Increased Transmission Capacity by Forced Symmetrization

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Abstract - **This paper deals with one-phase faults on high voltage transmission lines and possible methods of utilization of the transmission capacity of the sound phases. If an AC power grid has interconnections with damaged or disconnected single phases, non-symmetrical currents arise in the system. These non-symmetrical currents must be eliminated to provide an acceptable and secure operation of the power grid. Normally, if one phase of a transmission line is damaged, the whole line section or all three phases are disconnected from the grid to ensure the symmetrical mode of operation of the grid. The investigation in this paper is devoted to the case, when only the faulty phase is taken out of operation or disconnected while the two sound phases are still connected to the grid and transfer power. Special symmetrization compensators provide the needed symmetrical conditions at line terminals. In this case the transmission capacity of two sound phases can be utilized for further grid operation. Electrical parameters of the affected line as well as effective thermal power rating of the line will change. Theses changes are dependent on the particular symmetrization technique. Two symmetrization methods have been tried and compared in this work. Modern power electronics devices and measurement technology provide the necessary hardware basis for the practical implementation of such symmetrical compensators. The presented solutions increase the system reliability significantly and can be seen as competitive solution for an extensive grid expansion on the existing congestion routes.**

Keywords - **Transmission lines, Asymmetrical conditions, Symmetrization, Power electronics, FACTS, System reliability, Power system operation**

I. INTRODUCTION

The electrical power sector experiences nowadays a need in new techniques for increasing the capability of transmission systems. Firstly, the reason for this lies in increasing power flows due to increasing power consumption and, secondly, due to the deregulation of the electrical market demanding power flows to be more flexible, and thereby causing possible congestions. The conservative expansion of the high voltage grid could solve the problem, but it is often not desirable. The approval of new overhead transmission lines meets strong opposition in society. Furthermore it takes long time and is generally a risky long-term financial investment. The solution proposed in this paper can be a cheaper solution with short implementation times.

This paper describes an investigation of possibilities for enforced symmetrization on a damaged transmission line to ensure power transmission through the line even when one phase is damaged. The utilization of two remaining sound phases of the three-phase transmission line with a faulty phase can be an economically and ecologically beneficial way to ensure the system reliability.

In the present planning of high voltage networks the (n-1) criterion is mostly respected. This means, that the network should not be subject to any overload or voltage drops below given limits when any network element is disconnected. Based on the statistics, the single phase-to-ground faults are the most frequent faults in transmission systems. The percentage of phase-to-phase and three-phase faults is considerably smaller. Present planning procedures are often based on single outages of three-phase circuits, which do not take the actual fault pattern into account. For the single-phase faults it is necessary to avoid unsymmetrical conditions or unsymmetrical currents in the network. The reason for this is that the currents in the zero-sequence system mean earth currents, and those can be dangerous for personnel and cause adverse interaction with other systems. The zero sequence currents cannot in general be tolerated on the overhead transmission grid. The currents and voltages in the negative-sequence system are a concern to rotating synchronous machines like generators and motors, but if no such machines are connected to a network part, the negative-sequence voltages can be tolerated on that part.

Symmetrization means the suppression of both zero- and negative-sequence currents on the network side of the line section, so that the network do not experience any unsymmetrical conditions. This can be achieved by the installation of two FACTS-devices as shunt or series elements at the line terminals.

Two different arrangements and compensation strategies are considered in the paper. The proposed symmetrization techniques were tried on the IEEE 14 test case network for illustrating the methods. The simulation was fulfilled on a specially developed system simulator. The simulator is based on power flow calculation with multiple symmetrical system representation and allows simulation of the symmetrization effect in a meshed network. One of its important specialities is the ability to calculate zero sequence system currents through transformers. The fault currents in the negative- and zero-sequence systems as well as equipment rating can be studied directly.

Implementation of the proposed symmetrization technique can be a competitive solution for providing system reliability. Shorter installation times, easier way to get permissions and the possibility to use the installed equipment for auxiliary system services are supportive arguments for the new technology.

II. SYMMETRIZATION IDEA

The general idea of symmetrization is the following: to install devices on the terminals of the faulty transmission line section, which will provide the symmetrical conditions, that is currents and voltages, on the rest of the network. Such devices will be called "symmetrization compensators" or simply "compensators" in the following. The compensators can be both series and shunt devices, in the present paper we consider two similar methods of shunt compensation and one method of the combined compensation by both series and shunt devices.

