A FREQUENCY SCANNING METHOD FOR THE IDENTIFICATION OF HARMONIC INSTABILITIES IN HVDC SYSTEMS

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Abstract–**A Frequency Scanning Method is introduced in the paper to obtain a more accurate frequency characteristic for identifying harmonic instability in HVdc systems. An example of the application is used to identify the resonance frequencies in the CIGRE benchmark model. The paper shows that the Benchmark model is not tuned to the resonance frequency that it was designed for. Using the scanning method, the resonance frequency of the Benchmark model may be shifted to demonstrate a simulation of core–saturation type instability.**

Keywords **Harmonic instability, HVdc/ac system, Weak ac System, Electromagnetic transient simulation, Frequency Scanning Method.**

I. INTRODUCTION

Harmonic Instability is a phenomenon that occurs when the ac and dc side networks in an HVdc transmission system have impedances which result in the amplification of voltages or currents of one particular frequency [1]. It has often been assumed that harmonic instabilities arise if the ac and dc side networks are tuned to complementary frequencies, i.e., if the ac side has a resonance at a frequency f_1, and the dc side is resonant at a frequency f_2 where $f_1 - f_2 = \pm f_0$; f_0 being the fundamental operating frequency (60 Hz in our case). The reason given is that the converter transforms frequencies f on one side to frequencies $f \pm f_0$ on the other. Thus if resonances on either side differ by f_0, the converter action would couple them together and cause instability. A particularly severe case of harmonic instability (known as core saturation instability) arises when there is an amplification of the 2nd harmonic on the ac side. This is because currents on the ac side of 2nd harmonic frequency are routinely generated after faults because of asymmetrical transformer saturation. Such instabilities have been reported in literature [2][3]. In the most simplistic analysis for determining the frequencies f_1 and f_2 introduced earlier, one often considers each side (ac and dc) in isolation. For example the ac side resonance is calculated by considering only the ac system equivalent, the local load and the ac filters.

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As shown in this paper, the simplified approach can lead to an erroneous estimate of the true resonance frequency. In reality, the ac and dc sides are not in isolation but connected to each other through the complex switching matrix of the converter. The extreme non–linearities of the conversion process make analytical determination of the composite resonance frequency very difficult. A number of workers have attempted to solve this complex problem. Hammad [4] uses an eigenvalue approach, Bahrman et al [5] use an estimate of the ac side impedance reflected through the converter and verify their results on a dc TNA. Larsen et al [6] have developed an approach based on a linearized analysis of the interaction between the ac and dc sides of the converter. They also include the effect of controls.

In this paper, the system is set up on an electromagnetic transients simulation program and the harmonic instabilities can be identified by a frequency scanning technique. In this technique, a current source is used to inject a spectrum of frequency components into an operating dc system and the resulting harmonic voltages are observed. This method is readily extendable to any network size, and also includes the response of the control systems. The method is demonstrated on the First CIGRE HVDC Benchmark model [8] (Fig. 1) that was reported to have a second harmonic resonance on the ac side. Our analysis shows that it is resonant at a higher frequency and hence does not demonstrate instability. We were able to shift the resonance of the model by making modifications to the ac equivalent circuit and were able to demonstrate core saturation type instability.

II. DIGITAL SIMULATION

Historically, many power system problems have been studied with power–flow and transient stability computer programs. But those programs prove inadequate in dealing with the interaction problems such as harmonic instability. To achieve this, simulation with electromagnetic transients programs (EMTP–type programs) must be used. The ac and dc side impedances are represented by actual R, L, C and transformer models which are accurate to frequencies in the 1–2 kHz region. Also, the thyristors of the converter can be modelled as actual switches. Any other non–linearities can also be more accurately included.

One significant disadvantage of EMTP–type programs is that they work with finite time–steps. For HVdc control and

