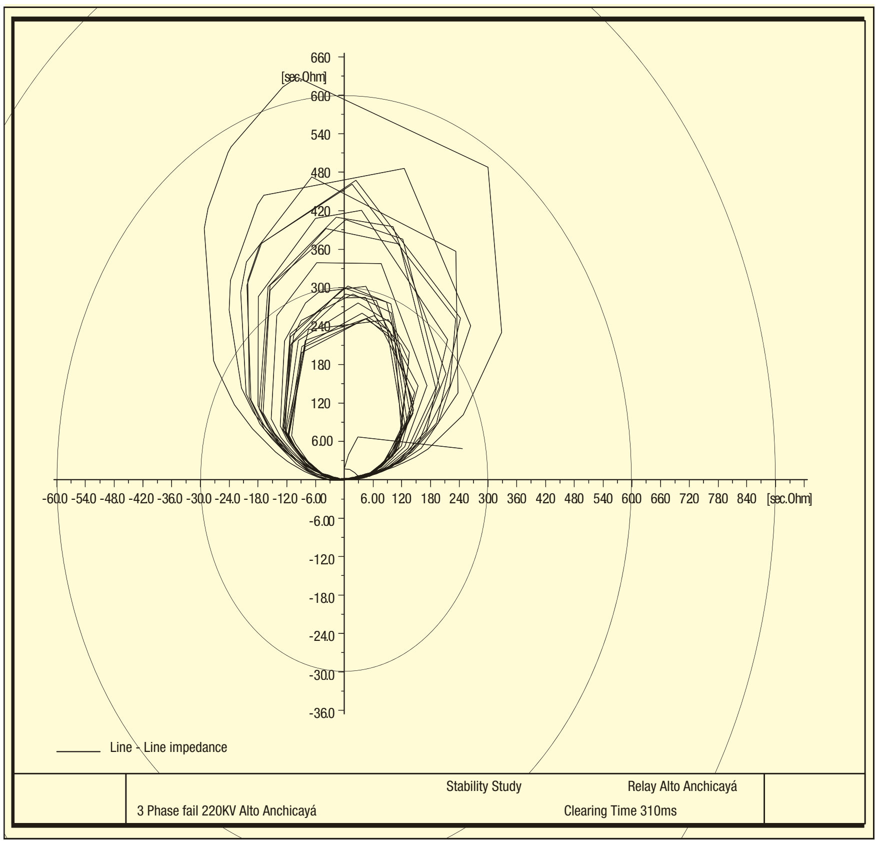
A Methodology for Setting up Generator Out-of-Step Protective Relays

MILLER ZULETA *
GLADYS CAICEDO**
FRANCISCO JAVIER MURCIA***
JOHN EDWIN CANDELO****



Resumen

En este artículo se presenta una metodología para el ajuste de la protección de pérdida de paso en generadores, que puede ser aplicada en cualquier generador del Sistema de Potencia Colombiano. Se presenta una comparación entre los criterios de ajuste propuestos en artículos de investigación y el de un fabricante. La aplicación metodológica requirió información como la reactancia transitoria de eje directo del generador, la reactancia del transformador y la impedancia del sistema, así como encontrar los tiempos críticos requeridos para un correcto ajuste de la protección. La metodología propuesta fue implementada en las protecciones de las centrales eléctricas de Salvajina y el Alto Anchicayá, mejorando la selectividad con nuevos criterios de ajuste.

Palabras clave: Centro eléctrico, generador eléctrico, pérdida de paso, relé de protección, oscilación de potencia.

* Electrical Engineer, Universidad del Valle
** Electrical Engineer, Ph.D, Universidad del Valle - GRALTA.
*** Electrical Engineer, Empresa de Energía del Pacífico EPSA.
**** Electrical Engineer, Ph.D Student, Colciencias, GRALTA - Universidad del Valle.

Fecha de recibo: junio de 2006 Fecha de aceptación: agosto de 2006

Abstract

In this article a methodology for setting up generator out-of-step protective relay, to be applied in any generator of Colombian Power System is presented. A comparison between settings proposed in research articles and a manufacturer was carried out. The application of the methodology required information as generator direct-axis transient reactance, transformer reactance, power system impedance and critical time for setting up protective relay. The proposed methodology for setting up generator out-of-step protective relay was applied in the Salvajina and Alto Anchicayá power plants, improving the selectivity with new settings approaches.

Key words: Electrical center, generator, out-of-step, protective relay, power swims.

1. Introduction

An intolerable operation condition of power system, conducting to the instability is produced by: large-load variations, large-generation variation, line outage and other events that affect the normal operation of power system. Power swims are produced when instability is presented, causing an out-of-step condition and large currents in generator windings and power transformers; this condition generates electro-dynamical efforts that reduce the useful life of elements.

