Abstract - Nowadays the stability of a power grid is fundamental for the proper functioning of a country, and as such, it is in constant innovation of its processes and products to thereby diminish its unavailability.

In this dissertation, the behavior of a 30 kV medium voltage network was studied by comparing the duration of voltage sags in a network with a typical circuit breaker against a network with a fast circuit breaker assisted by semiconductors model developed throughout this thesis.

To carry out this analysis, network models and their associated control mechanisms were developed for circuit breakers. A model (in Matlab / Simulink) of the electric arc and the driver circuit of the circuit breaker was also developed to allow for a more detailed analysis of the phenomenon of opening and closing of the circuit breaker under study.

Lastly, the results were compared, and conclusions were drawn about the implementation of a circuit breaker of this type in a 30 kV network compared against existing ones.

Index Terms - Circuit Breaker, Driver, Electric Arc, Voltage sag

I. INTRODUCTION

The notion of quality in our day-to-day life is usually related to the fact that a certain good or service satisfies our desires and expectations. The power quality of a power grid is usually associated with the quality of the voltage waveform, its availability and quality of service [4].

In this dissertation there will be a focus on the first topic, more precisely on the point relative to the value of the voltage module since the solution presented focuses on the decrease in the duration of the voltage sags.

For a best understanding of this phenomenon is important to define the depth of a voltage sag:

\[ D_{sag}[^\%] = \frac{V_{\text{Rate}} - V_{\text{sag}}}{V_{\text{Rate}}} \times 100 \]  

Within this topic on the quality of the shape of the voltage wave, it is worth noting the existence of the modified CBEMA curve; current ITIC / IEEE 1100 (Figure 1).

II. EXISTING CIRCUIT BREAKERS

A circuit breaker is an electromechanical device that allows for the protection of electrical circuits against overloads and short circuits, interrupting abnormally high currents or short circuits. The manufacture and operation of each circuit-breaker is strongly dependent on the voltage level at which it is going to work.

A. Low Voltage Circuit Breakers

In this range, thermal, magnetic and magnetothermal circuit breakers are of major importance (the latter being a combination of the two above).

1) Thermal Circuit Breakers

They operate under the basic principle of deformation of bimetallic plates caused by their heating. The opening of contacts caused by the deformation of these plates serves to protect the circuits against prolonged overloads. Despite being a simple and robust system, it is slow and not very accurate.
2) Magnetic Circuit Breakers

They work by the effect of a magnetic field created by the passage of the current, that is, there is a magnetic field created by the current that runs through the inductor. The magnetic field in turn moves the iron core that will mechanically move the contacts of the circuit.

The main function of this circuit-breaker is to protect electrical installations against short circuits. It is a precise system that triggers (opens the circuit breaker) according to a previously chosen time curve.

3) Magnetothermal Circuit Breakers

These circuit breakers are those normally installed in residential electrical switchboards, working with the combination of thermal and magnetic effects. They protect against overloads and short circuits.

B. Medium and High Voltage Circuit Breakers

In this range the circuit breakers operate in a totally different way. They work in partnership with a Protection / Relay that is responsible for the control part unlike the previous ones in which it is a single device responsible for the command and trip.

These relays receive information from the current transformers (CT) and the voltage transformers (VT) and, according to the set parameters, send the opening and closing commands to the respective circuit breaker. This difference is due to the magnitude of currents and voltages at play in this range.

Nowadays the circuit breakers are differentiated by[2][3][6]:

1) Isolation type:
   - Oil
   - Air
   - Vacuum
   - SF6

2) Type of use:
   - Indoor
   - Outdoor

3) Type of mechanism:
   - Spring
   - Magnetic
   - Hydraulic
   - Pneumatic

C. Chosen circuit breaker

The chosen circuit breaker was a vacuum operated magnetic circuit breaker with the following characteristics:
- Rated operational voltage: 36 kV
- Rated current: 630 A
- Frequency: 50/60 Hz
- Low duration short circuit current: 12,5 kA (3s)
- Shock insulation level (1,2/50us): 150kV
- Making capacity under short circuit: 31,5 kAp
- Breaking capacity: 12,5 kA

III. DEVELOPED MODELS

A. Network

As can be seen in Figure 2, the general model is a three-phase system composed of one source, two consumers and one circuit breaker. There are also the respective resistances and inductances of the 30 kV lines[1].

