Protection of Transmission Lines using Series Compensation Capacitors in Cameroon-Southern Interconnected System.

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Abstract-The continuous increase in disturbances on the Cameroon Southern interconnected electric power system resulting in its inability to reliably meet demands due to improperly protected and old unmaintained transmission and distribution systems, insufficient investment and upgrade of infrastructures. Furthermore, rapid load growth and low water levels of the reservoirs create much stress on the power balance problem and on the existing transmission lines. In this paper, a protection system for transmission lines using series capacitors is discussed in detail.

Keywords: Protection, Disturbances, Series compensation, Transmission system.

1. INTRODUCTION

The existing national electricity generation and transmission system in Cameroon under AES SONEL is principally separated in to three independent subsystems, the southern interconnected system, the northern system, and the eastern system

Currently the southern interconnected systems is not able to meet the demands, especially in the dry seasons due to disturbances, low water levels of the reservoirs, low rainfall levels, insufficient investment in transmission, distribution infrastructures, and thermal generation. The imbalance between the supply and the demand is exacerbated by many disturbances occurring on the lines and rapid demand growth over the last five years. The electricity in this interconnected system is mainly generated from old hydro power stations at Edea and Song- loulou, both on the Sanaga River.[4-6]

Since building new transmission lines are difficult and expensive, reinforcement and or optimisation of existing ones are the solutions in common used. The transmission systems are increasingly over-loaded. This may reduce system stability margins, thus accurate and fast fault clearance is needed.

In order to carry out transmission network reinforcement, a series capacitor compensation method being one of the simplest and cheapest methods is use. The series capacitor is used to increase power transfer capacity and voltage regulation ability, reduce power losses and inductive reactance of the transmission lines.

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However, series capacitors, having non-linear components including thyristor controls, turns to introduce harmonics, subsynchronous resonance in generators resulting from short circuits, line switching, This may undermine the effectiveness of distance protection relays. The distance protection relay looks at the voltage to current ratio to determine the fault distance and is able to detect if the fault is within or out of its protection zones. If it could be possible to know that the capacitor forms part of the fault circuit, then the settings of the relay could be corrected, but this is not always known in advance.

Furthermore, it is always very difficult to measure the fundamental frequency component of the voltage and current as placing the series capacitor; the system becomes an RLC resonant circuit. Determining whether or not the capacitor is in fact involved in any given fault loop and successful calculation of the compensated line current for the phase to ground faults are problems, using the dedicated logic for series compensation with the presence of harmonics may increase the security to the distance elements.

In this paper, different solutions are compared, discussed and solutions for the above issues are provided.

In general some compensation equipment in existence includes;

- High voltage power capacitors one phase and three phase units for film power and surge protection.
- High voltage capacitors banks.
- Enclosed automatic capacitor banks for medium voltage up to 36 kV.
- Harmonic filters and C – type filters which are use to reduce harmonic current due to non-linear loads.
- Low voltage power capacitor units.
- Fixed and automatic capacitor bank.
- Thyristor-switched capacitor bank. [9]

11. CAMEROON-SOUTHERN INTERCONNECTED SYSTEM

In Cameroon, the following voltages exist:

- Low voltage: 380V/220V
- Medium voltage: 10kV-15kV – 30kV
- High voltage: 90kV-110kV
- Very High Voltage: 225kV

The southern interconnected system is made up of;
- 480 km of 225kV lines
- 863 km of 90kV lines. [10]

