

## **ANEXO 31**

# **HERRAMIENTAS DE CÁLCULO UTILIZADAS**

# HERRAMIENTAS DE CÁLCULO UTILIZADAS

## POWER SYSTEM SIMULATOR FOR ENGINEERING (PSS/E)

El programa utilizado para análisis de sistemas de potencia para el Plan de Expansión del Sistema de Transmisión es el PSS/E, Power System Simulator for Engineering. El PSS/E es un paquete de programas desarrollado por Power Technologies, Inc. (PTI), compañía de consultoría para el análisis de sistemas eléctricos de potencia en las áreas de generación, transmisión, distribución y plantas ó sistemas industriales.

### DESCRIPCIÓN FUNCIONAL DEL PSS/E

El PSS/E es un programa integrado e interactivo, que se emplea para simular, analizar y optimizar el comportamiento de un sistema de potencia en condiciones de estado estable y dinámicas.

Este programa consta de diferentes módulos y puede realizar los siguientes cálculos de análisis de sistemas de potencia:

- a. Flujo de Carga
- b. Flujo de Carga Optimo (OPF)
- c. Análisis de Fallas Balanceadas y Desbalanceadas
- d. Simulación Dinámica
- e. Simulación Dinámica Extendida
- f. Análisis de Límites de Transferencia
- g. Reducción de Redes

El programa alcanza sus máximas capacidades por una estructura altamente modular y, en la simulación dinámica se pueden crear subrutinas que describan algún problema de interés cuando los procedimientos estándares de cálculo no son apropiados.

Aplicando estas herramientas en la secuencia apropiada, se puede manejar un amplio rango de variaciones en el tema básico de flujo de carga y estabilidad.

La versión 30.2 del PSS/E con que cuenta ETESA tiene la capacidad de modelar hasta 50,000 barras, 100,000 líneas, 20,000 transformadores y 12,000 generadores. A continuación se presentan las tablas que muestran la cantidad total de elementos que puede simular el PSS/E.

Table P-1. Standard Maximum PSS/E Program Capacities

	1000 Buses	4000 Buses	12000 Buses	50000 Buses
<b>TRANSMISSION NETWORK COMPONENTS</b>				
Buses (including "star point" buses of three-winding transformers)	1,000	4,000	12,000	50,000
Loads	2,000	8,000	24,000	100,000
Plants	300	1,200	3,600	10,000
Machines	360	1,440	4,000	12,000
Switched shunts	126	500	1,500	4,000
Branches (including transformers and zero impedance lines)	2,500	10,000	24,000	100,000
Two-winding transformers (including three-winding transformer members)	400	1,600	4,800	20,000
Three-winding transformers	100	400	1,200	5,000
Transformer impedance correction tables	16	32	64	96
Zero impedance lines	50	200	400	1,000
Multisection line groupings	100	400	800	1,600
Multisection line sections	250	1,000	2,000	4,000
Two-terminal dc transmission lines	20	30	40	50
Multiterminal dc lines	5	5	5	20
Converters per multiterminal dc line	12	12	12	12
dc buses per multiterminal dc line	20	20	20	20
dc circuits per multiterminal dc line	20	20	20	20
FACTS control devices	20	20	20	50
Interchange control areas	100	250	500	999
Interarea transfers	300	500	1,000	2,000
Zones	999	999	999	999
Owners	999	999	999	999

Table P-1. Standard Maximum PSS/E Program Capacities (Cont.)

	1000 Buses	4000 Buses	12000 Buses	50000 Buses
Machine owner specifications	720	2,880	8,000	24,000
Branch owner specifications	5,000	20,000	48,000	200,000
Zero sequence mutual couplings	500	2,000	3,000	4,000
<b>DYNAMIC SIMULATION ELEMENTS</b>				
Synchronous machines	360	1,440	4,000	12,000
Constant parameters (CONs)	12,500	40,000	80,000	200,000
Algebraic variables (VARs)	7,500	16,000	32,000	80,000
State variables (STATEs)	5,000	20,000	40,000	100,000
Integer parameters (ICONs)	10,000	20,000	40,000	100,000
Output channels	750	3,000	8,000	24,000
User model definitions	60	60	60	60
Activity CHAN/CHSB model entries	500	2,000	2,000	2,000
Load model table entries	1,000	4,000	12,000	50,000
Bus type load models	250	1,000	3,000	12,500
Owner type load models	999	999	999	999
Zone type load models	999	999	999	999
Area type load models	100	250	500	999
All type load models	5	10	15	25
Line relay model connection table entries	25	100	240	1,000
<b>ONE-LINE DIAGRAM ELEMENTS</b>				
Buses	500	1,000	1,000	1,000
Branches	1,000	2,000	2,000	2,000
Bus equipment elements	1,000	2,000	2,000	2,000
Text lines	350	700	700	700
Straight line segments	100	100	600	600
Symbols	250	500	600	600
Summation records	40	40	40	40
Summation participation records	300	300	300	300

## PROGRAMA DIGSILENT

El programa DigSILENT Power Factory (**D**igital **S**imulation and **E**lectrical **N**etwork calculation program) es una herramienta de ingeniería asistida por computador, diseñada como un paquete interactivo, integrado y avanzado, que se emplea para el análisis de sistemas eléctricos de potencia orientados a alcanzar los principales objetivos del planeamiento y optimización de la operación.

El programa permite trabajar de manera integrada con una interface gráfica en línea que posee funciones de dibujo de diagramas unifilares. Cada elemento en el diagrama unifilar se enlaza directamente con la base de datos que almacena toda la información de cada elemento que hace parte del sistema eléctrico, permitiendo con esto la edición de parámetros desde el unifilar. Adicionalmente, desde la interface gráfica se tiene acceso directo a todas las características de cálculo relevantes tanto dinámicas como estáticas.

Cada sistema eléctrico que se quiera modelar constituye para la aplicación un PROYECTO, de manera que cada proyecto debe contener la topología de la red (GRID), los parámetros técnicos de cada elemento (LIBRARY) definidos en unidades físicas (no en PU) y la definición del caso de estudio en donde se especifica qué sección de la red quiere estudiarse (STUDY CASE). En un mismo proyecto pueden haber tantas Grid. Libray y Case como se necesiten, lo cual permite modelar en un mismo proyecto un sistema con varias condiciones operativas (varias demandas, y/o varios despachos, y/o cambios topológicos) e incluso su evolución en el tiempo (expansión).

Las funciones que proporciona el DigSILENT están agrupadas por módulos, cada uno de los cuales puede adquirirse de manera independiente. Los principales módulos disponibles y sus funciones son los siguientes:

### **Basics**

- Elaboración de diagramas unifilares interactivos con la base de datos
- Cálculos de flujos de carga
- Cálculos de cortocircuito
- Cálculo de parámetros eléctricos de líneas de transmisión a partir de su configuración geométrica.
- Creación de tareas automatizadas (DPL)
- Acceso interactivo o en línea con sistemas SCADA.
- Posibilidad de importación o exportación de datos en forma dinámica con otras aplicaciones (Excel).