Standards in Colombia regulate that power plants must include out-of-step protection (ANSI 78), but the settings have been made with relay manuals and operator experience, being no optimal for the power system protection.

In this article a methodology for setting up generator out-of-step protective relay and its application in the Salvajina and Alto Anchicayá hydroelectric power plants are presented. The study was carried out with information from international article, protection relay manuals, books and other information extracted from internet.

2. General Concepts

Equation 1 corresponds to the active power transfer from the sending node to the receiving node as function of the power system angle (δ). This equation is called Active Power Transfer [1].

$$P_S = \frac{V_S * V_R}{X} \sin\delta \qquad (1)$$

where:

V_S = Sending voltage

V_R = Receiving voltage

X = Equivalent reactance between sending and receiving nodes.

When the mechanical power is equal to the electrical power, the generator operates in normal condition and operating angle (δ) is about 30º or 40º. After a disturbance, the power system equilibrium changes and angle increases. If angle exceeds 90º, the generator gets into the critical operating zone and losses synchronism with the system reference. The synchronism limit is about 120º and if this limit is not reached, the oscillation can be avoided with machine-speed regulator, but when the limit is exceed, the generator accelerates impeding the recuperation of the initial condition and an out-of-step is presented.

2.1 Stability and Instability types

Figure 1 shows the different stability and instability types that produce different effects over power system and the associated parameters [2]. The cases are:

a. Steady state stability and instability: when the system is stable and has the ability of responding to events, the electrical machine remains on synchronism with the system and the angle (δ) is smaller than 90º. Small disturbances can increase the angle gradually until it exceeds 90º, where instability is presented. This process can occur in long periods of time (from minutes to hours), as shown in Figure 1(a). For this condition, considerable changes in generators have not occurred and power swims are not presented.

