsional stresses in the turbine-generator unit, Electromagnetic Transient (EMT) analysis could be seen as only approach enabling detailed evaluation of the level of torsional stresses in such cases. However, detailed EMT analyses covering only all relevant fault sequences for limited number of fault locations and operational conditions may become rather time-consuming. To decrease the computational burden of detailed EMT analyses in connection of SSR TA related studies, carrying out frequency scans for the preliminary stages of the analysis, has been proposed in [2] and further applied in [3, 4]. The main target of the SSR TA screening study using frequency scanning technique has been in pin-pointing the fault cases and operational scenarios that represent the critical cases and thus, need to be studied in high detail.

The main objective of this paper is to discuss and demonstrate the main shortcomings of frequency scanning technique to assess the risk of SSR TA phenomenon, when the severity of the phenomenon needs to be studied in a meshed series compensated network. In meshed series compensated network the need for an effective screening study method is of great importance as the number of the fault cases that needs to be covered in screening study becomes easily extremely high. In general, due to nature of the phenomenon, it cannot be considered adequate that only the *N*-1 contingencies under typical short circuit level are being covered. The study shall address also different combination of transmission line and series capacitor outages as well as larger variations in short circuit levels. This basically implies that the screening study needs not only to cover 10000+ cases but the study tool must be also capable to represent the results in relevant and illustrative manner.

The structure of the paper can be divided into three parts. The first part of the paper discusses on the applicability and limitations of the EMT and frequency scanning based study approaches to assess the risk of SSR TA phenomenon in connection of series compensated network related studies. In the second part of the paper the applied electrical and mechanical system configurations are described briefly. Thereafter, in the third part of the paper feasibility of the frequency scanning technique to assess the risk of SSR TA phenomenon in the applied system configuration is evaluated by reflecting the results of the frequency scanning analysis to results of the detailed EMT-based analysis.

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II. Means for Assessing the risk of SSR Torque Amplification in series compensated networks

A. EMT analysis

Due to the great many factors affecting the level of torsional stresses in meshed series compensated networks undergoing faulted conditions [5], EMT-based modeling in connection of SSR TA related studies could be seen beneficial for many reasons. In general, use of the EMT modeling philosophy to study the SSR TA phenomenon, enables the representation of the dynamical characteristics of both the mechanical and the electrical parts of the power system, in a detailed manner. For instance, MOV protection of the series capacitors, which has been found to be in a significant role, when assessing the resulting level of torsional stresses due to SSR TA phenomenon, [6,7] could be easily incorporated into EMT-based model of the series compensated power system. In addition, EMT analysis as time-domain based modeling approach enables detailed evaluation of the impact of different time-dependent variables, such as fault duration and operation sequences of the protection devices, on the resulting level of torsional stresses.

However, especially in case of meshed series compensated networks, resonance characteristics of the network may vary significantly based on the topology and short circuit levels of the system. Thus, an extensive number of different operation conditions, including different transmission line and series capacitor outages and short circuit levels of the system should be analyzed to attain comprehensive insight on the level of risk associated with the SSR TA phenomenon. Moreover, taking into account the severity of the consequences, possibly resulting in case of SSR TA related incident in the system, the analysis shall not be limited only to the most probable operation conditions but also impact of more uncommon operational scenarios should be included in the analysis. To sum up, EMT studies covering all the possible combinations of the affecting factors may become extremely time-consuming and thereby, usually unfeasible to be executed in full extent within the time available.

B. Frequency scanning analysis

To decrease the calculation burden of detailed modeling approach in connection of SSR TA related studies, a frequency scanning-based method for the identification of the most critical operating conditions concerning the SSR TA phenomenon has been presented. [2] The approach is based on the identification of the electrical system resonance frequencies from the frequency-dependent reactance curve of the system, as seen from the neutral point of the turbine-generator unit. In more detail, it is proposed that over 5 % of reactance dip in the range of ±3 Hz from any complement of the torsional oscillation modes of the turbine-generator unit under study, may indicate a real risk of SSR TA phenomenon.

In short, the reactance value X_{min} at the frequency of the reactance dip f_e is compared to the reactance value X_{max} of the previous local maximum in the reactance curve. Thus, the index X_{dip} representing the severity of the reactance dip may be determined as follows:

$$X_{dip} = \frac{X_{\max} - X_{\min}}{X_{\max}} \cdot 100\% \qquad (1)$$

Moreover, complement of the detected electrical system resonance frequency in the mechanical system reference frame f_m is derived based on the nominal frequency f_0 of the system as follows:

$$f_m = f_0 - f_e \qquad (2)$$

Fig. 1 outlines graphically the main principle behind the proposed method.