The possibility of symmetrization and one possible configuration of the symmetrization are presented in [2]. The configuration is also shown on the figure 1. An additional "highground" or "HG" wire with low insulation level provides a secure path for zero sequence currents. The wire can be integrated into existing tower layout and it carries the zero sequence current, which otherwise would flow through the earth. The proposed active shunt compensators are able to inject both negative- and zero-sequence currents and, as it is shown in [2], the configuration is able to establish symmetrical conditions for the network outside the damaged line.

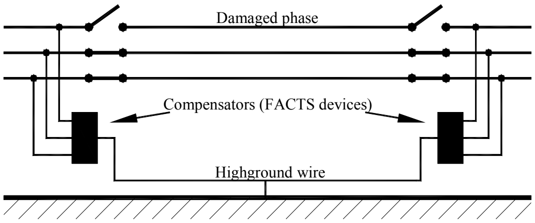

Figure 1: Diagram of a compensated circuit

Even during the compensation mode the sound phases operate with alternating current. Of course, one obvious symmetrization method would be the transformation of the considered transmission line into two-wire DC transmission system. Additional switching equipment can provide the adjustment to particular sound phases. This case is obviously more expensive and is not a subject of our investigation. The idea is to provide symmetrization by as small as possible modification of the existing system.

Another important point is the presence of the highground wire. It is needed in all cases, when zero sequence currents can flow in the system and are not stopped by delta-connected transformers. We have considered a common situation on the high voltage transmission systems, when transformers are grounded at the star point of the windings and therefore are able to carry the zero sequence system currents.

To visualize the possibility of symmetrization let us consider a simple example, see figure 2. A symmetrical network feeds a transmission line with a disconnected phase R. Let us suppose, that the symmetrization compensator on the input line terminal injects equal currents in all three phases, each current been opposite to the current R of the feeding network. In this way, the current into the R phase of the damaged line, which is the sum of currents from the feeding phase and from the compensator, will be zero, according to the fact, that the phase is out of operation. Currents in the S and T phases in the transmission line will also change their magnitudes and phase angles as it is shown in the picture. To provide such compensating phase currents, a three times greater current should flow through the highground wire, giving the sum of all currents through the system of three phase transmission plus HG-wire to zero. As consequence, no earth current will occur in such an operation mode.

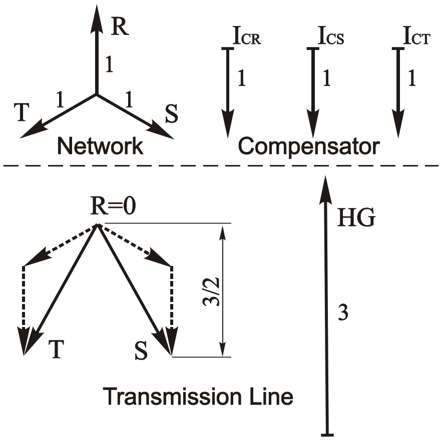

Figure 2: Possible current configuration

The task of the compensator in this case is to control the highground current and to distribute equally the highground current between the three phases. It can be done completely by power electronics or by mixed technology with aid of special transformer, as shown in figure 3.

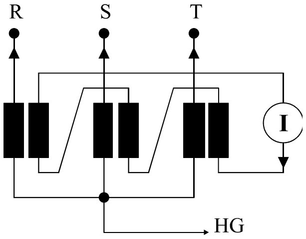

Figure 3: Mixed zero sequence compensator

The difference between the highground wire and a spare phase, which is used on some important routes, is in its insulation level. The HG-wire is supposed to carry zero sequence current, but no power and it needs only a low insulation level in comparison to the phase wires. It can even be earthed at one point, to provide a voltage reference and to ensure a low voltage level. It should thus be no problem to integrate the wire in the existing tower topology with minimum investments.

In general, all symmetrization methods influence the parameters of the considered transmission line as these parameters are seen from the rest of the network. The impedance of the transmission line changes significantly, thus changing the power flow in the network. The complex currents configuration on the line phases will, obviously, limit the line thermal capacity. These factors compete with the fact, that the line still provides a great part of its transmission capacity also during the two-phase operation.

III. INVESTIGATED SYMMETRIZATION METHODS

There are a lot of possible symmetrization methods. As can be seen in figure 2, the currents in the transmission line can be different. The important criterion is that the sum of all currents in the affected line be zero. This constraint means, that there is no earth current. If currents in phases S and T are opposite to each other, no HG wire is needed. Such a compensation scheme, based on Steinmetz coupling topology is described in [3].

For our investigation we have chosen two configurations, based on two different compensation philosophies. One philosophy, which was initially introduced in [1] is based on the active short-circuiting of the negative- and zero-sequence systems at line terminals, see figure 4. This active short-circuiting means that we guarantee the zero- and negative-sequence voltages at line terminals will be zero. These zero voltages provide the absence of zero- and negative-sequence currents into the connected networks.

