Electronic Petersen Coil

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***Abstract* — This paper presents the study of a resonant grounded network with an Electronic Petersen Coil (EPC).**

The topology considered to perform an Electronic Petersen Coil is based on the full bridge Single-Phase Voltage Source Inverter (VSI). To guarantee the minimization of filtering components to obtain high quality voltage and current waves at the output of VSI, three level Pulse Width Modulation (PWM) is used.

The control of the current injected by the VSI so that it reduces the network's single-phase earth-fault current is developed and properly validated by the carried out simulations.

In order to test the EPC, a Medium Voltage (MV) network is designed, including, MV Transformer, aerial lines and the loads.

The tests to validate the proposed EPC were done using Matlab/*Simulink* software.

***Index Terms* — Active earthing, Distribution Networks, Electronic Petersen Coil, Resonant Grounding, Single-Phase Voltage Source Inverter.**

I. Introduction

Usually, earthing systems are divided into two main categories: low impedance earthing and high impedance earthing. Low impedance earthing involve the solid earthing or through a current-limiting device, such as a resistor or reactor. In what concerns to high impedance earthing, it is achieved with Petersen Coils or left unearthed (isolated networks).

Utilities choose neutral connection based on historical, economical and safety requirements. However, they seek for improvements in order to enhance the power quality of electrical energy delivered and modernize their own distribution networks.

In resonant grounding, an adjustable reactance is installed between the system's neutral and the earth. This reactance must match the power system capacitances, to compensate the capacitive current over the fault location by an inductive current. This condition is usually called the resonant point of the network.

Typically, there are two different types of Petersen Coils and they are classified according to the method of adjustment:

- Reactors adjustable in finite steps, by means of taps on windings which are connected or disconnected through switches;
- Reactors which are continuously adjustable by variation of the reluctance of the magnetic circuit, which is achieved by varying the gap of the magnetic core of reactor.

These solutions aren't able to control the current that flows through the system neutral when a fault occurs, because reactors are passive elements.

The proposed Electronic Petersen Coil (EPC), aims to have the advantages of the traditional resonant networks and to control the neutral current, to guarantee controlled and reduced currents.

II. Study of Resonant Ground

Due to the order of magnitude of the positive-sequence component impedances of transformers and lines, those can be neglected when compared with the zero-sequence component. Hence, the analysis of the faulty resonant distribution system is done assuming symmetrical three-phase voltage sources and neglecting the resistance and inductance of the line.

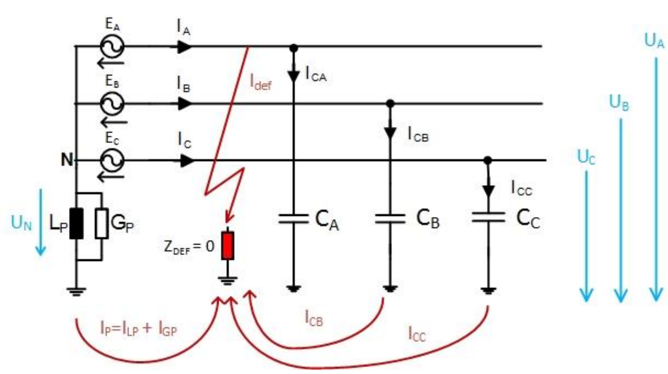

Figure 1: Equivalent circuit for a system with resonant earthing and an Earth-fault in phase A.

If the network is symmetrical, then:

$$C_A = C_B = C_C \tag{1}$$

$$G_A = G_B = G_C \tag{2}$$

Representing the system using the symmetrical components, the equivalent circuit is depicted in figure 2, where C_E is the-phase to-earth capacitance of the system and G_E is the phase-to-earth admittance, which represents the line losses.

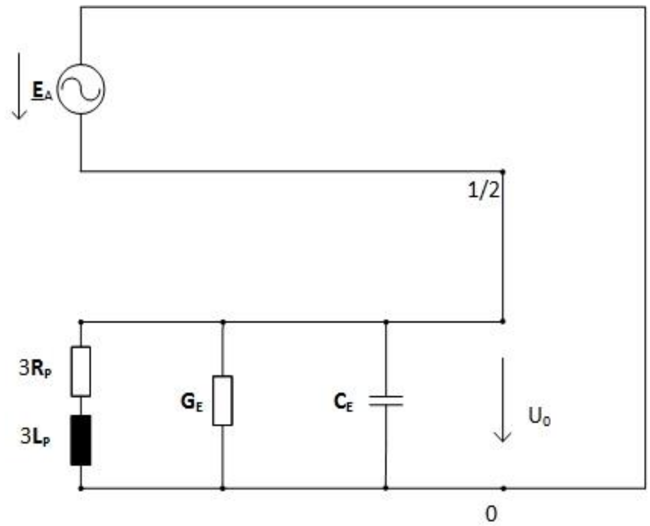

Figure 2: Equivalent circuit of the system using symmetrical components.