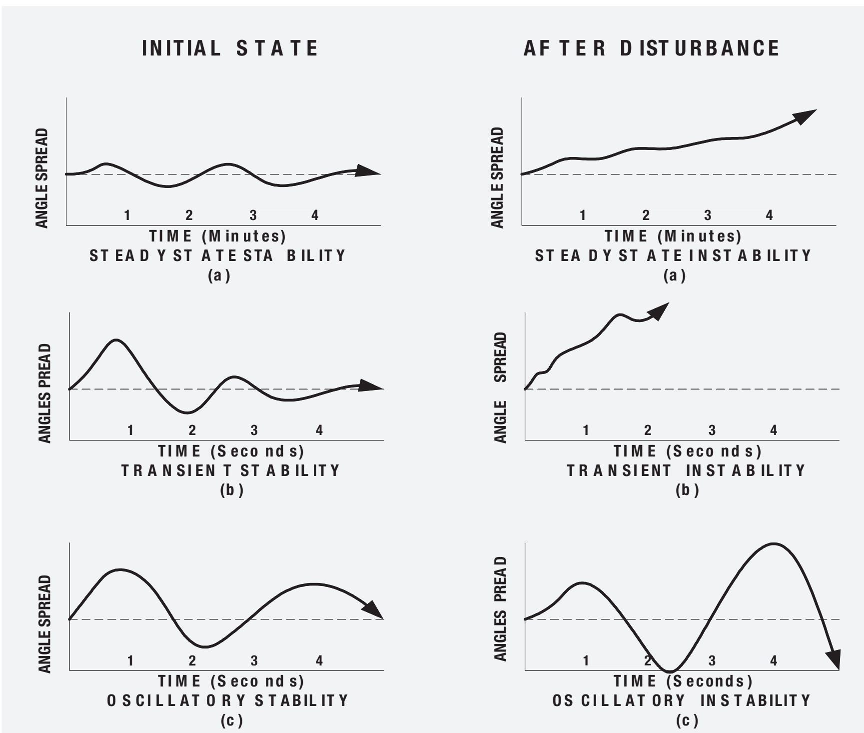


Figure 1. Stability and instability types

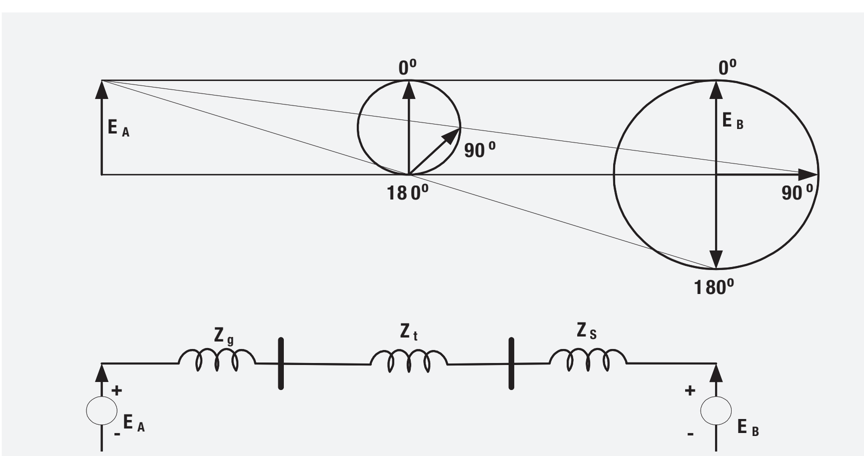


Figure 2. Power system electrical center

Although, the possibility of presenting an angle instability is lower, a special case of load increment could occurs, causing a generator-terminal voltage reduction; if the load is larger than the maximal generation, the angle increases gradually, passing the stability limit, and the system becomes unstable.

b. Transient stability and instability: is presented with large-disturbances occurrence. Figure 1(b) shows the angle variation over time; if perturbation is cleared rapidly, power system could have the ability of responding to the events and oscillation would be dampen, other way it would become a transient instability.

c. Oscillatory stability and instability: is presented with large-disturbance occurrence in power system and is recognized because the angle oscillates constantly over time, as shown in Figure 1c. These changes could be abrupt and rapids.

2.2. Electrical Center

Each voltage of the power system has a magnitude and a phase angle. As system operating point changes, the voltage phasors can be outside or inside the permissible operating zone, depending on the presented perturbation type.

Figure 2 shows a power system with its voltage magnitudes and angles, which can be different, depending on the impedance from the sending to the receiving zone and the operation condition of the power system. If the separation angle from sending node E_A to the receiving node E_B is 180º, it means that in some place along the network, the voltage has a value of zero [3] and for the elements it could be seen as a three-phased short circuit. The point where the voltage is zero is known as the electrical center of the system and it indicates that a power instability is presented, causing an out-of-step condition.

If loss-of-synchronism is presented, the equivalent impedance value changes with the relation E_A/E_B [4], as shown in Figure 3. If $E_A/E_B=1$, the impedance locus is along the line LM and perpendicular to the line A-B, bisecting the middle point. Impedance moves from point L to point M and angle δ increases; when the angle passes 120º, the system is considered unstable. The value δ=180º is the point where lines A-B and L-M are intercepted and is the electrical center, where voltage becomes zero.

If $E_A/E_B>1$, the impedance locus is a circle with center at total impedance line A-B, in the region (+X), in this case the electrical center is located in the intersection of the curve 1 and the line A-B. Similarly, when the relation is $E_A/E_B<1$, the impedance locus is a circle with center in the region (-X), in this case the electrical center is located in the intersection of the curve 2 and the line A-B.

Determination of the electrical center allows finding the operating zones of the out-of-step protective relay.

3. Protective Relay Operation

Out-of-step condition can be originated depending on the different behavior of power swims. Figure 4, shows the different power swims (curves 1, 2 and 3); the operating zone of out-of-step protective relay is between the two blinders (A and B) and the circle (Mho characteristic). The relay measures the system impedance, but it only operates when the impedance passes through the operating zone, from Blinder B to Blinder A.