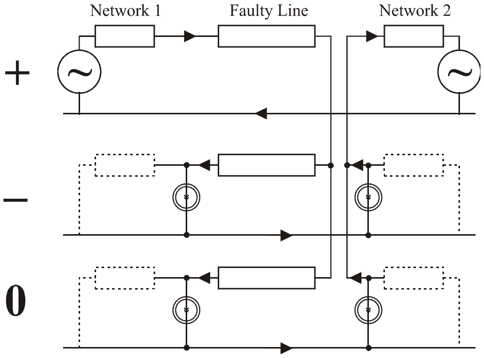

Figure 4: Symmetrization by short-circuiting of negative- and zero-sequence system

In this method generic power electronics devices have been used, which are able to commutate currents between four wires: three phase- and one highground wire. In the picture the highground wire is not shown for the sake of simplicity. It carries triple return current of the zero sequence system.

Another compensation philosophy is based on usage of both series and shunt devices and can be applied in cases with small series resistance of the line section. Series capacitors compensate series line impedance to zero. Shunt devices bypass zero sequence current, which flow in the line section into the highground wire. Figure 5 illustrates schematically the compensation idea. If the line resistance is much greater than zero, or, more precisely, if the line resistance is not much smaller, than the sum of zero sequence impedances of both networks, also active power must be pumped in series connection into the line to bring the effective line impedance to zero. This can be done by e.g. an UPFC, but is not considered in this paper. In case the line resistance is negligibly small, the line compensation can be fulfilled by series capacitors. Figure 2 illustrates the current configuration in this case. The current, which otherwise would flow through the phase, which is now disconnected, is redirected into the HG wire. The same currents, which are extracted from the other two phases are short-circuited within the line and circulate only in the line section. It is not needed to compensate negative-sequence currents and simpler equipment can be used, though the current loading is high.

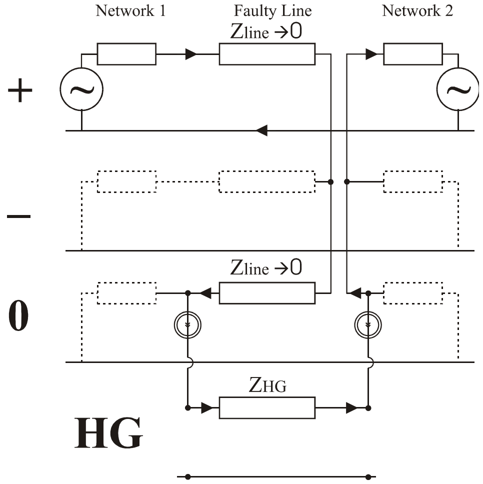

Figure 5: Compensation with line impedance compensation

IV. SIMULATION AND RESULTS

The IEEE 14 test network was used as an example of meshed network. The line section between buses 4 and 5 has been chosen for investigation of compensation techniques, see figure 6. The line is in the middle of the network, so the results of compensation effects are representative. The results are to be understood as guidelines to the equipment evaluation, exact ratings can vary from case to case, specially dependent on the particular zero sequence conditions.

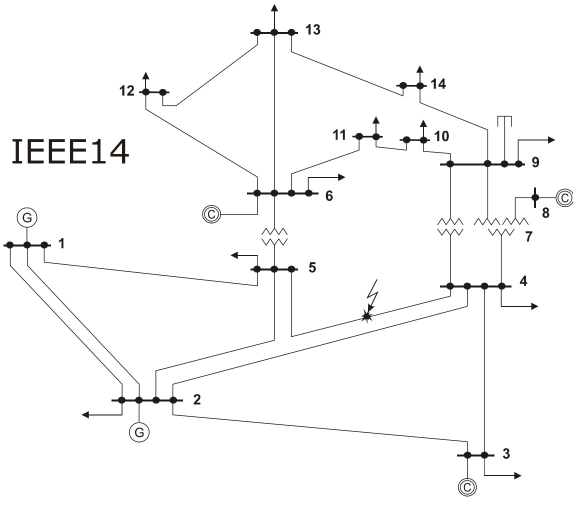

Figure 6: IEEE 14 Test Case Network

The ratio between maximal phase current and effectively transmitted power has been chosen for evaluation of the rest transmission capacity of the line. This ratio shows how efficiently power can be transferred through the line or how much energy the damaged line section can transfer at a given thermal limit.

