APENDICE I

CONSTANTES DEL MODELO LINEAL SIMPLIFICADO DE UN SISTEMA MAQUINA-BARRA INFINITA

APENDICE I

Constantes del modelo lineal simplificado de un sistema máquina-barra infinita presentado en la Figura 2.10 [6].

$$K_1 = k|V_\infty|[Eq_o(r_e\sin(\delta_o-\alpha)+(x'_d+x_e)\cos(\delta_o-\alpha))+Iq_o(x_q-x'_d)((x_q+x_e)\sin(\delta_o-\alpha)-r_e\cos(\delta_o-\alpha))]$$

$$K_2 = k\ [\ Iq_o\ (r_e^2 + (x_q+x_e\ )^2\ ) + Eq_o\ r_e\ ]$$

$$K_3 = \frac{1}{1 + k\ (x_d-x'_d)(x_q+x_e)}$$

$$K_4 = k\ |V_\infty|\ (x_d-x'd)\ (\ (x_q+x_e)\ \sin(\delta_o-\alpha) - r_e\ \cos(\delta_o-\alpha)\ )$$

$$K_5 = (k|V_\infty|x'_d\frac{Vq_o}{Vt_o})[r_e\cos(\delta_o-\alpha)-(x_q+x_e)\sin(\delta_o-\alpha)]-(k|V_\infty|x_q\frac{Vd_o}{Vt_o})[(x'_d+x_e)\cos(\delta_o-\alpha)+r_e\sin(\delta_o-\alpha)]$$

$$K_6 = (\frac{Vq_o}{Vt_o})\ [\ 1-x'_d\ (x_q+x_e)\ k\ ] - k\ (\frac{Vd_o}{Vt_o})\ x_q\ r_e$$

donde

$$Eq_o = \sqrt{(Vt_o-Ii_o x_q)^2+(Ir_o x_q)^2}$$

$$k = \frac{1}{r_e^2+(x_q+x_e)(x'_d+x_e)}$$

$$Vd_o = -x_q\ Iq_o$$

$$V_\infty=|V_\infty|\angle\alpha$$

$$Vt_o = 1.0, \quad I_g = I_r + jI_i = (\frac{P + jQ}{V_{to}})^*$$

$$Vq_o = Vt_o\left(\frac{Vt_o - Ii_o x_q}{Eq_o}\right)$$

$$|V_\infty| = \sqrt{(V_{to} - I_r r_e + I_i x_e)^2 + (I_r x_e + I_i r_e)^2}$$

$$\sin(\delta_o - \alpha) = \frac{V_{to}\ I_r\ (x_q + x_e)\ -\ r_e\ x_q\ (I_r^2 + I_i^2)\ +\ r_e\ V_{to}\ I_i}{Eq_o\ |V_\infty|}$$

$$Iq_o = \frac{I_r\ (V_{to}\ -\ I_i\ x_q) + I_i\ I_r\ x_q}{Eq_o}$$

$$Id_o = \frac{I_r^2\ x_q\ -\ I_i\ (V_{to}\ -\ I_i\ x_q)}{Eq_o}$$

APENDICE II

CONSTANTES DEL MODELO LINEAL DE UN SISTEMA MAQUINA-BARRA INFINITA QUE CONSIDERA DEVANADOS AMORTIGUADORES

APENDICE II

Constantes del modelo lineal de un sistema máquina-barra infinita que considera la dinámica de devanados amortiguadores. La Figura 3.8 muestra el correspondiente diagrama de bloques.

$$K_1 = \frac{1}{k}\{(x''_d - x''_q)\, I_{qo} + E''_{do}\}\,\{r_e|V_\infty|\cos(\delta_o - \alpha) - (x_e + x''_q)\,|V_\infty| sen\,(\delta_o - \alpha)\}$$

$$+ \frac{1}{k}\{(x''_d - x''_q)\, I_{do} + E''_{qo}\}\,\{r_e|V_\infty| sen\,(\delta_o - \alpha) + (x_e + x''_d)\,|V_\infty|\cos(\delta_o - \alpha)$$

$$K_{21} = I_{do} + \frac{r_e}{k}\{(x''_d - x''_q)\, I_{qo} + E''_{do}\} + \frac{(x_e + x''_d)}{k}\{(x''_d - x''_q)\, I_{do} + E''_{qo}\}$$

$$K_{22} = I_{qo} + -\frac{(x_e + x''_q)}{k}\{(x''_d - x''_q) I_{qo} + E''_{do}\} + \frac{r_e}{k}\{(x''_d - x''_q) I_{do} + E''_{qo}\}$$

$$K_{41} = \frac{(x_e + x_{q''})\,(x_d - x'_d)}{k}$$

$$K_{42} = \frac{(x_d - x'_d)\, r_e}{k}$$

$$K_4 = \frac{(x_d - x'_d)|V_\infty|}{k}\{(x_e + x''_q)\, sen\,(\delta_o - \alpha) - r_e\cos(\delta_o - \alpha)\}$$

$$K_{31} = \frac{k}{k + (x'_d - x''_d)\,(x_e + x_{q''})}$$

$$K_{43} = \frac{|V_\infty|\,(x'_d - x''_d)}{k}\{r_e\cos(\delta_o - \alpha) - (x_e + x_{q''})\, sen\,(\delta_o - \alpha)\}$$

$$K_{44} = \frac{k}{k + (x_e + x''_d)\,(x_q - x''_q)}$$

$$K_{45} = \frac{(x_q - x''_q)|V_\infty|}{k}\{r_e \, sen\, (\delta_o - \alpha) + (x_e + x''_d) \cos\, (\delta_o - \alpha)\}$$

$$K_{61} = \frac{-1}{k}\,\{\frac{V_{do}\,x''_q}{|V_{to}|}\,r_e + \frac{V_{qo}\,x''_d}{|V_{to}|}\,(x_e + x''_q)\} + \frac{V_{qo}}{|V_{to}|}$$

