A STUDY ON SOLUTION AGAINST CORE SATURATION INSTABILITY AT AN HVDC CONVERTER

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Abstract - The paper identifies a severe form of core saturation instability in an DC/AC interaction system. It then seeks solutions to the problem by HVDC control means. This is achieved by a proper design of the Voltage Dependent Current Order Limiter (VDCOL), the Current Regulator and Timing Pulse generator. Supplementary control loops have also been introduced to result in a satisfactory performance as compared to that obtained one with the use of uncharacteristic harmonic filter on the AC side. Robustness of all the options has been demonstrated through recovery performance of the DC link in response to both 1-phase and 3-phase 5 cycle faults on both rectifier and inverter commutating buses.

Key words : Core saturation instability, DC/AC interaction system, Voltage Dependent Current Order Limiter, Timing Pulse Generator, Firing Angle Modulation, Current Order Modulation.

I . INTRODUCTION

Over long distances bulk power transfer can be carried out by HVDC connection cheaper than by a long distance AC transmission line. Also, Bulk power of HVDC transmission scheme, as shown in Fig. 1., may be transmitted through very long cables or across borders where the two AC systems are not synchronized or operating at the same frequency.

Among this HVDC technology, one of the difficult technology is the low order harmonic resonance, associated with an HVDC system.

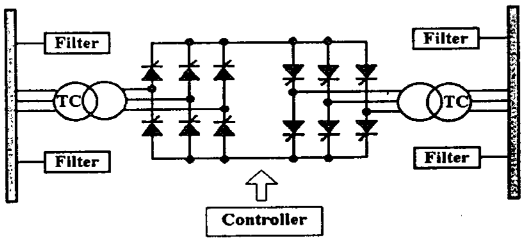


Fig. 1 HVDC system scheme

The phenomenon of HVDC converter transformer core saturation instability has been known for some time. It is characterized by extremely slow growth, and owing to the difficulty of its prediction, it is usually discovered during or after project commissioning.

Spontaneous appearance of core saturation instability is relatively rare. More typically the instability is initiated by ac system faults or switching operations such as transformer energization. However, systems which are susceptible to core saturation interaction demonstrate poor damping for 'steady-state' excitation at the interaction frequencies involved.

An HVDC converter acts as a source of harmonic currents of the AC side and harmonic voltages on the DC side. As the DC power transmission rating increases, the harmonics (both characteristic and uncharacteristic) generated by an link also increase in magnitude. Use of tuned filters for the low order characteristic harmonics and high pass(HP) damped filters for higher harmonics is a normal design practice. Uncharacteristic harmonics injected into poorly damped resonant networks can then become a difficult operating condition for then HVDC/AC system. This low order harmonic resonance can get more severe if there is a DC side series resonance at the complementary frequency of resonance in the AC side. Simulation of 'steady-state' core saturation instability or interaction is difficult in a traditional digital transients environment because of the long time constants involved in saturating the converter transformers and the relatively low levels of DC exciting currents in the valve windings of the converter transformers. This paper investigates the. the usefulness of HVDC control modifications for a configuration which suffers from a severe form of low order harmonic resonance problem due to Core saturation instability phenomenon. Also, it presents some new control modifications which make the use of uncharacteristic harmonic filters redundant. The investigation is performed by the time domain digital simulation using the EMTDC program.

Ⅱ. REVIEW FOR CORE SATURATION INSTABILITY

A very complex nonlinear interaction called core-saturation instability can disrupt HVDC performance [10.17]. This closed-loop interaction involves the ac and HVDC system resonances, transformer saturation converters, and the converter control and it is most likely to occur in a system with second-harmonic ac impedance resonance and fundamental DC admittance resonance.

This interaction, in simple terms, is described by the following: Consider that a minor disturbance has resulted in a small amount of converter transformer core flux offset. This offset causes second-harmonic current to be injected into the ac system. The resulting second-harmonic ac voltage distortion appears as fundamental on the DC side. The fundamental DC ripple is translated by the converter into second harmonic and DC currents. The DC currents can add to the core saturation, and the interaction may grow if the loop gain and phase shifts are sufficient. The HVDC control can respond to the current ripple in such a manner that a small amount of negative damping occurs. Thus, the interaction can grow in magnitude with potentially damaging or disruptive results.

To determine the converter transformer core saturation harmonic contribution, first the effect of a direct current on the transformer magnetization current is examined. It is best to consider the direct current on the transformer secondary and the magnetization current on the transformer primary.