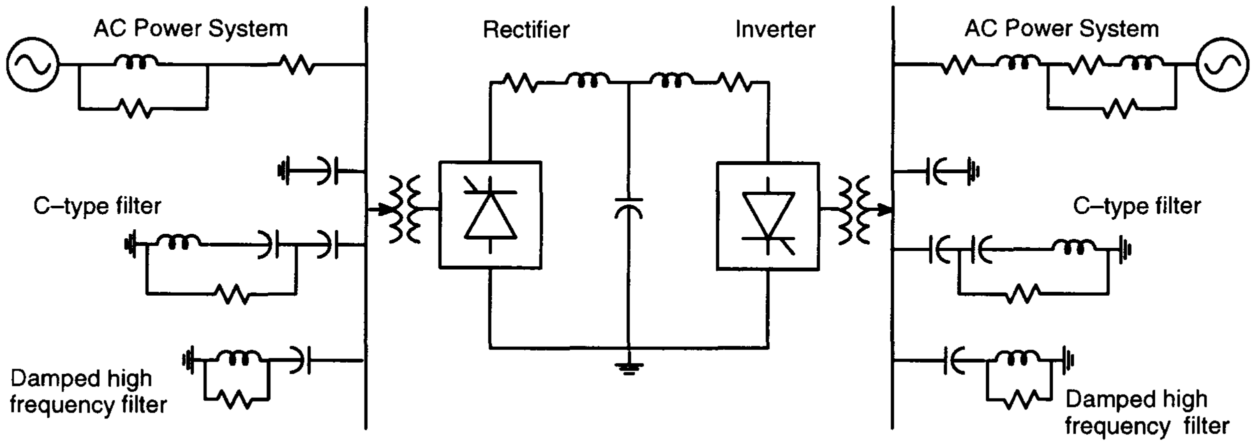


Figure 1. CIGRE Benchmark Model

system fault studies a time–step of 50 μs is customarily chosen. This time–step is slightly more than 1° for a 60 Hz waveform. This finite time–step approach is however problematic for our study here, because the 1° firing angle jitter can result in non – characteristic harmonic generation which interferes with our frequency scan. This difficulty is eliminated if the switchings (on and off) of the thyristors is interpolated to within a fraction of a time–step. We therefore chose to use an EMTP–type program capable of such interpolation (such as PSCAD/EMTDC or NETOMAC)

III. THE STUDY SYSTEM

The CIGRE benchmark model[8] is selected as an example system for the studies. The system shown in Fig. 1 represents a 12–pulse 500 kV HVdc link rated at 1000 MW. The control system is similar to that described in [10]. The firing control system is a dqo type phase looked loop based equidistant scheme as described in [11].

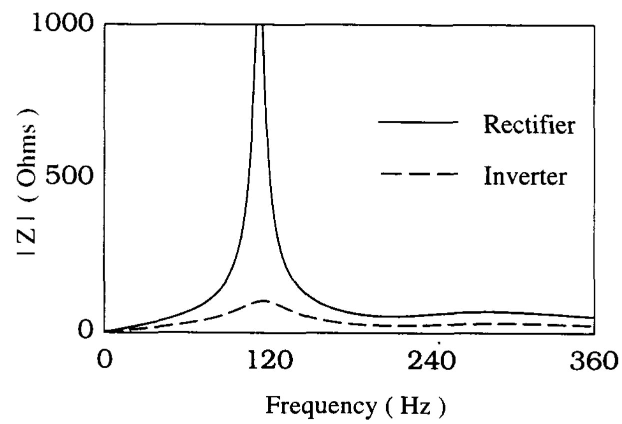


Figure 2. The Total AC System Impedance / Frequency

The total system impedance versus frequency plots for the ac systems in isolation, as viewed from the terminal buses are shown in Fig. 2. It shows the presence of a high parallel resonance at 120 Hz at the sending and receiving ends. The dc side impedance/frequency plot, as viewed from the converters, is shown in Fig. 3. There is a series resonance around 60 Hz which is the complementary frequency of the ac side resonance frequency. A possibility of harmonic instability is thus expected for this model. However, even with the damping considerably reduced from its specified value in the benchmark, the model is remarkably stable.

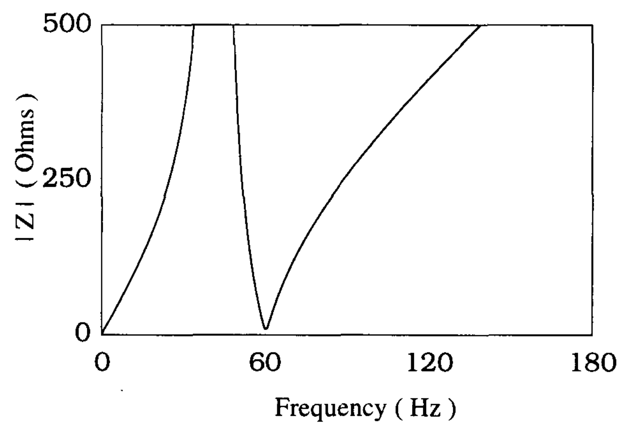


Figure 3. The DC Side Impedance / Frequency

IV. FREQUENCY SCANNING METHOD

The system impedance responses calculated above have not considered the connection between ac and dc sides. Under this condition, the dc system is considered as an ideal current source feeding into the ac system. Therefore, the dc system has no effect on the ac system. However, in the actual system the impedance might be affected by the dc system especially if the ac system is weak.