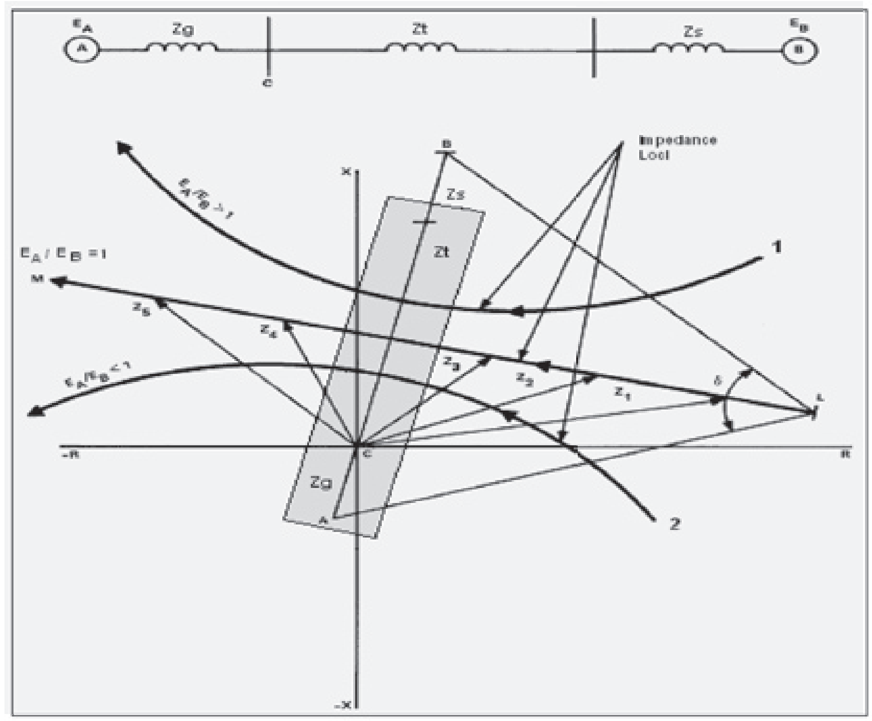


Figure 3. Electrical center as function of the voltage relation

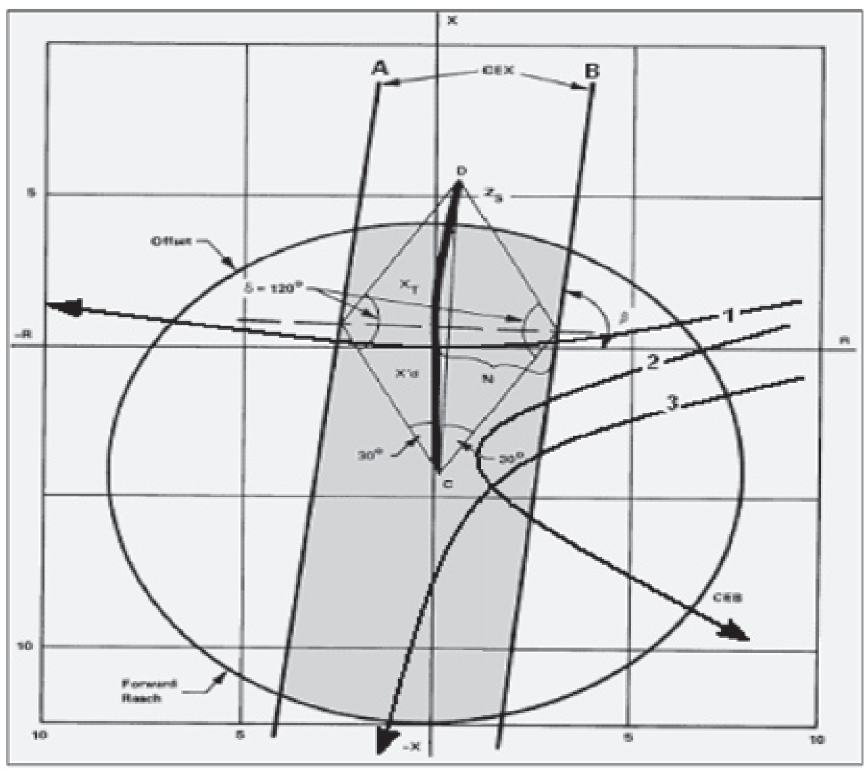


Figure 4. Operating zone of protection ANSI 78

Some times a power swim can get into the mho characteristic and reaches one of the blinders, but the protection settings will not allow operation until it reaches the other blinder. That settings are made because some oscillations can return to stabilization as shown in Figure 4 (curves 2 and 3).

4. Setting Criteria for Out-of-Step Protection

For setting up the protection, some parameters are required from power system and other must be calculated by computational tools. The invariant physical parameters are taken from generators (direct axis transient reactance X'd) and transformers (reactance X_T). Two studies are carried out: one-phase short circuit study in order to find the system impedance and a stability study to find the critical time (120º) and generator poles slip (180º).

Table 1 reviews two setting methods for the protection ANSI 78. Figure 5 shows the settings proposed in IEEE articles [5], using the Mho characteristic and the blinders. Figure 6 shows the settings criteria made by SIEMENS for the relay 7UM62 [6].

The settings for relay Siemens 7UM62 are similar to the proposed in articles IEEE, but relay 7UM62 uses operation zones denoted as characteristic 1 and 2 and not the Mho characteristic, as shown in Figure 6.