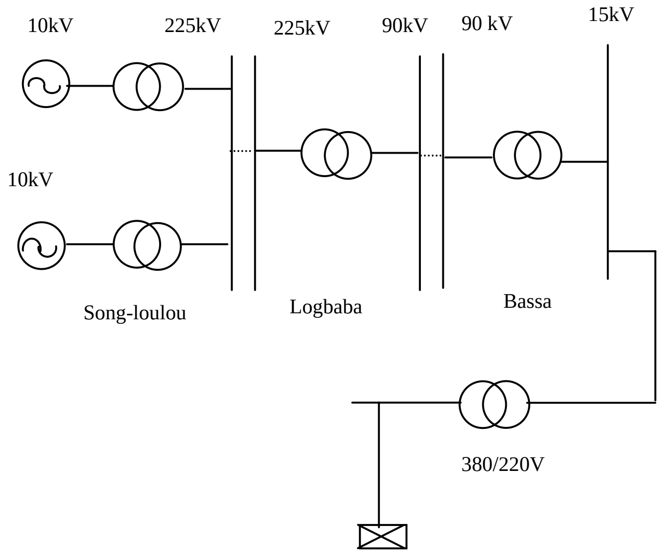

Fig.1.High Voltage and Very High Voltage

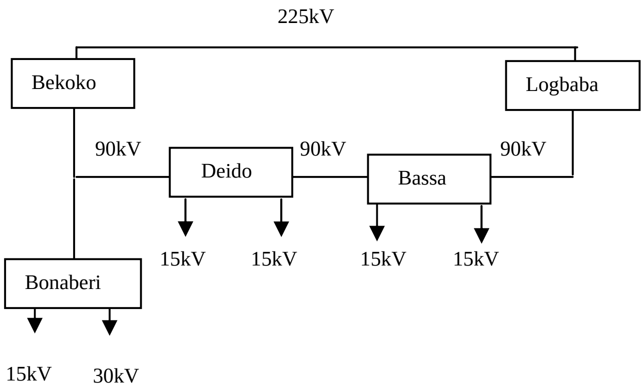

Fig.2. Interconnection of the Southern System

For the protection of lines we have:

Distance protection schemes (non pilot protections). The principle here is that the fault is detected by measuring the impedance on the line. This method allows for multiple Zone distance protections.

Pilot protection scheme uses a communication path to send signals from the relaying system at one end of the line to that at the other end. Since information for processing is from both ends of the line, the protection decisions made by relays are more intelligent. The conditions (currents and voltages) at both ends of the line are monitored. These signals are sent to the local relay equipment only, where trip signals may be generated and sent to the circuit breaker at the local relay location.
Phase comparison relaying, which is differential in nature and base on the fact that it compares the phase current at both ends of the line to see if there is any fault on the line. This method requires a communication between the line terminals, which is costly to install and maintained.

It is necessary having both the pilot and non-pilot protection schemes on the transmission lines. However, the non-pilot protection scheme is used here in preference to the pilot protection due to the following reasons:

- Non-pilot schemes are based on measurement of impedance and it is needless constructing communication links, which are the main elements in the pilot scheme thus reducing cost.
- The communication link is very weak and may lead to failure of the pilot system.
- The communication link is very costly to install and require regular maintenance.
- The communication link is volatile and communication can be lost if the relay involves fail to operate for an actual fault as they do not see a trip signal from the opposite end of the line or the relay involves operates when there is no fault due to the fact that there is no block signal seen.
- It is easily calculating the positive sequence impedance of the fault using only two quantities the resistance (R) and the reactance (X) and once it is interpreted, it become easy to locate the fault and then makes a relaying decision. [1], [3]

Reliable operation of the distance protection schemes depends on the accuracy of impedance measured. Due to uncertainty in these measurements, it is necessary to rely on stepped zones of protection not keeping aside the speed with which a fault can be cleared.

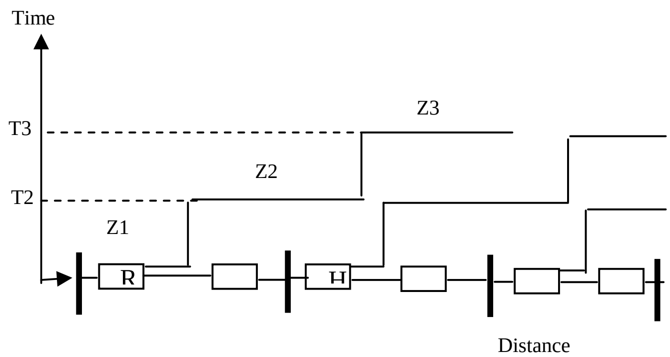

Fig.3. Three Zones of Distance Protection Relays.

This system protects any given zone of transmission line with multiple zones. The functioning of the system is as follows to avoid unnecessary tripping of the relays.