$$K_{62} = \frac{V_{do}}{|V_{to}|}\,(1 - \frac{x''_q}{k}(x_e + x''_d)) + \frac{V_{qo}}{|V_{to}|}\,\frac{x''_d}{k}\,r_e$$

$$k = r_e^2 + (x_e + x''_d)(x_e + x''_q)$$

$$V_\infty = |V_\infty| \angle \alpha$$

$$I_g = I_r + jI_i\ ,\ V_t = V_r + jV_i$$

$$\begin{bmatrix} I_{do} \\ I_{qo} \end{bmatrix} = \begin{bmatrix} \sin\delta_o & -\cos\delta_o \\ \cos\delta_o & \sin\delta_o \end{bmatrix} \begin{bmatrix} Real\ (I_g) \\ Imag\ (I_g) \end{bmatrix} = T\,\underline{I}_{ri} = I_{dqo}$$

$$V_{dqo} = T\,\underline{V}_{ri} = \begin{bmatrix} V_{do} \\ V_{qo} \end{bmatrix}$$

$$E''_{do} = r_e\,I_{do} - x''_q\,I_{qo} + V_{do}$$

$$E''_{qo} = r_e\,I_{qo} + x''_d\,I_{do} + V_{qo}$$

$$E_q \angle \delta = V_t + jx_q\,I_g$$

APENDICE III

ARTICULOS PRESENTADOS REFERENTES AL TRABAJO DE TESIS

APLICACION DE ESTABILIZADORES EN SISTEMAS ELECTRICOS LONGITUDINALES

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Resumen. Se presenta el proceso para mejorar la estabilidad transitoria y dinámica de un sistema de potencia mediante la aplicación de estabilizadores. El estudio reportado se realiza en el sistema eléctrico de la Comisión Federal de Electricidad (CFE), el cual presenta características típicamente longitudinales. Se resaltan las características dinámicas que impactan el cálculo, el análisis de oscilaciones electromecánicas y el diseño de controles para este tipo de sistemas. La aplicación que se presenta combina adecuadamente el análisis en el tiempo con técnicas en el dominio de la frecuencia para lograr una estabilización efectiva.

1. Introducción

El comportamiento dinámico de un sistema de potencia longitudinal presenta, debido a su estructura, características especiales. Su dinámica ante pequeñas perturbaciones muestra particularmente problemas de amortiguamiento en oscilaciones de baja frecuencia, estas situaciones pueden ser especialmente críticas en condiciones de máxima transferencia en líneas de interconexión. Como consecuencia de estas oscilaciones, la potencia a transmitir puede llegar a limitarse por problemas de amortiguamiento.

Por otro lado, el diseño de controles en este tipo de sistemas se impacta favorablemente debido a sus características dinámicas particulares. La ubicación de controles, así como la observabilidad modal de la señal de entrada, no se modifican substancialmente con cambios de condiciones operativas o de topología. Esto generalmente favorece el diseño de controles [1].

Los *modos* de oscilación que generalmente se tratan de amortiguar son los modos electromecánicos asociados a las inercias de generadores. Se asume que los controles del sistema se han sintonizado para amortiguar sus *modos* de oscilación naturales. Las frecuencias de oscilaciones inerciales dependerán del acoplamiento al sistema y de la inercia de los generadores, de ahí la importancia de la estructura del sistema longitudinal.

En este trabajo se documenta un estudio sobre la aplicación secuencial de estabilizadores de potencia (ESP) en un sistema de potencia real con características típicamente longitudinales. El sistema analizado forma parte del sistema troncal de transmisión de la CFE. El estudio resalta las características dinámicas de los sistemas eléctricos longitudinales y su impacto en el diseño de controles. Se presentan resultados del análisis modal y de simulaciones en el dominio del tiempo.

2. Descripción del Sistema

El Sistema Noroeste forma parte del Sistema Eléctrico de México, opera generalmente aislado del Sistema Interconectado Nacional. El diagrama unifilar de la Fig. 1 revela su estructura típicamente longitudinal. Se indican los principales centros de carga y generación, y las longitudes - en Km - de las líneas de transmisión de la red troncal de 230 kV.

El caso analizado corresponde a una demanda máxima de 1650 MW, en esta condición el sistema muestra un amortiguamiento reducido. Esto es evidente al observar en la Fig. 2 el comportamiento de los rotores de unidades generadoras ante la pérdida de una unidad de 120 MW. El sistema es dinámicamente inestable por falta de amortiguamiento.