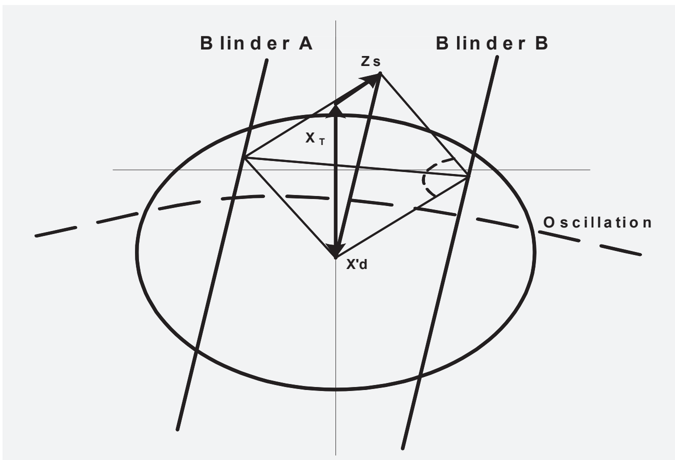


Figure 5. Operation Characteristic of relay SIEMENS 7UM62

Table 1. Difference between IEEE and Siemens relays settings

	Relay IEEE articles	Relay Siemens 7UM62
Generator	X'd must be multiplied by factor m, from 200% to 300 %.	Must be used 100% of generator impedance
Transformer	Xt must be multiplied by factor n from 150% to 200 %.	Must be used from 70% to 90% of transformer impedance
MHO Characteristic	$D_{Mho}= n*X_T + m*X'_d$ where: D_{Mho}= Mho circle diameter	Not Presented
Characteristic 1	Not Presented	Cart 1 = Zb + Zc where: Zb: X'd Zc: entre 70 al 90 % XT.
Characteristic 2	Not Presented	Cart 2 = Zd - Zc where: Zd: XSIS + XT.
Blinders	N= 0.289 *Z_{tot} where Ztot = X'd + Xt + Zsys N: Distance between total line impedance and a blinder	N= 0.289 *Z_{tot} where: Ztot = Xb + Xc o Ztot = Xb + Xd

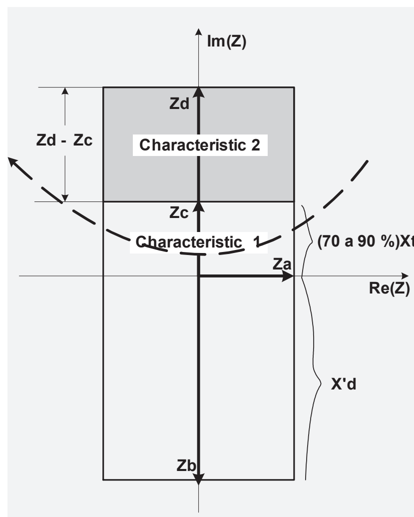


Figure 6. Operating characteristic of relay SIEMENS 7UM62

The characteristic 1 can be set to operate between 1 and 4 swims and the characteristic 2 allow between 2 y 8 swims.

5. Methodology for setting generator out-of-step protective relay.

The methodology was applied to relay Siemens 7UM62 located in the Salvajina and Alto Anchicayá hydroelectric power plants, using the computational tool DigSilent and data from the network of Valle del Cauca, Colombia (Table 2).

Table 2. Parameters and variables calculated with DigSilent

		Salvajina	Alto Anchivayá
Generator	X'd	0.2862 pu	0.25 pu
	V_N	13.8 kV	13.8 kV
	S	100 MVA	126 MVA
Transformer	X_T	9.99 %	13.14 %
	S	115 MVA	129 MVA
Measuring Transformers	TP	14400/120	14400/120
	TC	6000/5	8000/5
Relation	RTP	120	120
	RTC	1200	1600
System impedance	R	3.047Ω	3.155Ω
	X	26.690Ω	26.494Ω
	Z	26.864Ω	26.681Ω

The methodology was developed in four stages:

1. Obtaining information from the generator reactance X'd and transformer reactance X_T.
2. Carrying out one-phase simulations of generation bus, opening previously the associated power switch to obtain the system impedance.
3. Referring the system impedance values to the low-voltage side, where the relay is located.
4. Constructing the operating characteristic as shown in Figure 7. According to the simulation results the correct percents of covering zones of relay 7UM62 must be assigned.

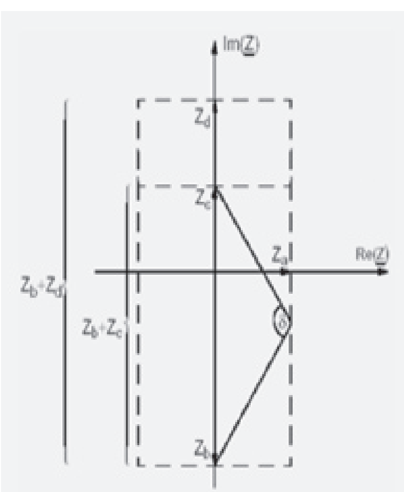


Figure 7. Blinder construction for relay 7UM62

6. Application of the methodology for setting protective relay 78 in Salvajina and Alto Anchicayá.

a. Required Information: The information X'd y XT was obtained from network data base of EPSA and is shown in Table 2.

b. One-phase short circuit: Table 3 shows the data obtained from one-phase short circuit at buses of Salvajina and Alto Anchicayá.

