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Decreasing the Harmonic Content of the Fault Current during Single-Phase to Ground Faults in Compensated Network

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***Abstract*--The harmonic content of the short circuit current during single-phase to earth fault is discussed in networks with compensated neutrals. An overview of different methods to decrease the harmonics in the fault current is given. The zero sequence active filtering method is analyzed in detail using computer simulations. Two compensation algorithms are compared based on their efficiency when operation is maintained during a single-phase to earth fault. Finally, a report of on-site measurements is presented, the measurement results are compared to the simulation results. Based on these results it is concluded that the method has proven to be effective in reducing the residual current and thus it is ready to be implemented in substations.**

***Index Terms*-- Active filters, Harmonic distortion, Measurement, Power distribution faults, Power distribution reliability, Power electronics, Power filters, Power quality, Power system harmonics**

I. INTRODUCTION

THE Hungarian rural medium voltage network is a compensated overhead line system with a total length of about 40000 km. Fault statistics of this system pointed out that more than 90% of the total faults originates from single-phase to ground faults. About 90% of these faults are through an arc which gives the chance to achieve a self extinction due to the compensation by the Petersen coil (resonance grounding). The compensation is an automatic process, and is operating in some percent overcompensation. The continuous operation of the system can be maintained during a single-phase to ground fault if some requirements are fulfilled. The residual current at the fault location has to be kept securely below 12 A in order to ensure, that the touch voltage should remain below 65 V during the steady state faulty operation. (This assumption considers a 5Ohm grounding resistance of the pole.)

Measurements are carried out regularly at the substations in order to check the above condition. In recent years these measurements showed, that in spite of having set the compensation to some 1-2 A fundamental residual current, the RMS of the residual current is in some substations greater than the allowed value. The analysis of the Fourier spectrum of the residual current shows that in these cases the harmonic content of the residual current is several times greater than the fundamental component. The circumstances resulting in the increasing of the harmonic content of the arc current and the possible solutions of the problem were outlined in [1] and [2].

In [3] the authors discussed the possible solutions for compensating the harmonic content of the residual current based on computer simulations.

This paper gives a brief overview of the problem and shows field test results performed on a test system in a 120/20kV substation using the zero sequence active filtering method.

II. OVERVIEW OF POSSIBLE METHODS

As already proposed in [1], basically there are 4 methods to eliminate or decrease the harmonic content of the residual current of the fault location:

1. Three phase filtering. This is a simple solution of connecting tuned filters to the busbar of the substation. The filters are present in both positive and negative sequence networks as shunt branches. This method improves normal operation conditions decreasing voltage distortion as well, even at the low voltage network. The solution can be used if a capacitor bank is necessary for power factor correction, but the extra cost and location of the filter reactor must be considered as well.
2. Zero sequence passive filtering. This is similar to the fundamental frequency compensation. If the zero sequence driving point impedance on a given harmonic order is tuned to give a parallel resonance, the harmonic content of the residual current on this frequency can be limited. When changing the network length, the elements of the filter must be tuned similarly to the Petersen coil.
3. Single-pole shunting the short circuit at the substation using single-pole circuit breaker. This method decreases the fundamental fault current as well, decreases its harmonic content; first of all that part, which originates from the supply network. The solution eliminates the resonance between the positive, negative and zero sequence impedances and decreases the influence of the capacitor bank built in at the substation for power factor correction.
4. Zero sequence active filtering. This is an appropriate method for decreasing the harmonic content of the fault

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current near to zero [4]. By means of a zero sequence harmonic current generator the control system forces the zero sequence harmonic voltages to be the opposite of the corresponding dominant sequence harmonic voltages (e.g. regarding the 5th harmonic, the zero sequence voltage should be approx. the opposite of the negative sequence 5th harmonic voltage measured on the busbar). In this case the harmonic current of the fault current will be near to zero.

The method of zero sequence filtering was chosen to be implemented and analyzed in this paper. Only the elimination of the greatest harmonic current (the 5th one) will be shown, but the method can be applied with minor modifications to any other harmonic as well.