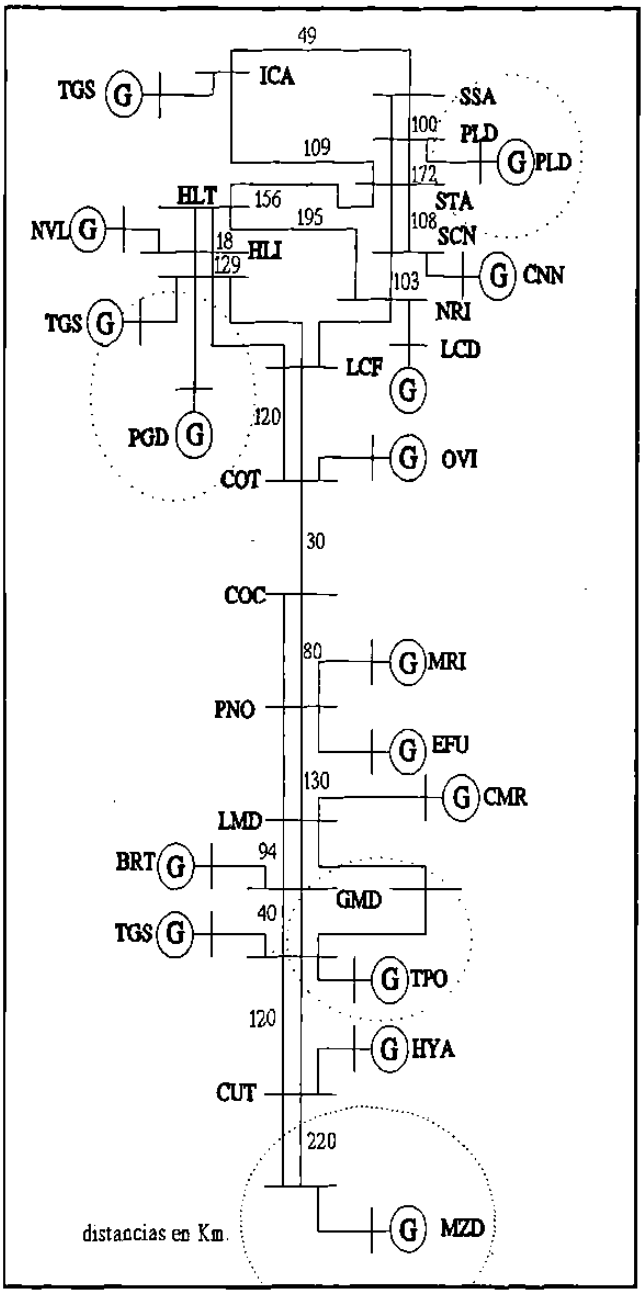

Fig. 1 Diagrama unifilar del sistema Noroeste de la CFE.

3. Aplicación de Estabilizadores

En la etapa inicial del estudio se efectúa el cálculo y caracterización de los modos de oscilación del sistema. Posteriormente, y en forma cíclica para cada estabilizador, se realiza un análisis modal completo, determinado su ubicación y realizando el diseño y validación mediante simulaciones en el dominio del tiempo.

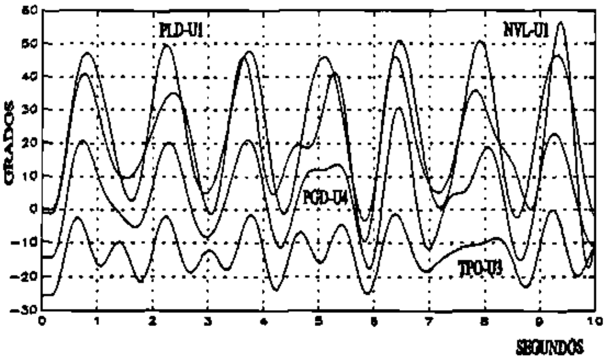

Fig. 2 Dinámica de rotores ante la pérdida de la unidad MZD-U1.

3.1 Caracterización de modos de oscilación

La Tabla 1 (Apéndice) presenta los modos de oscilación donde se involucra a más de una planta en el sistema. Se omiten los modos de oscilación entre máquinas de una misma planta. Se observa que en el modo de más baja frecuencia participan todas las máquinas del sistema. En este modo, las unidades de la parte norte del sistema oscilan contra las máquinas de la parte sur.

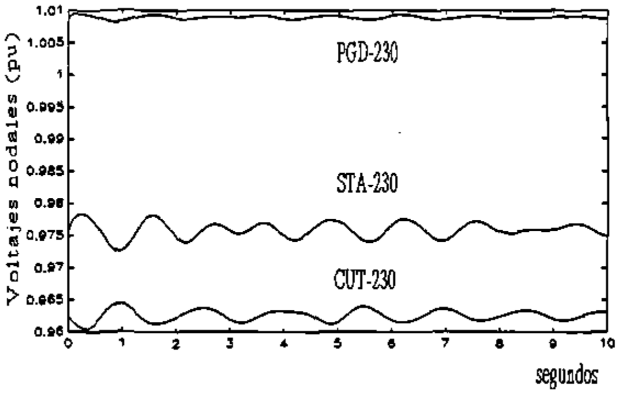

Fig. 3 Dinámica del modo de oscilación de 0.66 Hz en los voltajes nodales del sistema.

La Fig. 3 muestra la dinámica de algunos voltajes nodales cuando se excita el modo de más baja frecuencia. Los resultados corresponden a la condición de demanda máxima. Los otros modos de oscilación involucran máquinas en zonas del sistema bién localizadas, excepto para el modo de 1.03 Hz, donde la planta MZD tiene una participación muy pequeña.

3.2 Ubicación de ESP's

Es interesante observar en la Fig. 2 que la frecuencia de 0.66 Hz domina la respuesta dinámica de los rotores. Esto se manififiesta de manera explícita en la unidad PLD-U1. Para las otras unidades, el modo de 0.66 Hz también domina la respuesta, sin embargo, existen componentes de frecuencias mayores no identificadas claramente. Una situación similar se observa en el comportamiento de los flujos de potencia mostrados en la Fig. 4, el flujo en la línea PNO-230/LMD-230 muestra sólo una frecuencia de oscilación, mientras que la línea CUT-230/MZD-230 contiene distintas frecuencias.

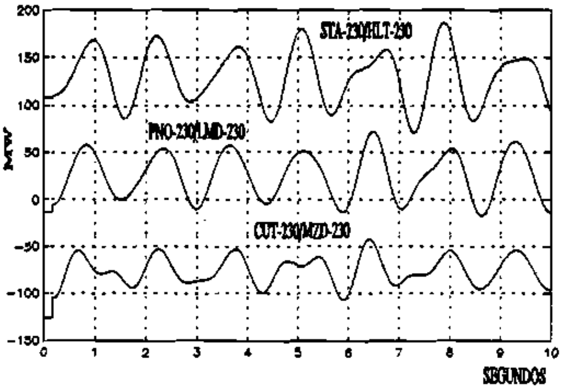

Fig 4. Comportamiento dinámico del flujo de potencia ante la pérdida de MZD-U1.

Para la condición base considerada, la Tabla 2 (Apéndice) muestra los elementos modales para el modo de oscilación de 0.66 Hz. Los elementos mostrados corresponden a las mayores desviaciones de velocidad. Estos resultados son la base para la ubicación de los estabilizadores de potencia [2,3].

En la aplicación coordinada de estabilizadores, el orden de prioridad parte generalmente del modo de más baja frecuencia y termina con el de mayor frecuencia. En este caso, el primer modo a considerar es el de 0.66 Hz, la planta con mayor participación en este modo es MZD.