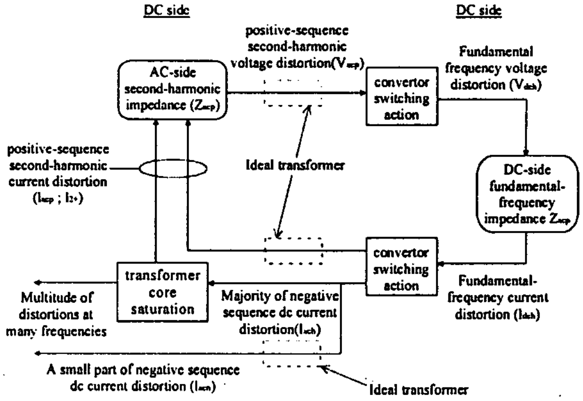


Fig. 2. Mechanism of instability

The mechanism of the phenomenon can be easily explained using the block diagram of Fig. 2. If a small-level positive sequence second-harmonic voltage distortion exists on the AC side of the converter, a fundamental frequency distortion will appear on the DC side. Through the DC side impedance a fundamental frequency current will flow resulting in a positive sequence second-harmonic current and a direct current flowing on the AC side. The direct current flowing on the AC side will begin to saturate the converter transformer, resulting in a multitude of harmonic currents being generated, including the positive sequence second-harmonic current. Associated with this current will be an additional contribution to the positive sequence second harmonic voltage distortion and in this way the feedback loop is completed. The stability of the system in determined by the characteristics of this feedback loop.

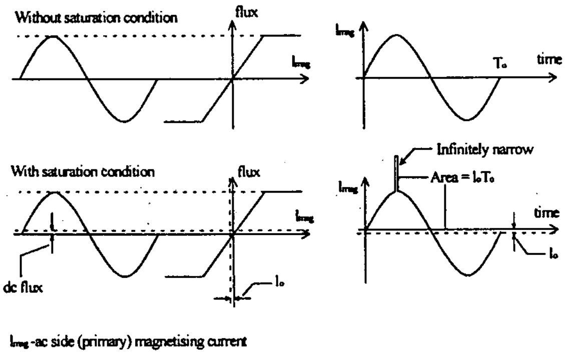


Fig. 3. Transformer saturation

Under the worst-case conditions, the transformer magnetization AC flux is assumed to be reaching the limits of the non-saturated part of its magnetization characteristics as shown in Fig. 3.

Under such conditions, even a small DC bias will force an asymmetrical magnetization current and cause transformer saturation to occur in one half of the fundamental cycle.

Converter generate harmonic voltages on DC side and harmonics currents on AC side. A converter of pulse number p generates harmonics principally of order $n = pq$ (q is integer) on the DC side and $n = pq \pm 1$ on the AC side. A harmonics consist of characteristic harmonics and non-characteristics harmonics. Characteristic harmonics are harmonics of n orders and non-characteristics harmonics are harmonics of other orders. Non-characteristic harmonics are never generated on the ideal converter system. But if the three-phase AC voltages are unbalanced, non-characteristic harmonics are generated on the converter system. In converter system with a harmonics, some of the undesirable effects may occur the same as overheating of capacitors and generators, instability of the converter control, and interference with telecommunication systems. In particular, harmonic instability can lead to the system collapse. The explanation of harmonic instability is below:

Fig. 4 shows a equivalent circuit for a harmonic. In Fig. 4, E_{st} is the voltage source, E_n is harmonic e.m.f, n is harmonic order and Z_n is harmonic impedance. The harmonic voltage V_n on the converter AC busbar depends on impedance Z_n and its phase angle ϕ_{sn}, harmonic order n, firing angle α, and relative phase θ of interfering e.m.f. The harmonics magnification due to converter operation is $M = V_n / E_n$. For high Z_n, high magnification can occur. This case is called "harmonic instability". To solve this problems, the following methods is researched.