Using simulation it is possible to identify the presence of a potential instability in the combined ac/dc system more accurately compared to the previous methods [7]. With the system in the steady state, a small current with a wide range of frequencies is injected into the ac bus as in Fig. 4, where the ac system impedance is defined. The system impedance can be calculated by measuring the ac bus harmonic voltage $\mathbf{V_h}$ in response to the injected harmonic current $\mathbf{I_h}$.

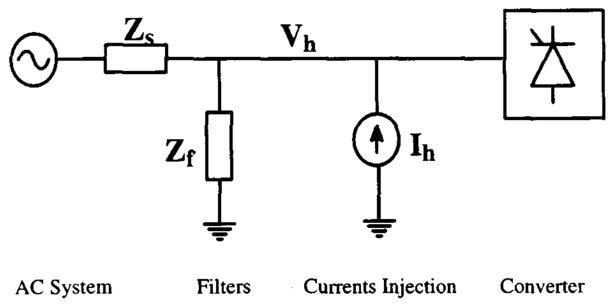


Figure 4. Frequency Scanning method for System Impedance

The dc system behavior is nonlinear. Strictly speaking the superposition principle which is true only for a linear system does not apply. But if the disturbance caused by the injected harmonic is small enough, the dc operation can be considered as nearly linear around the operating point. This can be checked by monitoring the firing angle of the HVdc converter. Normally, if the oscillation in firing angle cause by injected harmonics is less than half degree (0.5°), the Frequency Scanning Method is considered valid. Another check on the method is that it should not give a significantly different result for the impedance scan when the magnitude of the injection is reduced. Of course, if the magnitude is reduced too much, the measurements get buried in background noise. Thus a compromise must be made– the signal should be small so as to satisfy the superposition principle, but as large as possible so that one has a sufficiently strong signal to work with.

One method of generating the injected signal is to add sinewaves of a sequence of frequencies as shown in Eq. 1. However, the time domain plot for this signal is shown in Fig. 5a and shows a train of large spikes with a period equal to the lowest frequency. The signal is impulse–like: it is almost zero everywhere and takes on very large values at certain times.

$$I_h = \sum_{n=0}^{120} A \sin\ (2\pi f_n\ t\ ) \qquad \dots\ (\ 1\ )$$

where $f_i = 80 + n$ (Hz)
(as we are only interested in frequencies between 80 Hz to 200 Hz)

The large spike can cause interference with the steady state behavior of the model and thus negate the small–signal requirement mentioned above. It is possible to package the same harmonic amplitudes for each frequency in a manner that does not cause such a constructive interference. One way is to stagger the phase of each harmonic signal by a different amount. For example, we use the quadratic phase shift for each frequency component as shown in Eq. 2 (a linear phase shift gives a similar spiked response as the signal in Eq. 1). This results in a time–domain waveform as shown in Fig. 5b. The energy in the signal is now spread out and not bunched into large spikes. The signal of Eq. 2 does not interfere with the steady state operation of the model as much as the earlier signal. It is thus possible to use much larger amplitudes of the individual harmonic components.

$$I_h = \sum_{n=0}^{120} A \sin\ (2\pi f_n\ t + \frac{\pi}{180} n^2\ ) \qquad \dots\ (\ 2\ )$$

A. Frequency Scanning of CIGRE System

The actual system impedance response of the CIGRE system was obtained by the frequency scanning method described above. In steady state, a series of small harmonic currents (i.e. 80 Hz, 81 Hz, ... 200 Hz at the magnitude of 2 Amps, or less than 0.1% of the fundamental current in ac source) are injected into the rectifier ac bus in the manner described above. The rectifier resonance is the major cause of sustained oscillation in the CIGRE system, since the 2nd harmonic resonant impedance on the rectifier ac bus is much higher than that on the inverter ac bus (Fig. 2). Therefore, the scan is applied on the rectifier ac bus.