Table 3. One-phase short circuit data

		Salvajina	Alto Anchicayá
System impedance	R	3.047Ω	3.155Ω
	X	26.690Ω	26.494Ω
	Z	26.864Ω	26.681Ω

c. Values referred to the low-voltage side: The value obtained from Table 2, must be referred to Ω-sec (ohm-secondary), because of the measuring transformers, according Equations (3), (6) and (8).

For generator:

$$X'd_{\Omega\_pri} = \frac{kV_{base}{}^{2} * X'd_{pu}}{MVA_{base}} \quad (2)$$

$$X'd_{\Omega\_sec} = X'd_{\Omega\_pri} * \frac{RTC}{RTP} \quad (3)$$

$$Z_b = X'd_{\Omega\_sec} \quad (4)$$

For transformer:

$$X_{T\Omega\_pri} = \frac{kV_{base}{}^{2} * X_T}{MVA_{base}} \quad (5)$$

$$X_{T\Omega\_sec} = X_{T\Omega\_pri} * \frac{RTC}{RTP} \quad (6)$$

For system:

$$X_{SYS\Omega\_pri} = \frac{MVA_{base} * X_{SYS}}{kV_{base}{}^{2}} \quad (7)$$

$$X_{SYS\Omega\_sec} = X_{SYS\Omega\_pri} * \frac{RTC}{RTP} \quad (8)$$

d. Construction of the operating characteristic: to set up blinders as shown in Figure 7, the operating characteristic is calculated as:

$$Z_a = \frac{Z_{tot}/2}{\tan(\delta/2)} \quad (9)$$

where δ = 120º

$$Z_a = \frac{Z_{tot}/2}{\tan(120^{o}/2)} \quad (10)$$

$$Z_a = 0.289 * Z_{tot} \quad (11)$$

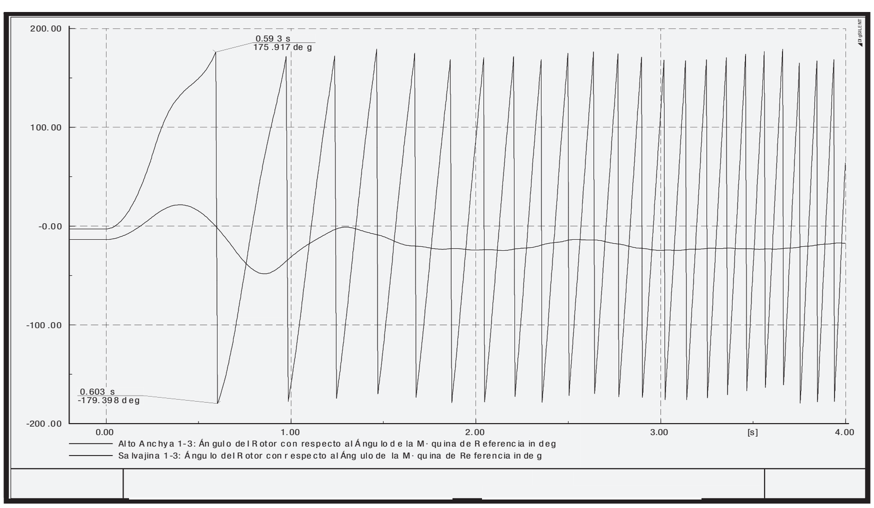


Figure 8. Generator rotor angle T_{des} = 260 ms

The total system impedance is expressed as:

$$Z_{tot} = Z_b + Z_c \quad (12)$$

for power swim angle between generator and transformer, and

$$Z_{tot} = Z_b + Z_d \quad (13)$$

for power swim angle between generator and system network.

The critical fault-clearing time as the maximum time to avoid instability, the time where generator rotor angle reaches 120º and the time for poles slipping (180º) are calculated by three-phase faults simulations at generation high-voltage buses, using an approximation method before and after the critical fault-clearing. Also the number of power swims and the swim behavior through the impedance locus are obtained.

Figure 8 and Figure 9 show the three-phase short circuit study at bus 230 kV of Salvajina. The rotor angles behavior and apparent impedance seen for the relays, after a fault-clearing time of 260 ms is shown. Figure 9 shows the impedance swings for an out-of-step condition.