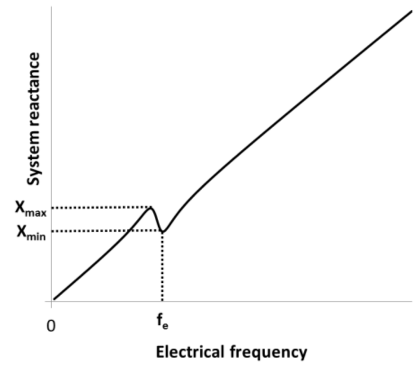

Fig. 1. Detection of the electrical system resonance frequencies

In general, the presented frequency scanning-based method for assessing the risk of SSR TA phenomenon provides a straightforward approach for the identification of the resonance conditions in the electrical system. However, it does not provide means for evaluating e.g. the impact of the fault duration or the protection measures of the series capacitors, on the amplification of torsional stresses. Thereby, results of the frequency scanning-based study approach could only be considered as indicative and applicability in connection of SSR TA related studies relatively limited. Despite the distinct shortcomings of the presented frequency scanning-based approach for assessing the risk of SSR TA phenomenon, feasibility of the approach in connection of SSR TA related studies has not been thoroughly evaluated.

III. Applied system configuration

A. Applied electrical system configuration

Often, the impact of series compensation on the level of torsional stresses resulting from disturbances is demonstrated by applying highly simplified system representations. [8,9] However, the analysis methods developed for such systems could sometimes be proven insufficient, when applied to cases of more complex system structures. Along the more complex system structure the different aspects of the studied phenomena may become more important and thus, the study technique needs to be further developed so that the relevant information can be effectively extracted from the study results. To address the challenges relating to the risk of SSR TA phenomenon in cases of meshed system topologies and provide a platform to feasibility testing of SSR TA analysis methods, a meshed series compensated network shown in Fig. 2 was developed and it has been applied in the studies presented in this paper.

The developed series compensated network comprises of 15 buses and interconnections to surrounding power systems and to lower voltage levels, represented by five 400 kV and seven 110 kV equivalents, respectively. Altogether 12 series capacitors are used in the system to improve its power transfer capability. Only the structure of the network illustrates clearly one of the main challenges related to SSR analysis of meshed series compensated network. Based on the structure it is easy to see that for extensive analysis the number of study cases covering only different *N*-2 combinations of 19 transmission lines and 12 series capacitors, 10 fault locations for each line as well as normal and minimum short circuit level for the equivalent sources, the number of fault cases reaches easily range of 10000 - 20000 cases even if not all the combinations are covered systematically.

To make the model relevant also for EMT-based studies the voltage rating of the MOV protection of the series capacitors was set to 2. 3 p.u.. The turbine-generator model connected to bus 1 is based on the model presented in [8] with frequency modification to 50 Hz and increasing the MVA rating of the unit to 1000 MVA.

B. Applied mechanical system configuration

The mechanical shaft of the generator unit under study was modeled as a two-mass with modal frequency of f_n=15 Hz and modal inertia of H_n=3. (Fig. 3) The mechanical damping of the shaft was neglected in the analysis.

The two-mass model of the shaft configuration could be seen advantageous in cases of preliminary SSR TA related studies. The reason is that in the case of a two-mass shaft configuration the impact of the applied fault on the studied oscillation mode could be examined rather accurately; in cases of multi-mass shaft configurations the information relating to the impact of the fault on a specific oscillation mode, would be lost due to presence of oscillations relating to multiple oscillation modes. In more detailed studies, use of the actual multi-mass shaft configuration could be seen as necessary e.g. to enable proper evaluation of the distribution of the torsional stresses between the shaft segments.

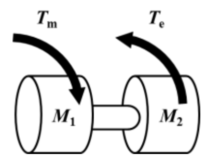

Fig. 3. Applied mechanical system configuration

IV. Frequency Scanning-Based Assessment of the Risk of SSR Torque Amplification

A. Applied tool for the frequency scanning analysis

To illustrate the feasibility of the frequency scanning-based assessment of the risk of SSR TA phenomenon, a fit-for-purpose frequency scanning analysis tool in Matlab, was developed. The main purpose of the developed frequency scanning analysis tool is to provide a straightforward approach for frequency scanning-based screening analysis and thereby, to enable the analysis of a large number of different operation conditions to be conducted in an efficient and orderly manner. The developed frequency scanning tool is based on the original work reported in [10].