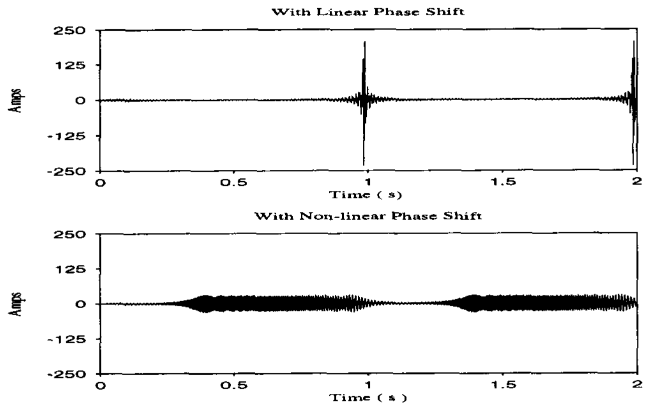


Figure 5. Effect of Phase Shift between Harmonics in the Total Injected Current

The frequency spectrum of the ac bus voltage contains harmonic components from 80 Hz to 200 Hz in response to the injected harmonic currents. Note that the distortion in the ac bus voltage is very small (< 0.2%) and guarantees the assumption of a small disturbance that does not significantly change the operation of the dc system.

The rectifier ac impedance can be easily obtained by calculating the ratio of ac bus voltage to the injected harmonic current (known, 2 Amps) at each frequency. The measured rectifier ac impedance/frequency characteristics obtained by the frequency scanning method is shown in Fig. 6. The results are plotted together with the calculated frequency responses using the simplified formulation presented earlier (Fig. 2) for comparison.

Comparing the spectra from the simplified calculation and scanning method from 80 Hz to 200 Hz in Fig 6, there are some major differences between the simplified analysis method and frequency scanning method. Note that the resonant frequency measured by the frequency scanning method is shifted to a higher frequency (about 140 Hz instead of 120 Hz). In the simplified analysis, the dc system is assumed to be a current source with infinite impedance. As in the frequency scanning method, the high (not infinite) equivalent impedance of the dc system is reflected in the simulation result. This causes the shift of the resonance peak. Also, the dc system provides some damping to the harmonics which results in the considerably lower resonant impedance magnitude measured by the frequency scanning method.

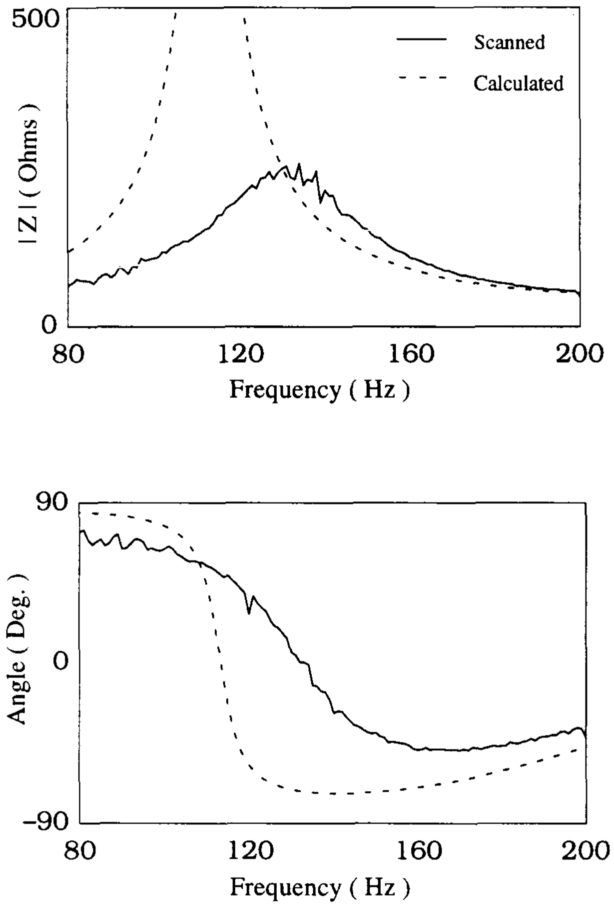


Figure 6. AC System Impedance / Frequency Characteristic

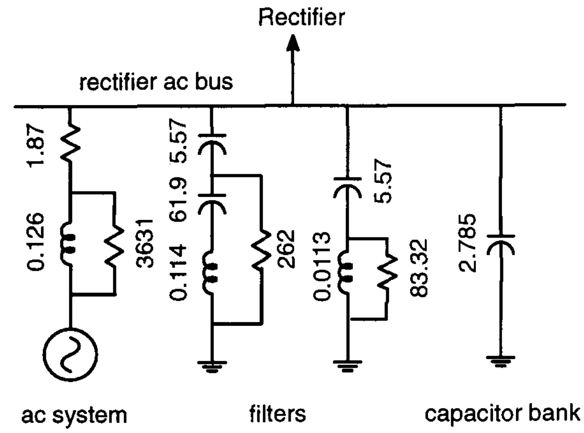
We thus conclude that simplified analysis is sometimes grossly approximate. This is because the ac and dc systems are inherently coupled and it is not always correct to consider individual resonances on each side. Thus a 2nd harmonic resonance may be calculated at the ac side by considering only the system and filters, but in reality the resonance may be at a different frequency.