### **Stability**

- Simulaciones de estabilidad transitoria
- Creación de modelos de usuario (DSL)
- Simulaciones de estabilidad dinámica
- Análisis modal
- Reducción de redes.

### **Otros Módulos**

- Armónicos
- Confiabilidad
- Protecciones

## **Diagrama Unifilar**

De acuerdo con la filosofía de la aplicación, cada elemento en el DIgSILENT es un objeto, y todos los objetos son almacenados en una base de datos estructurada en árbol (similar al sistema de administración de archivos de Windows), la información gráfica al interior del DIgSILENT es conservada por medio de objetos gráficos. Un diagrama unifilar de una red en particular, por ejemplo, es almacenada como un objeto Single Line Graphic.

En el DIgSILENT se tienen disponibles cuatro tipos de objetos gráficos:

- ◆ Diagramas unifilares que se utilizan para la definición de las redes eléctricas y para mostrar resultados de cálculo.
- ◆ Diagramas de subestaciones para mostrar la topología de una subestación en particular y los resultados de cálculo.
- ◆ Diagramas de bloques para la creación de circuitos lógicos (controles) y relés.
- ◆ VIP's que pueden emplearse para la creación de gráficas, por ejemplo de resultados de simulaciones de estabilidad, cálculos de armónicos, etc.

Las ventajas de esta herramienta son las siguientes:

- ◆ El enlace entre la representación gráfica y los datos de objetos, sin tener necesariamente una relación 1:1 entre los objetos y los símbolos gráficos.

- ◆ Además de permitir dibujar objetos existentes en la base de datos, permite crear objetos nuevos.
- ◆ Permite ubicar y editar objetos de la base de datos más ágilmente.
- ◆ Los resultados se presentan de una manera más clara para el usuario.

## **Flujo de Cargas**

El problema del flujo de cargas consiste en el cálculo de flujos de potencia y voltaje de barras de un sistema eléctrico bajo condiciones normales de operación. Comúnmente los sistemas de transmisión son balanceados, y en estos casos es posible emplear una representación monofásica para su análisis. En sistemas de distribución, en cambio, lo más común es que se presenten desbalances debido a que las cargas son normalmente desbalanceadas y, por tanto, requieren la representación de las tres fases. El módulo de flujo de cargas del DIgSILENT permite ambos cálculos, sin que por ello sea necesario la información de las tres fases cuando los análisis monofásicos sean suficientes.

Todas las restricciones que existen en los sistemas de potencia (tales como límites de capacidad de generadores, límites de cambiatomas, límites de transferencia de líneas, etc.) pueden ser o no considerados en los cálculos de flujo de carga. Así mismo, es posible definir elementos como máquinas asincrónicas, cargas especiales, FACTS, cambiatomas automáticos, etc., especificando su comportamiento individual.

En el DIgSILENT la función de SLACK del sistema no necesariamente la cumple una sola máquina sino que es posible definir que varias máquinas la cumplan (SECONDARY CONTROLS). Así mismo es posible controlar la tensión en una barra del sistema con la participación de los reactivos de varias máquinas (STATION CONTROLS).

Los resultados de un flujo de carga pueden observarse en forma tabular (UOUTPUT window), en los diagramas unifilares (GRAPHIC windows), o en la base de datos (DATA MANAGER) y pueden imprimirse o ser guardados en archivos de aplicaciones de office.

Las ventajas del cálculo de flujos de carga con DIgSILENT son las siguientes:

- ◆ La información de salida puede darse de varias maneras tal como tablas, gráficos, archivos, lo cual resulta práctico para la elaboración de los informes.
- ◆ Al analizar un resultado, se puede determinar con facilidad qué elementos dentro del sistema violan valores establecidos o se encuentran en rangos

determinados, tanto de manera tabular como gráfica, lo que agiliza el proceso de ajuste del flujo de cargas.

- ◆ La alta velocidad de cómputo es notable para sistemas grandes.
- ◆ El cálculo se basa en un algoritmo Newton–Raphson no desacoplado modificado de tal forma que siempre se garantiza la convergencia.

### **Cortocircuito**

El DIgSILENT ofrece los siguientes métodos de cálculo de cortocircuitos:

- ◆ Norma Alemana VDE 0102
- ◆ Norma Americana ANSI y IEEE C37
- ◆ Norma Internacional IEC 909
- ◆ Método "complete"

El DIgSILENT permite calcular:

- ◆ Corrientes de cortocircuito máximas, las cuales sirven para determinar la capacidad de los equipos eléctricos a instalar
- ◆ Corrientes de cortocircuito mínimas, que sirven como base para el cálculo de fusibles o mecanismos de protección.
- ◆ Corrientes de cortocircuito tomando como referencia el perfil de tensiones de un flujo de carga.

El programa tiene las siguientes ventajas:

- ◆ El modelamiento que se requiere para el cálculo de flujos de carga permite también el cálculo de corrientes de cortocircuito trifásicas.
- ◆ Para el cálculo de fallas asimétricas es necesario haber definido las impedancias de secuencia de los elementos del sistema: líneas, transformadores y máquinas.
- ◆ El programa permite calcular corrientes de cortocircuito en varias subestaciones a la vez.
- ◆ El programa permite calcular corrientes de cortocircuito para fallas simultáneas en varias subestaciones.
- ◆ Para sistemas grandes es notoria la alta velocidad de cálculo.
- ◆ Los resultados del cálculo se presentan en la ventana de salida en forma tabular (indicando los aportes por cada elemento conectado al punto de falla) y en los diagramas unifilares (mostrando el flujo de corrientes por todo el sistema graficado). Estos resultados pueden imprimirse o convertirse en archivos con formato de office.

### **Estabilidad**

La función de simulación de transitorios del DIgSILENT permite analizar la dinámica del comportamiento de un sistema de potencia en el dominio del tiempo. La librería de modelos propia del programa incluye varios modelos de generadores, motores, controles de plantas, cargas dinámicas



y elementos pasivos de redes tales como líneas, transformadores, cargas estáticas y compensaciones.

Los transitorios en sistemas eléctricos de potencia pueden ser divididos principalmente en tres dominios de tiempo:

- ◆ Corta Duración (transitorios electromagnéticos)
- ◆ Media Duración (transitorios electromecánicos)
- ◆ Larga Duración (transitorios)

DlgSILENT cubre el rango completo de los fenómenos transitorios en sistemas eléctricos de potencia. Consecuentemente, hay tres funciones diferentes de simulación disponibles:

- ◆ Una función básica que usa un modelo de red (RMS) de estado estable simétrico para estudio de transitorios de media y larga duración bajo condiciones de red balanceada.
- ◆ Una función trifásica que usa un modelo de red (RMS) de estado estable simétrico para estudio de transitorios de media y larga duración bajo condiciones de red balanceada y desbalanceada.
- ◆ Una función de transitorios electromagnéticos (EMT) con modelo de red dinámico para estudio de transitorios electromagnéticos y electromecánicos bajo condiciones de red balanceada y desbalanceada.