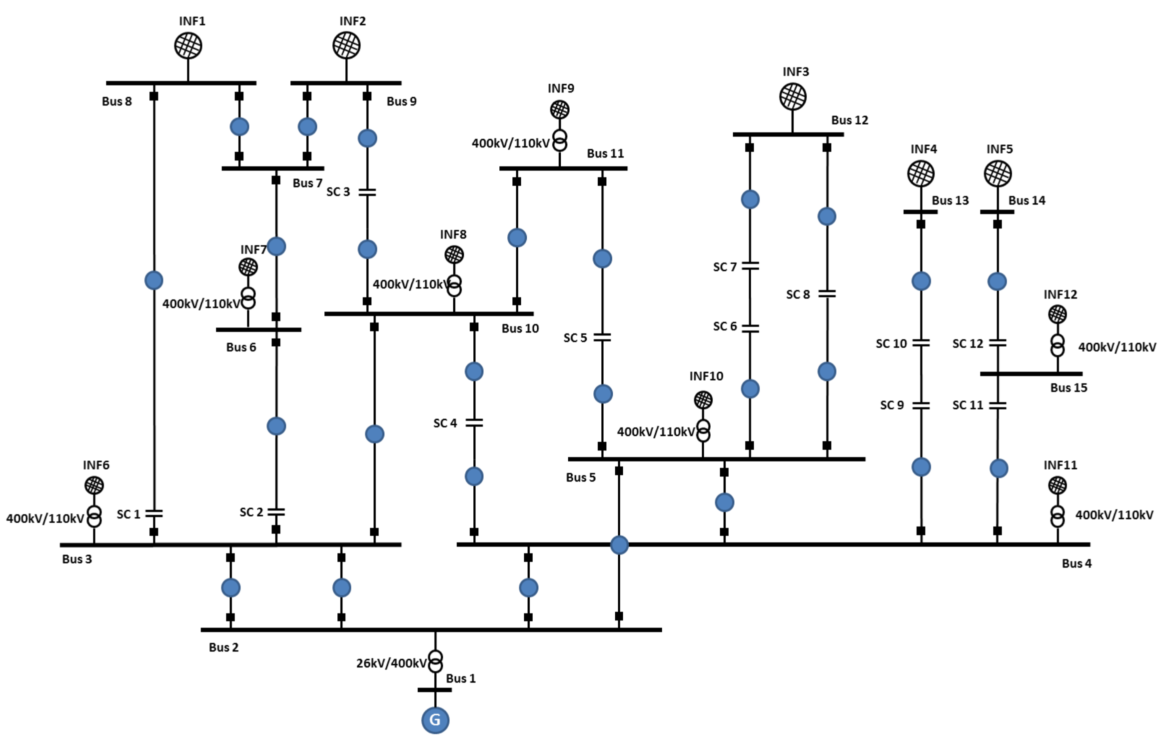

Fig. 2. Topology of the applied electrical system configuration

B. Frequency scanning analysis related to different operational conditions

In general, clearance of the fault in meshed series compensated network will leave the system into *N*-1 condition, whose ensuing topology and associated resonances, seen by the turbine-generator unit, will be related to the location of the fault. Thereby, the frequency scanning analysis-based assessment of the significance of a single operating condition from the SSR TA point-of-view will be expanded to analysis of a number of different *N*-1 system configurations. In addition, during the fault period a low-impedance connection to the ground at the fault location may affect significantly the resonances seen by the turbine-generator unit. However, possible nonlinear behavior of the series compensated network during the fault period, for example due to activation of MOV protection, could be considered to affect negatively the reliability of the results provided by the frequency scanning based study method. Thereby, frequency scanning based results presented in this paper covers only analysis of different pre-fault and post-fault system conditions.

By way of example, reactance curve representing an arbitrary pre-fault system condition and reactance curve representing the post-fault system condition resulting after clearance of an arbitrary fault from the system are presented in Fig. 4. Moreover, the electrical system resonance frequencies are given in Table I, together with the significance of the reactance dips detected from the reactance curves.