V. SIMULATION RESULTS

The results in this paper are obtained from computer simulation using the time domain electromagnetic transients simulation program PSCAD/EMTDC [9].

A. The CIGRE System

First, the CIGRE system in Fig. 1 is simulated with the damping reduced considerably in order to excite harmonic instability. The rectifier ac filter configuration is as in Fig. 7. There is no harmonic injection present as in the frequency scanning approach.



All resistances in Ω, inductances in H and capacitances in μF

Figure 7. Rectifier AC Filter Configuration of the Benchmark System

Shown in Fig. 8 is the rectifier dc current during the start–up and steady state for the benchmark system. An oscillation is evident in the dc current. From a Fourier analysis of waveforms (Fig. 9) we observe the presence of a 140 Hz component in the ac bus voltage and the presence of an 80 Hz oscillation (140 Hz – 60 Hz) in the dc current. This confirms the frequency scanning results presented earlier. which showed the 140 Hz resonance condition.

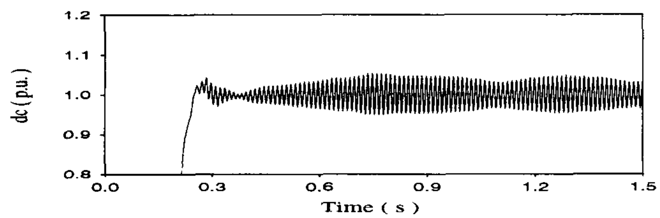


Figure 8. Rectifier DC Current during the Start–up and Steady State of the CIGRE System

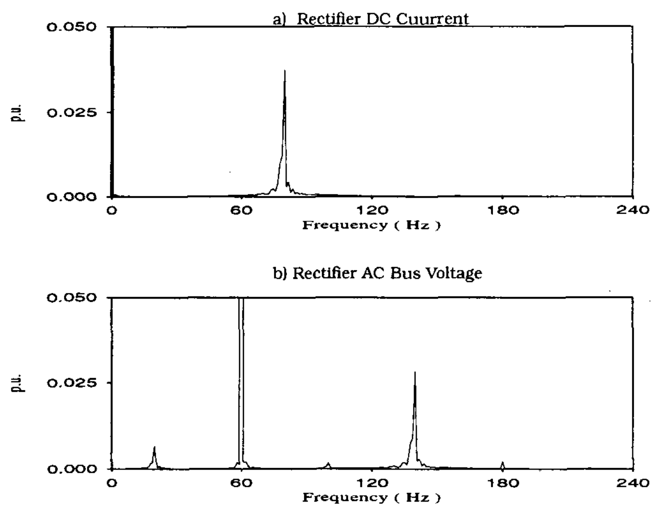


Figure 9. Fourier Analysis of the Waveforms

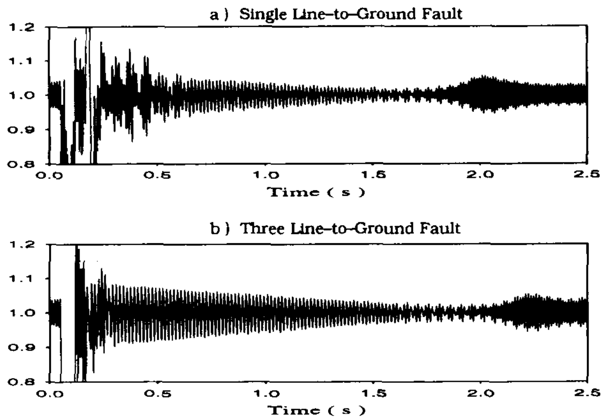


Figure 10. Rectifier DC Current during the Fault Recovery of the CIGRE System

From the steady state, a single line–to–ground 3.5 cycles fault is applied on phase A of the rectifier ac bus at 0.05 seconds. The following facts can be observed from Fig. 10a: During system recovery, the dc current has a 60 Hz oscillation which decays gradually. After about 2 seconds, the 60 Hz oscillation in dc current dies out and the 80 Hz oscillation (the pre–fault oscillation) returns.