Adicional al cálculo de transitorios, pueden realizarse dos cálculos adicionales:

- ◆ Identificación de Parámetros
- ◆ Análisis Modal

Basado en la solución de un cálculo de flujo de carga, la función de simulación del DlgSILENT determina las condiciones iniciales de todos los elementos del sistema de potencia, cumpliendo los requerimientos de que la derivada de todas las variables de estado de cargas, máquinas, controles, etc., sean cero.

En esta etapa del proceso de simulación, se determina también qué tipo de representación de red debe ser usada, que paso de integración, cuáles eventos simular y dónde almacenar los resultados.

El DlgSILENT ofrece las siguientes ventajas:

- ◆ Su librería contiene modelos detallados de máquinas síncronas y asíncronas, con una sofisticada representación de los sistemas de secuencia cero y negativa, sistemas de compensación estática controlada con suicheo automático de condensadores, modelos de carga general con dependencia de la tensión estática y transitoria y equipos de protección (relés de frecuencia).

- ◆ La librería también incluye diversos tipos de controles (velocidad, tensión, potencia, estabilizadores, etc.) así como de turbinas (calderas, sistemas hidráulicas, turbinas a gas).
- ◆ Además de la disponibilidad de modelos dinámicos prediseñados, el usuario tiene la posibilidad de definir sus propios tipos de modelos matemáticos que le permitan aproximarse más a sus requerimientos particulares.
- ◆ Durante la simulación el valor de todas las variables monitoreadas pueden imprimirse en la pantalla de salida. Sin embargo, estos resultados también son almacenados en un archivo que posteriormente puede procesarse y estudiarse mediante tablas o gráficas.
- ◆ El proceso de simulación puede ser interrumpido para la introducción de fallas, operaciones de suicheo, impresión de resultados intermedios o el cambio de las variables de monitoreo.

### **Confiabilidad**

La valoración de índices de confiabilidad básicamente comprende 5 etapas:

1. Modelamiento de fallas
2. Modelamiento de cargas
3. Generación de estados de la red
4. Análisis de efecto de fallas
5. Análisis estadístico

Los modelos de falla describen la manera en la cual las componentes del sistema pueden fallar, qué tan a menudo pueden fallar y cuánto toma reparar las fallas. Los modelos de carga requieren la definición de un modelo más discretizado en tiempo, comparado con otros análisis eléctricos, del comportamiento en el tiempo de las cargas y puede basarse en pronósticos precisos de demanda y escenarios de crecimiento de demanda. El modelo utilizado aquí es la curva de duración de carga anual.

La combinación de una o más fallas simultáneas y una condición de carga específica es lo que se conoce como “estado del sistema”. El modelo de generación de estados del sistema usa los modelos de falla y de carga para construir la lista de estados del sistema relevantes. La tarea del módulo de Análisis de Efecto de Falla (FEA) es analizar los estados del sistema fallado imitando las reacciones del sistema a esas fallas, calculando la demanda de carga atendida. La tarea básica del FEA es determinar si las fallas del sistema ocasionarán interrupciones de carga y cuando ese sea el caso, qué cantidad de carga y por cuánto tiempo estará interrumpida.

Los resultados del FEA son mezclados con los datos que provee el módulo de generación de estados del sistema para actualizar las estadísticas. Los datos de

estado del sistema describen la expectativa de frecuencia de ocurrencia de los estados del sistema y su duración esperada. La duración de esos estados del sistema no debe confundirse con la duración de las interrupciones.

Con base en las estadísticas de falla en equipos se establecen los índices de disponibilidad, frecuencia y duración históricos de fallas que permiten implementar un modelo de fallas para cada generador, línea y transformador de su sistema eléctrico.

Para la evaluación de la confiabilidad se representa en detalle todo el sistema de generación, transmisión y distribución dependiendo del grado de detalle con el cual se requiera analizar la red. Las simulaciones se realizan utilizando el método de Montecarlo disponible en el programa DlgSILENT, el cual ejecuta una simulación cronológica de las fallas en el sistema, empleando para ello un generador numérico estocástico, y determina en cada caso la energía racionada y los índices de confiabilidad de las cargas y barras del sistema.

Se determinan los índices de confiabilidad de todos los puntos de carga, subestaciones y el sistema global.

Los indicadores de confiabilidad que se entregan en este análisis son los más utilizados en los sistemas de transmisión:

### **Cargas**

- **LPIT:** Tiempo de interrupción esperado (Horas/Año)
- **LPIF:** Frecuencia Anual de Interrupciones (Veces/Año)
- **AID:** Duración promedio de cada interrupción (Horas/año)
- **LPENS:** Energía no suministrada (MWh/Año)

### **Barras**

- **AIT:** Tiempo promedio de interrupción anual (Horas/Año)
- **AIF:** Frecuencia promedio de Interrupciones anual (Veces/Año)
- **ENS:** Energía no suministrada (MWh/Año)

## Sistema

- **SAIFI:** Frecuencia promedia de interrupciones en el sistema (Veces/Año)
- **CAIFI:** Frecuencia promedia de interrupciones por consumidor afectado (Veces/Año-Consumidor)
- **SAIDI:** Duración promedio de interrupciones en el sistema (Horas/Año)
- **CAIDI:** Duración promedio de interrupciones por consumidor afectado (Horas/Año-Consumidor)
- **ASAI:** Disponibilidad promedia (%)
- **ASUI:** Indisponibilidad promedia (%)
- **ENS:** Energía promedia no suministrada (MWh/Año)
- **AENS:** Energía promedio no suministrada por consumidor afectado (MWh/Año-Consumidor)