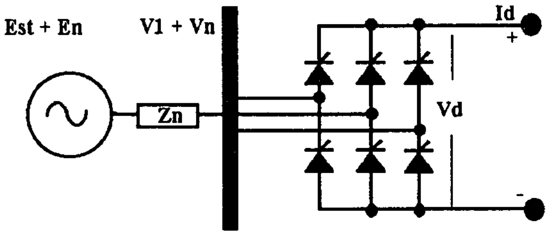


Fig. 4. Equivalent circuit for a harmonic

A. Tuned filter installation method on AC side
B. VDCOL changing method
C. Optimizing method of the current regulator
D. Firing angle modulation method
E. Current order modulation method

A. Tuned Filter Installation on AC Side

HVDC converter acts, from the AC point of view, as a source of harmonic currents, and from DC point of view, as a source of harmonic voltage. one of the methods to solve this problem is the use of a filter, as shown in Fig. 5.

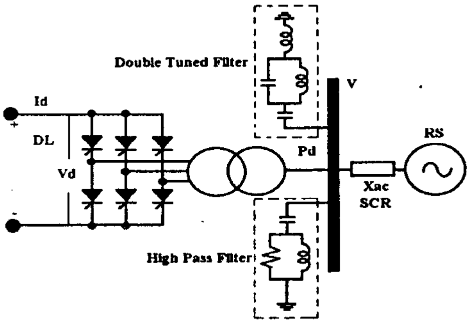


Fig. 5. Tuned filter installation method on AC side.

But a filter installation method has not ability to remove unexpected non-characteristics harmonics. And the installation of additional filters for unexpected non-characteristics harmonics is not economics. Because of the complexity and costs of filters there have been several methods to achieve harmonics control by other means as followings:

- Magnetic flux compensation
- harmonic injection

Fig. 6. shows the magnetic flux compensation method. A magnetic flux compensation method is illustrated in Fig. 6. A current sensor is used to detect the harmonic components coming from the non-linear load. these are fed, through an amplifier, into the tertiary winding of a transformer in such a manner as to cause cancellation of the harmonic currents concerned.

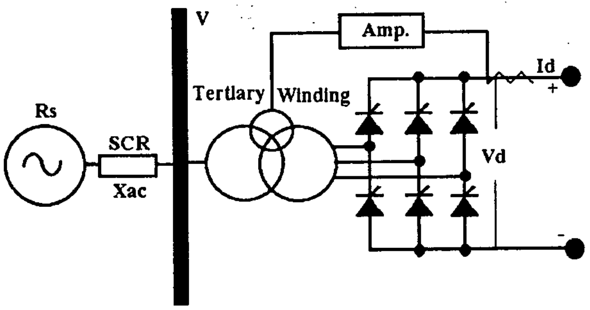
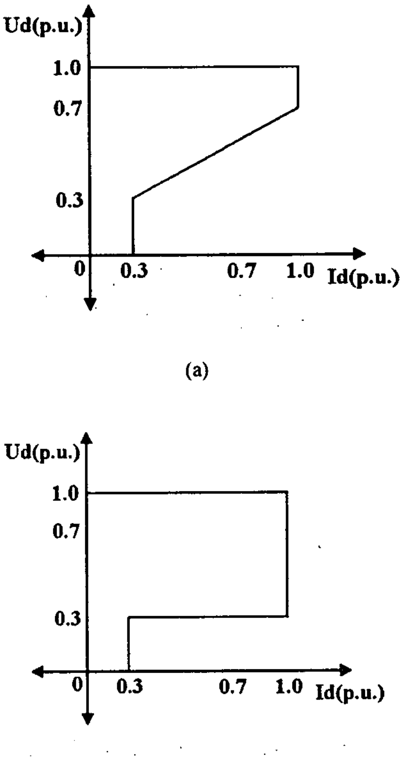


Fig. 6. Magnetic flux compensation

A harmonic injection method is to modify the converter rectangular current waveform by adding a harmonic current from an external source. This methods have disadvantages view point of costs and performance.

B. Change in Voltage Dependent Current Order Limiter(VDCOL)

The need of VDCOL is for the implementation to control not only DC current to be contained when the DC voltage falls but th current to be reduced. In Fig. 7(a); VDCOL is found useful only where the AC systems on both rectifier and inverter can support fast recoveries or delayed power reductions after a severe fault. But, in weak AC systems with poor damping offered by the loads, it is much better to control the current for recovering AC system with a suitable ramp rate(with time constant) as shown in Fig. 7(b). VDCOL with time constant, as shown in Fig. 7(b), is chosen after investigation of operation through a range of disturbances, particularly those involving faults or low voltages. VDCOL shown in Fig. 7(b) has improved control characteristics for all types faults.