III. THE ZERO SEQUENCE ACTIVE FILTER CONTROL ALGORITHM

For the derivation of the control algorithm the method of symmetrical components and a simplified network model will be used. In case of a single-phase to ground fault (in phase "a") the three symmetrical component networks have to be connected in series at the fault location. The resulting network scheme is shown for the 5th harmonics in Fig. 1.

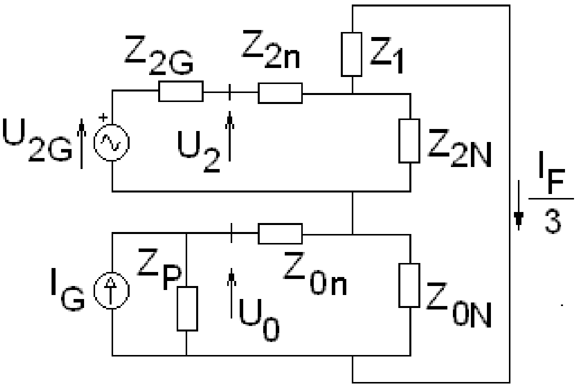

Fig. 1. Simplified positive-, negative and zero sequence network scheme for the 5th harmonics in case of a single-line to ground fault

In Fig. 1. Z_1 is the total positive sequence impedance, Z_{2G} is the negative sequence impedance of the supply system, Z_{2n} and Z_{2N} are the negative sequence impedances of the faulted line before and behind the fault location, Z_{0n} and Z_{0N} are the zero sequence impedances of the faulted line before and behind the fault location, Z_P is the zero sequence impedance of the Petersen-coil, U_2 and U_0 are the negative and zero sequence voltages at the busbar, I_F is the fault current. The dominant part of the 5th harmonic currents and voltages in the non-faulted case composes a negative sequence system, therefore the 5th harmonic voltage generator exists only in the negative sequence system. The zero sequence active filter can be modeled as a controlled current source I_G connected in parallel to the Petersen coil.

The control algorithm tends to minimize an error term ΔU in order to decrease the 5th harmonic component in the fault current.

In the following two different definitions of ΔU will be investigated.

The first attempt was presented in [3]:

$$\Delta U = | \underline{U}_{2,pre\text{-}fault} - \underline{U}_{2,\,actual} | \qquad (1)$$

where $\underline{U}_{2,pre\text{-}fault}$ is the negative sequence voltage at the busbar just before the fault occurs, and $\underline{U}_{2,\,actual}$ is the negative sequence voltage at the busbar during compensation.