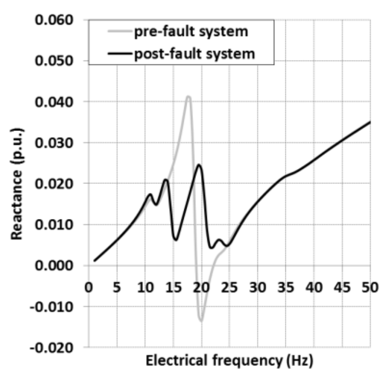

Fig. 4. Reactance curve for pre-fault and post-fault system conditions corresponding to an arbitrary fault and operating conditions of the system

Table. I. Reactance dips detected from the reactance curves of Fig. 4

	$f_{e,1}$ (Hz)	$f_{e,2}$ (Hz)	$f_{e,3}$ (Hz)	$f_{e,4}$ (Hz)	$X_{dip,1}$ (%)	$X_{dip,2}$ (%)	$X_{dip,3}$ (%)	$X_{dip,4}$ (%)
pre-fault	12.0	22.5	-	-	9.4	99.9	-	-
post-fault	12.0	15.5	22.0	24.5	13.9	70.3	82.1	23.5

Results of Fig. 4 and Table I demonstrate clearly that clearance of the fault in meshed series compensated network may result in significant differences between reactance curves representing pre-fault and post-fault system conditions.

C. Example of screening analysis conducted for the meshed series compensated network model

An extensive screening analysis covering all probable *N*-1 and *N*-2 contingencies and randomly selected set of short circuit levels for equivalent sources was conducted to assess the effectiveness of the frequency scanning-based approach to identify the most critical operating conditions regarding the SSR TA phenomenon. Based on the results of the analysis, two operating conditions with different line outage and short circuit levels were selected to illustrate the challenges related to SSR TA analysis in the special case of meshed series compensated network. "Case I" was chosen to represent a case for which the traditional SSR TA method indicates a negligible risk of SSR TA related to the mechanical oscillation mode at 15 Hz. Likewise, “Case II” was chosen to represent a case for which high risk of SSR TA was identified for the 15 Hz mode.

Fig. 5 and Fig. 6 present the reactance dips X_{dip} detected for pre-fault and post-fault system conditions relating to the operation conditions Case I and Case II. The crosses in the figures represent the resonance conditions detected for the post-fault conditions and the dots represent the resonances of the pre-fault condition.

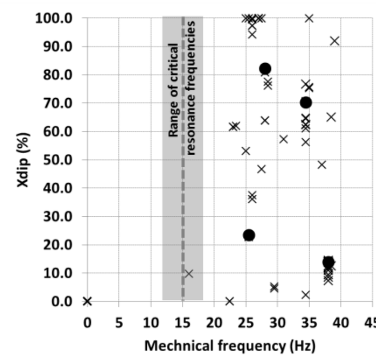

Fig. 5. Reactance dips for pre-fault and post-fault system conditions detected for Case I

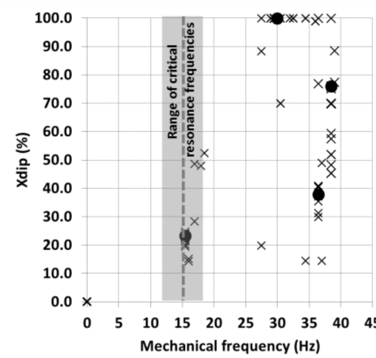

Fig. 6. Reactance dips for pre-fault and post-fault system conditions detected for Case II

Based on the results of Fig. 5, the reactance dips detected for Case I indicate that significant risk of SSR TA phenomenon should not be expected for mechanical oscillation mode of 15 Hz. It was only in one case of post-fault operation conditions, at a resonance frequency at around 16 Hz, that such a risk could be detected. However, analysis related to Case II (Fig. 6) indicates almost a direct coincidence of the complement of electrical system resonance frequency and the mechanical oscillation mode at 15 Hz at the various post-fault conditions. Thus, based on the conditions defined in [2] significant risk of SSR TA phenomenon related to the studied mechanical oscillation mode could be expected, if fault is occurring in operation condition referred as Case II.

D. Relation between reactance dips and subsynchronous damping of the system

The approach presented in [2] for the identification of the most critical operation conditions proposes that the reactance dips detected in the range of ±3 Hz from any complement of the mechanical oscillation modes of the turbine-generator unit, may indicate a possible risk of SSR TA phenomenon. However, the presented approach does not consider the relationship between the reactance dips and insufficient subsynchronous damping of the system. That is, the level of electrical damping often decreases, resulting in sustained or growing subsynchronous oscillations due to SSR Torsional Interaction (TI) phenomenon, at frequencies that are located at the vicinity of the reactance dips.