Zone 1: The tripping within this zone of protection is with no intentional delay. This zone must underreach the remote end of the line, since it is not possible to distinguish the exact location of the faults near the remote bus. This zone covers 85 to 90% of the total line length for phase relays and about 75% for ground relays.
Zone 2: The purpose of this zone is to cover the remote end of the line not covered by zone 1 protection. Zone 2 must reach well beyond the remote bus. This requires a time delay in order to coordinate with the zone 1 protection of the adjacent line relay at H.

About 0.25seconds plus the adjacent breaker opening time is usually recommended to assure this coordination. If the remote relay is a time over-current relay rather than a distance relay, a longer coordination time setting is recommended.
The impedance setting of zone 2 protections should be at least 120% of the protected line impedance. Zone 2 of the relay R protection should not overreach the zone 1 of the adjacent downstream relay.

Zone 3.The primary purpose of this zone of protection is to backup the failure of the breaker at H. If this breaker fails to open for a fault on its protected line, the breaker at R should be caused to open as a backup protection. The time delay for zone 3 protections should be much longer at about 1 to 2 seconds.

Delay tripping at **zones 2** and **3** faults allows time for **zone 1** reaction of the relay on the adjacent line if the fault is actually on that line section and also ensures co-ordination thus avoiding the shutting down of longer sections of the line than needed for fault clearing. The faults occurring at zone 2 turn to cause more damage to the system since the faults cannot be cleared instanteously from remote ends. [1]

III. EFFECTS OF SERIES CAPACITOR ON DISTANCE PROTECTION RELAY

All series capacitors are equipped with protective elements to either reduce or eliminate over voltage across the capacitors. The protection can be a spark gap set to flashover at a given voltage (introducing a varying resistance component) or a metal oxide varistor using complex energy monitoring schemes (introducing a varying and a non –linear resistance) or a circuit breaker which closes during a fault creating a bypass around the capacitor for high fault currents.

The simplest series capacitor protection scheme (spark gap) removes the series capacitor when the series capacitor voltage exceeds a chosen threshold. However, the spark gap firing voltage threshold should be high enough that the spark gap does not fire the external faults.

The metal-oxide varistors on the other hand does not fully remove the series capacitor, thus the capacitive reactance can be very non-linear. The effective reactance of the metal-oxide varistor protected bank can be approximated using an iterative model.
A series capacitor also creates discontinuity in the apparent impedance of the line when view from the relay site and this is due to the negative reactance value of the capacitor, thus far end faults may appear to be outside zone 1 and may not trip during zone 2 time while close in faults will appear to be reverse faults due to the fact that the reactive component of the fault impedance seen is negative and relay may trips for faults it shouldn't.

However the above problems are solved using a time delay, which gives the capacitor's protection time to arc and effectively removed the capacitor from the circuit altogether and accurate measurement of impedance.

As the transmission line load increases, the impedance seen by the relay decreases and the relay turn to confuse normal load for a fault at some points (loadability limits)

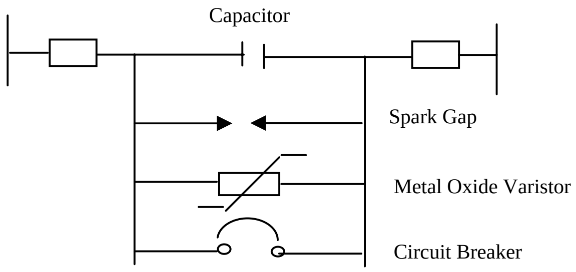

Fig.4. Series capacitor protection

IV. THREE PHASE SYSTEM

On considering a three-phase system, there are total of ten different types of faults to be handle by six relays (three phase distance and three ground distance relays) for each transmission line. The figures below are used to represent the symmetrical component of each fault, which are the positive, negative and the zero sequence impedances interacting in different ways based on the system operation state.

