TRIPPING ANALYSIS OF GENERATOR NEGATIVE SEQUENCE RELAY DURING A TRANSFORMER ENERGIZATION

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ABSTRACT

An incorrect tripping of the negative sequence relay (46G) of group 3, of Governador Parigot de Souza (GPS) power plant of COPEL, during the power plant recomposition was analysed with simulations with the ATP, version 7.

The system recomposition step consisted in the energization with no load of the power transformer that had just been switched off.

Besides the modelling of the electric power system all the algorithm for obtaining the negative sequence rms current and also the equation to obtain the path of the transformer flux was modelled using MODELS. This simulation used the statistical switch to maximize the current. Several other routines of the ATP were also used, like BCTRAN to model the power and current transformers, HYSTDAT to model the histeresis characteristic of the power transformer and CABLE CONSTANTS to model the cables.

The conclusions of this work are that the negative sequence relays of the generators of this power plant are not fully effective and corrective measures are proposed. The main simulation and powerful features of the ATP are emphasized in this application.

1. INTRODUCTION

During the recomposition of Governador Parigot de Souza (GPS) power plant, after a disconnection caused by the failure of the earth protection of a 230 kV line circuit, for a phase-to-earth fault in this line, there was an incorrect operation of the negative sequence protection of group 3 (generator and transformer). This operation ocurred at the time of the energization of the 230 kV bus through the group breaker. The 230 kV bus was connected only to the TF-5 transformer which was with no load (with the breakers at the 138 kV and 13,8 kV sides opened). Figure 1 shows the configuration for this situation.

To analyze the operation of the protection 46G the ATP program - version 7 - was used and this allowed the simulation of this occurrence and the generator negative sequence current monitoring using the MODELS routine.

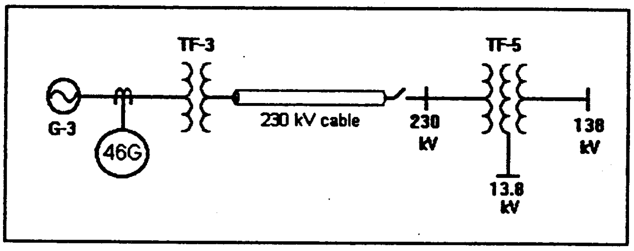

FIGURE 1. Power plant configuration when the tripping ocurred

2. MODELLING

The modelled system is show in Figure 1. The generator (68,6 MVA and 13.8 kV), was modelled by the complete machine model type 59. The integration step adopted was 11,11 μs. The modelling used for other equipment is described below.

2.1. 230 kV POWER CABLES

The power cable that connects the step-up transformer to the substation is about 1200 m long. This cable is of type OF produced by PIRELLI and its components are shown in Figure 2.

To model the cable and to obtain the resistence [R], the inductance [L] and the capacitance [C] matrices the routine CABLE CONSTANTES was used. The constructive details of the cable (like dimensions of the layers) were obtained from reference [2]. The data for the resistivity and relative permittivity of the conductor, of the shield, of the sheath and to the armour, as well as the data of the relative permeability and permittivity of the insulation layers were obtained from catalogs of PIRELLI, although some of them were estimated.