Fig. 11 shows the Fourier analysis of the rectifier dc current at time=0.25 seconds (immediately after fault clearance) and time=1 seconds (during fault recovery). After fault clearance, the transformer saturates and injects all the integer uncharacteristic harmonics (2nd, 3rd, ...) into the ac system, which die out gradually. The harmonic currents are modulated onto the dc side as the 1st, 2nd, ... harmonics, which also die out gradually as seen by comparing the spectra at 0.25 s and 1.0 s respectively.

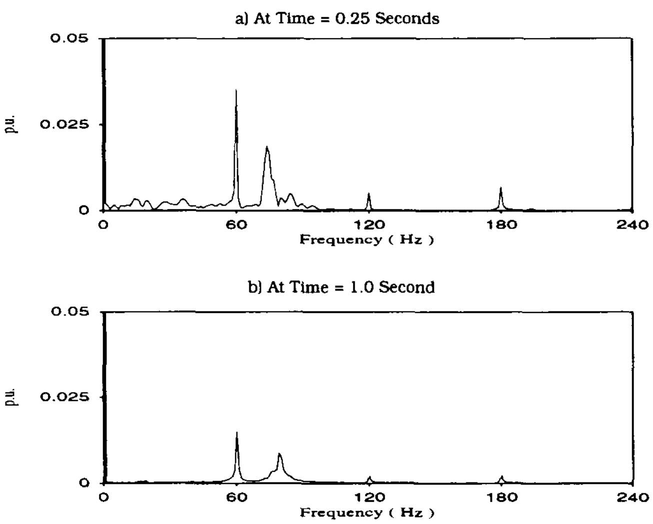


Figure 11. Fourier Analysis of DC Current During Fault Recovery

Similar phenomena are observed for the three line–to–ground fault at the ac rectifier bus (Fig. 10b). The post–fault 120 Hz voltage component on the ac side and the 60 Hz current component on the dc side persist for about one second (after which the original 140/80 Hz oscillations return). This is due to the fact that although there is no 120 Hz resonance in the basic CIGRE model, the 120 Hz impedance is still high. However we are not able to simulate a sustained 2nd harmonic oscillation.

VI. MODIFICATIONS TO THE CIGRE MODEL

As shown by frequency scanning, the true resonance of the CIGRE benchmark is at 140 Hz and not at 120 Hz on the ac side. We can tune the resonant frequency to 120 Hz if an SCR=1.8 (instead of the original 2.5) is used for the ac source at the sending end. This corresponds to an ESCR = 1.18 (originally 1.88) The system frequency characteristic obtained by the frequency scanning method is shown in Fig. 12.

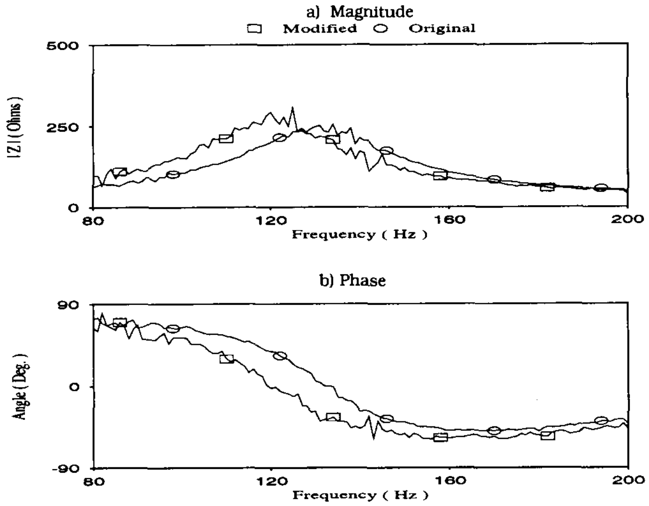


Figure 12. AC System Frequency Characteristic with the Changed SCR=1.8

With lower SCR, the ac resonance is shifted to 120 Hz. This is the real resonant frequency in the HVdc system including the effect from converter. The original impedance frequency response plot is shown alongside for comparison. Note also that the phase of the impedance now passes through 0^{o} at f=120 Hz, as expected from a true resonance.

System start–up and steady state operation in Fig. 13 shows that the system still experiences the steady oscillation similarly as that in the CIGRE system. However, the Fourier analysis results depicted in Fig. 14 show that it moves closer in frequency to 60 Hz (It is precisely 67 Hz). There is a corresponding 127 Hz frequency component in the ac voltages. We can thus see that the the oscillation frequencies have moved closer to the values predicted by the scan.