3.3 *Característica de fase y ajuste de parámetros*

Siguiendo la metodología presentada en [1,4], se diseñó un estabilizador para la unidad MZD-U3. La característica de fase a compensar se obtiene a través del análisis par-ángulo en la máquina de interés [4,5]. La Fig. 5 muestra el ajuste de fase del estabilizador en el rango de frecuencias deseado. También se presentan los parámetros seleccionados para el estabilizador después de ajustar la curva de fase del estabilizador con la característica combinada del sistema y la señal de entrada. En el estudio todos los estabilizadores utilizan como señal de entrada la potencia acelerante de la unidad.

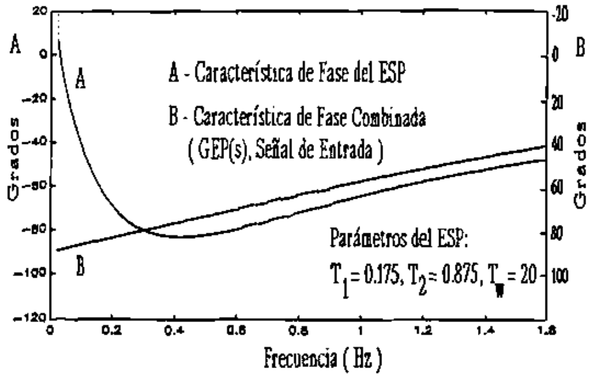

Fig. 5 Ajuste de fase para el ESP en MZD-U3.

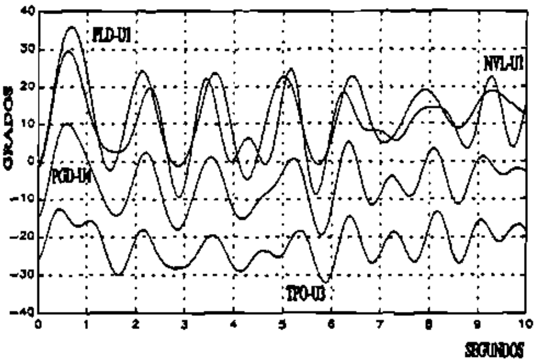

Fig. 6 Dinámica de rotores con ESP en MZD-U3.

La Fig. 6 muestra la dinámica de los rotores de varias unidades, ante la pérdida de la unidad MZD-U1, después de instalar el estabilizador. Al comparar las curvas con las de la Fig. 2 se observa un mayor amortiguamiento en el modo de 0.66 Hz (PLD-U1), mientras que los otros modos presentes en la respuesta sólo son afectados ligeramente. Esto es consistente con los resultados del análisis modal, ya que la planta MZD tiene una participación muy reducida en los modos con frecuencias mayores.

3.4 *Aplicación secuencial de estabilizadores*

La Tabla 3 (Apéndice) presenta los vectores modales para el modo de 0.66 Hz después de instalar el estabilizador en MZD-U3. Es interesante comparar estos resultados con los de la Tabla 2. Se observa una gran similitud entre los valores de ambas tablas, la inclusión del estabilizador en MZD-U3 prácticamente no altera el patrón dinámico modal, lo cual es característico en sistemas con estructura longitudinal.

El amortiguamiento para el modo de 0.66 Hz, observado en la Fig. 6, aún no se considera aceptable (ζ=0.04), por lo que se procede a instalar otros estabilizadores para mejorar la respuesta. La ubicación de estos estabilizadores se basa en la información de la Tabla 3, la cual presenta un análisis modal completo que incluye el estabilizador previamente instalado. La Fig. 7 muestra el comportamiento de las mismas unidades de la Fig. 6, después de instalar ESP's en todas las unidades de la planta PLD y en la unidad CMR-U2. El modo de 0.66 Hz finalmente presenta un amortiguamiento aceptable (ζ=0.21). Las Figs. 8 y 9 presentan el detalle del ajuste de fase en los estabilizadores de estas máquinas.

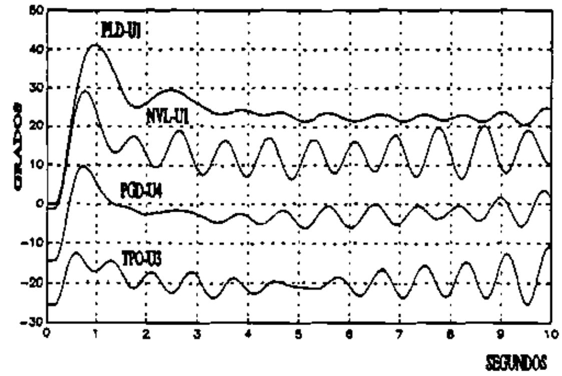

Fig. 7 Comportamiento dinámico de rotores con ESP en MZD, PLD y CMR.

Es interesante observar que a medida que se amortigua este modo, los otros modos se manifiestan más explícitamente. En este caso, el modo de oscilación de 1.17 Hz se identifica en las unidades NVL-U1 y PGD-U4. El modo de 1.25 Hz se asocia a la unidad TPO-U3.

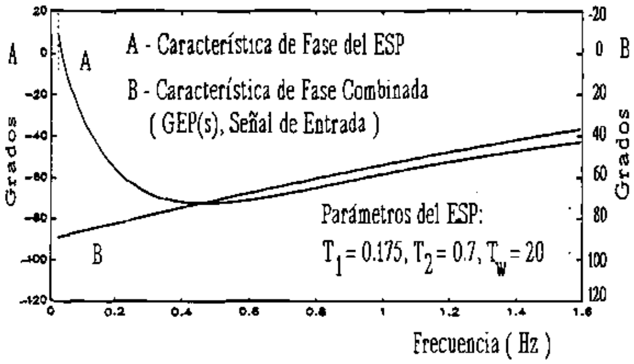

Fig. 8 Ajuste de Fase del ESP en planta PLD.