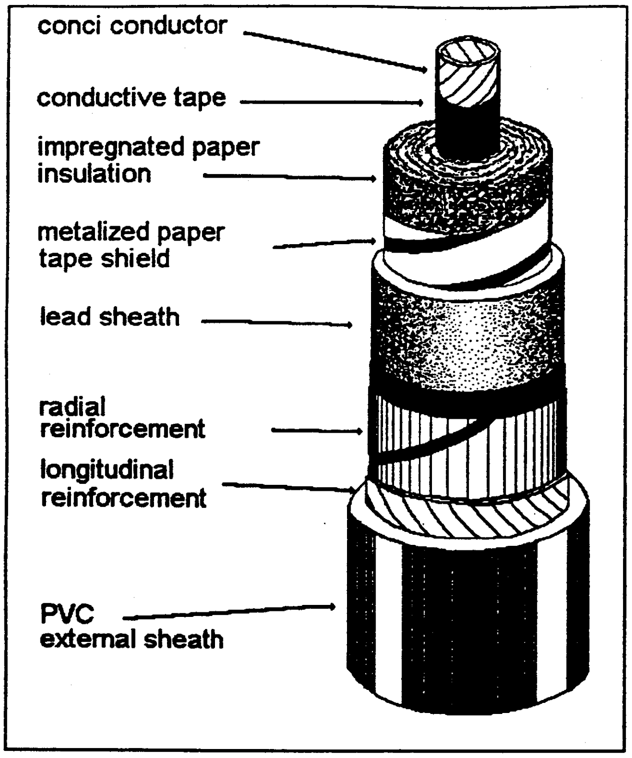

FIGURE 2. Pirelli 230 kV OF cable

The model of the cable considered the metalized paper tape, the lead sheath and the radial belt as shielding. This shielding was considered earthed in both sides of the cable.

2.2. TRANSFORMERS

The three phase transformers of core type, TF-3 (13.8/230 kV-70 MVA) and TF-5 (230/138/13.8 kV-67.5/67.5/29.5 MVA) were modelled with the suporting routine BCTRAN to obtain the matrices for resistence [R] and inductance [L] of the transformers. All data were obtained from the test report of the transformers except for the zero sequence excitation current that is not available in the test report from the factory. Since the transformer has a delta connection in the low voltage side the zero sequence excitation current representation is not critical. A good aproximation is obtained representing the zero sequence excitation current equal to the positive sequence excitation current(3).

2.3. TRANSFORMERS HYSTERESIS

The hysteresis characteristic of TF-3 and TF-5 transformers were modelled with the suporting routine HYSDAT based on the respective excitation curves. The hysteresis characteristic (Flux versus Current) of an inductor with silicon oriented cores, type ARMCO Mn, was obtained (3).

In order to visualize the flux density in the transformer TF-5 the flux expression shown below was modelled with MODELS:

$$\varphi(t) = \varphi(t-\Delta t) - \int_{t-\Delta t}^{t} \left[e_k(u) - e_m(u) \right] du$$

Using the trapezoidal integration rule the flux density path was ploted together with the histeretic curve of transformer TF-5.

2.4. CURRENT TRANSFORMERS

The current transformers were modelled in the same form as the power transformers: with the BCTRAN routine for the CT and with the HYSDAT for the histeresis characteristic. This models showed a very good precision when compared with laboratory tests made in a measuring CT with a 5/5 relation(4). Figure 3 shows the comparison between a laboratory test result (dotted line) and a simulation with the ATP (full line) for a case which considers a high level of saturation of the measuring CT. As can be seen there is quite no difference between test results and simulation results and this means that the model is accurate enough.

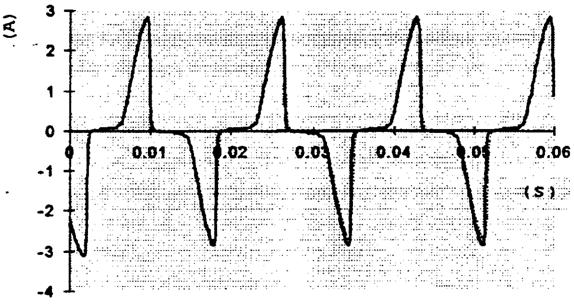

FIGURE 3. Comparison between test and simulation

2.5. NEGATIVE SEQUENCE ALGORITHM

To obtain the generator rms negative sequence current the Gabriel Benmouyal algorithm was used (5). With the expression for the negative sequence current:

$$\dot{I}_2 = \frac{1}{3}\left(\dot{I}_a + a^2.\dot{I}_b + a.\dot{I}_c\right)$$

the following expressions are obtained:

$$I_{d2} = \frac{1}{3}\left[I_{da} - \frac{1}{2}\left(I_{db} + I_{dc}\right) + \frac{\sqrt{3}}{2}\left(I_{qb} - I_{qc}\right) \right]$$

$$I_{q2} = \frac{1}{3}\left[I_{qa} - \frac{1}{2}\left(I_{qb} + I_{qc}\right) + \frac{\sqrt{3}}{2}\left(I_{dc} - I_{db}\right) \right]$$

and the negative sequence phasor:

$$I_2 = \left|I_2\right| = \sqrt{I_{d2}^2 + I_{q2}^2}$$

The phase (Id) and quadrature (Iq) currents of each phase may be obtained with any algorithm.

