Resumen

Este artículo presenta el diseño de un sistema de seguridad para oscilaciones bruscas de frecuencia para un sistema de potencia débilmente interconectado y que ocasionalmente opera aislado de un sistema de potencia fuertemente interconectado. Este sistema de seguridad debe operar en tiempo real y se basa en algoritmos de decisión que tienen como objetivo evaluar el riesgo de pérdida de estabilidad y determinar una combinación de disparo de unidades de generación y/o circuitos de carga. Para determinar las combinaciones de disparo, se considera la topología y punto de operación del sistema de potencia débilmente interconectado. Los algoritmos de decisión se desarrollaron combinando técnicas de inteligencia artificial con algoritmos secuenciales. La efectividad de las combinaciones de disparo obtenidas a través de los algoritmos de decisión, se
1. Introduction

A sudden active power imbalance in a power system can be produced as a result of a topology change, for example, a line or generation outage [1]. This power imbalance affects the system frequency.

In weakly interconnected power systems, the frequency stability is a first-order problem due to the interconnected line outage produces high-frequency variations and being able to conduct the power system to a collapse when the frequency is over limited [2].

When a high-frequency deviation exists, the system can be conducted to an emergency condition, therefore it is necessary to take corrective actions using the security scheme, which allows restarting the normal operating condition of the power system.

The security scheme is implemented in the power system to avoid the instability, to minimize the risk of damage to generating plants, to diminish the possibility of cascade events as a consequence of the generation unit outage due to the high-frequency oscillations and to restore the system frequency close to a normal value. The security system presented in this article is based on two types of disconnections:

Under-frequency load shedding UFLS: its function is to avoid under-frequency instability when the generation is reduced after a disturbance [3], [4], [5].

Over-frequency generation tripping OFGT: its function is to avoid over-frequency instability when the generation exceeds the load after a disturbance [6], [7], [8].

This centralized scheme allows tripping generation and shedding loads to maintain the power system stability of weakly interconnected power systems after an interconnected line outage. In this case is necessary: Monitoring the generation unit status, the interconnected line status and the load power, in order to evaluate the risk of reaching system instability, selecting the best shedding or tripping combination and sending the opening signals to

2. Critical power transfer

The system frequency variation \( \frac{df}{dt} \) depends on the operating frequency, the power imbalance \( P \), and the system inertia \( H \), as shown in Equation (1).

\[
\frac{df}{dt} = \frac{f_0 P}{2H}
\]

In Fig 1, a weakly interconnected power system is illustrated, the power imbalance between the generation and the load is reflected in the power transfer through the interconnected line, therefore the critical power transfer is the maximum power imbalance that a power system can support before reaching instability. It is considered that a system is unstable if the frequency varies in a divergent form outside of the operating limits. It means that the system cannot operate over the frequency limit \( f_{\text{over}} \) for an over-frequency condition and under the frequency limit \( f_{\text{under}} \) for an under-frequency condition.

Figure 1. Simplified diagram of a weakly interconnected power system.
the lines and the limit \( f_{\text{over}} \) at generation nodes, for over-frequency conditions. Similarly for under-frequency conditions, the generating power is decreased until finding the power imbalance in lines and the limit \( f_{\text{under}} \) at generation nodes.

3. **Security system**

From the topology and the operating conditions of the power system, the different load shedding and generation tripping combinations are evaluated and the best combination is chosen in order to maintain the system stability. These operations allow maintaining the frequency response inside a secure operating range.

The security system monitors: The generated active power and the breaker status for each generating unit, the active power demand of the automatic load shedding circuits, the active power flow and the breaker status of the interconnected lines. From these variables and the operating constraints of the weakly interconnected power system, the security function determines a load shedding and generation tripping combination in order to maintain the system stability after the interconnected line outage.

The load shedding or generation tripping determined by the decision algorithms guarantees four technical operating criteria:

1. Operation of the generating units inside an allowed range, after the units are tripped.
2. System stability after the load shedding and generation tripping combination is carried out.
3. Selectivity of the provided service to the consumers, according to the economic-technical criteria considered by the electric power companies.
4. Minimum load shedding for each under-frequency condition.

   A. Over-frequency condition

   The first criterion implies two conditions:

   **Condition 1**: Maximum operating power

   \[
   P_G^{\text{max}} \geq PD \tag{2}
   \]

   

   **Condition 2**: Minimum power generation.

   \[
   P_G^{\text{min}} = \frac{P_d}{n} \tag{3}
   \]

   

   Where:

   - \( P_G^{\text{max}} \): Maximum generating power for all the system units.
   - \( P_G^{\text{min}} \): Minimum generating power for all the system units.
   - \( P_d \): Power system demand.
   - \( n \): Number of generating units.