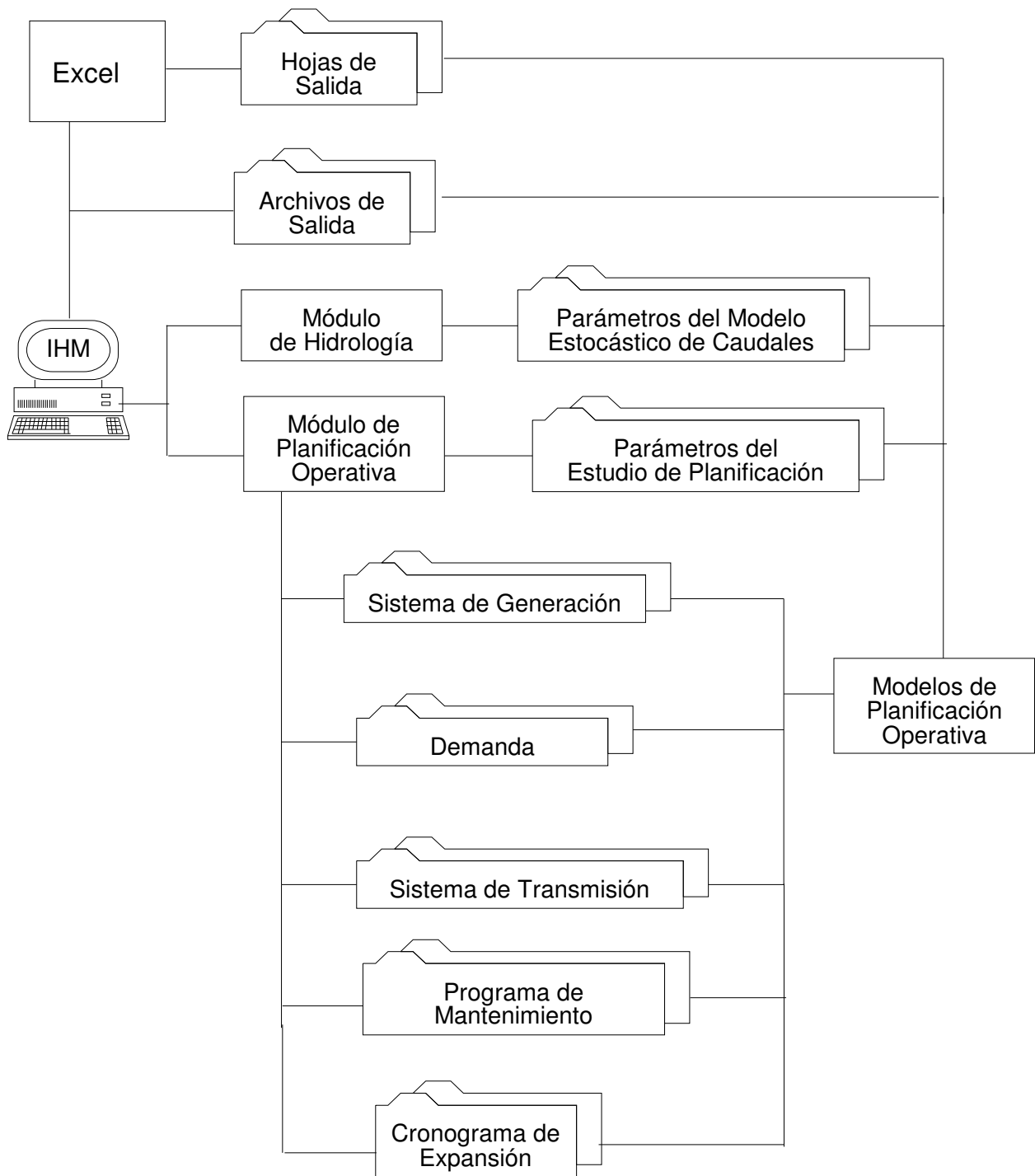
# STOCHASTIC DUAL DYNAMIC PROGRAMMING (SDDP)

## ESTRUCTURA DEL MODELO

El modelo SDDP se compone de dos módulos principales:

1. **Módulo de Planificación Operativa** - Determina la política operativa más económica para los embalses, teniendo en cuenta las incertidumbres en las afluencias futuras y las restricciones en la red de transmisión; simula la operación del sistema a lo largo del período de planificación, para distintos escenarios de secuencias hidrológicas; calcula índices de desempeño tales como el promedio de los costos operativos, los costos marginales por barra y por bloque de carga, y los intercambios óptimos entre empresas; determina la operación óptima de corto plazo
2. **Módulo Hidrológico** - Determina los parámetros del modelo estocástico de caudales.

La Figura presenta el flujo de ejecución de los módulos, los principales datos de entrada, y los enlaces entre los módulos de cálculo de política operativa y simulación.



**Flujo de Ejecución de la Planificación Operativa**

## **FLUJO DE DATOS**

Los datos de entrada para el módulo de la política operativa incluyen:

1. Datos del sistema:
  - características del sistema hidroeléctrico (topología de los embalses, coeficientes de producción, límites de almacenamiento, límites de turbinamiento etc.)
  - características de las centrales térmicas (potencia instalada, factores de disponibilidad, costos operativos etc.)
  - programa de mantenimiento de los equipos
  - características del sistema de transmisión (topología de la red, susceptancia y límites de flujo en los circuitos)
2. Demanda para cada etapa, cada bloque y cada barra de carga
3. Parámetros del modelo estocástico de caudales

Los datos de entrada para el módulo hidrológico incluyen:

- topología de los embalses
- datos históricos de los caudales

## **PROGRAMACION DINAMICA DUAL ESTOCASTICA**

La programación dinámica dual estocástica es la que permite efectuar la valoración del agua en sistemas hidrotérmicos con numerosos embalses. El concepto de valoración del agua almacenada permite efectuar un desacoplamiento temporal del problema de operación hidrotérmica. Esta valoración del agua hace que las plantas hidroeléctricas, para efectos de despacho, puedan ser consideradas como plantas termoeléctricas, asignándoles el costo correspondiente a la valoración del agua. En esta forma, el despacho se realizaría de acuerdo con el orden de mérito del conjunto de recursos térmicos e hidroeléctricos.

La programación dinámica dual estocástica parte de una representación estocástica de las series temporales hidrológicas pertinentes. La versión del SDDP utilizada permite representar los aportes hidrológicos mensuales por medio de sus medias, desviaciones típicas, coeficientes de asimetría, estructura de correlación temporal dada por un modelo auto regresivo hasta de orden 6 y la estructura de la correlación espacial. Esta representación permite utilizar los parámetros para una generación de secuencias hidrológicas igualmente probables, las cuales preservan las características de la serie original. Dichas secuencias permiten simular el sistema hidrotérmico y observar su comportamiento para cada una de ellas. Dado que ellas son igualmente probables, de los resultados de las simulaciones es posible inferir acerca del comportamiento probabilístico de diversas variables producto de la operación del sistema.

La programación dinámica dual estocástica opera en dos fases: en una primera fase el modelo halla la política de operación por medio de cortes de Benders, los cuales, en la práctica, lo que permiten es valorar el agua en cada uno de los embalses del sistema como función del contenido de los mismos y de la historia hidrológica en períodos anteriores. Una vez se ha obtenido la política operativa el modelo efectúa una simulación para cada una de  $N$  secuencias generadas sintéticamente.

El modelo SDDP permite efectuar una representación bastante detallada de cada una de las plantas del sistema, el suministro de combustible, la disponibilidad hidrológica, la demanda y la red de transmisión bien sea incluyendo pérdidas en el sistema o sin incluirlas.