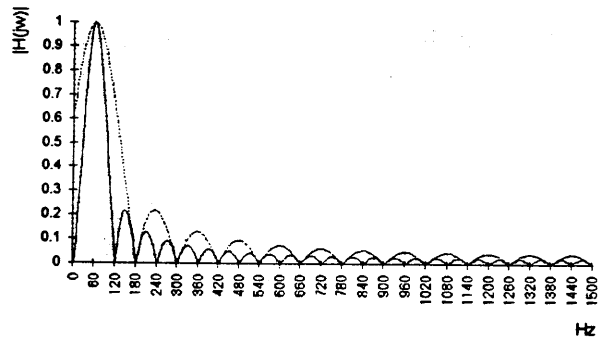

FIGURE 4. Frequency response

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MODELS ---- INICIO DO MODELO ----
INPUT ---- ENTRADAS PROVENIENTES DO ATP ----
 IGA {I(R46A)},IGB {I(R46B)},IGC {I(R46C)}
MODEL SEQNEGAT
CONST ---- CONSTANTES DO MODELO ----
C  VAL:1500     -- AMOSTRAS/CICLO DE CALCULO
  NA {VAL:30}    -- PASSO P/ RETENCAO DA AMOSTRA
  N {VAL:50}     -- AMOSTRAS/CICLO DO ALGORITMO
  N1 {VAL:24}    -- N/2-1
  N2 {VAL:25}    -- N/2
INPUT --- ENTRADAS CORRESPONDENTES NO MODELO ---
  IA, IB, IC
VAR -----VARIAVEIS LOCAIS DO MODELO -----
 ISA, ISB, ISC, ICA, ICB, ICC, SENO, COSSE,
 HISTA[1..55] HISTB[1..55] HISTC[1..55]
 IDA, IDB, IDC, IQA, IQB, IQC, I, ID2A, IQ2A, I2A
INIT -----INICIALIZACAO DO MODELO -----
 FOR K:=1 TO N DO
   HISTA[K]:= 0  HISTB[K]:= 0  HISTC[K]:= 0
 ENDFOR
  ISA:=0; ISB:=0; ISC:=0; ICA:=0; ICB:=0; ICC:=0
ENDINIT
EXEC -----EXECUCAO DO MODELO -----
C
C ALGORITMO DE SEQUENCIA NEGATIVA
C
 I:=I+1
 IF (I=NA) THEN
  FOR M:=1 TO N1 DO
   SENO:= SIN(2*PI*M/N)
   COSSE:= COS(2*PI*M/N)
   ISA:=ISA + HISTA[N2-M]* SENO
   ISB:=ISB + HISTB[N2-M]* SENO
   ISC:=ISC + HISTC[N2-M]* SENO
   ICA:=ICA + HISTA[N2-M]* COSSE
   ICB:=ICB + HISTB[N2-M]* COSSE
   ICC:=ICC + HISTC[N2-M]* COSSE
  ENDFOR
  IDA:= 4*ISA/N
  IDB:= 4*ISB/N
  IDC:= 4*ISC/N
  IQA:= 4*(-IA + ICA)/N
  IQB:= 4*(-IB + ICB)/N
  IQC:= 4*(-IC + ICC)/N
  ID2A:= (IDA-(IDB+IDC)/2 + SQRT(3)*(IQB-IQC)/2)/3
  IQ2A:= (IQA-(IQB+IQC)/2 + SQRT(3)*(IDC-IDB)/2)/3
  I2A:= SQRT((ID2A*ID2A + IQ2A*IQ2A)/2)
 FOR K:=1 TO N1 DO
  HISTA[N2-K+1]:= HISTA[N2-K]
  HISTB[N2-K+1]:= HISTB[N2-K]
  HISTC[N2-K+1]:= HISTC[N2-K]
 ENDFOR
  HISTA[1]:= IA  HISTB[1]:= IB  HISTC[1]:= IC
  I:=0 ISA:=0 ISB:=0 ISC:=0 ICA:=0 ICB:=0 ICC:=0
 ENDIF
ENDEXEC
ENDMODEL ---- FINAL DA DESCRICAO DO MODELO ----
USE SEQNEGAT AS INEGA --MODELO "SEQNEGAT" NO ATP
 INPUT
  IA:=IGA IB:=IGB IC:=IGC
ENDUSE
RECORD --- VARIAVEIS PARA PLOTAGEM ---
  INEGA.I2A AS I2A
ENDMODELS --- FINAL DA SECAO DO MODELS NO ATP
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FIGURA 5. Algorithm listing for the negative sequence with MODELS