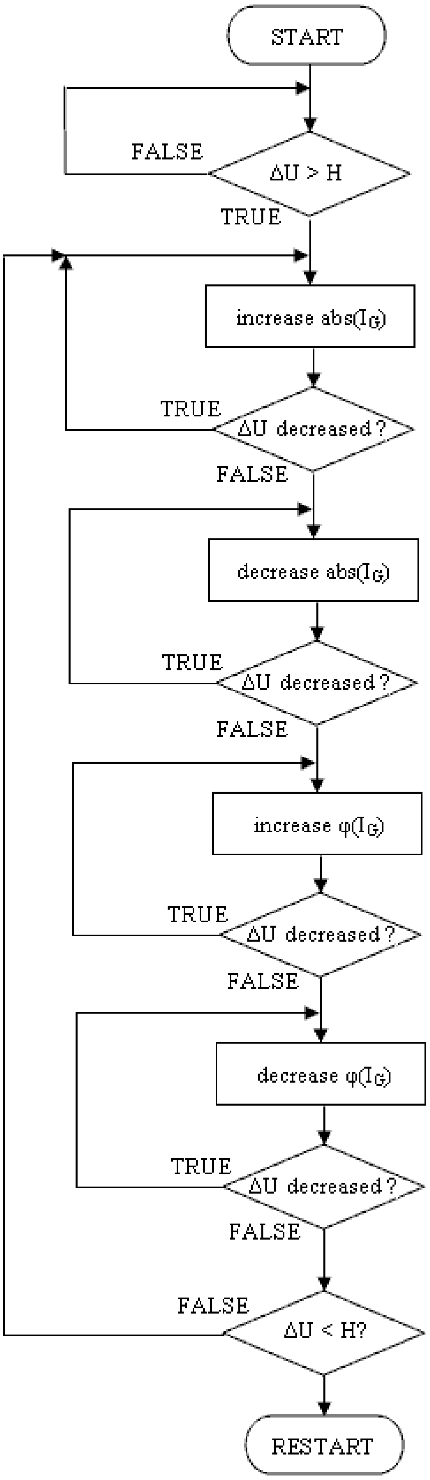

Fig. 2. Simplified flow-chart of the control algorithm for the current injection

From Fig. 1 it can be seen that if (and only if) the current I_F is zero (and assuming that the voltage source and all other network elements in the negative sequence network are approximately constant), then U_2 will be equal its pre-fault value and ΔU in (1) will be zero.

One of the possible algorithms for minimizing ΔU is presented in Fig. 2, where H is a small threshold.

Simulations have shown that the above algorithm leads to the minimization of the 5th harmonic component in the fault current. (See Section IV.)

However, if the operation of the system is maintained during a single-phase to ground fault for several hours, then the negative sequence voltage of the supplying network can change with time. Thus, using the error term in (1) could result in a permanent error in the compensation. (For simulation results see Section IV.)

In order to overcome this shortage, as the second attempt the following error term is proposed:

$$\Delta U = \left| -\underline{U}_0 - \underline{U}_2 \right| \qquad (2)$$

As an explanation of (2) consider, that

- Z_1 can be neglected (i.e. the voltage drop at the positive sequence network is negligible)
- Z_{0n} can be neglected (as compared to Z_P), therefore U_0 approximately equals the voltage drop at Z_{0N}

Thus from Fig. 1. it can be seen, that if $-\underline{U}_0 = \underline{U}_2$ then there will be no 5th harmonic current flowing through the fault location.

IV. SIMULATION MODEL AND RESULTS

The simulation model used in this chapter is shown in Fig. 3:

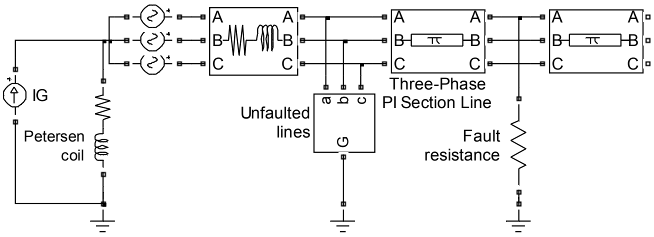

Fig. 3. Three-phase model of the network

It is a three-phase frequency-domain model, where the faulted distribution line is represented by several three-phase pi line sections, and the non-faulted lines are represented together as capacitors, see Fig. 4.

The substation is fed by a 120/22 kV, 40 MVA transformer. The Petersen coil has an inductivity of L_{Pet} = 348.5 mH. (The Petersen coil is tuned to keep 2 A overcompensation.) The faulted line consists of approx. 47 km overhead lines and 6 km cables (including all side-lines). The fault distance between the substation and the fault location is approx. 9.5 km. The fault resistance was set to 0.1 Ω.

The voltage generators in the supply network represent a three-phase negative sequence 5th harmonic voltage which is present at the MV network due to the non-linear loads supplied from the MV network and due to the harmonic voltage distortion originating from the upstream network (120 kV).