To illustrate the subsynchronous damping that exists in the system in the post-fault period for Case I and Case II, refer to Fig. 7 and Fig. 8. By taking into account the positive impact of mechanical damping on the overall damping of the mechanical oscillation modes in reality, electrical damping of the 15 Hz mode in the case of the post-fault conditions relating to Case I could be considered more or less sufficient. However, in Fig. 8 clear impact of closely aligned electrical and mechanical system resonance frequencies, as presented in Fig. 6, on the insufficient damping of the 15 Hz mode could be observed in Case II related analysis.

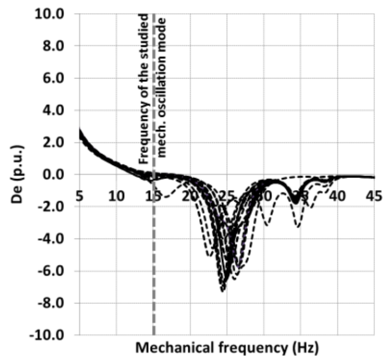

Fig. 7. Subsynchronous damping of the system after the fault clearance in Case I

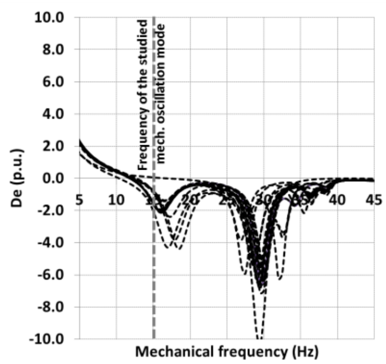

Fig. 8. Subsynchronous damping of the system after the fault clearance in Case II

To sum up, close alignment of complements of electrical system resonance frequencies with any of the mechanical oscillation modes, in addition to indicating increased risk for SSR TA phenomenon in terms of method presented in [2], may also indicate insufficient damping of the studied mechanical oscillation mode. Thus, despite indication of increased risk for SSR TA phenomenon, operation of the system under such condition would not be possible due to SSR TI related instability of the system. Thereby, it can be concluded that the method presented in [2] itself, without e.g. simultaneous subsynchronous damping analysis , could not be considered to provide sufficient basis for identification of the most critical operation conditions concerning the SSR TA phenomenon.

V. EMT Analysis Based Assessment of the Level of Torsional Stresses

A. Execution of the EMT analysis based study

Following the frequency scanning analysis, an EMT analysis of the level of torsional stress resulting from the disturbance in the meshed series compensated network was conducted, for operating conditions referred to as Case I and Case II. Even though frequency scanning analysis -based results presented in Fig. 8 indicated insufficient damping of mechanical oscillation mode of 15 Hz after a fault in operation condition Case II, it was still selected as a reference case for the EMT analysis based studies due to indication of high risk of SSR TA phenomenon (Fig. 6).

The EMT-based study was executed by applying 5 faults (Z_{fault}=1 Ohms) at every transmission line (altogether 19 lines) of the system with equal distances from each other. Following the fault time duration, the fault was cleared from the system by disconnecting the faulted line. Peak torsional stress T_{max} for fault durations from 50 ms to 150 ms with 10 ms time intervals were examined and in case of every fault location the highest peak torsional stress resulting due to the applied fault, denoted as T'_{max}, was selected to represent the worst-case scenario for amplification of torsional stresses. Consequently, altogether over 1000 simulation runs were executed for the single operating condition of the meshed series compensated network. To enable a more detailed evaluation of the effects of the series compensation on the level of peak torsional stress, similar analysis were conducted for the non-compensated system configuration. Basically, all capacitors shown in the studied network were bypassed in order to create the described reference case.

As an example of EMT-based study, Fig. 9 shows the electrical torque T_e and the torque between masses T_{12} for the case of a 150 ms fault applied at line between bus 4 and SC9. Fundamentally, during the fault period a decaying DC component in the currents of the turbine-generator unit will result in an oscillation component with a nominal frequency at the electrical torque. However, due to the series compensated network topology, additional frequency components will result at the complements of the electrical system resonance frequencies, as observed in Fig. 9. Due to relatively small time window selected for the analysis (approximately 500 ms of post-fault operation) possible insufficient damping of subsynchronous oscillations could not be considered to affect significantly the peak torsional oscillations resulting during the post-fault system conditions.