In this work the Fourier algorithm was chosen. With this algorithm samples of the variable for a cycle are correlated with stored samples from fundamental sinusoidal and cossenoidal waves in order to obtain the complex value of the fundamental component in the retangular form. The choice of the data window for the Fourier algorithm was based in the analysis of the characteristic of the frequency response. With the sampling rate of 50 samples per cycle the frequency response of the Fourier algorithm may be seen in Figure 4. The full cycle algorithm (full line) rejects all the harmonics and the continuous current leaving to pass only the fundamental. The half cycle algorithm (dotted line) allows to pass more than 60% of the zero harmonics (continuous current) and second harmonic. The even harmonics starting from the fourth harmonic are attenuated to below 20 %. From 1500 Hz the frequency response curve repeats itself as if there were a mirror in this point. From the 25th harmonic on has not to much significance since the amplitude of this harmonics is too low.

For the analysis been done it is important that the algorithm does not filter all the harmonics because the negative sequence relay is electromechanical, made with circuits composed with resistors, capacitors and indutors. The full cycle data window is, therefore, not adequate to obtain the generator phase and quadrature components because they are corrupted with the high level of harmonics and of direct current due to the no load switching of the transformer (inrush current). Although the half-cycle algorithm is the indicated in this case, both algorithms were simulated and analysed. The expressions for both cases are the following:

a- for the one-cycle data window (full-cycle):

$$I_d = \frac{1}{N}\left[2\sum_{n=1}^{N-1} I_{k-N+n}.\mathrm{sen}\left(\frac{2\Pi}{N}n\right)\right]$$

$$I_q = \frac{1}{N}\left[I_{k-N} + I_k + 2\sum_{n=1}^{N-1} I_{k-N+n}.\cos\left(\frac{2\Pi}{N}n\right)\right]$$

b- for the half-cycle data window (short window):

$$I_d = \frac{4}{N}\sum_{n=1}^{N/2} I_{k-N/2+n}.\mathrm{sen}\left(\frac{2\Pi}{N}n\right)$$

$$I_q = \frac{4}{N}\sum_{n=1}^{N/2} I_{k-N/2+n}.\cos\left(\frac{2\Pi}{N}n\right)$$

~~where I_k is the current of the kth sample and N is the~~ number of samples per cycle.

The new MODELS routine, available since version 5 of ATP, was used to implement the algorithm. Figure 5 shows the listing of the Fourier algorithm for the short window. The implementation of the Fourier algorithm for the full-cycle was done similarly.

3- SIMULATION

The simulation was basically the no load energization of transformer TF-5 through closing the breaker of group 3 and then to monitor the negative sequence current of the generator. Since the energization of the transformer TF-5 was made closing the breaker there is a probability of inrush current that can be greater or lower acording to the instants of closing of the breaker poles. The closing times of the poles distribute themselves aleatorily in a time span that can be pre-defined. In this case the pre-defined span was set to 8,3 ms (180°).