(a)

(b)

Fig. 7. Voltage Dependent Current Order Limiter(VDCOL) Characteristics

C. Optimizing the current regulator

In harmonic resonance problem, one can optimize the current regulator by reducing the control gain offered to problematic frequencies, while still maintaining a sufficiently fast dynamic response from the regulator. Fig. 8 shows the current regulator block diagram of HVDC system. But Improvement of this kind is not good enough to guarantee recovery from all faults.

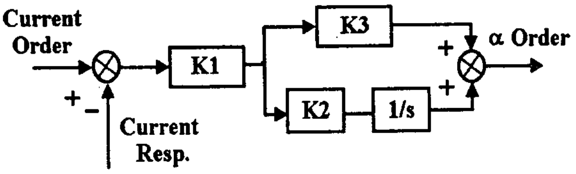


Fig. 8. Current Regulator Block Diagram

D. Firing angle modulation method

In the presence of unbalance caused by distortion from the ac system, or ac currents arriving on the DC line, or small unbalances within the converter station (e.g commutation reactance unbalances), converter tend to operate in an unbalanced manner. The solution is to modulate firing angles (via the common 12-pulse oscillator) in a closed-loop manner to equalise the 12 γ s. The fast main loop still remains to control absolute γ by using γ -balance, 3rd harmonic balance, α -balance method (by GEC Alstom). The DC components in the converter transformer windings can simultaneously eliminate all DC components on the ac side by using Firing Angle Modulation method for Elimination Transformer DC current (by A.M.. Gole).

The firing scheme in an HVDC system correspond to the firing of valves at an interval of T/12 seconds for a 12 pulse converter. It is therefore possible for the current regulator to over correct for changes in the DC current for certain combinations of AC/DC configuration. For stable operation of the DC link, it is therefore necessary to reduce the response of the current regulator for undesirable harmonics in the DC current. This can be achieved efficiently by subtracting from the firing angle and proportional to the harmonic content in the DC current. This correction has no effect on the current regulator operation or the DC quantities. Fig.10 is the block diagram of a filter circuit which is a combination of a low pass and a band pass filter. This type of characteristics is desirable to extract mainly the magnitude of frequencies in the band between 3rd and 5th harmonies. This ensures that the correction is not delayed beyond the firing of one valve in a twelve pulse configuration.

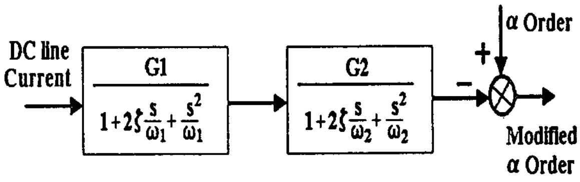


Fig. 9. Block diagram of firing angle modulation scheme

E. Current order modulation method

Just as modulating the firing angle order improves the performance of the test case, it is possible to achieve similar results by modulating the current order. This method also extracts the information for the harmonics in the band from the 3rd and 5th and subtracts it from the error between current order and current response. The filter circuit used is as shown in Fig. 12. Because of the integrating characteristic of the current regulator, the parametric values in this cast are more critical than in the firing angle modulation control. For best results the cancellation of current harmonics between the 3rd and 5th should be exact.

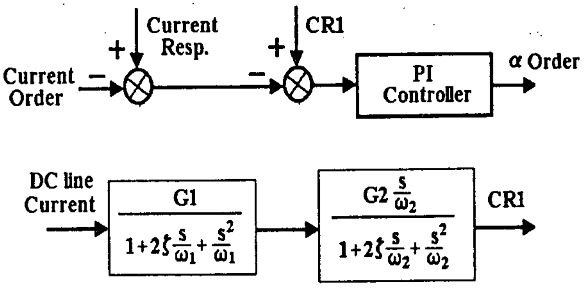


Fig. 10 Block Diagram of Current Order Modulation Scheme

Ⅲ. HVDC CONTROLLER DESIGN USING MODIFIED PI CONTROLLER

In conventional control system, the characteristics of a system PI controller have to have following function :

if error is large then K_p is large
if error is small then K_p is small
if error is large then K_I is small
if error is small then K_I is large

where, K_p is the proportional gain and K_I is the integral gain.

Since the above equations are a non-linear function, in this paper, Fuzzy controller was used to implement the above control function by using conventional PI controller. Fuzzy controller can be made by an exponential function or a triangle function; an exponential function is based on linear membership function, otherwise a triangle function is based on crisp function. This fuzzy functions have a different advantages each other, an exponential function is can be implemented easily on digital condition or analogue condition.