   

   **Condition 2**: Minimum power generation.

   \[
   P_G^{\text{max}} \leq PD \tag{5}
   \]

   

   With:

   \[
   P_G^{\text{min}} = \sum_{i=1}^{n} P_r_i \tag{6}
   \]

   

   Where:

   - \( P_G^{\text{min}} \): Minimum generating power for all the system units.
   - \( P_r_i \): Minimum operating power for the online unit \( i \).

   The second criterion implies two conditions:

   **Condition 1**:

   This condition guarantees that the accelerating power after tripping generators does not conduct to over-frequency instability.

   \[
   P_a \leq P_{\text{CRS}} \tag{7}
   \]

   

   With:
\[ P_a = P_d - P_T \]  \hspace{1cm} (8)

Where:
- \( P_a \): Accelerating power after tripping generators.
- \( P_d \): Total tripped power
- \( P_{CRB} \): Critical power transfer for over-frequency condition.

Condition 2:
This condition guarantees that the accelerating power after tripping generators does not conduct to under-frequency instability.
\[ P_a \geq P_{CRB} \]  \hspace{1cm} (9)

Where:
- \( P_a \): Accelerating power after tripping generators.
- \( P_{CRB} \): Critical power transfer for under-frequency condition.

The technical criteria 3 and 4 are not applied for over-frequency conditions.

B. Under-frequency condition

The first criterion implies two conditions:

Condition 1:
\[ P_{G_{\text{max}}} \geq P_D \]  \hspace{1cm} (10)

With:
\[ P_{G_{\text{max}}} = \left( \sum_{i=1}^{n} P_{G_i} \right) \]  \hspace{1cm} (11)

\[ P_D = \left( \sum_{i=1}^{n} P_{G_i} \right) + P_T P_e \]  \hspace{1cm} (12)

Where:
- \( P_{G_{\text{max}}} \): Maximum tripped power.
- \( P_D \): Total power shedding for the considered load combination.
- \( P_e \): Minimum tripped power.

Condition 2:
This condition is similar to the over-frequency condition.

The second criterion implies two conditions.

Condition 1:
This condition guarantees that after shedding the load circuits, the system reaches no over-frequency condition.
\[ P_e \leq P_{\text{max}} \]  \hspace{1cm} (13)

With:
\[ P_{\text{max}} = P_T + P_{\text{max}} \]  \hspace{1cm} (14)

Where:
- \( P_{\text{max}} \): Maximum tripped power.

Condition 2:
This condition guarantees that after shedding the load circuits, the system reaches no under-frequency condition.
\[ P_e \geq P_{\text{min}} \]  \hspace{1cm} (15)

With:
\[ P_{\text{md}} = P_T - P_{\text{min}} \]  \hspace{1cm} (16)

Where:
- \( P_{\text{md}} \): Minimum tripped power.

In the third criterion, the electric company must define the priority in providing the service to the power demand. This priority is represented by means of a vector \( P \), whose elements contain the loads that are part of the automatic load shedding; the position of each element defines the priority in the provided service. For example, if the electric power company defines the vector \( P \) as Equation (17), then the load shedding circuits are C1, C2, C3, C4 and C5 and the load shedding orders in an emergency condition are C5, C4, C1, C3, and C2.
\[ P = [ C5 \ C4 \ C1 \ C3 \ C2] \]  \hspace{1cm} (17)

In the fourth criterion, the algorithm searches for a load shedding combination, whose total power
is approximately equal to the load shed power, as defined in Equation (18)

\[ P_{\text{shedding}} = |P_T| - |P_{\text{CRB}}| \]  

(18)

4. Determination of the tripping and shedding combinations

The selection of a load shedding or generation tripping combination is carried out using criteria to conduct the searching among the possible solutions, which is determined by the topology and the operating point. Besides, the shedding or tripping combination must comply with the operating criteria.

A Load shedding algorithm

Due to the searching space size of a load shedding combination depends on the amount of the connected distribution circuits to the power system, a genetic algorithm is used as a technique oriented to the search of a shedding combination that complies with the established operating constraints in the technical operating criteria.

The genetic algorithm is based on two basic ideas: The representation of the combination by means of binary strings and the execution of an operator created from the genetic laws. Using the representation by binary strings, the size of the searching space depends on the amount of bits used to represent the shedding combination., if a binary string of L bits is used, the size of the searching space is \(2^L\), it correspond geometrically to a hypercube of L dimensions. The convergence of the genetic algorithms for this representation has been tested in [10].

The representation of the shedding combination is carried out similar to the chromosomal information in biological systems. Therefore, each gene represents the breaker status of a load shedding circuit and each chromosome corresponds to the shedding combination.