The total admittance of the zero-sequence component is given by:

$$\overline{Y_0} = j\omega C_E + \frac{1}{3R_{LP} + j3X_{LP}} + G_E \tag{3}$$

After some calculations, and with the assumption that $R_{LP} \ll X_{LP}$, (3) becomes in (4):

$$\overline{Y_0} = j\omega C_E \left(1 - \frac{1}{3\omega^2\, L_{LP}\, C_E}\right) + G_E \tag{4}$$

To minimize the current,, it is necessary that the impedance is maximal, which implies that the imaginary part of (4) is zero.
And it follows:

$$\omega_0 C_E = \frac{1}{3\omega_0 L_{LP}} \tag{5}$$

Where ω_0 is the resonance frequency of the circuit.

$$\omega_0 = \frac{1}{\sqrt{3L_{LP}\, C_E}} \tag{6}$$

At this point, the current at the neutral is equal to the capacitive current of the network, and the system is in resonance.

It is usual to define the detuning factor ν and the damping d as follows [1].

$$\nu = \frac{I_{LP} - I_{C_E}}{I_{C_E}} = 1 - \frac{1}{3\omega^2\, L_{LP}\, C_E} \tag{7}$$

Where, I_{C_E} is the capacitive current of the system ($I_{C_B} + I_{C_C}$) and I_{LP} is the current from the Petersen Coil (neutral).

$$d = \frac{G_E}{wC_E} \tag{8}$$

Rewriting the admittance of the zero-sequence component:

$$\overline{Y_0} = \omega\, C_E\, (j\nu + d) \tag{9}$$

Thus, the fault current can be expressed in terms of the detuning factor and damping.

$$\overline{I_{DEF}} = 3\, E_A\, \omega C_E\, \left(j\nu + d\right) \tag{10}$$

III. STUDY OF THE VSI

The topology of the inverter is shown in figure 3. The converter has two arms, and each one with two IGBTs two IGBT's (Insulated Gate Bipolar Transistor) and diodes connected in anti-parallel.

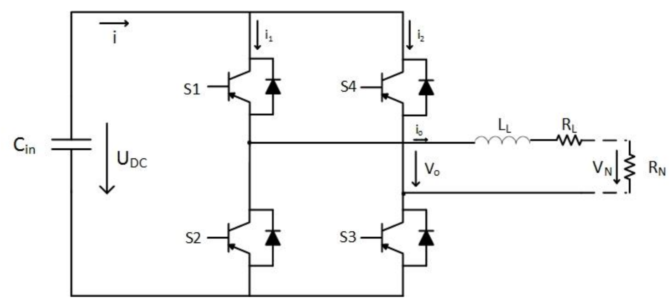

Figure 3: Topology of the Full Bridge VSI.

Since, the inverter is connected to the neutral point of the distribution network, only when an earth-fault occurs in the network side, it can be assumed that the VSI sees an equivalent resistance R_N connected to its terminals.

$$R_N = \frac{V_N}{I_N} \tag{11}$$

The inverter is modulated by the three level PWM technique, so, the output voltage can present one of three voltage levels: $+U_{DC}, 0, -U_{DC}$.

In order to guarantee the correct functioning of VSI, the following relation must be respected.

$$U_{DC} > V_N \tag{12}$$

The connection between the VSI and the neutral is done by a coupling transformer, which provides the necessary galvanic isolation and reduces the voltage level to comply with the limits of power semiconductors.

A. *Sizing of Coupling Transformer*

The connection of the VSI to the neutral point is illustrated in figure 4.

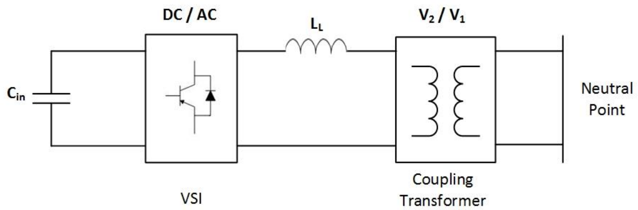

Figure 4: Representation of the connection of the VSI to the neutral point through a coupling transformer.