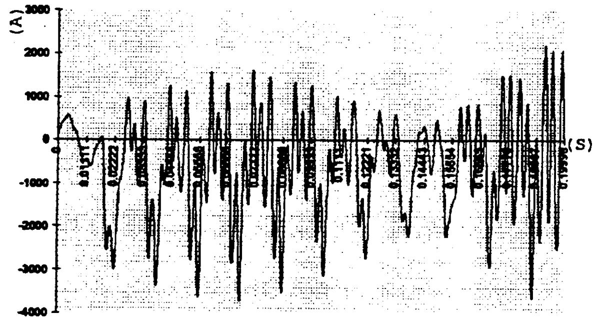

FIGURE 6-(a) Phase a

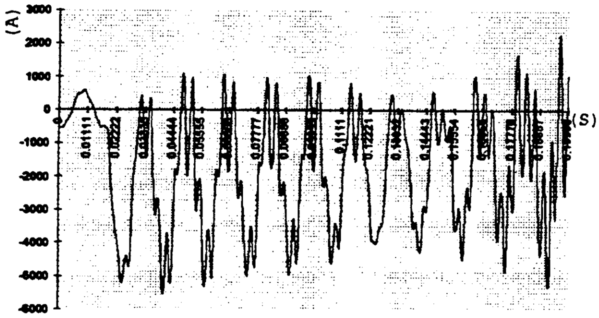

FIGURE 6-(b) Phase b

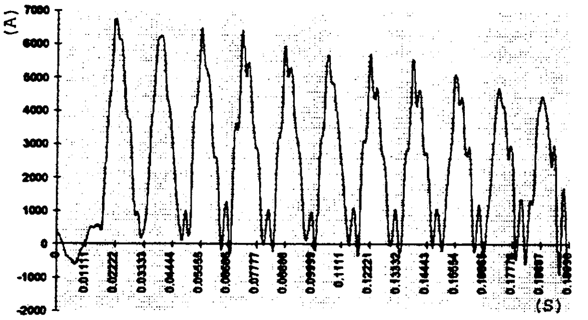

FIGURE 6-(c) Phase c

FIGURE 6. Currents in the group terminals

Another aspect that affects the magnitude of the inrush current of the transformer is the flux that remains in the transformer core when it is switched off. Taking in consideration all this, 100 energizations were simulated varying aleatorilly the closing time in the time span refered before. Every energization considered the remaining flux in the core of TF-5. With this considerations the negative sequence current obtained was maximized.

4. ANALYSIS OF THE SIMULATIONS

The energization that resulted in the greater negative sequence current is analysed with more details in this item. Figure 6 shows the currents in phases "a", "b" and "c" of the generator terminals.

It is possible to verify that the steady state no-load current of the generator (first half cycle of any phase in Figure 6) is very high due to the high capacitance of the 230 kV power cables that interconnect the group to the substation. This current has a magnitude of about 425 A and is highly affected by the first insulation level of the cable.

The negative sequence current is obtained, through a digital algorithm, from the current of the secondary of the current transformers of the generator terminals where the 46G relays are installed. The CTs ratio is 3000/5 A.