La Tabla 4 presenta los vectores modales de estos modos de oscilación. Para esta condición se tiene que laplanta NVL presenta la mayor participación en el modo de oscilación de 1.17 Hz, mientras que la planta TPO tiene una participación importante en el modo de oscilación de 1.25 Hz. Se debe notar que en la secuencia de aplicación de estabilizadores se efectúa un análisis modal completo para cada ESP a instalar. Este análisis considera los estabilizadores previamente instalados.

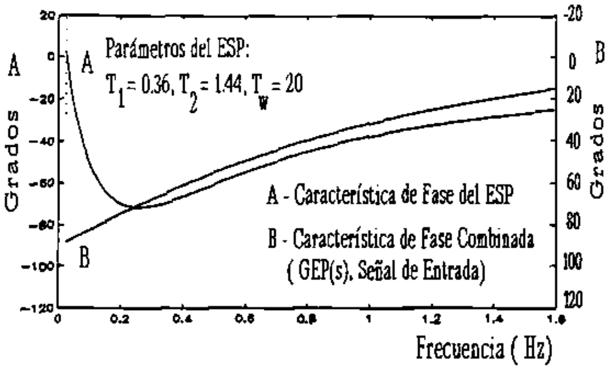

Fig. 9 Ajuste de Fase del ESP en CMR-U2.

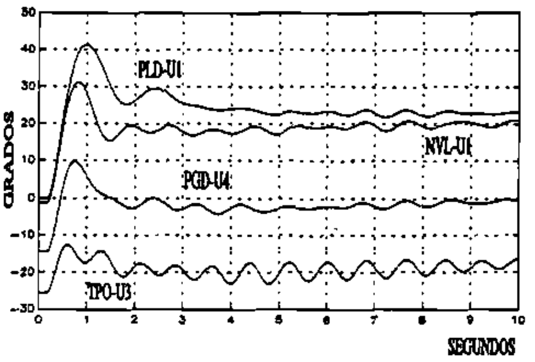

Fig. 10 Desplazamiento angular de rotores con ESP's en MZD, PLD, CMR y NVL.

En este punto, el interés se centra en estabilizar el modo de 1.17 Hz. Este modo es claramente amortiguado al instalar un estabilizador en las máquinas de la planta NVL, como lo muestra la Fig. 10. Finalmente, la Fig. 11 muestra la dinámica angular en máquinas después de instalar un estabilizador en la unidad TPO-U3.

El procedimiento de aplicación coordinada de estabilizadores finaliza cuando se consigue un nivel de amortiguamiento establecido para todas las frecuencias de interés en el sistema, considerando un grupo de perturbaciones y condiciones operativas del sistema.

3.5 Evaluación de ESP's ante perturbaciones

La Tabla 5 presenta los valores de frecuencia y relación de amortiguamiento para estos modos después de instalar estabilizadores en MZD-U3, PLD-P, CMR-U2, NVL-P y

TPO-U3. Las Figs. 12 a 15 presentan el comportamiento angular de distintas máquinas para otras perturbaciones en el sistema. Se analiza la pérdida de las unidades PGD-U3 y TPO-U3, antes y después de la instalación de los estabilizadores. De estos resultados se concluye que la aplicación de estabilizadores en este sistema requerirá la instalación de estabilizadores adicionales para cubrir oscilaciones dinámicas de mayor frecuencia.

La aplicación de la metodología del estudio garantiza una adecuada coordinación de acciones de estabilización y conduce a un número mínimo de unidades generadoras seleccionadas para amortiguar los modos de oscilación críticos.

4. Características Dinámicas de SEP's Longitudinales

En la determinación de frecuencias de oscilación es factible utilizar modelos simplificados del generador. Los valores de frecuencia que se obtienen al utilizar modelos más completos son muy similares. El efecto de los controles principalmente se manifiesta en el amortiguamiento de los modos de oscilación.

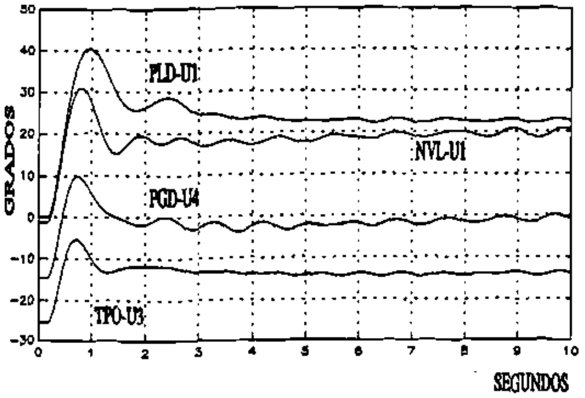

Fig. 11 Dinámica de rotores después de instalar un ESP en TPO-U3.

En los modos de oscilación de más bajas frecuencias participan muchas máquinas, lo que hace que los factores de participación de los generadores sean muy pequeños, dificultando la identificación de las plantas más importantes en estos modos de oscilación [7]. Para verificar la participación de máquinas se recomienda la excitación de modos de oscilación mediante análisis de la respuesta en el tiempo. Este proceso permite reproducir la oscilación en plantas que participan de manera importante en el modo y determinar también las líneas de transmisión donde se manifiesta la oscilación.

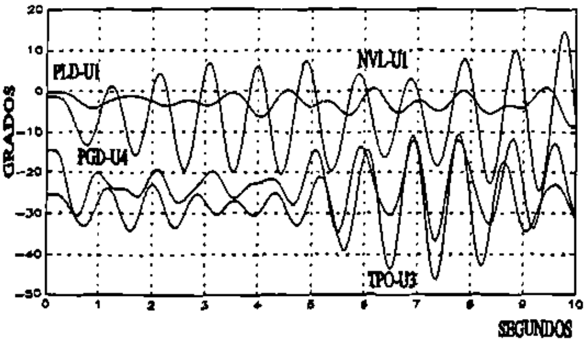

Fig. 12 Comportamiento de rotores ante la pérdida de la unidad PGD-U3 antes de instalar ESP's.