The summary of the characteristics of the coupling transformer are in the table below.

Table 1: Characteristics of the coupling transformer.

Parameter	Value
Frequency	50 Hz
Nominal Power	100 kW
Primary Voltage	15 kV
Secondary Voltage	400 V

Since, this transformer is monophasic, the maximal voltage at the neutral is:

$$V_N = \sqrt{2}\,\frac{400}{\sqrt{3}} \approx 327\,V \tag{13}$$

In order to guarantee that (12) is valid, 1.2 kV IGBTs were chosen.

B. *Filtering Inductance*

The filtering inductance, L_L, is calculated as follows [2].

$$L_L = \frac{U_{DC}}{4\,f_s\,\Delta I_0} = 0{,}0417\,H \tag{14}$$

Where, U_{Dc} is the DC link voltage, f_s is the switching frequency and $\Delta I_0$is the current ripple.

Table 2: Summary of the quantities used for the calculation of the filtering inductance.

Parameters	Value
Switching Frequency	3 kHz
DC Voltage	500 V
Current ripple	10 %

IV. CONTROL OF THE VSI

The VSI is controlled using a linear approach. This means that the block diagram of the current control can be represented as in figure 5, where K_i represents the gain of a current sensor.

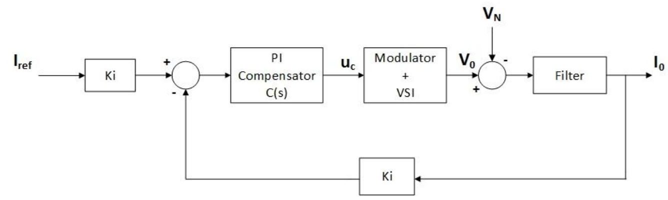

Figure 5: Block diagram of the current control.

The modulator and the power converter may be represented as a first order model [2].

$$G_C(s) = \frac{V_{0av}(s)}{u_c(s)} = \frac{K_D}{1 + sT_d} \tag{15}$$

The gain K_D depends on U_{DC} voltage and on the maximum $u_{c_{max}}$ value of the modulating voltage.

$$K_D = \frac{U_{DC}}{u_{c_{max}}} \tag{16}$$

The pole T_d is the average delay time, which is one half of the switching period.

$$T_d = \frac{T_s}{2} \tag{17}$$

To control the current injected by the VSI, it is usual to choose a PI compensator, since it guarantees fast response times and zero steady-state error to the step response.

$$C(s) = \frac{1 + sT_z}{sT_p} \tag{18}$$

To cancel the compensator zero T_Z , it is made coincident with the pole introduced by the filter (RL).

Then, the closed loop transfer funtion of the current controlled VSI is:

$$G_{cf} = \frac{I_0(s)}{I_{ref}(s)} = \frac{\dfrac{K_D K_i}{T_p T_d\,(R_L + R_N)}}{s^2 + \dfrac{1}{T_d}\,s + \dfrac{K_D K_i}{T_d T_p(R_L + I}} \qquad (19)$$

Then, comparing to the second order transformer function in the canonical form the expression for T_P is obtained.

$$T_p = \frac{2\,K_D K_i\,T_d}{R_L + R_N} \qquad (20)$$

A. *Reference current*

In order to guarantee that the current injected by the VSI cancels the earth-fault current (10), it is necessary that the current and the voltage at neutral point are in quadrature.

Since the neutral voltage is imposed during an earth-fault, and it is easy to measure the neutral point voltage, the strategy to obtain the reference current is detailed in the figure 6.

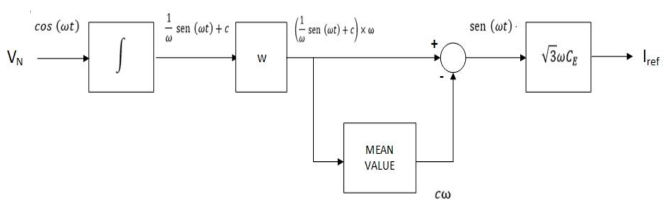

Figure 6: Block diagram used to obtain the reference current for the VSI.

This algorithm is validated by the performed simulation, as can be seen in figure 7.