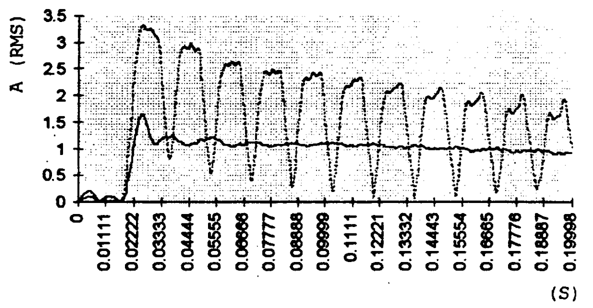

FIGURE 7. Negative sequence current

The phase currents contain a high level of harmonics and of continuous currents. For this conditions the POQ relay will probably operate outside of its nominal characteristics since it is composed of R and L circuits, whose negative sequence filter is tuned for the fundamental frequency. A possibility of obtaining the negative sequence current that takes in considerations at least part of the harmonics and of the continuous current is through the short window Fourier algorithm. To do this, 50 samples per cycle were used what assures a reconstitution of a signal containing harmonics of at least 1500 Hz according to the sampling theorem of Nyquist. Since the amplitude of the harmonics above this frequency are insignificant in the generator terminal currents, the "anti-aliasing" filter was not necessary. The full-cycle Fourier algorithm, that acquires only the fundamental component, was also used as a conservative form of analysis of the actuation of the POQ relay. The negative sequence current in rms ampères obtained in this condition may be seen in Figure 7. The maximum negative sequence current obtained during the TF-5 transformer energization was 3.3 A when acquired by the short window Fourier algorithm (dotted line) and of 1.65 A when acquired by the full-cycle Fourier algorithm (full line). It is possible to verify that even with the full-cycle algorithm the POQ relay has enough condition to operate since it is calibrated to 0,8 A. This POQ relay is an old Westinghouse relay. It is instantaneous but has a temporization adjusted externally in 5 seconds through a timer type RE250 of FIR. In the tap of 0,8 A the 46G relay operates with a current magnitude of 1.38 A and drops out with a current magnitude of aproximatelly 0,7 A.

In Figure 7 it is seen that the negative sequence current decreases very slowly. Taking this in consideration and extrapolating one concludes that the 46G relay operated correctly, although not accordingly to the aspect of the system. The timer RE250 of FIR may have also actuated well before the completion of the 5 s of the setting since this type of relay has had bouncing problems with the contacts $^{(6)}$.

Figure 8 shows the inrush current in the high voltage side of the transformer TF-5, in the phases "a", "b" and "c" respectively.

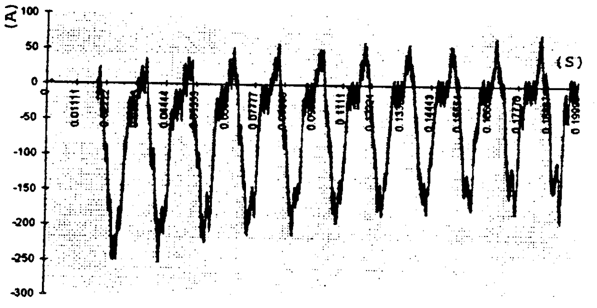

FIGURE 8-(a) Phase a

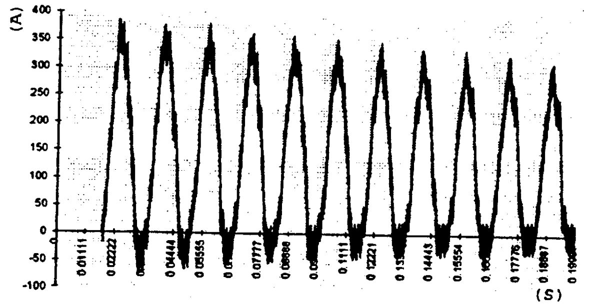

FIGURE 8-(b) Phase b

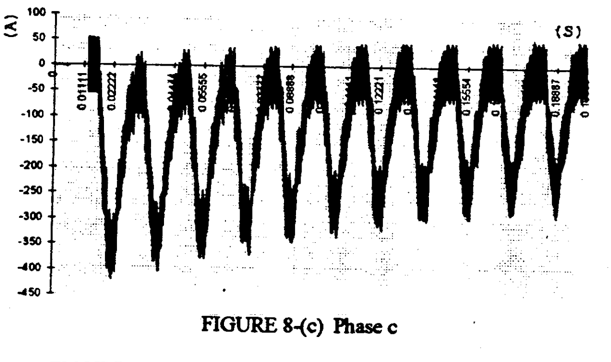

FIGURE 8-(c) Phase c

FIGURE 8. High voltage side current of transformer TF-5

The inrush current in this energization was of 1.75 pu in phase "c". Figure 9 shows the magnetic flux behaviour in the phases "a", "b" and "c" of the transformer core. The full line is the dynamic behaviour of the flux during the energization and the dotted line is the maximum hysteresis cycle of the transformer TF-5. It is possible to verify the influence of the assimetry of the currents in the magnetic flux of the transformer. For this case only 80 ms of the simulation are presented in Figure 9 in order to have a clearer figure and to better visualize the initial behaviour of the inrush current.