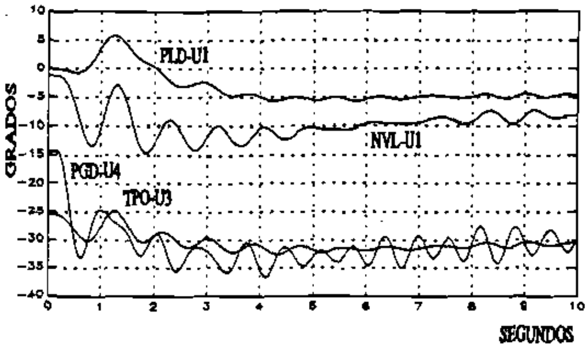

Fig. 13 Comportamiento de rotores después de instalar ESP's en MZD, PLD, CMR, NVL y TPO.

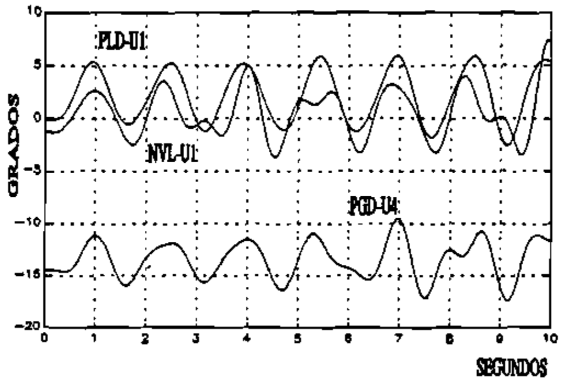

Fig. 14 Dinámica de rotores ante la pérdida de la unidad TPO-U3 antes de instalar ESP's.

Para los modos de oscilación de interés, una característica importante de los SEP's longitudinales es que los vectores modales no cambian substancialmente con la inclusión de un estabilizador (ver Tablas 2 y 3). Esto simplifica la ubicación de controles en una aplicación coordinada.

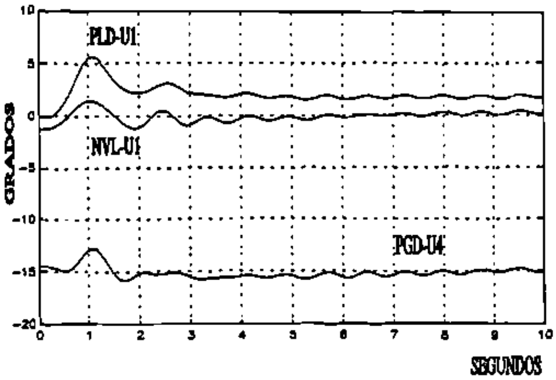

Fig. 15 Dinámica de rotores ante la pérdida de TPO-U3 (ESP's en MZD, PLD, CMR, NVL, TPO).

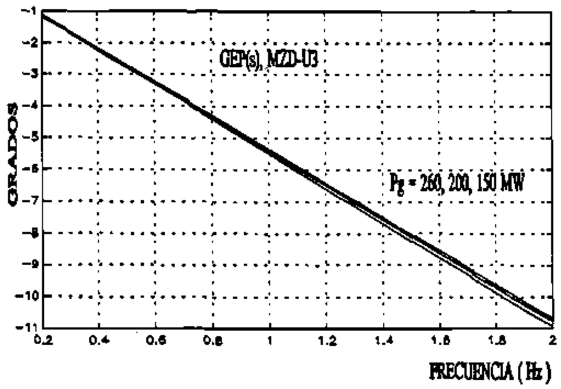

Fig. 16 Variación de fase para GEP(s) en MZD-U3.

Adicionalmente, la lista de generadores que participan más activamente en un modo de oscilación no se modifica, lo cual evita realizar un análisis modal completo para la ubicación de cada nuevo estabilizador.

Por otro lado, la característica de fase a compensar por el ESP sólo varía ligeramente para un rango amplio de condiciones de operación, lo cual evita nuevos ajustes o sintonización. Un ejemplo de ésto se muestra en la Fig. 16, para la unidad MZD-U3. El rango de frecuencias considerado incluye todos los modos de oscilación de interés, considerando distintas condiciones operativas. Se observa una variación pequeña para la fase de la función GEP(s).

En el sistema analizado los efectos de interacción entre modos o controles no es crítico. Debido a la estructura de la red, cada máquina en el sistema tiene una participación importante en modos de oscilación bién definidos, generalmente en dos o tres modos de oscilación, ya sean modos locales, o entre grupos de máquinas cercanas eléctricamente, o bién modos de oscilación entre áreas. El nivel de participación individual dependerá básicamente de la ubicación y la capacidad de la unidad, así como del tipo de sistema de excitación.

En sistemas robustos, la aplicación de un estabilizador en una máquina permite mejorar el amortiguamiento de cierto modo, pero también puede también disminuir el amortiguamiento de otros modos. Así mismo, en estos sistemas generalmente no es sencillo encontrar una señal de entrada con alto contenido modal para un modo de oscilación particular. Para sistemas del tipo longitudinal, cada modo de oscilación se manifiesta en una región del sistema, facilitando la elección de la señal.

Es importante señalar la necesidad de combinar en el ciclo de análisis estudios en el dominio de la frecuencia y simulaciones en el tiempo. Esto garantiza el ajuste adecuado de ganancias y límites a la salida del estabilizador, así como la minimización de interacciones negativas entre modos y controles al incluir nuevos estabilizadores.

5. Conclusiones

- Debido a la debilidad de sus interconexiones, los sistemas de potencia longitudinales presentan un amortiguamiento inherentemente reducido.
- En sistemas del tipo longitudinal, la frecuencia de los modos de oscilación inerciales dependerá en gran medida del acoplamiento al sistema y de la inercia de los generadores, de ahí la importancia de la estructura.
- Mediante la excitación de modos de oscilación se identifican las plantas que participan de manera importante en el modo y las líneas de transmisión donde se manifiesta la oscilación.
- En modos de oscilación entre áreas generalmente todas las máquinas participan activamente. Las máquinas en los puntos extremos del sistema muestran la mayor actividad modal.
- En un sistema longitudinal los cambios en la red y la condición operativa no modifican substancialmente el patrón modal. Esto impacta favorablemente el diseño y la ubicación de estabilizadores.

