



Title: Desarrollo del algoritmo genético heurístico para la coordinación de protecciones

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Introducción (Concepto de Coordinación)

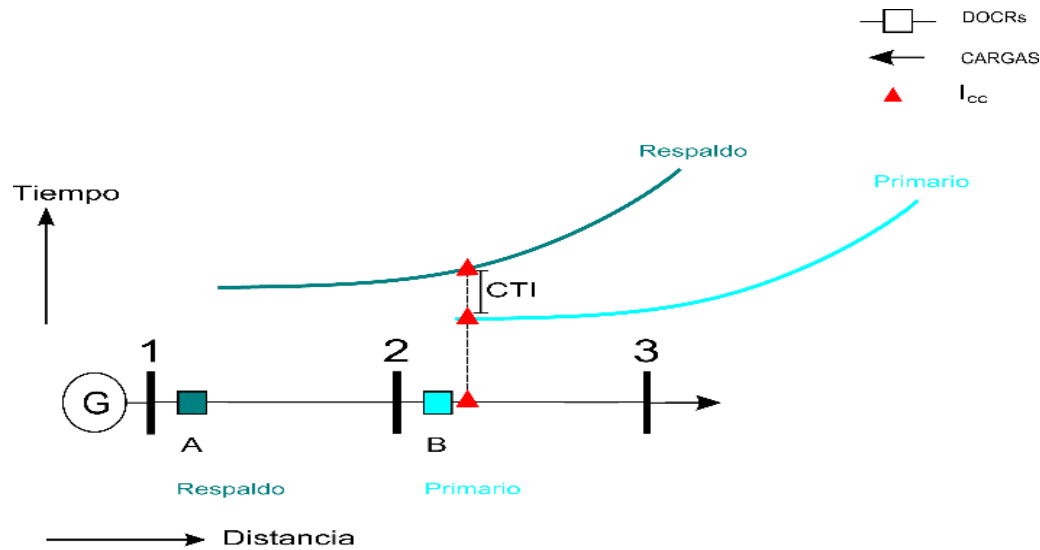


Figura 1 Protección primaria y respaldo en una línea radial de una solo fuente. *Elaboración propia.*

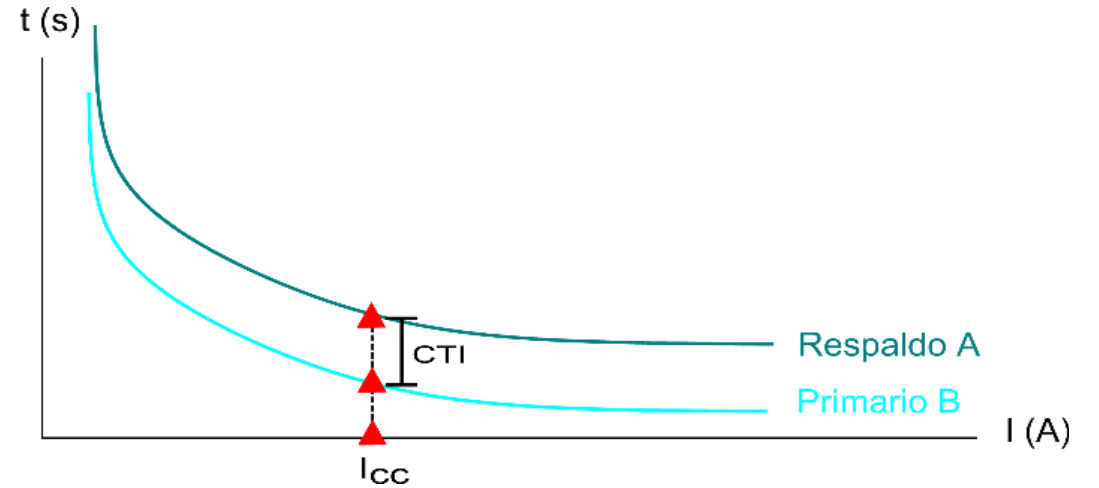


Figura 2 Concepto de protección primaria y respaldo con las curvas de tiempo inverso. *Elaboración propia.*

$$t = \left[\frac{A}{\left(\frac{I_{sc3\phi max}}{I_p} \right)^n} + B \right] * dial \dots (1)$$

| Norma | Curva | A | B | n |
|-------|-------|--------|--------|------|
| IEEE | MI | 0.0515 | 0.114 | 0.02 |
| | VI | 19.61 | 0.491 | 2 |
| | EI | 28.2 | 0.1267 | 2 |