Using membership functions, the gains of the controller are determined.

$$\begin{aligned} K_p &= \frac{w_1 * K_{p1} + w_2 * K_{p2}}{w_1 + w_2} \\ &= \frac{w_1 * f_1^{-1}(w_1) + w_2 * f_2^{-1}(w_2)}{w_1 + w_2} \\ &= F(w_1, w_2) \\ &= F`(error_1, error_2) \qquad (1) \end{aligned}$$

where, w_1 and are the membership, that w_2 is an exponential function.

Similarly, K_I can be determined. Finally, the gains of K_p and K_I are obtained.

$$\begin{aligned} K_p &= (K_{p1} - K_{p2} * e^{-K_{P3}|error|}) \\ K_I &= K_{I1} * e^{-K_{I2}*|error|} \qquad (2) \end{aligned}$$

The PI gains used in this paper can be arbitrarily determined as long as they are in the range of a stable region. However comparing to a conventional PI gain, this approach does not guarantee the desired system performance and HVDC system need some particular characteristics to prevent commutation failure and instability caused by AC network. Therefore, the selecting method of controller gains is as follow ;

1) Since K_{12} determine the system K_{P3} determine the system response, this gains correspond to the characteristics of VDCL response
2) Determine K_{P1}, K_{P2} and K_{P3} by classic method
3) In order to guarantee stability, select this condition $K_{P1} \phi K_{P2}$

Ⅳ. EMTDC SIMULATION

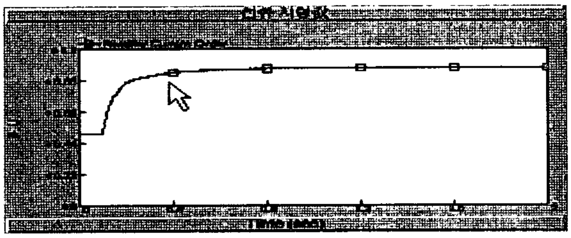
For the purpose of validating the proposed control method to eliminate core saturation instability, the modified CIGRE benchmark HVDC systems are set up on the transient simulation program PSCAD/EMTDC.

Modified system of CEGRE benchmark model
Frequency : 60Hz
Rectifier AC system : SCR = 11.5 @68.0 deg, 345.0 kV

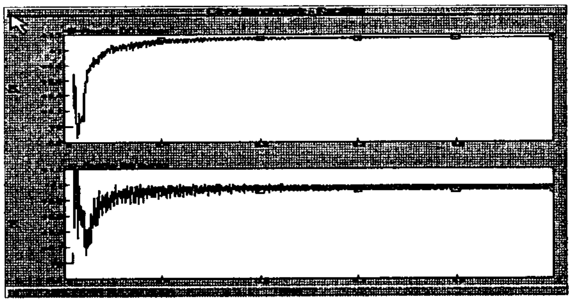
Transformer Characteristic
0.13 leakage reactance
0.2 air core reactance
1.25 knee voltage
0.2% magnetizing current

the converter-transformer magnetizing current are lowered, from 1% to 0.2%, to achieve a highly susceptible transformer.

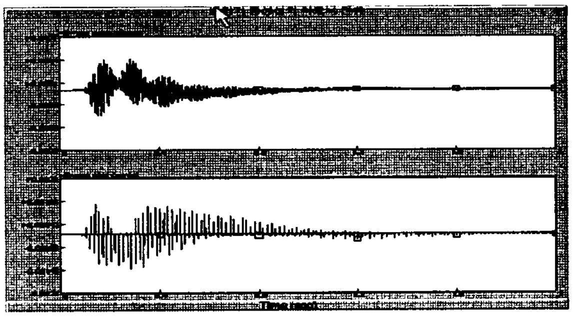
The transformer leakage reactance is also lowered, from 0.18p.u. to 0.13p.u. to further shorten the commutation period and hence reduce the amount of apparent damping on the system. First, the EMTDC simulation results in Fig. 12, Fig. 13 confirm the presence of core saturation instability according to VDCOL. Second, Fig. 14, Fig 15, Fig 16 and Fig. 17 show the effect of filter. The last, Fig 18 show that instability of system by a fault was diminished by robust controller.