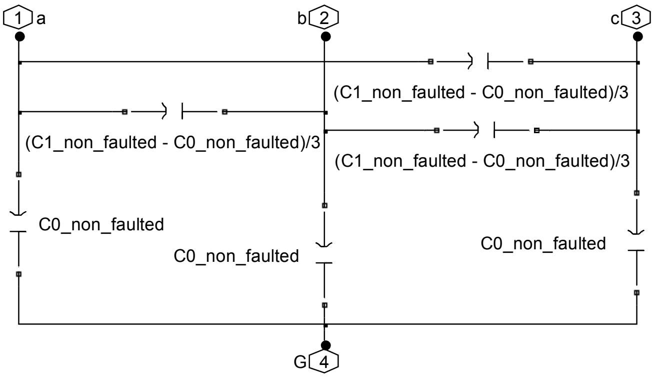

Fig. 4. Three-phase model of the non-faulted lines

The simulations shown below start with a negative sequence 5th harmonic voltage of U_{2G} =150 Vrms. In order to simulate that the faulted line is not tripped and during operation the voltage of the supply network can change, U_{2G} =200 Vrms (and a phase shift of 15°) is applied at the simulation step 50 instead of the original 150 Vrms, 0°.

In Fig. 5. the results of the simulation according to the algorithm shown in Fig. 2 and using (1) as the error term are shown.

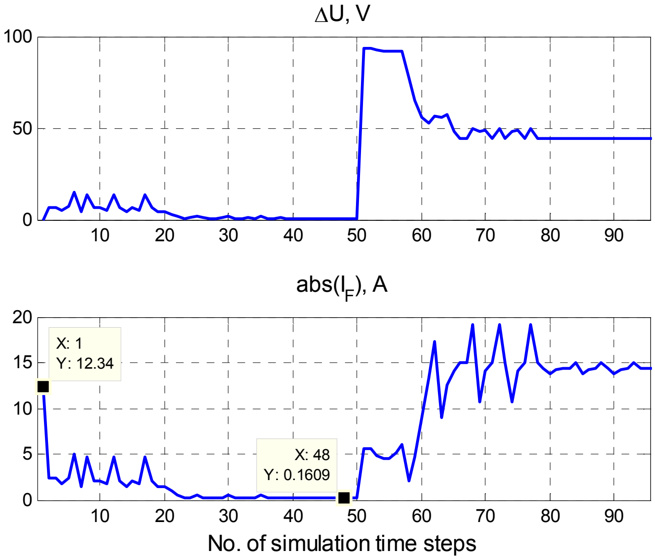

Fig. 5. Simulation results using the error term in (1)

The simulation results prove that the 5th harmonic content of the residual current decreased at the beginning of the fault from 12.34 A to 0.16 A, but when the harmonic content of the supply network is changing, the algorithm is not able to reduce the 5th harmonic content of the residual current again, since it uses the pre-fault negative sequence voltage as a reference.

The simulation results using the error term in (2) are shown in Fig. 6.

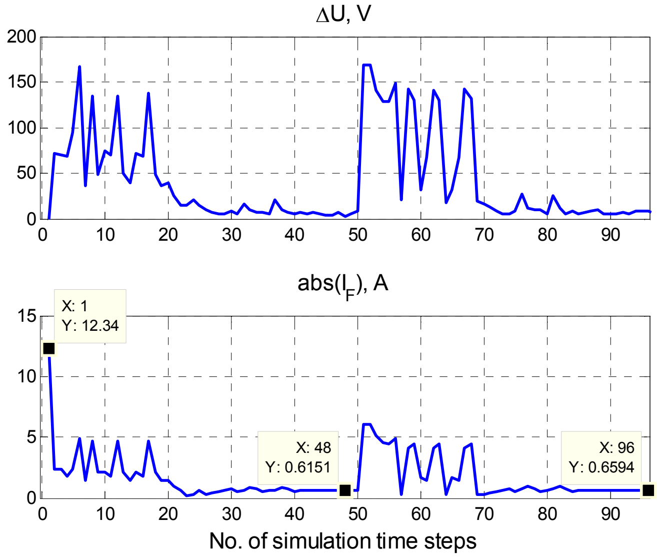

Fig. 6. Simulation results using the error term in (2)

It can be observed that the 5th harmonic content of the residual current was decreased from 12.34 A to 0.62 A, and when the harmonic content of the supply network changed, the algorithm was able to reduce it again to 0.66 A.

During this simulation the zero sequence current flowing into the faulted line was also recorded (for the sake of comparison with the measurement results) and is shown in Fig. 7.