Tabla 1 Constantes del Estándar IEEE. Fuente: *IEEE Standard Inverse-Time Characteristic Equations for Overcurrent Relays, IEEE std C37.112-1996.*

Metodología (Coordinación-Optimización)

$$f(x) = \left(\frac{NV}{NCP}\right) + \left(\frac{\sum_{a=1}^{NCP} t_{pa}}{NCP}\right) * \alpha + \left(\frac{\sum_{b=1}^{NCP} t_{bb}}{NCP}\right) * \beta + \left(\sum_{L=1}^{NCP} E_{CTIL}\right) * \delta \dots(2) \quad \rightarrow \text{Función de aptitud}$$

$$CTI_{real} = t_b - t_p \dots(3) \quad \rightarrow \text{Restricción de igualdad}$$

$$CTI_{error} = CTI_{real} - CTI_{preestablecido} \dots(4) \quad \rightarrow \text{Indicador de CTI}$$

$$dial_{min} \leq dial \leq dial_{max} \dots(5) \quad \rightarrow \text{Restricción de desigualdad}$$

$$I_{pmin} \leq I_p \leq \min(I_{scmin}, I_{pmax}) \dots(6) \quad \rightarrow \text{Restricción de desigualdad}$$

Metodología (Optimización por GA)

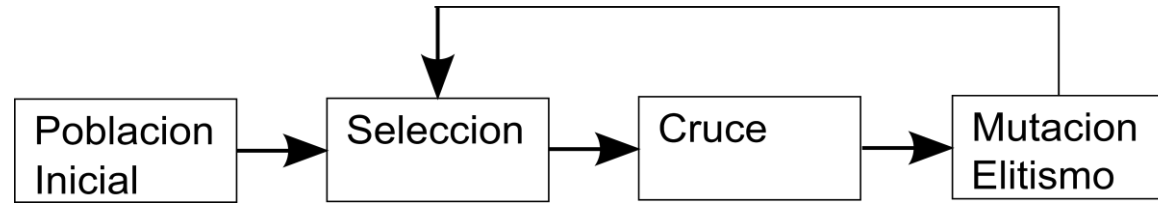


Figura 3 Las etapas principales del GA. *Elaboración propia.*

$$P = \begin{bmatrix} dial_{(1,1)} & \dots & dial_{(1,NR)} & Ip_{(1,NR+1)} & \dots & Ip_{(1,NR*2)} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ dial_{(NC,1)} & \dots & dial_{(NC,NR)} & Ip_{(NC,NR+1)} & \dots & Ip_{(NC,NR*2)} \end{bmatrix} \dots(7)$$

→ Población Inicial

$$p(x) = \frac{1}{\sum_1^{NC} f(x)} \dots(8)$$

→ Selección (Probabilidades de la rueda de ruleta)

$$P(x, y)_{G+1} = \frac{(P(x,y)_G + P(z,y)_G)}{2} \dots(9)$$

→ Cruce (recombinación aritmética simple)

$$P(x)_{G+1} = \begin{cases} P(U\%)_{G+1} = (B_C)_G \\ P(V\%)_{G+1} = rand(P(lower, upper)) \end{cases} \dots(10)$$

→ Elitismo y Mutación (si f(x) 10 generaciones)

Metodología (Optimización por GA)