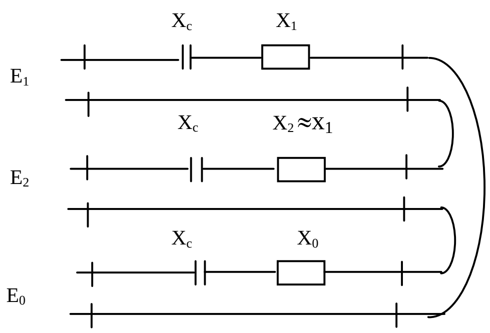

Fig.5. Phase to Ground Fault Symmetrical Network

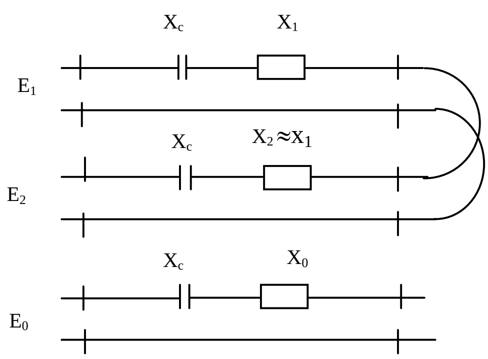

Fig.6. Phase-to-Phase Fault Symmetrical Network

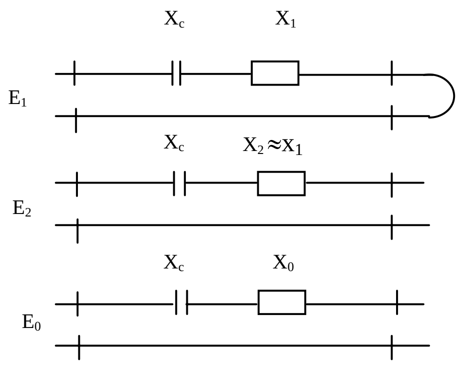

Fig.7. Three Phase Fault Symmetrical Network

Let us assumed that the fault is known, than we have three cases:

- **Case of a three-phase fault**. Any phase voltage should be divided by the respective phase current to have the fault impedance.

- **Phase to phase or phase to phase to ground faults.** The difference between the two affected phase voltages is used as the necessary voltage and the difference of the corresponding phase currents serves as the necessary current. A ratio is calculated and the imaginary portion of the result tells us the inductive reactance to the fault.

- **Single phase to ground faults**. Here, the fault impedance is calculated as follows;

$$\mathbf{Z_{fault}} = \frac{V_{phase}}{I_{phase} + mI_o}$$

$$\text{With m} = \frac{Z_0 - Z_1}{Z_1 - Z_c}$$

The value of **m** is when the capacitor is switched in to the line and based on fault location.

$\mathbf{Io} = \frac{1}{3}$ **(Ia+I$_b$+Ic)** and is the zero sequence current.

An iterative method shall be used here to find the solution since the value of **m** is not known. The algorithm first get the frequency of the appropriate voltage and currents and look for the subsynchronous values which indicates that the capacitor was present in the line during the fault and with a strong value, a guess is made for the value of **m** and if this value is not found, then the fault impedance is determined. If it occurs at 50% of the line, then the fault impedance is found based on this value, which is used to generate a good idea on the actual fault location, thus use to get a new estimate for **m**.
This process continuous until the change in fault impedance reaches the tolerance value.

The impedance of a typical transmission line is highly inductive and the phase angles depending on bundling, spacing of conductors and size will range between 65-85 degrees.
The impedance, however, doesn't include the impedance of the fault itself, which is typically an arcing resistance (fault arc resistance) in series with the tower, footing and grounding resistances. As per Warrington, it is calculated thus:

Rarc = 8750(s+ut) / $I^{1.4}$
Where:

Rarc = fault arc resistance (Ω)
S= conductor spacing (ft)
u = wind velocity (mi/hr)
t = time(s)
I = rms fault current (A)

The below figure shows the Cameroon-Southern Interconnected System having series capacitors at one end and fault located at the end of the line. The connected series capacitor, transmission line and the system source may result in an RLC resonant circuit. When there are any switching operations external to protection lines section, it can lead to changes in source impedance.