In general, the genetic algorithm consists of three stages.

- Determination of the population in a systematic form.
- Systematic crossover of genetic information
- Constraints verification.

1) Determination of the population in a systematic form: Searching for the load shedding combination that complies with the equation (19).

\[ P_e \geq P_{\text{shedding}} \]  

(19)

Where

- \(P_e\) Total active power of the selected load shedding combination.
- \(P_{\text{shedding}}\) Load shed active power

2) Systematic crossover of genetic information: This process allows to generate load shedding combinations for all the load breakers, therefore, two initial chromosomes are generated, Father 1 and Father 2, which are characterized by:

Father 1: To characterize this chromosome, a binary number of n bits are generated, where n represents the size of the population and for each gene a bit of the binary number is assigned.

Father 2: the genes of this chromosome are opposed to the genes of chromosome Father 1.

Once the chromosomes are characterized, a systematic interchange with genetic information is carried out in order to form the chromosomes Son 1 and Son 2, which represent the possible load shedding combinations. Fig. 2 shows this process.
3) **Constraints verification:**

   It verifies that one of the chromosomes Son complies with the operating constraints. For example, if the population is characterized by the vector \( V = [X_1 \ X_2 \ X_3 \ X_4 \ X_5] \) and the chromosome Son is characterized by the vector \([0 \ 1 \ 1 \ 0 \ 1]\), it means that the load shedding combination is \([X_2 \ X_3 \ X_5]\). If no Son complies with the criterion, the algorithm creates new Fathers and returns to the second stage.

   **B Generation tripping algorithm**

   As a searching strategy, the generation tripping combination is generated in a systematic form, according to the breaker status and active power of each generating unit, then a generation tripping combination is searched, which complies with the technical operating criteria; if a solution exists, the searching strategy is able to find it, but if the space is large enough, the required time to find it can be long enough. Therefore, the searching strategy has a fast time of response in small power systems.

   **C Integrated Algorithm**

   The security system for high-frequency oscillations requires an integrat-
Figure 4. Flow chart of the generation tripping algorithm

Figure 5. Flow chart of the integrated algorithm

ed algorithm for the decision algorithm operation according to the power flow direction through the interconnected lines. Figure 5. shows the flow chart of the integrated algorithm.

5. Validation of the decision algorithms

The validation of the decision algorithm was carried out in a small power system interconnected to a large power system in radial distribution. Therefore, this system is appropriated to validate the decision algorithms for the proposed security system. A simplified single-wire diagram representation of the system is shown in Figure 6.

This power system has two 13 MW generators and two 24 MW
generators. Maximum load and generation were assumed in order to validate the decision algorithm.

The effectiveness of the proposed security scheme is evaluated by means of comparing the power system frequency with and without load shedding and generation tripping operation.

Table 1 shows the operating conditions of the power system before the interconnected lines outages. Fig. 7 shows the simulation results. Characteristic 1 shows how the system becomes unstable in a period less than 1.5 seconds, when no generators are tripped. Characteristic 2 shows the system stability when the determined generating units by the decision algorithm are tripped, for this operating condition units G1 and G4 are tripped, after the interconnected line outage.

Tables 2 and 3 show other operating conditions before the interconnected line outages. Fig. 8 presents the simulation results. Characteristic 1 shows how the system becomes unstable during a period less than 2 seconds when no generators are tripped. Characteristic 2 shows how the system becomes unstable during a period less than 1 second when no load shedding is carried out. The decision algorithms for this condition obtained that units G1 and G3 must be tripped, besides loads C1, C2 and C3 must be shed in order to obtain the balance between the power generation and the power demand when an interconnected lines outage is presented.

Due to the considered power system only has four generating units, there are a maximum number of 14 possible tripping combinations for an over-frequency condition and it means that there is not always possible to find a tripping combination to maintain system stability for an over-frequency condition, because it can be tripped more
than the required power and reaching under-frequency instability. Therefore it is not necessary to trip generating units to avoid over-frequency instability and to shed load circuits to avoid under-frequency instability. The load shedding and generation tripping obtained by the
decision algorithm are effective for an over-frequency condition.

6. Conclusions

The security system for abrupt frequency oscillation in isolated power systems is characterized by:

- Online operation.
- Being adaptable for different operating conditions of the power system.
- Guaranteeing the frequency stability of the weakly interconnected power system.
- Using optimization criteria for load shedding.
- Recovering frequency of the weakly interconnected power system when it operates isolated from a stronger interconnected power.

The methodology conception for the OFGT and UFLS function design is flexible, generic and includes the operating system constrains.

The operating constraints are used independently of the searching process; therefore they can be eliminated or added. This allows the design to be adaptable to other weakly interconnected power systems.

Bibliography