# MODELO DE EXPANSIÓN AUTOMÁTICA DE TRANSMISIÓN

## Transmission Network Expansion Planning Under a Tabu Search Approach

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*Abstract*—This paper describes an implementation of Tabu Search to cope with long-term transmission network expansion planning problems. Tabu Search is a metaheuristic proposed in 1989 to be applied to combinatorial problems. To assess the potential of our approach we will test it with two cases of transmission network expansion planning. The results obtained by our approach let us to conclude that TS is a robust and promising technique to be applied in this problem.

*Index Terms*—Integer programming, metaheuristics, optimization, Tabu Search, transmission network expansion planning.

### I. INTRODUCTION

THE BASIC purpose of long-term transmission network expansion planning (TNEP) is to determine when and where to install new equipment to meet both optimal operational and economical criteria. The main difficulty to solve this problem is the existence of integer investment variables, which requires the use of combinatorial algorithms. Another difficulty resides on the dynamic considerations when there is more than one stage (year) within the planning period [3]. However, this paper addresses the static transmission network expansion planning problem (STNEP) which consists in minimizing investment cost in new transmission facilities subject to operational constraints for just one year in the future.

One of the first approaches developed to solve STNEP was proposed by Garver [3], who formulated the problem as a power flow solved via a linear programming algorithm. As a result the most direct routes from generation to loads could be identified and reinforced. Afterwards, a lot of different approaches have been proposed; see [4] for a partial review of the literature.

The search for metaheuristic approaches such as Simulated Annealing [11], GRASP [13] and Genetic Algorithms [12] has been stimulated due to the fact that STNEP is an integer and nonconvex problem. Classical decomposition approaches, e.g., Benders Decomposition [6], may fail to converge to optimal solutions due to the nonconvex nature of the problem.

Tabu Search (TS) is a metaheuristic method proposed by Glover in 1989 to solve combinatorial problems [10]. Briefly,

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TS is an iterative search procedure that moving from one solution to another looks for improvements on the best solution visited. The basic concepts of TS are movements and memory. A Movement is an operation to jump from one solution to another while memory is used with different objectives such as to guide the search to avoid cycles. Using the concept of memory, specific movements are made forbidden or taboo (Tabu Movement).

In 1997, Wen and Chang reported an application of TS to solve the STNEP problem [14]. In our approach, the Tabu Search concepts (short-term memory, Tabu List, Aspiration criterion, etc.) are used in a different way. Furthermore, we design intensification and diversification phases, using medium- and long-term memory concepts.

This paper is organized as follows: Section II describes the transmission network expansion planning problem. Section III provides a brief description of basic concepts of Tabu Search. Section IV describes the application of Tabu Search to the transmission network expansion problem. Section V shows the computational results analyzing two cases. Section VI summarizes the conclusions of our work.

### II. TRANSMISSION NETWORK EXPANSION PLANNING PROBLEM

The STNEP problem can be formulated as an integer-mixed nonlinear optimization problem, as follows:

Minimize

$$v = \sum C_{ij}n_{ij} + \sum \alpha_i r_i \quad (1)$$

Subject to:

$$B(x + \gamma^0)\theta + g + r = d \quad (1.1)$$

$$f_{ij} - (\gamma_{ij}^0 + x_{ij})(\theta_i - \theta_j) = 0 \quad (1.2)$$

$$|f_{ij}| - x_{ij}\phi_{ij}^{\max} \leq \gamma_{ij}^0\phi_{ij}^{\max}; \quad \phi_{ij}^{\max} = f_{ij}^{\max}/\gamma_{ij}^0 \quad (1.3)$$

$$0 \leq g \leq g^{\max}; \quad 0 \leq r \leq d \quad (1.4)$$

$$x_{ij} = n_{ij}\gamma_{ij}; \quad 0 \leq n_{ij} \leq n_{ij}^{\max}; \quad \forall (i, j) \in \Omega \quad (1.5)$$

where:

$C_{ij}$

cost of building a new circuit in branch  $i-j$ ;

$n_{ij}$

number of circuit additions to the branch  $i-j$ ;

$\alpha$

penalty parameter associated with loss of load caused by lack of transmission capacity;

$r$

array of load curtailments;

$B(\cdot)$	Susceptance matrix;
$g$	array of bus active powers;
$d$	array of predicted bus loads;
$f_{ij}$	active power flow through branch $i-j$ ;
$\gamma_{ij}^0$	initial susceptance in branch $i-j$ ;
$x_{ij}$	total new circuit susceptance added to the branch $i-j$ ;
$\theta_i, \theta_j$	voltage angle at bus $i$ and $j$ ;
$\gamma_{ij}$	circuit susceptance;
$f_{ij}^{\max}$	flow limit in branch $i-j$ ;
$g^{\max}$	maximum bus generation capacity array.
$n_{ij}^{\max}$	maximum number of new circuits in branch $i-j$ .

The set of all candidate circuits is represented by  $\Omega$ .

The objective function of STNEP (1) represents the investment costs in new transmission facilities (new transmission lines, new transformers etc.) plus a higher penalty for load curtailments. The penalty factor should be large enough to ensure that load curtailment equals zero (or near zero) at the optimal solution. Typically, the parameter  $\alpha$  is determined from statistical studies which identify the impact caused to consumers by shortages of electricity. This parameter expresses to the maximum price that the consumers are willing to pay for a continuous supplying of electricity. Remark that a zero load curtailment corresponds to a network with no overloaded circuits.

The constraints (1.1) and (1.2) model the linear power network—Kirchhoff's laws (KCL and KVL). Constraints (1.3) and (1.4) state operational limits while constraints (1.5) represent the integrality of the decision variables.

Note that if the vector of new susceptances,  $x^k$ , is known, i.e., if the transmission network expansion plan is already done, problem (1) becomes a linear programming (LP) problem:

Minimize

$$w = \sum \alpha_i r_i \quad (2)$$

Subject to:

$$B(x^k + \gamma^0)\theta + g + r = d \quad (2.1)$$

$$f_{ij} - (\gamma_{ij}^0 + x_{ij}^k)(\theta_i - \theta_j) = 0 \quad (2.2)$$

$$|f_{ij}| - x_{ij}^k \phi_{ij}^{\max} \leq \gamma_{ij}^0 \phi_{ij}^{\max} \quad (2.3)$$

$$0 \leq g \leq g^{\max}; \quad 0 \leq r \leq d \quad (2.4)$$

which can be solved by a Dual Simplex algorithm [15].

One of the most successful approaches proposed to solve this problem consists in applying the Benders Decomposition algorithm [6]. In this way, the whole problem is decomposed into two sub-problems. The first one deals only with investment variables and proposes transmission plans. The second tests the adequacy of each proposed plan and sends back new constraints (Benders cuts) to the investment sub-problem. The main drawbacks in applying Benders decomposition approach to solve STNEP are two: first it may converge to local optimum solutions due to nonconvexities of the transmission network expansion planning problem (remark that Benders cuts may cut-off the

feasible region in this case). Second, the solution of each investment sub-problem may require expensive computational time, because each sub-problem is a combinatorial problem itself. The first difficulty was handled by the hierarchical approach of Romero and Monticelli [1], however the application of this approach to networks with a large number of candidate circuits was limited by computational limitations.