Figure 10 and Figure 11 show the rotor angle behavior generators and the apparent impedance seen for Alto Anchicayá and Salvajina in a three-phase short circuit at bus 230 kV with a fault-clearing time of 310 ms. Figure 11 shows a strong power swim and an out-of-step condition originated when a long fault-clearing time is presented.

7. Application of out-of-step protective settings for Salvajina and Alto Anchicayá.

Table 4 shows simulation results for setting up both generator out-of-step protective relays. Data

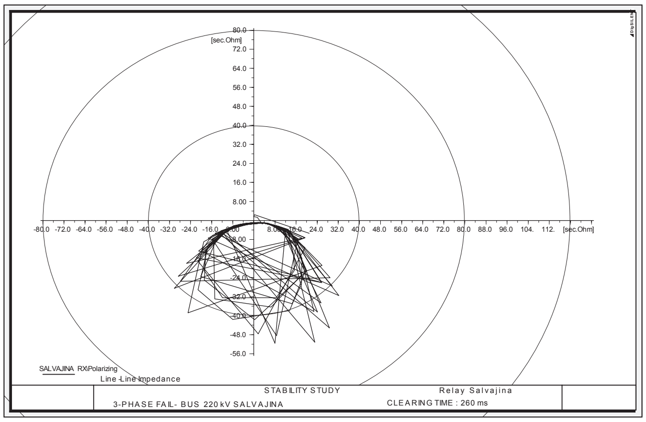


Figure 9. Apparent impedance seen from Salvajina T_{des}=260ms

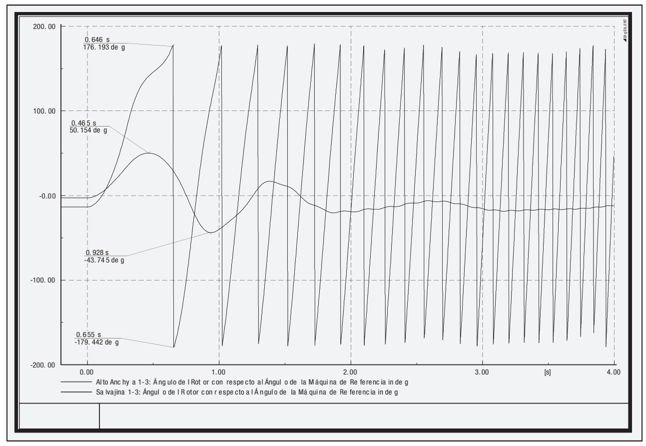


Figure 10. Generator rotor angle T_{des} = 310

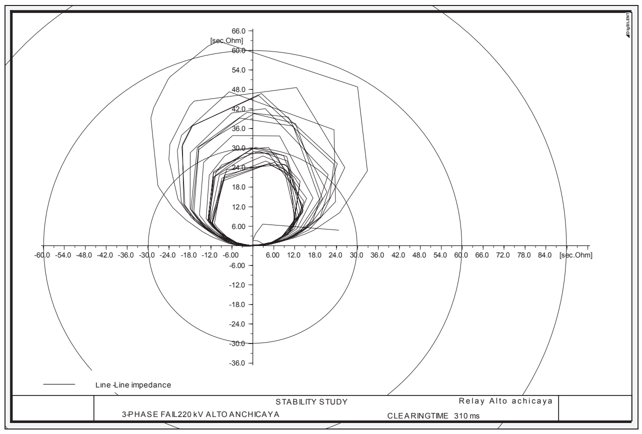


Figure 11. Apparent impedance seen from Alto Anchicayá T_{des} = 310 ms

for constructing the out-of-step relay operating characteristic is obtained from Tables 2, 3 and 4. Table 5 shows the relay settings for Alto Anchicayá and Salvajina obtained with equations mentioned above.

Figure 12 shows the operating zone settings of generator out-of-step protective relay of Alto Anchicayá.

Table 4. Obtained parameters (Ω-secondary)

	X´d (Ω sec)	X_T (Ω sec)	X_S(Ω sec)
Salvajina	5.45	1.9025	0.9196
Alto Anchicayá	5.037	2.6480	0.5514