- Adicionalmente, la característica de fase a compensar para el estabilizador sólo varía ligeramente para un rango amplio de condiciones operativas, lo cual evita ajustes o sintonizaciones.

- En sistemas del tipo longitudinal generalmente los efectos de interacciones entre modos o controles no son críticos.

- Dada la estructura radial del sistema, cada modo de oscilación se manifiesta en una región específica del sistema, lo cual facilita la elección de la señal de control.

6. Referencias

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Apéndice

Tabla 1 Modos de oscilación del Sistema Noroeste de la CFE.

f (Hz), ζ	Máquinas con mayor participación
0.66,-0.016	TODAS (MZD-P, PLD-P, CMR-P.......)
0.84, -0.004	PLD-P, NVL-P, PGD-P
1.03, -0.013	NVL-P, PGU-P, PLD-P, PGD-P, MZD-P
1.17, -0.017	NVL-P, PGU-P, TPO-P, EFU-P, CMR-P
1.20, -0.003	CMR-P, PGU-P
1.26, -0.007	TPO-P, PGU-U3, TPO-P, CMR-P
1.36, -0.005	CCT-TGS, PGU-P, CMR-P, EFU-P, HYA-P, BRT-P
1.368,-0.005	PGU-P, PGD-P, CCT-TGS, OVI-P, TPO-P
1.38,-0.009	TPO-U3, EFU-U3, HYA-P, CCT-P
1.41,-0.013	TPO-P, BRT-P, CCT-P

Tabla 2

Vectores modales para el modo de oscilación de 0.66 Hz.

MAQ	$\lvert p_{ik} \rvert, \angle p_{ik}$	MAQ	$\lvert u_k \rvert, \angle u_k$	MAQ	$\lvert R_i \rvert, \angle R_i$
MZD-U3	0.140, -6	MZD-U1	0.26,-144	MZD-U3	1.87, 90
MZD-U1	0.078, -3	MZD-U3	0.25, -145	MZD-U1	0.65, 83
PLD-U4	0.033, -4	CMR-U2	0.23,-143	PLD-U2	0.26, 86
PLD-U3	0.033, -4	CCT-TGS	0.21, -143	PLD-U3	0.26, 86
PLD-U2	0.033, -4	HYA-U1	0.19, -144	PLD-U4	0.26, 86
PLD-U1	0.033, -4	BRT-U2	0.16, -144	PLD-U1	0.26, 86
CMR-U2	0.020, 1	BRT-U1	0.15, -143	CMR-U2	0.09, 61
CCT-TGS	0.010, 2	PLD-U4	0.15, 35	HYA-U1	0.05, 54

Apéndice #...

Tabla 3
Vectores modales asociados al modo de oscilación de 0.66 Hz después de instalar un ESP en MZD-U3.

MAQ	$\lvert p_{ik}\rvert$, $\angle p_{ik}$	MAQ	$\lvert u_k\rvert$, $\angle u_k$	MAQ	$\lvert R_i\rvert$, $\angle R_i$
MZD-U3	0.140, 28	MZD-U1	0.25, -110	MZD-U3	1.67, 75
MZD-U1	0.084, -13	CNN-MOT	0.24, 76	MZD-U1	0.74, 100
CNN-MOT	0.036,-1.9	LCD-MOT	0.23, 76	PLD-U3	0.26, 82
PLD-U3	0.033, 4	MZD-U3	0.21, -94	PLD-U1	0.26, 82
PLD-U4	0.033, 4	CMR-U2	0.20, -112	PLD-U4	0.26, 82
PLD-U1	0.033, 4	CCT-TGS	0.19, -112	PLD-U2	0.26, 82
PLD-U2	0.033, 4	HYA-U1	0.18, -111	CMR-U2	0.094, 86
LCD-MOT	0.030, 1.7	BRT-U2	0.14, -114	CNN-MOT	0.057, 17
CMR-U2	0.020, -18	BRT-U1	0.14, -114	LCD-MOT	0.054, 19
CCT-TGS	0.013, -17	PLD-U3	0.13, 81	HYA-U1	0.054, 79
HYA-U1	0.011, -15	PLD-U2	0.13, 81	CCT-TGS	0.045, 78

Tabla 4
Vectores modales para los modos de oscilación de 1.17 y 1.25 Hz.

MAQ f = 1.17 Hz	$\lvert p_{ik}\rvert$	MAQ f = 1.17 Hz	$\lvert R_i\rvert$	MAQ f = 1.25 Hz	$\lvert R_i\rvert$
NVL-U3	0.59	NVL-U3	0.10	TPO-U3	1.04
NVL-U2	0.57	NVL-U2	0.09	MZD-U1	0.52
NVL-U1	0.57	NVL-U1	0.09	PGU-U3	0.44
PGD-U4	0.38	PGU-U3	0.05	MZD-U3	0.31
PGD-U3	0.37	TPO-U3	0.03	EFU-U3	0.20
MZD-U1	0.37	PGD-U3	0.02	PGD-U4	0.17
MZD-U3	0.31	PGD-U4	0.02	PGD-U3	0.17
TPO-U3	0.21	MZD-U3	0.01	EFU-U2	0.13
PGU-U3	0.18	EFU-U1	0.01	EFU-U1	0.13

Tabla 5
Modos de oscilación de baja frecuencia en el Sistema Noroeste después de instalar estabilizadores.

f (Hz)	ζ	real	Imag
0.653	0.221	-0.908	4.01
0.83	0.012	-0.064	5.18
0.96	0.120	-0.72	5.97
1.18	0.210	-1.54	7.27
1.29	0.012	-0.102	8.14

DYNAMIC STABILITY ANALYSIS OF THE INTERCONNECTED COLOMBIA-VENEZUELA POWER SYSTEM

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***Abstract*-. This paper presents the operating problems of the interconnection between Colombia and Venezuela power systems through a single 230 kV transmission line. It describes the technical analysis carried out for the stabilization of a sustained power flow oscillation of 0.22 Hz. The analysis includes results of simulations and field recordings obtained in the system. Operating strategies adopted and the conclusions of the study are also summarized.**

***Keywords* - Inter-area oscillations, power system stabilizers, excitation control, modal analysis, weak power systems.**

I. INTRODUCTION

During 1993 Colombia and Venezuela power systems were weakly interconnected by a single 230 KV transmission line. The interconnection, initially planned as a double-circuit line, would permit power exchanges during normal and emergency conditions.