This situation has stimulated several researchers toward non-conventional algorithms like Genetic Algorithm, Simulated Annealing, GRASP, etc. These algorithms can be applied to large systems and have provided solutions that compare favorably with those obtained by traditional approaches. In this direction, TS may be an interesting and promising algorithm to be used to solve STNEP problems.

In our approach the basic TS concepts are combined with the LP problem (2) resulting in a customized TS method capable of solving real world transmission network expansion planning problems.

### III. BRIEF REVIEW OF TABU SEARCH

Tabu Search is a metaheuristic search that has been applied to a large spectrum of integer problems, ranging from graph to mixed-integer ones. A basic algorithm of Tabu Search is based on the concepts of: Movement, Tabu List, Aspiration Criterion, Intensification and Diversification, which are seen in following. To review the basic concepts of TS consider the following combinatorial problem:

$$\text{Minimize } c(x): x \in X, \quad (3)$$

where

- $x$  is the vector of variables,
- $c(x)$  is the objective function and
- $x \in X$  are the constraints.

If  $x$  belongs to the set  $X$  it is a feasible solution of the problem. A large number of combinatorial problems can be written as (3), including problem (1).

Suppose we have a feasible solution,  $x$ , at  $k$ th iteration. A movement  $s$  from  $x$  can be defined as a mapping over the neighbor solutions of  $x$ ,  $X(s)$  in  $X$ :

$$s: X(s) \rightarrow X. \quad (3.1)$$

Thus, associated with each feasible solution,  $x$ , there is a set of possible movements  $S(x)$  that consists of all movements  $s$  that can be applied to  $x$ , i.e.,:

$$S(x) = \{s \in S | x \in X(s)\}, \quad (3.2)$$

where  $S$  is the set of all feasible movements belonging to  $X$ . We can also write  $X(s) = \{x \in X | s \in S(x)\}$ . Remark that the functions  $S(x)$  and  $X(s)$  are, respectively, the set of moves from  $x$  and the set of neighbors of  $x$  [9], [10].

A natural choice for the next solution to go to is to select the movement that minimizes the objective function of the problem. However, TS does not stop if there are no minimizing movements in the neighborhood of the  $k$ th solution. Thus, it continues seeking by improvements allowing movements that deteriorate the current solution. To prevent cycles, TS implements

a short-term memory, named *Tabu List* (TL) that stores historical information extending up to the last  $t$  iterations, where  $t$  is a user parameter. For example, let

$$TL = \{s \in S: s(x) \text{ violates the last } t \text{ tabu conditions}\}.$$

Then, the next movement to do would be:

$$s_k: c(s_k) = \text{Minimum} \{c(s(x)): s \in \{S(x) - TL\}\},$$

that is, the best movement within the neighborhood that does not belong to TL.

The size of TL is an important TS parameter. If it is too large, interesting moves may be forbidden and the power of TS would be jeopardized, and if it is too small, cycles may occur. The optimal value for  $t$  is the smallest value able to avoid cycles [9]. However, there are situations where a tabu move could be beneficial and does not produce cycles. For example, suppose that a given tabu movement ( $s_i(x) \in TL$ ) leads to an improvement in the incumbent solution. It is clear that this movement does not cause any cycle because the new solution,  $s_i(x)$ , was never visited before. In order to allow such movements, TS implements an *Aspiration criterion* (AC) that consists of a set of rules to override the tabu condition of a movement.

Two features of search methods (as TS) are *intensification* and *diversification*. Intensification is to explore regions where potential good solutions may exist. Diversification is to drive the search for unexplored regions. For example, pure random search methods are good in diversification but poor in intensification while a pure local search method is the opposite.

#### IV. TABU SEARCH FOR TRANSMISSION NETWORK EXPANSION PLANNING

The solution for the transmission network expansion planning problem, stated in (1), corresponds to a set of new transmission facilities that must be built. The cost of each solution is equal to the investment costs plus the load curtailment costs (evaluated by the LP problem (2)). However, in long-term planning studies the network is usually not totally connected because of new generation units or new load centers. Then, the LP problem (2) does not have a solution. This drawback is handled by adding non tabu candidate circuits (explained below) with minimum cost in order to connect the network. This procedure stops when the network is fully connected, therefore allowing a solution for problem (2).

##### A. Neighborhood

TS is a metaheuristic search procedure that jumps from one solution to another. Suppose, without loss of generality, that we have a current solution. Then, the neighborhood of the current solution is the set of all solutions that could be obtained by adding or removing any candidate circuit. Instead of solving an LP problem (2) to each neighbor solution, the number of LP could be very high, or electing just a part of the neighborhood to explore, we use a sensitivity index to choose the next neighbor solution to go to. This index is the sum of three different indices obtained either from the network data or from the solution of problem (2).

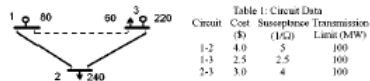


Fig. 1. Illustrative example.

TABLE I  
GRADE VALUES USED BY TS ALGORITHM

Circuit	Grades			Final Grade
	$\sigma_{ij}$	Cost	Susceptance	
1-2	1	1	3	5
1-3	2	3	1	6
2-3	3	2	2	7

The first index corresponds to the Lagrange multiplier of problem (2) with respect to candidate circuits susceptance. This index, expressed by,

$$\sigma_{ij} = (\pi_i^0 - \pi_j^0) (\Theta_j - \Theta_i); \quad \forall (i, j) \in \omega \quad (4)$$

estimates the impact on the objective function of problem (2) regarding marginal changes of candidate circuit susceptance  $i-j$ . We rank the  $n$  best candidates in a list called ranking list (RL), where  $n$  is a user parameter, assigning a grade varying from  $n$  (for the best) to 1 (for the worst) to each component of the list. The second index is the cost of each candidate circuit. In this way, we rank all candidate circuits of the previously formed list by decreasing costs, adding to the preview values a grade  $n$  (for the cheapest) and so on. The third index considers susceptance of candidate circuits. The susceptance of a circuit increases with voltage, so high voltage circuits have a global impact in transmission expansion plans. Thus, this index filters candidate circuits with good multipliers and low costs but poor global impacts, such as lower voltage transmission lines. The classification process is similar; i.e., the grades of the candidate circuits are updated by new values,  $n$  (for high voltage level) and so on. At the end, we select to add to the network the candidate circuit not classified as tabu (explained below) with the highest grade. If two or more candidates have the same final grade, we select the one with the highest loading degree (the ratio between the power flow and the circuit capacity).