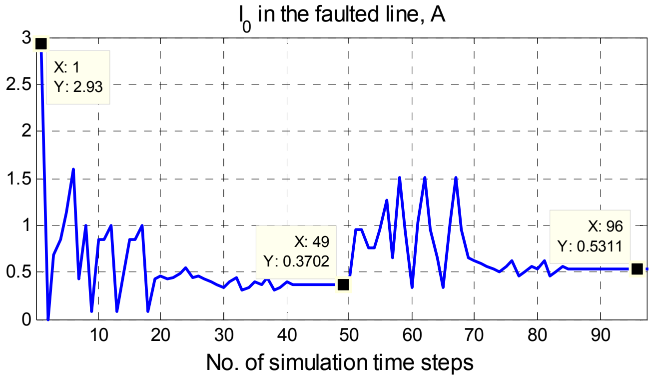

Fig. 7. Zero sequence current of the faulted line, using the error term in (2)

It can be seen that this current component is also decreased by the compensation.

V. FIELD TEST MEASUREMENT RESULTS

The measurements were carried out in a 120/20 kV substation. The network under test consists of 6 20 kV branches (named “A” to “F”), the branch “D” was the one where the artificial single-phase to ground fault was established. The parameters of this line are the same as described in Section IV.

The block diagram of the zero sequence active filter is shown in Fig. 8.

The measuring and data logging equipment was developed at the Department and is shown in Fig. 9.

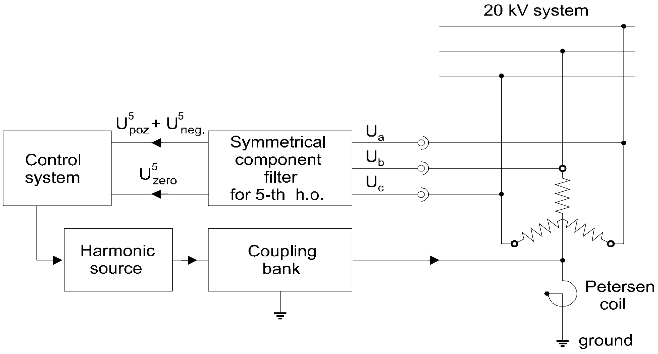

Fig. 8. Block diagram of the zero sequence active filter

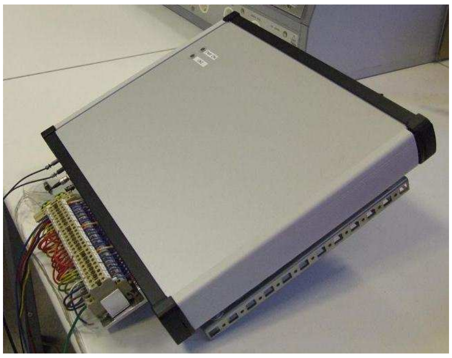

Fig. 9. Measuring and data logging equipment

The inverter had a rated power of 20 kVA and was supplied from the substation’s auxiliary transformer.

Fig. 10. DC bank of the voltage source converter

During the tests the algorithm used for compensation was based on (2). The zero sequence 5th harmonic currents at each branch have been recorded and their RMS values are shown in Fig. 11, together with the RMS of the sum of these currents.

Fig. 11. shows that

- the faulted line “D” had the greatest current (4.5 A), which was then decreased to 0.58 A
- the measured results show a similar behavior as the simulated ones.

Further the fault current has also been recorded and analyzed in real-time, but due to technical difficulties it has not