![Figure 2 - Network Model](image)

B. Driver

Schematic of the electro-magnet driver responsible for opening the circuit-breaker contacts (Figure 3).

![Figure 3 - Driver Schematic](image)

C1: Energy storage capacitor
R1: Internal resistance of the capacitor C1
Q1: Semiconductor responsible for circuit control
D1: Free wheel diode
L1: Electromagnet

Operation:

Measuring the current in the line and having fixed a certain value of current as “threshold”, to open the circuit breaker is
given a conduction order to the semiconductor Q1 which in turn will cause the circuit to close, thus energizing the coil through the discharge of the capacitor and consequently beginning the opening process.

The simulink model used is shown in figure 4.

![Figure 4 - Driver's Model](image)

By measuring the current passing through the solenoid explained above we can calculate the $F_{em}$ exerted by the coil, by subtracting $F_{magnet}$ we obtain $F_{total}$.

This Magnet is responsible for "latching" in the open and closed limit positions of the circuit breaker contacts [10].

$$F_{em} = F_{m} \cdot \mu_0 \cdot \frac{A}{2d^2}$$

$$F_{m} = Ni$$

$$F_{total} = F_{em} - F_{magnet}$$

$F_{em}$: Electromagnetic force
$F_{m}$: Magnetic force
$\mu_0$: Magnetic permeability of the void ($4\pi \cdot 10^{-7} \text{ H/m}$)
A: Mobile element area ($0.01 \text{ m}^2$)
d: Distance between the solenoid and the metal part ($0.01 \text{ m}$)
N: Number of turns (50)
I: Current flowing through the electromagnet
$F_{magnet}$: Magnet force (110 N)

Through $F_{total}$ we obtain the value of acceleration using Newton’s second law of motion. The successive integration of the acceleration leads to the value of the position.

$$F_{total} = m \cdot a$$

$$a = \frac{dv}{dt} = \frac{d^2x}{dt}$$

m: mass (0.5kg)
a: acceleration
v: velocity
t: time
x: position

This position is interpreted as the distance between the metal contacts of the circuit breaker.

![Figure 5 - Circuit Breaker contact distance](image)

The Graph of Figure 5 is representative of the evolution of the distance between the contacts of the circuit breaker in the 3 phases provided by the model of the actuator presented previously for a short circuit at 0.2s.

Note that the distance between the contacts is normalized where 0 is the closed position and 1 is the open position.

C. Electric Arc

The electric arc is a phenomenon that is based on the passage of electric current through an insulating medium due to its dielectric rupture and consequent plasma (ionized gas) production.

Although arcs are more often observed in the air, the phenomenon can occur in several types of gases and vapors at various pressures. These gases and vapors serving as conductors in the dielectric medium are originated partly by the contacts themselves and partly by the surroundings. Essentially, the arc behaves as a non-linear resistance exhibiting a low voltage drop[3].

Let’s now discuss the process of its extinction. The basic idea of arc extinction is to force the current to zero. Since there is a sinusoidal alternating system, the current is zeroed (zero) in each half period.

In the case of a stabilized electric arc as soon as the arc current rises its resistance decreases due to the increase in temperature which increases the ionization process of the medium and when the current decreases its resistance increases.

Note that near the natural zero crossing of the current, the arc extinguishes briefly until it is formed again in the opposite direction in case there are conditions for this. That is, the condition is to prevent the reignition of the arc in the passages by zero of the current and therefore the process of deionization of the arc after the passage through zero is of extreme importance.

In order to be successful in the extinction, the dielectric capacity of the material must withstand the voltage that is being imposed around the dielectric by the circuit (TRV) (Figure 6) in an attempt to reestablish the current, this voltage is a function of the circuit constants.
In Figure 6 we have two distinct examples of transient recovery voltages (TRV).
We can note that case 2 will not cause the current to be restored in the circuit thus extinguishing the current.