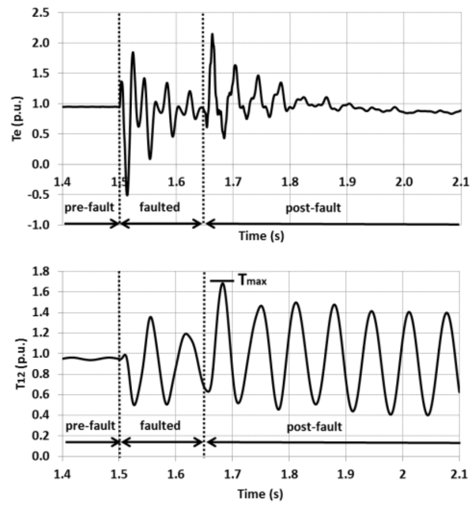

Fig. 9. Electrical torque and torque between masses of the two-mass shaft model for the case of a 150 ms fault at line between bus 4 and SC9

It should also be noted that the studies presented in this paper are limited only to cases of low-impedance faults with predefined range of fault durations to enable illustration of the shortcoming of the traditional frequency scanning analysis based approach for identification of possible SSR TA risk cases. However, the probability of different fault events, fault durations and operating conditions of the system should also be taken into account in the analysis, when conducting more detailed assessment of the risk of SSR TA phenomenon in the system.

B. Assessing the level of torsional stresses by means of EMT analysis

Fig. 10 and Fig. 11 present the highest peak torsional stress T'_{max} resulting from a disturbance applied at a pre-defined fault locations of the series compensated and non-compensated networks. The X-axes in Fig. 10 and Fig. 11 represent the voltage dip at bus 2 during the applied disturbance, denoted as $U_{dip,bus2}$. T_0 in Fig. 10 and Fig. 11 represents the level of torsional stress between the masses of the two-mass model in pre-fault condition and could basically be considered to be directly related to the real power generation of the unit before the applied fault. Furthermore, the amplification of the torsional stresses, denoted as T_A, is determined by the difference between the highest peak torsional stresses existing in the non-compensated and in the series compensated cases, for the same kind of fault.

In the non-compensated network case, a near-linear correlation between the highest peak torsional stress T'_{max} and the voltage dip at bus 2 $U_{dip,bus2}$ may be observed in both studied cases. However, in the series compensated network the correlation is quite different, since any clear relation between the highest peak torsional stresses resulting in different fault locations could not be detected.

The frequency scanning analysis based results presented in Fig. 5 and Fig. 6 showed that there are cases of negligible risk (Case I) and cases of high risk (Case II) relating to the SSR TA phenomenon affecting the mechanical oscillation mode at 15 Hz. However, a detailed EMT-based analysis for the same operating conditions showed an almost similar level of torsional stresses in both cases. Clear differences between the highest peak torsional stress T'_{max} values related to operation conditions Case I and Case II could be observed only in case of faults resulting in the most significant voltage dip at bus2. In these cases the highest peak torsional stress T'_{max} values related to Case II exceed the stresses resulting in Case I. The similarity of the results can be explained mainly by the fact that MOV protection of the series capacitors could be expected to limit effectively the amplification of torsional stresses in both cases.

In any case, frequency scanning-based method for identification of the most critical operation conditions presented in [2] could not be considered to provide sufficient means for detailed assessment of the level of torsional stresses resulting in case of disturbances in the meshed series compensated network model.