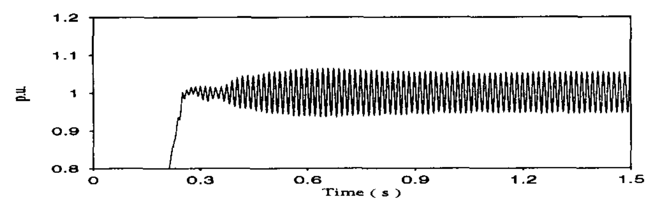


Figure 13. Rectifier DC Current during the Start–up and Steady State of the System with SCR=1.8

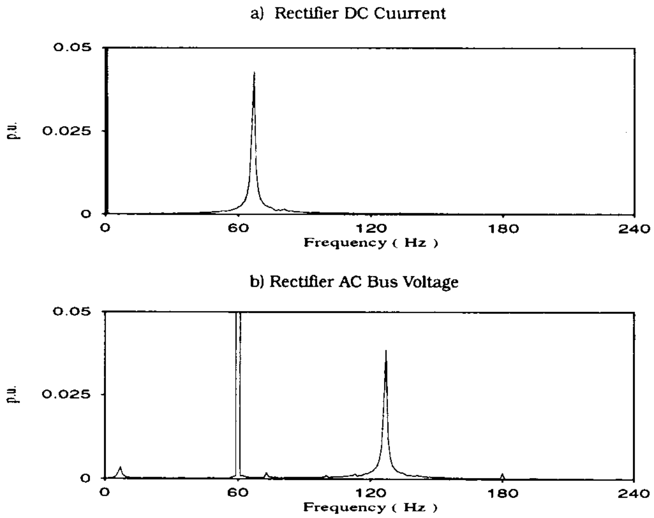


Figure 14. Fourier Analysis of the Waveforms during Steady State

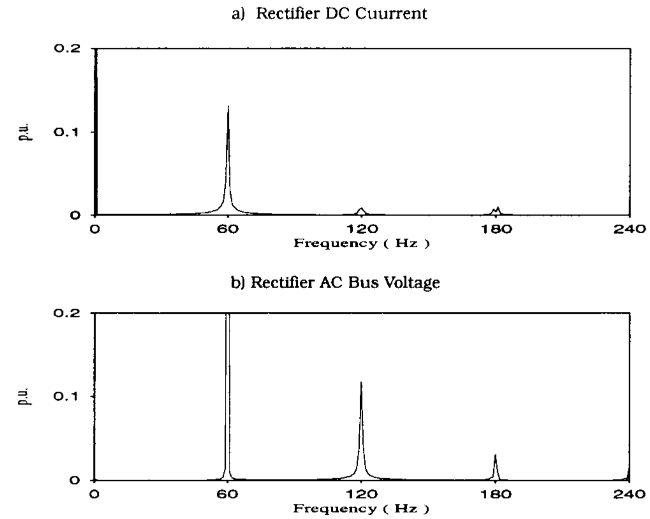


Figure 16. Fourier Analysis of the Waveforms during Fault Recovery

From the steady state, a single line–to–ground 3.5 cycles fault is applied on phase A of the rectifier ac bus at 0.05 seconds. The following facts can be observed form Fig. 15a: During system recovery, the dc current has a 60 Hz oscillation which does not decay. Similar phenomena are observed for the three line–to–ground fault at the ac rectifier bus.

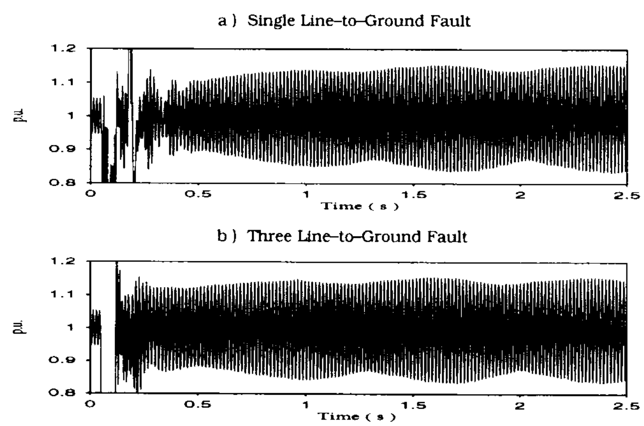


Figure 15. Rectifier DC Current during the Fault Recovery in the System with SCR=1.8

The Fourier analyses of the waveforms are shown in Fig. 16. After fault clearance, the transformer saturates. It injects all the integer uncharacteristic harmonics (2nd, 3rd, ...) into ac system and results a high 2nd harmonic voltage on ac bus (Fig. 16b). The saturation of the transformer presents a further source of second harmonic currents which helps to sustain the resonance. This is therefor a true simulation of core saturation instability. The frequency scanning method allows us to investigate the true resonance frequencies and thus experimentally tune the system to the desired characteristic.