1) Model types

There are several ways to characterize the electric arc, most involve complex differential equations [9].
The 3 most commonly used types of models are [5] [12]:

The Physical Models
• Describe physical phenomena
• Used in the design of appliances
• Mathematically demanding

The Parameter Models
• "Black Box" models, but more accurate
• Parameters are derived from complex functions and tables

"Black Box" type models
• Describe the approximate behavior of the arc
• Used for simulation of arc and circuit interaction
• Not used for appliance design

2) Used Model

For the elaboration of the arc model we chose to use a model of the "black box" type, more concretely the model elaborated by Cassie.
This model, which was presented by Cassie in 1939, was one of the first models of differential equations to describe the dynamic behavior of the electric arc [5] [7] [12].
Figure 7 shows a description of the electric arc geometry [8].

This model is based on the following basic assumptions [2][11]:
• Constant arc temperature
• Constant current density
• Constant electric field
• Diameter of the arc variable with current and time
• Thermal convection as the main cause of process energy losses

\[
\frac{d}{dt} \ln g = \frac{1}{\tau_c} \left( \frac{U_{arc}^2}{U^2} - 1 \right) \tag{7}
\]

\[
g = e^{\tau_c} \left( \frac{U_{arc}^2}{U^2} - 1 \right) dt + g_0 \tag{8}
\]

\[U = Ed \tag{9}\]

\(g\): arc conductance
\(\tau_c\): Arc time constant (8 ms (taken from manufacturer’s data))
\(U_{arc}\): Arc voltage (measured at the circuit breaker terminals)
\(U\): Static arc voltage
\(T\): Time cycle
\(g_0\): Initial conductance of the circuit breaker (10 µS)
\(E\): System voltage constant (30000 V)
\(d\): Distance between circuit breaker contacts

It should be noted that the association of the driver model previously explained with the arc model is done by the dependence of the distance between the contacts in the \(U\) parameter of the previous formula.

It can be observed the conductance generated by the arc model (Figure 8) for a short circuit from 0.2s to 0.4s.
D. Circuit Breaker in Simulink

To model the circuit breaker in Simulink, a way had to be found to relate it to the conductance generated by the electric arc model. A controlled voltage source was selected (Figure 9).

![Figure 9 - Voltage source used to model the circuit breaker](image)

By reading the current passing through the circuit-breaker and the conductance generated by the model, the voltage value is obtained:

\[ V = RI \quad \Rightarrow \quad V = \frac{I}{g} \quad (10) \]

V: Voltage  
R: Resistance  
I: Current  
g: Conductance

E. Fast Circuit Breaker assisted by Semiconductors

We can observe the used architecture and its components in figure 10.

![Figure 10 - Fast circuit breaker assisted by semiconductors model](image)

In order to calculate the number of semiconductors to be used, it is necessary to take into account some data of the network, note that the semiconductors will drive in the two arcs of the current, so the number of devices in series will have to be duplicated.

\[ N_{\text{series}} = \frac{V_{\text{peak}}}{V_{\text{CE}}} = \frac{24421}{6500} \approx 4 \rightarrow 8 \quad (11) \]

\[ N_{\text{parallel}} = \frac{I_{\text{scmax}}}{I_c} = \frac{2200}{600} \approx 4 \quad (12) \]

2) IGBT’s Snubber

A "snubber" is a device built to dampen transient voltage fluctuations in electrical circuits.