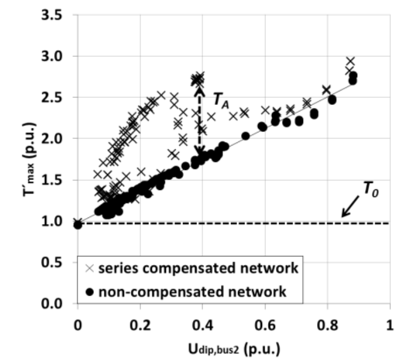

Fig. 10. The highest peak torsional stresses T'_{max} detected in Case I

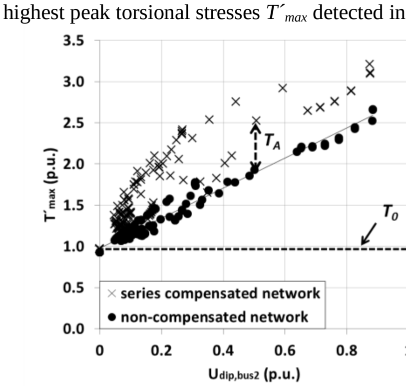

Fig. 11. The highest peak torsional stresses T'_{max} detected in Case II

C. Impact of series capacitor charging on the level of torsional stresses

In addition to resonance conditions introduced by the series compensated network also the MOV protection level of the series capacitors have been found to affect the level of torsional stresses resulting due to the SSR TA phenomenon. [6,7] This can be explained by the fact that the maximum level of energy accumulation in the series capacitor may be taken to be determined by the MOV protection level of the series capacitor. Moreover, the energy accumulation in the series capacitor during the fault period could be considered to be directly related to the amplitude of the discharging current of the series capacitor after the fault clearance. Thereby, discharge of the energy accumulated to the series capacitor after the fault clearance, even at frequencies outside the ±3 Hz range from the complements of the mechanical side oscillation modes, could be considered to potentially affect to the level of torsional stresses resulting for the turbine-generator unit.

To illustrate this effect, Fig. 12 presents the relationship between the average series capacitor charging during the fault period and the resulting amplification of torsional stresses in case of operation condition referred as Case I. The average series capacitor charging relating to a specific fault location was determined by summing up the normalized voltage levels of the series capacitors during the fault period and dividing this value by the number of series capacitors in service. Due to the presence of significant transients in the voltages of the series capacitors during the first few cycles of the fault period, the charging of the series capacitors was determined during the last cycle of the 150 ms fault study case.

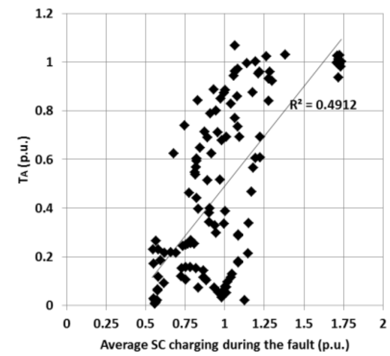

Fig. 12. Average series capacitor (SC) charging during the fault period vs. amplification of torsional stresses in Case I

The results in Fig. 12 indicate that the average series capacitor charging during the fault period varies between 0.5 p.u. and 1.75 p.u. depending on the location of the fault. Even though a direct relationship between the average series capacitor charging and amplification of torsional stresses could not be found, a positive correlation between these variables could still be observed. Consequently, the probability of amplification of torsional stresses is likely to increase with increasing levels of average series capacitor charging during the fault period. In particular, fault locations with maximum levels of average series capacitor charging (~1.75 p.u.) resulted also in high amplification of torsional stresses (T_A≈1.0 p.u.).

As a conclusion, estimation of the charging levels of the series capacitors during the fault period could be considered to provide additional information on the *criticality* of different fault locations, when assessing the overall risk of SSR TA phenomenon under different operating conditions. Thereby, development of methods enabling such estimation to be carried out already in connection of frequency scanning -based studies could be seen to provide additional value for the preliminary stage screening analysis.

VI. Conclusions

In some occasions, disturbances in series compensated network have been found to result in increased torsional stresses for the turbine-generator unit connected to the system. Amplification of torsional stresses in such events is commonly explained to be caused by SSR TA phenomenon. It is addressed in this paper that whereas EMT-based analysis related to single operation conditions could be considered to provide the most accurate information on the stress levels possibly resulting due to SSR TA phenomenon, execution of EMT-based screening analysis for meshed series compensated network, which would cover all probable fault scenarios of the system, could not usually be considered as a feasible alternative. To enable limitation of the fault scenarios requiring EMT-based detailed analysis, frequency scanning-based technique for preliminary stage assessment of the most critical operation conditions related to SSR TA phenomenon has been presented in [2].

In this paper feasibility of the presented frequency scanning technique to assess the severity of SSR TA phenomenon is demonstrated in connection of generic meshed series compensated network related studies. Comparison between EMT and frequency scanning-based results revealed that due to lack of ability to take into account e.g. the impact of series capacitor protection measures on the resulting level of torsional stresses, the applied frequency scanning-based approach could not be considered to yield conclusive evidence to identify all of the most critical operating conditions relating to the SSR torque amplification phenomenon. Nonetheless, owing to some excellent properties of the frequency scanning analysis in the screening of meshed series compensated network topologies, further development of the technique is ongoing.

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