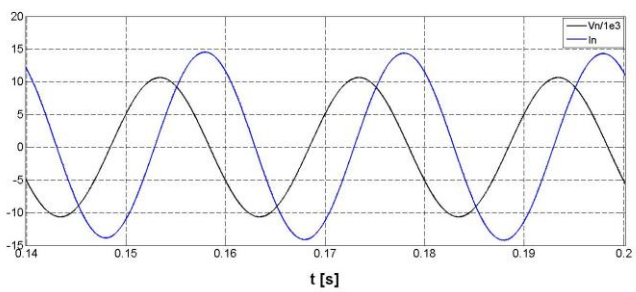

Figure 7: Neutral Voltage divided by 1e3 (black) and neutral current (blue).

B. *DC Link Voltage*

Nowadays, the use of diode rectifiers in substations is widespread. Typically, all the auxiliary services of substations are provided by a dedicated transformer [3], and that is why it is usually named Auxiliary Services Transformer (AST).

In order to optimize the solution, and to avoid oversizing it with the introduction of an individual diode rectifier only dedicated to the VSI, it is assumed that the DC voltage can be provided by the existent rectifiers.

This can be done because the AST reduces the voltage from de MV to the LV (low voltage), 400 V, and since the rectifier is fed by the AST the maximum output voltage is given by (21).

$$U_{DC_{max}} = \sqrt{2}\,400 \approx 566\,V \qquad (21)$$

Considering a variation of 10% for the DC voltage, it is assumed that the DC voltage is around 500V.

V. ELECTRONIC PETERSEN COIL

The proposed EPC is presented in figure 8.

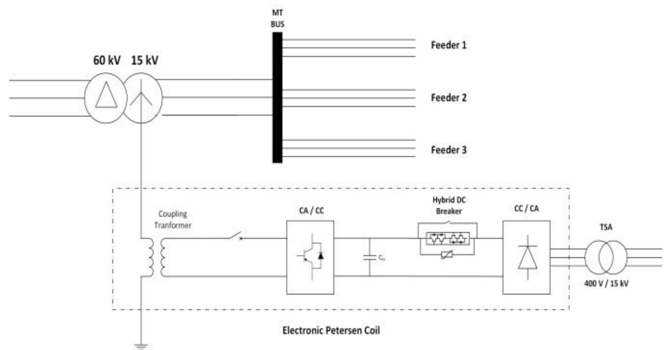

Figure 8: Schematic of a distribution network earthed by an Electronic Petersen Coil.

A. *Protection of the DC link*

To protect the DC link, in particular, power electronics semiconductors, ir is proposed to use a Hybrid DC breaker, in order to guarantee selectivity of a faults at DC side.

This technology was based on the ABB Hybrid HVDC Breaker, for further details see [4], [5].

At figure 9 is presented the scheme of the ABB technology.

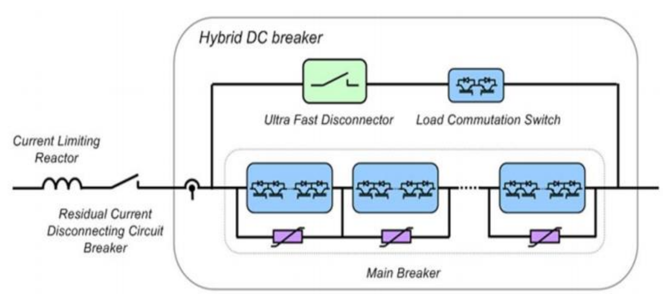

Figure 9: ABB Hybrid HVDC Breaker scheme.

For the protection of the EPC, only one IGBT will be necessary in the main breaker to break the current in either direction.

VI. Simulation Results

To simulate the EPC it was used the MatLab software, in the *Simulink* environment.

The model simulated was based on figure 8. It comprises the distribution network model, the VSI inverter model and its own control, the coupling transformer and the substation transformer (60kV/15kV).

To avoid seeing the transient phenomenon and to observe the result of EPC operation, the earth-fault was simulated over six periods (120 ms). The end of the earth-fault occurs when the breaker at MV Bus opens.

In the next figures are shown the voltages and the currents of the network at the faulty feeder.

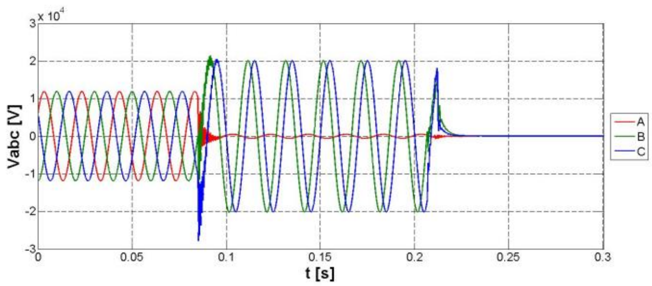

Figure 10: Network line-to-earth voltages with the EPC.