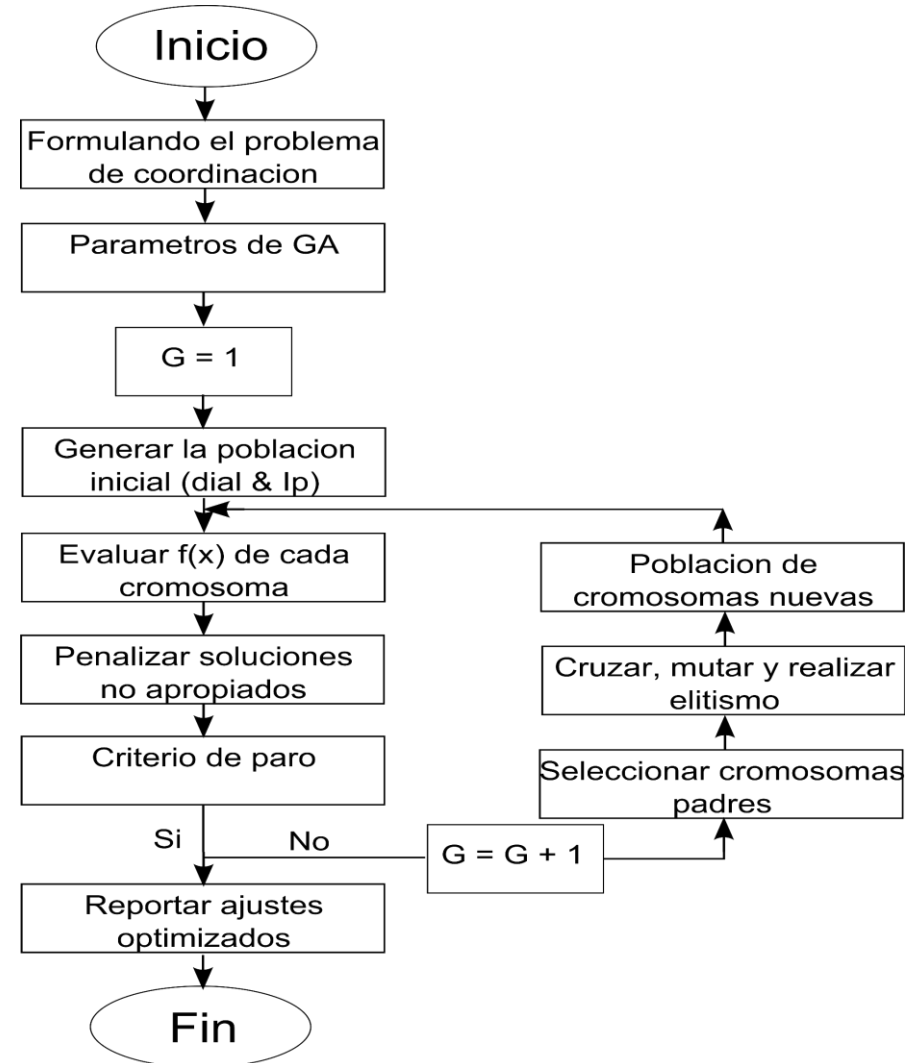


Figura 4 Diagrama de flujo de coordinación de DOCRs usando GA.
Elaboración propia.

Simulación

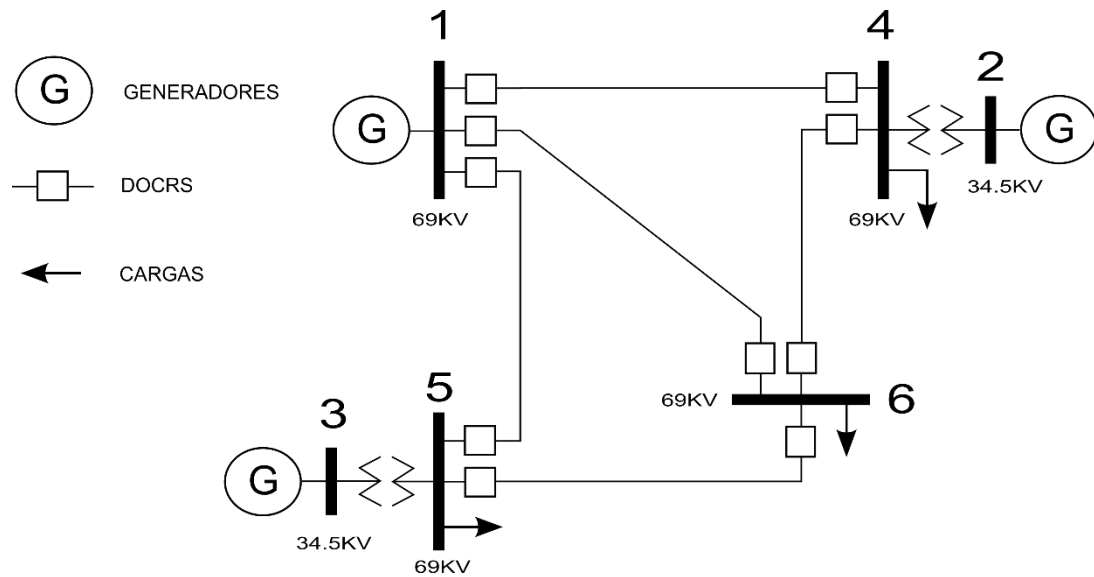


Figura 5 El sistema de 6 buses mallasado. Fuente: Hadi Saadat, *Power system analysis*, McGraw-Hill, ISBN 0-07-561634-3, 1999.