Another manner in which the network can be modified to shift the resonance to 120 Hz on the ac side is to change the admittance on the filter bus. This allows us to maintain the same SCR level (although the ESCR changes to 1.73 from 1.88) as the system thevenin equivalent impedance is unchanged. Fig. 17 shows a plot of a frequency scan with the admittance increased by a factor of 24 % . As can be seen the same resonance frequency is again shifted to 120 Hz. Fig. 18 shows the simulation results following ac side faults. The core saturation instability does decay in this case, probably because of the marginally lower impedance magnitude. However the steady state 127/67 Hz instability returns in the steady state indicating poor damping in the vicinity of 120 Hz.

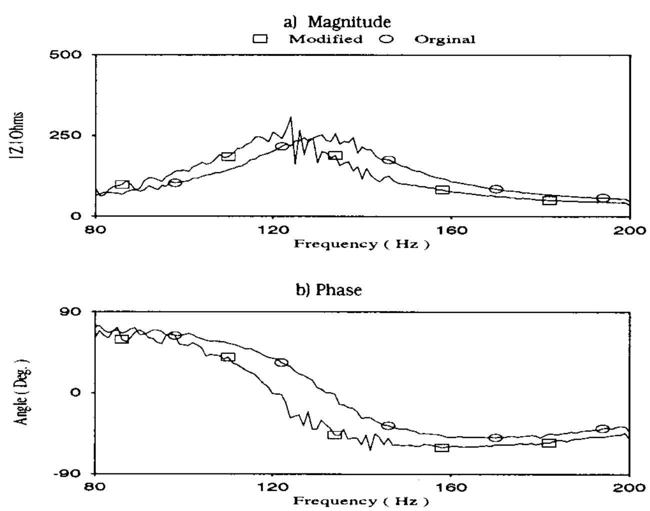


Figure 17. AC System Frequency Characteristic with the Changed Filter Admittance

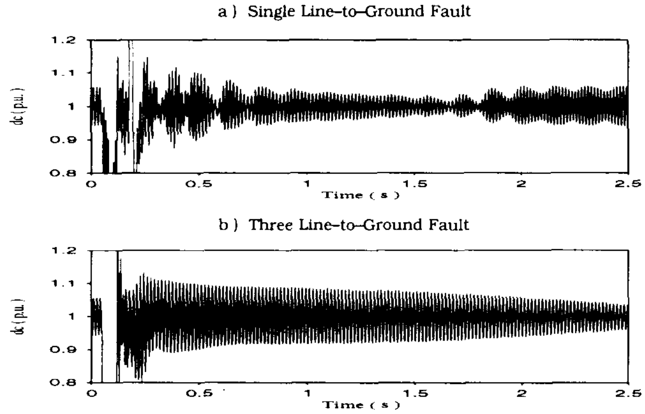


Figure 18. Rectifier DC Current during the Fault Recovery in the System with the Changed Filter Admittance

VII. CONCLUSIONS

The frequency scanning method has been shown to yield a more accurate picture of the resonance conditions in an ac–dc system. The results can be significantly different from those predicted with a simplified analysis.

The method of generating the injected current signal by using a quadratic phase shift between frequency components allows for larger harmonic amplitudes (for a more accurate measurement) without disturbing the steady state operation of the system.

The characteristic of the CIGRE benchmark model can be modified so that it demonstrates core–saturation instability. The simulation results on the modified system confirm the accuracy of the Frequency Scanning Method.

VIII. ACKNOWLEDGMENT

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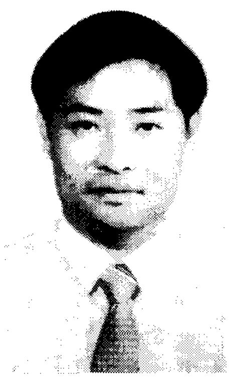
X. BIOGRAPHIES



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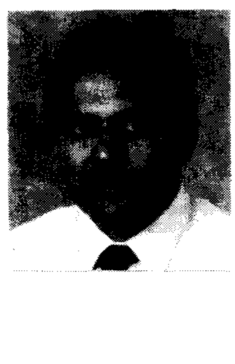

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