For better understanding, consider the network illustrated in Fig. 1 as the current solution. Solving problem (2) we get the following indices,  $[\sigma_{1-2}, \sigma_{1-3}, \sigma_{2-3}] = [0.00, 0.09, 1.27]$ . From these indices it is possible to compute the first component of the ranking. To complete the RL it is necessary to include the other indices in order to determine the circuit to be built. In this example, the indices obtained are shown in Table I. Based on these results, the candidate circuit 2-3 is chosen to be built.

##### B. Tabu List and Aspiration Criterion

The concept of Tabu List is implemented with two objectives: first to prevent cycles and, second to avoid the addition of a large number of parallel circuits. Then, whenever a new circuit is built

it is made tabu for the next  $J$  iterations, i.e., it cannot be removed (preventing cycles) and its parallel candidate circuits cannot be built while it belongs to the TL, unless an Aspiration criterion is satisfied. The Aspiration criterion used is the traditional one; i.e., whenever a tabu addition leads to improvements it can be made, otherwise it is neglected.

### C. The Expansion Phase

If we apply this procedure—add the best candidate circuit based on the three indices—over and over, either we find or we fail in finding a feasible network (eliminating all overloads). This procedure, i.e., the search for feasible networks, is called Expansion Phase (EP). Also note that we can easily produce different expansion plans by running the EP several times, either starting from different initial solutions (fully connected networks) or considering small modifications on the movement criterion, e.g., varying the cardinality of the list. Using this fact, it is possible to identify, through a medium-term frequency-based memory, those candidate circuits that appear at most in different EP solutions, independent of the starting point and the movement criteria adopted, which make these circuits robust and consistent. In case that EP fails, we do not update this frequency index and re-start the expansion phase.

After executing the expansion phase  $T$  times, an extra EP is performed considering as starting point the addition of the  $M$  most frequent candidate circuits, computed by the medium-term memory during the last  $T$  expansion phase iterations.

At the end of EP, the solution may have useless additions. An addition is useless if it can be removed from the transmission expansion plan and the network continues feasible (without overloads). The procedure to remove these additions is simple and direct: try to remove, one at a time, all candidate circuits previously added in reverse order of their investment costs, checking for network feasibility. Those circuits that if removed do not cause any overload are definitely removed from the expansion plan. As a result of this phase we get a feasible and consistent transmission expansion plan, which is the starting solution for the intensification phase described next.

### D. The Intensification Phase

During Intensification phase (IP) the concept of a movement changes. In IP a movement consists in swapping two or more circuits, i.e., one candidate circuit previously built is removed and another is added. Again, we use the same indices except the susceptance index to select which are the candidate circuits that must be built.

The intensification phase implemented is subdivided into two iterative procedures: the difference between them is that the first (IP<sub>1</sub>) allows movements only for solutions with smaller investment costs, while the second (IP<sub>2</sub>) permits movements to more expensive solutions in order to bypass optimal local solutions. Both of them do movements only within of the feasible region.

To illustrate consider, without loss of generality, that the current solution is the one provided by the EP. At each IP<sub>1</sub> iteration, a previously built candidate circuit is removed and a different one is chosen to be built if both, its addition recovers the

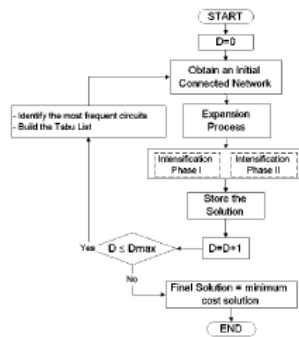


Fig. 2. TS algorithm for STNEP.

network feasibility that had been lost when the first circuit had been removed and the final solution is cheaper than the previous one.

At the end of an IP<sub>1</sub> iteration, the same procedure to remove a useless addition must be executed. Then, the solution provided by IP<sub>1</sub> procedure is better or equal than the one obtained by EP. Considering that IP<sub>1</sub> can be restrictive, IP<sub>2</sub> is performed from the IP<sub>1</sub> solution, and tries to exchange all previously built candidate circuits by others but in this phase, movements for more expensive solutions are allowed, since the final solution is within a pre-specified tolerance ( $\epsilon$ ). Again, the procedure to remove a useless addition is executed after each IP<sub>2</sub> iteration. Notice that it is not possible to ensure that the solution obtained by IP<sub>2</sub> is better than the IP<sub>1</sub> solution.

Remark that, once IP<sub>1</sub> is implemented, the procedure IP<sub>2</sub> can be easily obtained, just making a simple modification in IP<sub>1</sub> to allow the swap between circuits even when this results in an increase of investment cost below the tolerance  $\epsilon$ .

### E. The Diversification Phase

In order to make a more aggressive search we introduce a diversification scheme. The objective is to drive the search to unexplored regions of the search space. The diversification phase uses the long-term memory of TS and makes tabu the most frequent candidate circuits for the next EP; e.g., the  $d$  candidate circuits that appear most often in the last iteration are made tabu for the next expansion phase. Notice that this procedure forces EP and IP to search for different trial solutions for STNEP, visiting up to now unexplored regions.

The stopping criterion adopted by our Tabu Search algorithm is the number of diversification phases performed ( $D$ ). As in other metaheuristic procedures, it is not possible to guarantee global optimality. However, for appropriate fixed choices of parameters, our method has provided optimal and near optimal solutions for all case studies, showing its robustness. Fig. 2 summarizes our TS approach, which has an outer iterative process defined by the execution of each diversification phase. In addition, the approach has inner iterative processes defined by the execution of the Expansion or Intensification phases.

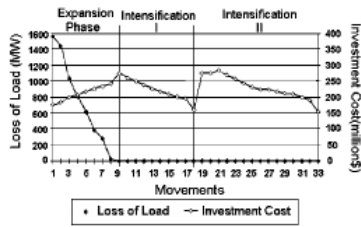


Fig. 3. Evolution for the first outer Tabu iteration.

## V. VALIDATION TEXT SYSTEMS

We use two real-world Brazilian transmission network expansion planning studies to illustrate our Tabu Search approach: the first one corresponds to the 1980 Brazilian Southern system and the second to the 2000 Southeastern system. The data used by the model are susceptance, network topology, circuit capacities and power injections. Further, the model requires the investment costs of candidate circuits.

The computational environment used to process all the tests was an Intel microcomputer, processor 80 486 DX4 100 MHz with 24 Mbytes of memory. The programming language used was Fortran Lahey compiler with full optimization options.

Our TS approach requires setting some parameters. Next, we describe the best results obtained over several tests. The complete study of the sensitivity of tabu parameters can be found in reference [2].

### A. Brazilian Southern Case Study

This case study corresponds to a reduced configuration of the Southern Brazilian System. The power network has 46 buses (8 generators, 2 of which are disconnected in the initial configuration) and 62 circuits. To alleviate the overloads, one may select new circuits from a list of candidates defined by three duplications in each one of the 79 rights-of-way, resulting in a total of 237 binary decision variables. The optimal solution for this case study was first reported by Romero and Monticelli [1] and has investment cost equal to \$154.42 million.