| Parámetros | GA |
|-------------------------|------------------------------|
| CTI | 0.3 |
| dial | [0.5:2.0] |
| I_p | [1.4:1.6]*I _{carga} |
| α, β, δ | 2, 1, 2 |
| Población/cromosomas | 100 |
| Iteración/generaciones | 2,000 |

Tabla 2 Parámetros de optimización. *Elaboración propia.*

Simulación

| Bus | Bus | R | X | 1/2 B |
|-----|-----|-------|-------|--------|
| 1 | 4 | 0.035 | 0.225 | 0.0065 |
| 1 | 5 | 0.025 | 0.105 | 0.0045 |
| 1 | 6 | 0.040 | 0.215 | 0.0055 |
| 2 | 4 | 0.000 | 0.035 | 0.0000 |
| 3 | 5 | 0.000 | 0.042 | 0.0000 |
| 4 | 6 | 0.028 | 0.125 | 0.0035 |
| 5 | 6 | 0.026 | 0.175 | 0.0300 |

Tabla 3 Parámetros de las líneas. Fuente: Hadi Saadat, *Power system analysis*, McGraw-Hill, ISBN 0-07-561634-3, 1999.

| Bus | Generación | | | | Carga | | |
|-----|------------|-------|----|--------------|-------|-----|------|
| | X'd | V | MW | Limites Mvar | | MW | Mvar |
| | | | | Min | Max | | |
| 1 | 0.20 | 1.060 | | | | | |
| 2 | 0.15 | 1.040 | 50 | 0 | 40 | | |
| 3 | 0.25 | 1.030 | 30 | 0 | 20 | | |
| 4 | | | | | | 100 | 70 |
| 5 | | | | | | 30 | 5 |
| 6 | | | | | | 20 | 5 |

Tabla 4 Parámetros de los generadores y las cargas levemente modificados. Fuente: Hadi Saadat, *Power system analysis*, McGraw-Hill, ISBN 0-07-561634-3, 1999.

Resultados

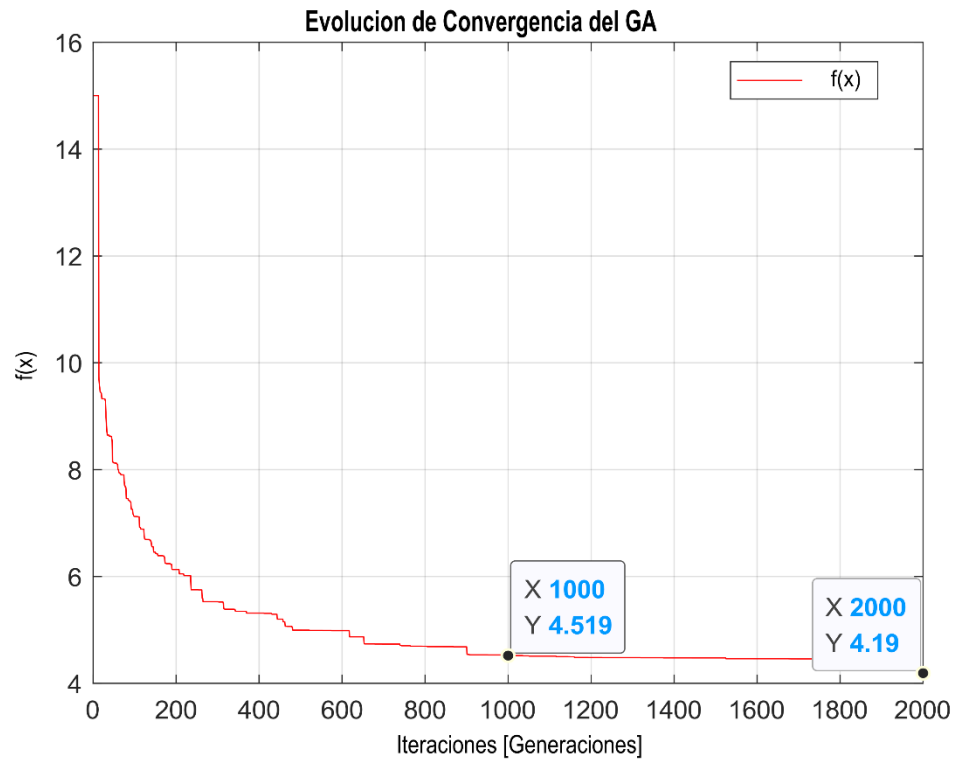


Figura 6 Convergencia del GA promediada para el sistema de 6 buses mallado en 100 corridas de simulaciones independientes. *Elaboración propia.*