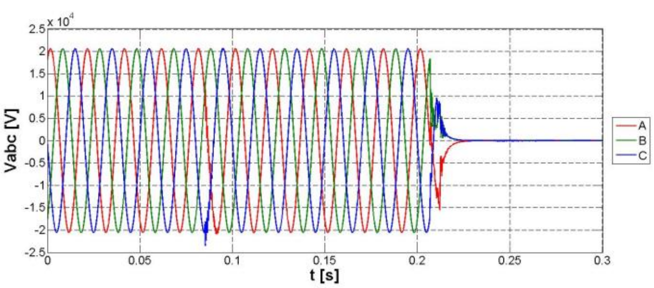

Figure 11: Network line-to-line voltages with the EPC.

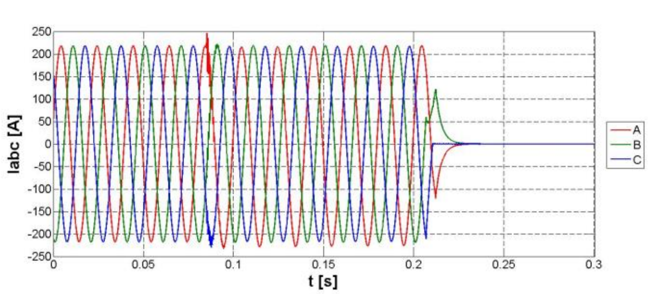

Figure 12: Network line currents with the EPC.

The presented results show the expected behavior, as this is the behavior of a traditional resonant ground.

As seen in figure 10, as soon as, the earth-fault occurs the unfaulty phases rise to the value of the line to line voltage ($\sqrt{2}$ 15 kV) and the faulty phase (A) is earthed.

From figure 11 it can be concluded that, as expected, the symmetry of the voltages triangle is kept, despite of the earth-fault [6]. This, associated with the behavior seen at figure 12 (line currents kept unchanged despite of the earth-fault, because the EPC compensates the earth–fault current) provides a particular advantage for this type of grounding system. For this reason, in the resonant grounding, the continuity of supply is greatly improved [7], [8], [9] and [10].

To finish the simulation results we can see that the earth-fault current is reduced to below of a tens of amperes, figure 13.

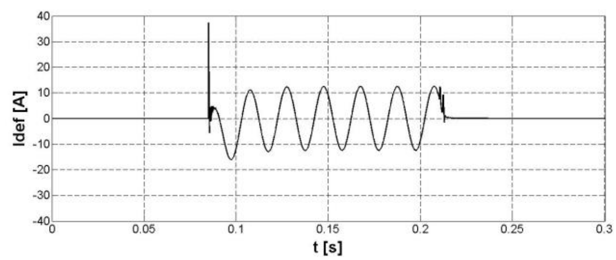

Figure 13: Earth- Fault current at the EPC earthing.

In figure 14, is depicted the neutral current. It is in opposite phase with the earth-fault current, which would be expected, because it is situated upstream of the MV bus, while the earth-fault current is downstream.

It is still worth to mention that the neutral current is controlled by the VSI.

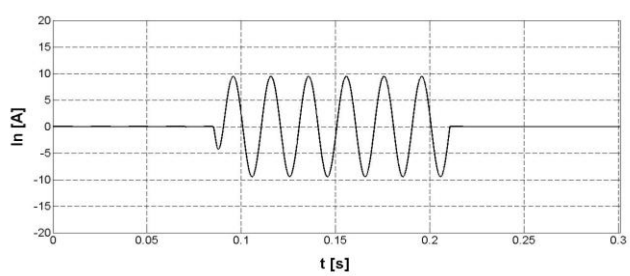

Figure 14: Neutral current at the Electronic Petersen Coil earthing

VII. Conclusions

This goal of this paper was to propose an EPC. The developed solution included a coupling transformer, a voltage source inverter, and some filtering components connected between the neutral and the VSI. The transformer is required to provide galvanic isolation and to reduce the voltage level of the neutral point to the semiconductors used in the VSI.

The control of the VSI was explained and the simulation results indicate that the current at neutral point is controlled.

For rapid and selective protection of DC link, was proposed a modern Hybrid DC breaker technology was proposed.

The solution proposed in this paper has the advantages of a classical resonant grounding with the possibility to control the current that flows through the neutral point, in contrast with the traditional Petersen Coil made by reactors. The EPC can be fitted easily on existent substations without the necessity to add a new diode rectifier to provide the DC voltage to the VSI.

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