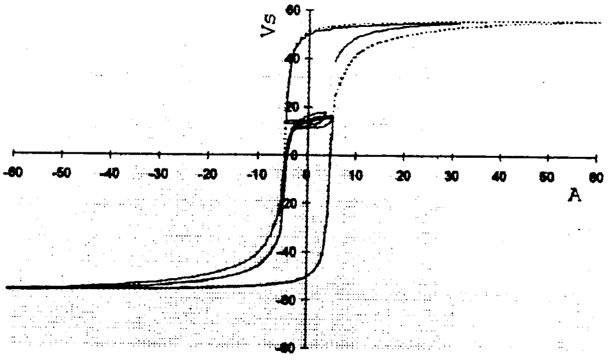

FIGURE 9-(a) Phase a

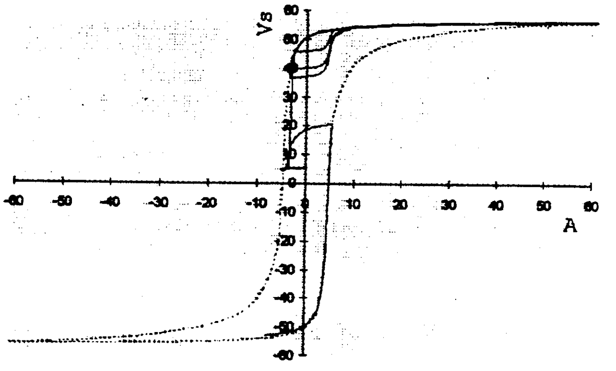

FIGURE 9-(b) Phase b

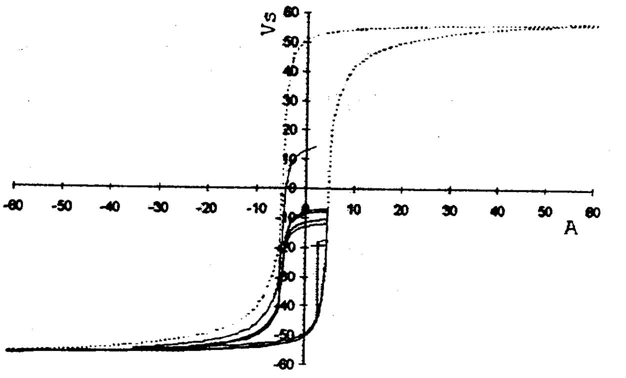

FIGURE 9-(c) Phase c

FIGURE 9. Magnectic flux in the core of transformer TF-5

5- CONCLUSIONS

a) Considering only the protection aspect the simulations indicated that the operation of the 46G protection of group 3 was incorrect although undesirable under the power system operating aspect. The negative sequence current level generated during this occurrence could be withstand by the generator for about 10 minutes without exceeding the generator withstand characteristic established by the standard equation for hydrogenerators: $i_2^2t = 40$. It is also possible to verify by this equation that for negative sequence currents in the range from 10% of the nominal current (continuous withstand) until 28.8% (that is the minimum pick up current for the tap = 0,8A), there is no protection. In certain loading and system configuration conditions the opening of one phase of a transmission line may actuate the overcurrent directional protection (67N) and eliminate the fault but this is not the general rule. Considering what was exposed it is possible to conclude that the negative sequence relay presently installed to protect each generator group of the GPS power plant is not adequate because its time characteristic is definite. To solve this problem the maintenance people of COPEL is providing negative sequence relays that take into consideration the $i_2^2t = 40$ characteristic of the generator for all the four groups of the power plant.

b) Considering the simulation aspect the use of the ATP program was very efficient since that besides allowing the modelling and simulation of all the necessary details of the power system allowed also the implementation of the algorithms to obtain the negative sequence current through the usage of a specific language with the MODELS routine. Besides the potentiality of the ATP to simulate the power system problems with MODELS one can catch a glimpse of powerfull usages in the power system protection field.

6- REFERENCES

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