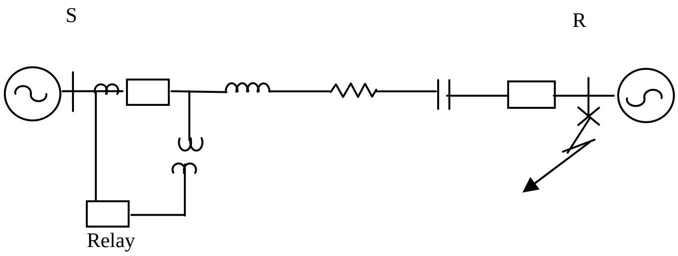

Fig.8.Series Capacitors and a Fault at the end of the line

The above transmission line is a 50% series compensation system i.e. the series capacitor reactance is equal to 50% of the positive sequence line reactance. If there is a fault at the receiving station as shown, the underreaching distance relay located at sending end station should not operate. What happens if we set the reach at about 80% of compensation impedance? The inductance and the series capacitor will create subharmonic that can cause severe overreach of the distance element.

V. HOW TO STOP OVERREACH OF DISTANCE ELEMENT

The voltage drop at the end of the line of figure 8 due to a phase to ground fault, can be calculated using the equation below:

$$V_{cal} = (I_A + K_o.I_G)\, Z_L - jI_A X_C$$

Where:

V_{cal} = Voltage drop at end of the line
I_A = A phase current at the relay location
K_0 = Zero sequence compensation factor
I_G = Ground current at relay location
Z_L = Line Impedance at positive sequence
X_c = Capacitive reactance seen by relay

Now the ratio of the measure voltage to the calculated voltage would result in unity, if the fault resistance and the mutual coupling are ignored.

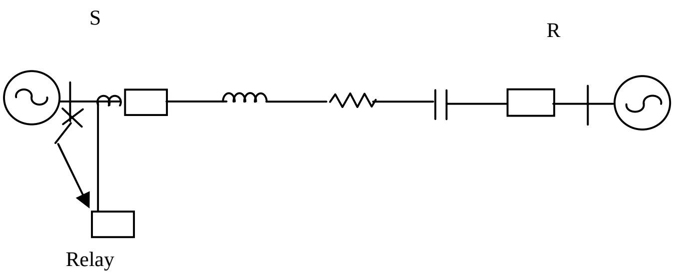

Fig.9. Fault moves to the other end of the line

If this fault is moved to the other side of the line (series capacitor), the calculated voltage turn to decrease since it include the series capacitor while the measure voltage increases due to the fact that the series capacitor is no longer found between the fault and the relay and this line looks electrically longer. On getting the ratio of the measured voltage to the calculated voltage, it is non-longer unity but greater than unity. [7], [8]

VI. CONCLUSIONS

Distance protection relays for transmission lines have been given. Possible effects on the working reliability of the distance relay for a transmission line having series capacitors are discussed.

For faults near the far end of the line, just beyond the threshold, the fault must be cleared by all means. This is done by providing more than one distance-relaying element within the same relay package and setting the different elements to different thresholds and with different delay times.
When the ratio of the measured to the calculated voltage is less than a pre-defined threshold, the Zone 1 distance element should operate, otherwise it is blocked.

The paper only gives some principle methodology how to deal with the protection of transmission lines using series compensation capacitors. Simulations and practical tests are critically needed. This problem will be approached be further study and work.

VII. ACKNOWLEDGMENT

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IX. BIOGRAPHIES

Dan Nchelatebe Nkwetta was born in Ndungweh lebang Fontem, Southwest Province of Cameroon on March 12, 1975. He received a Bachelor degree in 1998 and a master degree in 2000 both in Electrical Engineering from the University of Douala, Cameroon. He was the head of Electrical Engineering Department and Lecturer of University College of Technology Buea, Government Technical College Limbe and St.Hubert's College Douala Cameroon. His area of interest is Disturbances in Electrical Power Systems. Currently, he is a predoctoral student at the Katholieke Universiteit Leuven, Belgium.

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Ronnie Belmans (S'77-M'84-SM'89-FM'05) received the M.S. degree in electrical engineering in 1979 and the Ph.D. degree in 1984, both from the K.U.Leuven, Belgium, the Special Doctorate in 1989 and the Habilitierung in 1993, both from the RWTH, Aachen, Germany. Currently, he is a full professor with the K.U.Leuven, teaching electric power and energy systems. His research interests include techno-economic aspects of power systems, power quality and distributed generation. He is also guest professor at Imperial College of Science, Medicine and Technology, London-UK. Since June 2002 he is chairman of the board of directors of ELIA, the Belgian transmission grid operator.