In this case it will be in parallel with each semiconductor avoiding oscillations resulting from the abrupt passage to the off state. By means of the mentioned formulas (13)(14)(15)(16)(17) we can size the snubber.

\[ R_s = \frac{t_{\text{on}}}{3C_s} \quad (13) \]

\[ C_s = \frac{I_c \cdot t_{\text{off}}}{2V_{\text{ce}}} \quad (14) \]

\[ E = \int V_{\text{ce}} \cdot I_c \, dt = V_{\text{ce}} \cdot I_c \cdot \Delta t \quad (15) \]

\[ t_{\text{on}} = \frac{E_{\text{on}}}{V_{\text{ce}} I_c} = 1,15 \, \mu s \quad (16) \]

\[ t_{\text{off}} = \frac{E_{\text{off}}}{V_{\text{ce}} I_c} = 1,1 \, \mu s \quad (17) \]

After these calculations, we were able to obtain the values for the resistance and for the capacitance of the IGBT snubber:

\[ R_s = 7,6 \, \Omega \]

\[ C_s = 50,8 \, \text{nF} \]

3) Snubber

As described in the previous topic a snubber was introduced to suppress the voltage transients, however this will be in parallel with all the semiconductors thus providing a damping solution for the general system.

Most relevant data:
- \( I_c = 600 \, \text{A} \)
- \( V_{\text{ce}} = 6500 \, \text{V} \)
- \( V_{\text{ge}} = +15 \, \text{V} \)
- \( E_{\text{on}} = 4,5 \, \text{J} \)
- \( E_{\text{off}} = 4,3 \, \text{J} \)
Damping Capacitor:

\[
C_A = \frac{L I^2}{U^2} \tag{18}
\]

\[
L = L_{\text{fonte}} + L_{\text{inha}} = 1,1 \text{ m}\Omega \tag{19}
\]

I: Short circuit RMS current (1500 A)
U: Rated voltage (30kV)

Condition of Convergence:

\[
h < \frac{\tau}{2} \Rightarrow R_A > \frac{2h}{C_A} \tag{20}
\]

h: Calculation step (20 µs)
\(\tau\): Time constant \((R_A C_A)\)

After these calculations, we were able to obtain the values for the resistance and for the capacitance of the snubber.

\[
R_A \geq 14,55 \text{ \Omega}
\]

\[
C_A = 2,75 \mu\text{F}
\]

4) Surge Arrester

The surge arrester is of extreme importance in an electrical system. Its function is to protect the devices against overvoltage in the network. These dischargers were modeled through an anti-series diode with a voltage source, which simulates the zener voltage.

IV. SIMULATION RESULTS

In order to test the model of the fast circuit breaker, simulink simulations were carried out. Simulating the behavior of the network for 0.8 s by forcing a short circuit from 0.2 s to 0.4 s on consumer 2, we intend to observe the implications of this event on consumer 1. Two simulations will be done: one using the typical circuit breaker model and another using the fast circuit breaker model with semiconductors.

A. Common Circuit Breaker

Observing Figure 11 we can verify that when the short circuit occurs at 0.2 s there is a very high increase in the line current and the circuit breaker takes approximately 60ms (3 cycles) to extinguish the current. Thereafter a successful reconnection attempt occurs.

B. Fast Circuit Breaker assisted by Semiconductors

In figure 12 the behavior of the voltage at consumer 1 can be observed throughout the event.
There is a voltage sag with a depth of about 50% for 60 ms consistent with the breaking time of the circuit breaker. This voltage drop is due to the line voltage drop due to the significant increase of current in the circuit.
Using the modeled fast circuit breaker, a substantial decrease in the extinction time of the fault current can now be observed (Figure 13). It is noted that it lasts about 30 ms (1 cycle and a half), which is half the time of the typical circuit breaker.

Figure 14 - Consumer 1 Voltage

In relation to consumer 1 voltage (Figure 14) there is a voltage sag with approximately the same depth (50%) but with a substantial decrease in duration compared to the typical circuit breaker, about 30 ms duration of the voltage sag instead of the 60 ms seen previously.

V. CONCLUSION

By analyzing the results of the simulation, it can be verified that there is a decrease in the current extinction time and a consequent decrease on the consumer 1 voltage sag.

In the consumer 1 voltage graph, in the case of the classic circuit breaker, the voltage sag has a duration of about 60 ms whereas in the fast circuit breaker assisted by semiconductors- the voltage sag lasts for approximately 30 ms.

By comparing with the limits of the CBEMA ITIC curve, it can be concluded that with this new system, electronic devices would not feel a disturbance in their operation during a voltage sag, since it respects the zone of safe operation of the curve.

REFERENCES