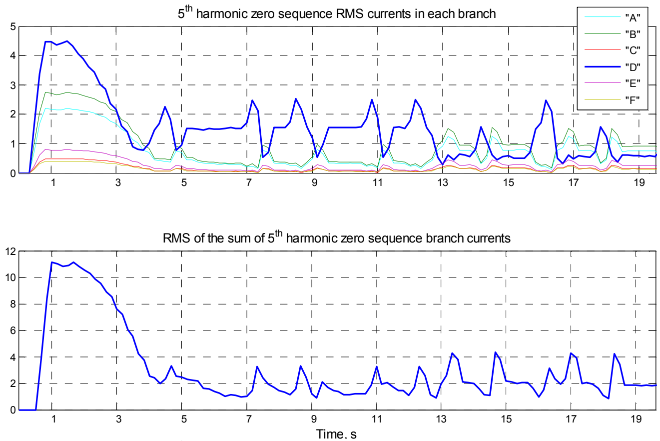

Fig. 11. Measured 5th harmonic zero sequence currents of each branch

been logged. The on-site analysis showed that the 5th harmonic content of the residual fault current was decreased (almost completely eliminated), and thus the RMS of the residual current was also decreased to around 3 A.

VI. ECONOMIC ASPECTS

The order of magnitude of the investment cost of the compensation equipment is about 50.000 to 70.000 EUR. (One equipment per Petersen coil is needed, but there is no need to install such an equipment in each substation, only in the ones where continuity of supply is a very important issue.)

Let us assume a substation transformer and one of its branches which supplies 10 MW industrial load. Let us further assume that

- the average outage time of this branch is 0.6 hours/outage
- the energy price is 0.1 EUR/kWh
- the cost of outage is 70 times higher than the cost of not supplied energy (for industrial consumers).

Then the cost of one outage will be

$$10\cdot1000\cdot0.6\cdot0.1\cdot70 = 42000 \text{ EUR}.$$

This means that the investment cost of the equipment will return after 2 single-phase to ground faults in that branch supplied by the substation transformer. (It has to be mentioned that the utilities have to pay fines if their SAIDI and SAIFI indices are poor, and these fines can be reduced using the proposed method and equipment.)

VII. CONCLUSION

As a conclusion the simulated and measured results show a good coincidence, and the method presented in Section III. is capable of reducing the 5th harmonic content of the residual current of single-phase to ground faults. (Only the harmonic current of greatest magnitude has been reduced, however, the active filter allows injecting higher order harmonics, too.) Thus the RMS value of the residual current can be kept securely below 12 A and therefore the touch voltage will remain below 65 V during the steady state faulty operation. This allows the operators to maintain operation in case of single-phase to ground faults for several hours (until the fault is located), and thus achieve better continuity of supply indices (SAIDI and SAIFI).

The method has proven to be effective and the installation of a prototype is underway in two substations.

VIII. REFERENCES

[1] A.M. Dán, Zs. Czira: “Harmonics in Compensated Medium Voltage Overhead Systems during Single-phase to Earth Fault”, Proceedings of the International Conference on Electric Power Quality and Supply Reliability, pp 122-125. 1999, Tallinn, Estonia

[2] H. Schau, D. Stade : Influence of harmonics on the line-to-ground fault currents. Ibid pp 116-121.

[3] András Dán, Zsuzsa Czira, Dávid Raisz: “Comparison of different methods to decrease the harmonic content of the fault current during single-phase to ground faults in compensated networks”, IEEE PowerTech Conference 27-30 June, 2005, StPetersburg, Russia

[4] Janssen, M. Kraemer, S. Schmidt, R. Winter: “Residual current compensation (RCC) for resonant grounded transmission systems using high performance voltage source inverter”, IEEE PES Transmission and Distribution Conference and Exposition, Sept. 7-12, 2003, pp. 574- 578

[5] A.M. Dán: “Identification of Individual Distorting Loads and Evaluating their Harmonic Emission Level: Method of Monoparameter Variation“, Proceedings of the 7th IASTED International Multi-Conference, Palm Springs, California, USA, 2003, pp-. 471

IX. BIOGRAPHIES

Dr. András M. Dán (SM’90) received MSc degree from Budapest Technical University in 1966, PhD and DSc degrees in Electrical Engineering from the Hungarian Academy of Sciences in 1983 and 2005 respectively. He has been at Budapest Technical University since 1970 where he currently holds the rank of professor and acts as a consultant for local industry. His expertise is in power electronics, power quality, reactive power compensation especially associated with power system harmonics. Dr Dán is a member of the Hungarian Electrotechnical Association

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