At normal operation line section 4-5 supplies the following power into bus 4:

$P = 62.31\ MW \qquad Q = -7.39\ MVAR$

The phases loading is symmetrical:

$I_{Pos} = 0.61\ pu \qquad I_{Neg} = 0.00\ pu \qquad I_{Zero} = 0.00\ pu$

Current per phase: $I = 0.61\ pu$

$I_{max} / S = 9.7 \cdot 10^{-3}\ pu/MVA, \qquad where\ S = abs(P + jQ)$

The same line section with disconnected phase R supplies into bus 4:

$P = 44.17\ MW \qquad Q = -11.52\ MVAR$

Phase loading is not symmetrical in this case:

$I_R = 0.00\ pu \qquad I_S = 0.71\ pu \qquad I_T = 0.70\ pu$

What corresponds to considerable non-symmetrical currents:

$I_{Pos} = 0.45\ pu \qquad I_{Neg} = 0.34\ pu \qquad I_{Zero} = 0.10\ pu$

$I_{Max} / S = 15.6 \cdot 10^{-3}\ pu/MVA$

Such operation mode is not allowed normally, but it is included here just for comparison.

In case of short-circuiting of zero- and negative-sequence systems by symmetrization compensators we get the following conditions:

Power supply into bus 4:

$P=53.06\ MW \qquad Q = -14.22\ MVAR$

with symmetrical currents of I = 0.54 pu.

On the line section itself (behind the compensator) we have as expected non-symmetrical conditions:

$P = 53.06\ MW \qquad Q = -14.56\ MVAR$

$I_R = 0.00\ pu \qquad I_S = 0.84\ pu \qquad I_T = 0.84\ pu$

$I_{HG} = 0.41\ pu$

$I_{Pos} = 0.54\ pu \qquad I_{Neg} = 0.42\ pu \qquad I_{Zero} = 0.14\ pu$

$I_{Max} / S_{Useful} = 15.37 \cdot 10^{-3}\ pu/MVA$

Compensator currents:

$I_{Pos} = 0.001\ pu \qquad I_{Neg} = 0.41\ pu \qquad I_{Zero} = 0.14\ pu$

$I_{HG} = 0.41\ pu$

In case of the mixed compensation by series capacitors and shunt compensation of the zero-sequence system the following conditions are valid:

Power supply into bus 4:

$P = 73.86\ MW \qquad Q = -19.24\ MVAr$

with symmetrical currents of $I = 0.75\ pu$

On the line section itself (behind the compensator) we have, of course, non-symmetrical conditions:

$P = 73.86\ MW \qquad Q = -30.89\ MVAR$

$I_R = 0.00\ pu \qquad I_S = 1.36\ pu \qquad I_T = 1.36\ pu$

$I_{HG} = 2.35\ pu$

$I_{Pos} = 0.78\ pu \qquad I_{Neg} = 0.00\ pu \qquad I_{Zero} = 0.78\ pu$

$I_{Max\ Phase} / S_{Useful} = 17.80 \cdot 10^{-3}\ pu/MVA$

$I_{HG} / S_{Useful} = 30.82 \cdot 10^{-3}\ pu/MVA$

The compensator currents are:

$I_R = 0.82\ pu \qquad I_S = 0.76\ pu \qquad I_T = 0.77\ pu$

$I_{HG} = 2.35\ pu$

The both series capacitors must have rated power at least 7.8 MVAr (per unit basis of 100 MVA).

Now let us analyse the results. As concerns to the thermal load ability of the line section, the compensation solutions are very different. The first solution gives the biggest thermal limit, over 60% of the original value can be achieved. In the second compensation solution it should be distinguished between thermal limit of the phase wires and of the highground wire. The phase wires limit the transmission capacity to about 55% compared with non-disturbed operation, whereas the highground sets the limit to about 30% of the original value. The highground wire, which is to be installed additionally, should be dimensioned to higher currents than the phase wires, to do not become a limiting factor.

It is clear, that the more flexible solution, which we have with the first compensation method, gives also better technical results. The more flexible shunt symmetrization compensators can be used during normal operation for reactive compensation and power flow control. It should be emphasized, that at the second compensation technique more simple equipment, though with higher ratings, has been used.

V. CONCLUSIONS

This paper has demonstrated the possibility to enhance system availability by use of symmetrization compensators. The efficiency of these depends on system structure, but the results in the paper indicate that competitive solution can be provided.

Modern technology opens flexible possibilities in operation of electrical power grids. The presented possibilities for symmetrization compensation of line sections with one damaged phase can be used in cases when higher reliability is required, but usual grid extension is not desired or is difficult. The solutions provide an environment friendly, faster and probably cheaper way in comparison to construction of new lines.

It should be mentioned, that it is also possible to compensate cases with two damaged phases, but this is out of scope of this paper.

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