| GA | | | | | |
|----------|------|--------|---------|---------|----------|
| | f(x) | t(seg) | tp(seg) | tb(seg) | CTI(seg) |
| Max | 5.12 | 127 | 0.81 | 1.70 | 0.89 |
| Min | 3.30 | 125 | 0.51 | 1.28 | 0.77 |
| Promedio | 4.19 | 127 | 0.63 | 1.50 | 0.87 |
| SD | 0.41 | 4.11 | 0.07 | 0.15 | 0.10 |

Tabla 5 Resultados máximos, mínimos, promedios y desviación estándar en 100 corridas de simulaciones independientes. *Elaboración propia.*

Resultados

| Primario | Respaldo | GA | | | Primario Icc(A) | Respaldo Icc(A) |
|----------|----------|-------|-------|--------|--------------------|--------------------|
| | | tp(s) | tb(s) | CTI(s) | | |
| 4 6 | 1 4 | 0.59 | 1.47 | 0.88 | 7,493 | 2,338 |
| 1 5 | 4 1 | 0.90 | 2.15 | 1.25 | 7,676 | 1,900 |
| 1 6 | 4 1 | 0.52 | 2.10 | 1.59 | 8,572 | 1,921 |
| 5 6 | 1 5 | 0.55 | 1.08 | 0.52 | 6,554 | 3,676 |
| 1 4 | 5 1 | 0.42 | 1.52 | 1.10 | 7,955 | 2,363 |
| 1 6 | 5 1 | 0.52 | 1.45 | 0.93 | 8,572 | 2,508 |
| 6 4 | 1 6 | 0.95 | 1.30 | 0.35 | 4,370 | 2,127 |
| 6 5 | 1 6 | 0.75 | 1.22 | 0.47 | 5,366 | 2,231 |
| 1 4 | 6 1 | 0.42 | 2.53 | 2.11 | 7,955 | 1,451 |
| 1 5 | 6 1 | 0.90 | 2.06 | 1.17 | 7,676 | 1,633 |
| 6 1 | 4 6 | 0.62 | 1.17 | 0.55 | 5,620 | 3,186 |
| 6 5 | 4 6 | 0.75 | 1.21 | 0.45 | 5,366 | 3,104 |
| 4 1 | 6 4 | 0.43 | 1.96 | 1.54 | 7,590 | 2,433 |
| 6 1 | 5 6 | 0.62 | 1.14 | 0.52 | 5,620 | 2,405 |
| 6 4 | 5 6 | 0.95 | 1.26 | 0.31 | 4,370 | 2,216 |
| 5 1 | 6 5 | 1.04 | 1.35 | 0.32 | 5,291 | 2,413 |
| PROMEDIO | | 0.68 | 1.56 | 0.88 | -- | -- |

Tabla 6 Tiempos de operación primario, respaldo, CTI y las corrientes de falla de las parejas de coordinación. *Elaboración propia.*

| DOCR | GA | |
|------|------|-----|
| | dial | Ip |
| 1 4 | 0.66 | 664 |
| 4 1 | 0.66 | 666 |
| 1 5 | 1.72 | 304 |
| 5 1 | 1.88 | 298 |
| 1 6 | 0.96 | 438 |
| 6 1 | 1.00 | 445 |
| 4 6 | 0.95 | 607 |
| 6 4 | 1.08 | 614 |
| 5 6 | 0.94 | 452 |
| 6 5 | 1.24 | 417 |

Tabla 7 Ajustes de dial y corriente de arranque para los relevadores de sobre corriente. *Elaboración propia.*

Conclusiones

| Coordinación para sistemas mallados | Manual | GA |
|--|----------------|---------|
| Tiempo | Días o semanas | Minutos |
| Satisfacer todas las restricciones | A veces | Si |
| Posibilidad de adecuarse para esquema de protección adaptativa | No | Si |
| Posibles errores en los cálculos | Si | No |
| Cansancio | Si | No |

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