(a) Current order value

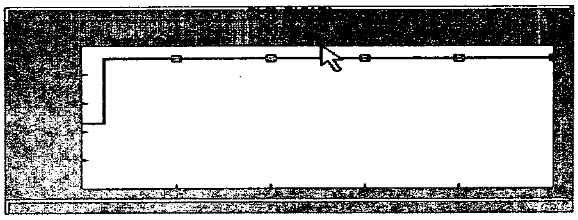


(b) DC voltage, current in Rectifier side

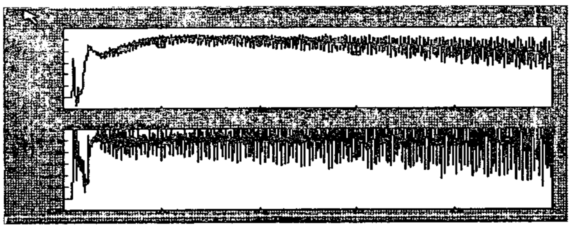


(c) C.Tr neutral line current

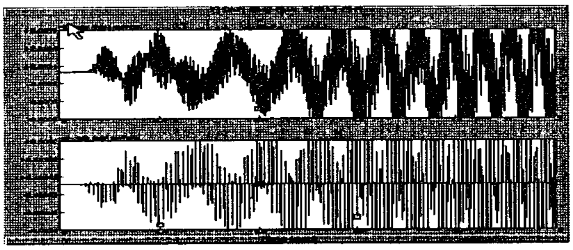
Fig. 12 Slow ramp current order value



(a) current order value

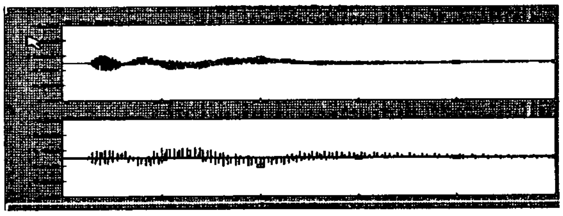


(b) DC voltage, current in Rectifier side

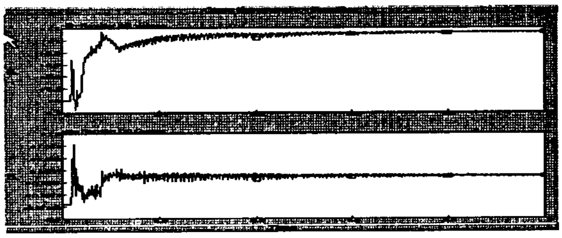


(c) C.Tr neutral line current

Fig. 13 Steep ramp current order value

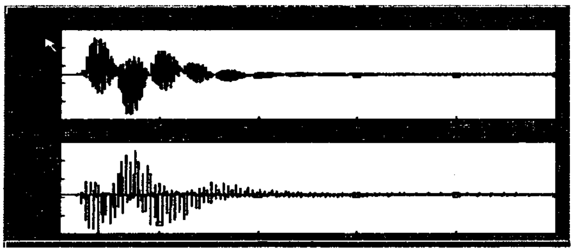


(a) C.Tr neutral line current

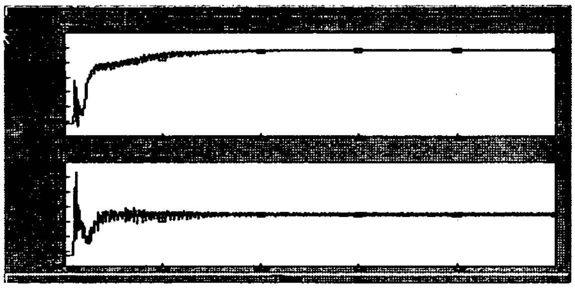


(b) DC voltage, current in Rectifier side

Fig. 14 60Hz component elimination (DC voltage) after Using filter

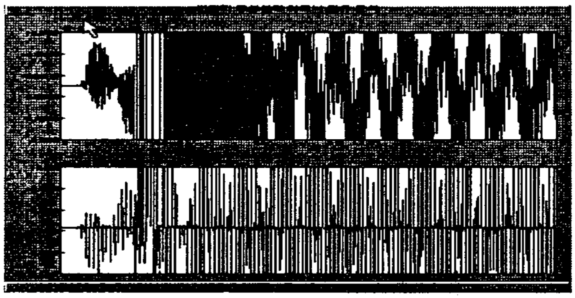


(a) C.Tr neutral line current

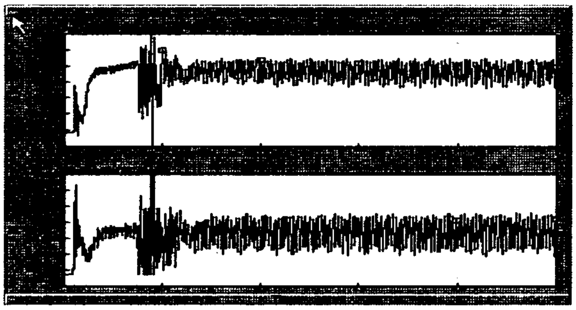


(b) DC voltage, current in Rectifier side

Fig.15 Steady State

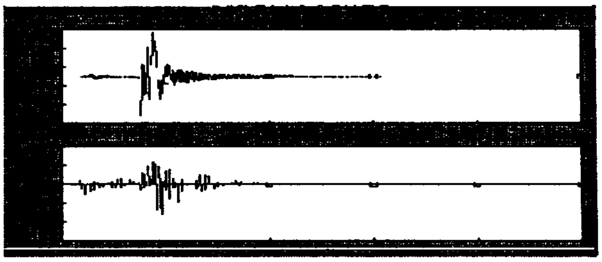


(a) C.Tr neutral line current

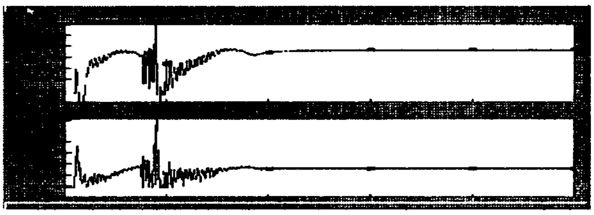


(b) DC voltage, current in Rectifier side

Fig. 16 At one phase fault



(a) C. Tr neutral line current

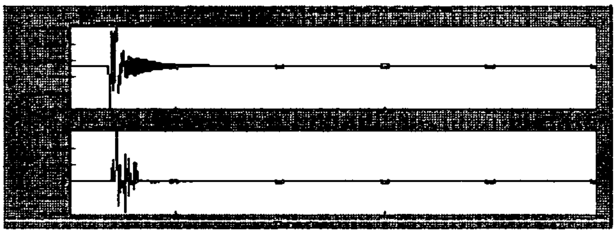


(b) DC voltage, current in Rectifier side

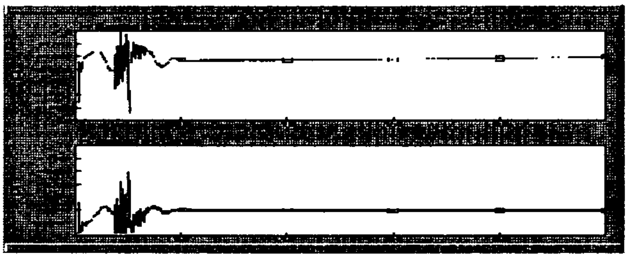
Fig. 17 60Hz component elimination (DC voltage) &

60 Hz component elimination (DC current)

after Using filter At one phase fault



(a) C. Tr neutral line current



(b) DC voltage, current in Rectifier side

Fig. 18 Replacing PI controller with robust controller at one phase fault

The EMTDC simulation results in Fig. 13, Fig. 16 confirm the presence of the spontaneous type of core saturation instability.

The EMTDC simulation described clearly depicts the case of core saturation instability. It not only confirms the 'grow-from-nothing' nature of this type of harmonic instability, but also shows that as the saturation develops the effect of the transformer will increase concurrently accelerating the development of the instability.

V. CONCLUSION

This paper has examined the mechanism of converter transformer core saturation instability and indicated the settlement of the problem.

A dc link can be operated according to the basic control modes and thus remain passive to any special needs of the interconnected ac systems. Alternatively the link can be provided with more dynamic controls, capable of responding to any deviation from the normal operating condition in the ac or dc systems. The exclusive use of the basic controls often gives rise to unwanted interaction between the ac and dc systems, which is manifested in a variety of voltage, harmonic and power instabilities. When full advantage is taken of the fast and adaptable converter controllability a more useful interaction can be achieved, which manifests itself in stable ac and dc system operation.

The degree of interaction obviously depends on the strengths of the ac and dc systems.

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