A complete tour of the first Tabu iteration (expansion, intensification and diversification phases) is described as following. The first task of each outer iteration of our Tabu Search is evaluating several different feasible transmission plans in order to estimate the consistency of the circuit candidates circuits. Then,  $T = 24$  feasible configurations are produced using the sensitivity indices and the TS concepts (Tabu Lists, Aspiration criterion) described earlier. Using a medium-term memory, the 20% most frequent additions overall the first 24 configurations are computed. These circuits are added as the starting point of the final iteration ( $T + 1$ ) of the expansion procedure. This is exactly the point illustrated as the original transmission expansion plan in Fig. 3. The initial transmission expansion plan was not yet feasible (it requires a load shedding of 1600 MW in order to alleviate all overloaded circuits) and had investment cost equal to \$175 million. After 8 expansion-phase movements

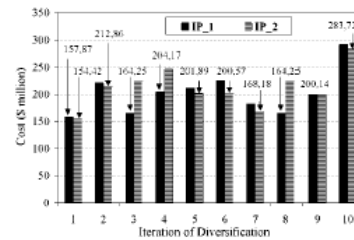


Fig. 4. Evolution of solutions in the diversification process.

the first feasible transmission expansion plan was found, costing \$275 million.

The intensification phase started from this solution applying IP\_1 procedure, so that all additions are removed, one at a time, in order to seek for other candidates that also lead to feasibility and, after 9 movements (swapping), resulted in a feasible solution with investment cost equal to \$157.87 million.

The second part of intensification phase IP\_2 also considers swapping movements but allows a certain degree of deterioration in the objective function in order to explore more intensively the neighborhood of the solution provide by IP\_1. Then, we accept movements leading to solutions up to 15% more expensive than the solution provided by the IP\_1 phase. In the first iteration, the IP\_2 solution is the optimal solution for this case study, costing \$154.42 million.

Fig. 3 shows the evolution of the first outer Tabu iteration (for EP and IP). Remark that, 6 out of 16 additions of the solution belong to the starting point of the last expansion phase, which validates the consistency measure of the candidate circuits in the expansion phase.

Since optimality of the TS method cannot be assured theoretically, 10 diversification phases were processed using a long-term Tabu List which made tabu, the most frequent candidate circuit ( $d = 1$ ) in the last intensification phase. The most frequent candidate circuit is made tabu for the next two outer Tabu iterations. In Fig. 4 we illustrate the best solutions obtained by intensification phases for all outer Tabu iterations. For these configurations, 5 solutions were found by IP\_1 and the other 5 solutions were obtained by the IP\_2. As mentioned earlier, the best solution was found at the first outer Tabu iteration, and required the addition of 16 circuits, costing \$154.42 million. The total computational time by TS was around 8 minutes.

Another important feature of TS is its ability to find not only the “optimal” solution but also a set of good feasible solutions. This characteristic (common for almost all metaheuristic methods) is a very important feature in the case of transmission network expansion planning studies, because subsequent studies (power flow, security analysis, etc.) are needed to validate the plan that will be selected. Only to illustrate, in this case our approach provides two other near optimal solutions: the first solution costs \$157.87 million (12 additions—8 are common with the best solution) was obtained by IP\_1 in the first outer Tabu iteration. The second solution costs \$164.25 million

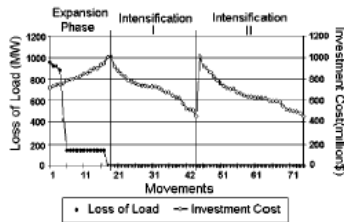


Fig. 5. Evolution of the first outer Tabu iteration.

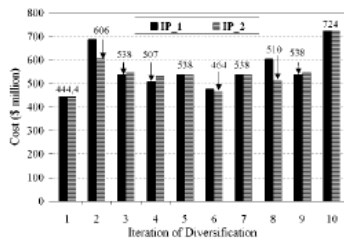


Fig. 6. Evolution of solutions in the diversification process.

(16 additions—12 common with the best solution) was found by IP\_1 in the third outer Tabu iteration.

### B. Brazilian Southeastern Case Study

The second power system corresponds to a reduced South-eastern Brazilian network. This system has 79 busses and 155 circuits. For all 143 candidates rights-of-way 3 duplications are allowed (429 binary variables).

Fig. 5 depicts the same first outer iterations illustrated for the last case. Observe that, the evolution of the inner iterations in the expansion and intensification phases is quite similar to that illustrated in Fig. 3 for the first study. Conversely, in this case study, intensification phase IP\_2 did not improve the solution found by intensification phase IP\_1.

As before, 10 diversification phases were processed to look for alternative solutions. Fig. 6 illustrates the different solutions—investment costs—obtained in all outer Tabu iterations. For these 10 configurations, half of the solutions were found by IP\_1 and the others by IP\_2.

In this case the best solution found for the first configuration is also the best one, where 21 circuits were added at a cost of \$444.49 million. Nevertheless, one cannot discard the diversification phases because they are able to provide different solutions and also undertake broader searches over the very large search space. Only to illustrate, a near best solution was found in outer Tabu iteration 6, costing \$464.62 million. This last solution also contains 21 additions and 14 of which are common with the best solution. The total computational time required by TS was 46 minutes.

Remark that in this case 18 out of 21 additions of the best solution belonged to the starting point of the last expansion phase. This result is more meaningful than the one obtained in the first case and emphasizes the valid consistency measure of the candidate circuits computed in the expansion phase.

## VI. CONCLUSION

This paper presents an investigation of a Tabu Search method to cope with the transmission network expansion planning problem. The results shown for two real-world case studies allow us to conclude that TS is a feasible and powerful technique to be applied to this problem.

Further, the CPU time spent by TS to obtain the best known solution in both case studies was very small, considering the IBM PC-486 microcomputer used.

The good quality of results produced by the intensification phase in both case studies qualify the strategy used, i.e., to look for consistent candidate circuits (those that appear in different plans) to build a consistent transmission expansion plan.

Although the diversification scheme was not effective in both cases reported, it cannot be considered useless because: i—it is a good mechanism to execute a more effective exploration of the search space; and ii—it is able to provide a set of good solutions which is an important feature for engineering studies.

Currently a computational model based on the algorithm proposed in this paper has been used extensively in transmission expansion planning for the Colombian system. Considering the huge number of scenarios to be analyzed (there are uncertainties related to load and generation), this tool has shown to be extremely useful since computational burden is considerably reduced.

The principal improvement of this approach, comparing with classical methods of optimization, is related to its ability in avoiding local optimum solutions, consequently having a greater chance to find the global optimum. Furthermore it is important to say that the data required for the model are the same as required for a model based on a classical optimization algorithm. Likewise, the approach does not require greater skill in its use.

With respect to other approaches based on metaheuristics, our experience with Genetic Algorithm [16], [17] shows that, we can expect both of them presenting a similar performance.

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