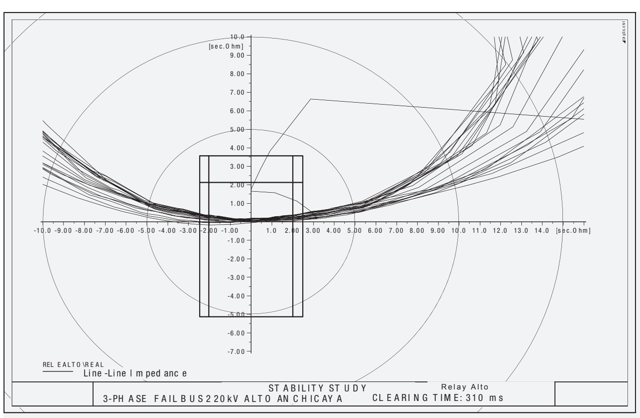


Figure 12. Operating characteristic of Alto Anchicayá

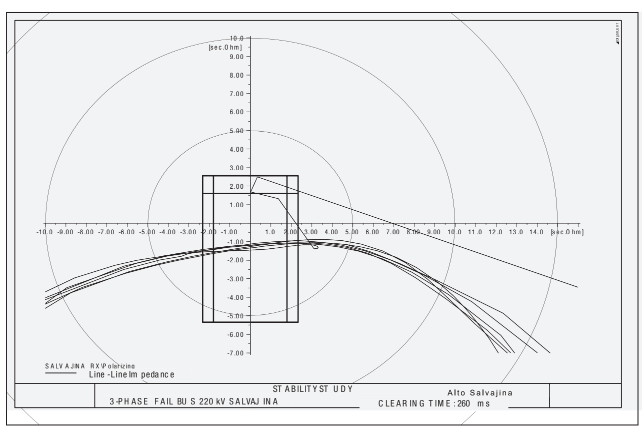


Figure 13. Operating characteristic of Salvajina

Table 5. Calculated parameters for relay Siemens 7UM62.

	Alto Anchicayá	Salvajina
Zb=X'd	5.037 Ω/sec	5.45 Ω/sec
Zc=80% Covering X_T	2.1184 Ω/sec	1.522 Ω/sec
Zd= $X_S + X_T$	3.5676 Ω/sec	2.4539 Ω/sec
Zd – Zc = Caract 2	1.4492 Ω/sec	0.9319 Ω/sec
Za (characteristic 1)	2.0679 Ω/sec	1.8443 Ω/sec
Za (characteristic 1 and 2)	2.4867 Ω/sec	2.2842 Ω/sec

Figure 13 shows the operating zone settings of generator out-of-step protective relay of Salvajina. In Table 6, the recommended values for setting up generator out-of-step protection of Salvajina and Alto Anchicayá are registered.

8. Conclusion

When comparing the relay 78 settings of Alto Anchicayá with the settings recommended in this article, some differences were founded in the covering areas of characteristics 1 and 2, because it was considered to be larger than the obtained one with computational studies.

A methodology for setting up generator out-of-step protective relay, in two different ways was presented. The first one proposed in IEEE articles and the second one proposed for protection ANSI 78, relay Siemens 7UM62 of Salvajina and Alto Anchicayá.

Three-phase fault simulations over high-voltage buses allowed verifying the out-of-step condition and the critical fault-clearing time and order to set up protection ANSI 78.

Although, the relay operating characteristics proposed by IEEE articles and Siemens are similar, the investigation results indicate that criteria implemented by Siemens are more selective, because this protection allows zoning the operating characteristic in two parts, which have different setting approaches. The configuration of these operation areas avoids tripping when impedance swings are presented, that can be detected outside of the involved area of the generator-transformer group. Also, the blinders for relay Siemens 7UM62 are set up with characteristic 1 or are set up to cover both characteristic 1 and 2, in order to determinate if power swim is stable or unstable, avoiding generator tripping in stable conditions.

Table 6. Recommended data for protection ANSI 78

Settings	Salvajina	Alto Anchicayá
Za	1,8443 Ω-Sec	2,0679 Ω-Sec
Zb	5,45 Ω-Sec	5,037 Ω-Sec
Zd-Zc	0,9319 Ω-Sec	1,4492 Ω-Sec
Polygon	90º	90º
Swims characteristic 1	1	1
Swims charactistic 2	4	4
T-signal	0.04	0.04

This methodology can be applied for other generator out-of-step protective relays and contribute to define approaches that are used in the standards CREG.

9. Bibliographic

[1] J. J. Grainger, W. D. Stevenson. Análisis de Sistemas de Potencia. Ed. McGraw-Hill. 1998.

[2] P. Kundur. Power System Stability and Control. Ed. EPRI, Ed. McGraw-Hill. 1994.

[3] P. M. Anderson. Power System Protection. IEEE Press Power Engineering Series, Ed. McGraw-Hill. 1999.

[4] J. Berdy, "Out-of-step Protection for Generators", General Electric Company, [documento en internet], disponible en: http://www.beckwithelectric.com/infoctr/techpapers/genprot01.pdf.

[5] IEEE Guide for AC Generator Protection", ANSI/IEEE C37.102-2002

[6] SIPROTEC "Multifunction Generator, Motor and Transformer Protection Relay 7UM62". SIEMENS Company. 2002