Transient stability planning studies anticipated potential undamped low frequency oscillations due to the interconnection, however no specific corrective actions were implemented. During line commissioning the oscillatory behavior was confirmed, and sustained oscillations appeared making impossible to operate the interconnection.

As a consequence of the problems detected, system dynamic behavior was studied in detail in order to find effective means to damp these power flow oscillations. A frequency-domain approach, combined with time-domain simulations were used in the analysis. Tie line power flow oscillations were effectively damped following study recommendations. Study results were verified step by step using field measurements.

This paper presents the description of the interconnected systems, the dynamic stability analysis performed, the results obtained from simulations, the tuning of power system stabilizers, and the operating strategies implemented.

II. DESCRIPTION OF THE SYSTEM

A. Colombian power system

Electrical energy in Colombia is supplied by several regional entities coordinated and supervised by Interconexion Eléctrica S. A. (ISA). The bulk transmission system is formed by 230 kV and 500 kV transmission lines. Peak load demand in 1992 was 6098 MW, and at that time the system had an installed capacity of 8489 MW.

In the period of the study a single 500 kV transmission line tied the Central and North areas of the system (San Carlos-Sabanalarga). At the end of 1993 a second parallel circuit was added to the system.

B. Venezuelan power system

Venezuela's power system is integrated by several power companies covering most of the country, which is divided in several areas; North, Central, West and Guayana.

Guayana area is a major hydro generation center, that includes Raúl Leoni hydro plant - GURI - with 10,000 MW of installed capacity. Guayana area is also a main industrial load center. The distance between Guayana and Central areas is about 650 km. Power transmission takes place through 765 kV, 400 kV and 230 kV transmission lines. From the Central area, the distance to the western areas is 300 km. At the time of the study, peak load demand was 11800 MW with an installed generating capacity of 15270 MW.

C. Colombia-Venezuela Interconnection

Fig. 1 shows a simplified diagram of the network structure

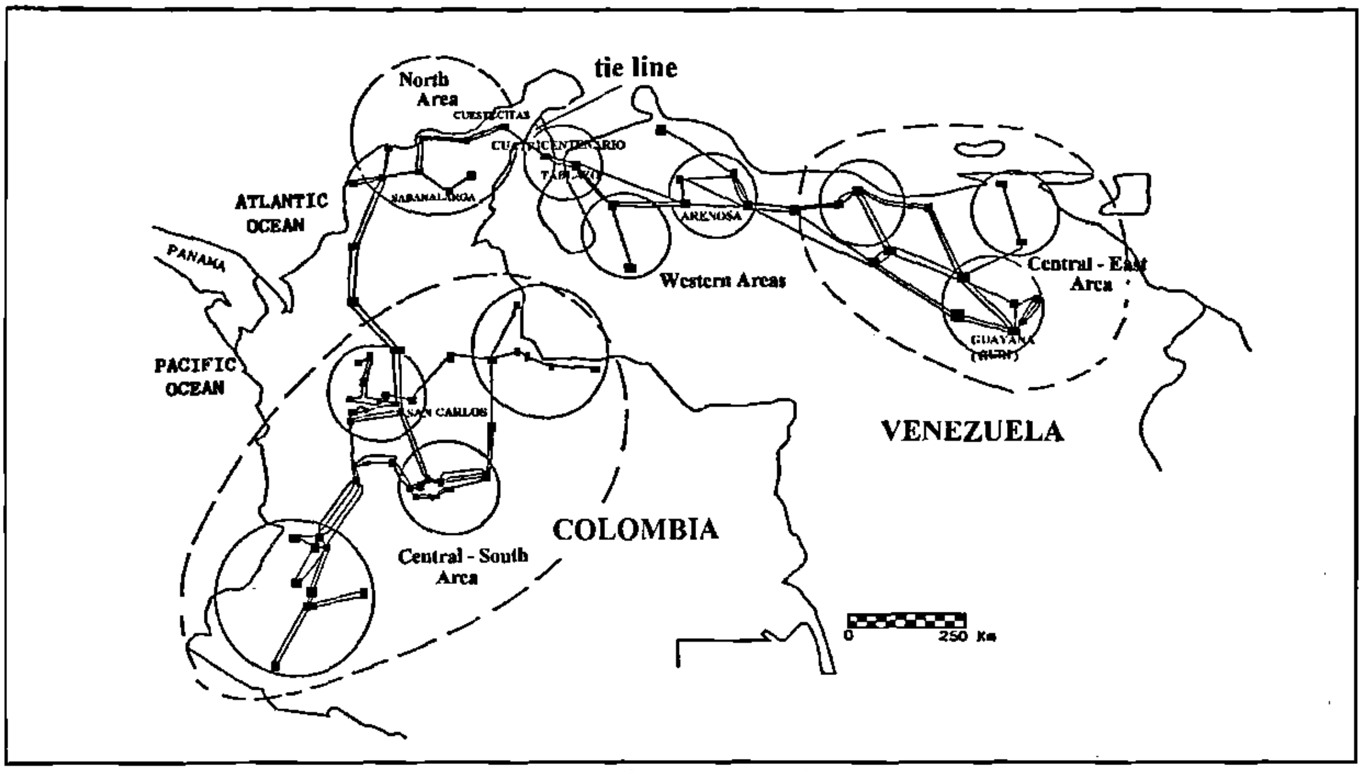

Fig. 1 Interconnected Colombia-Venezuela power system.

including the interconnection line (Cuestecitas - Cuatricentenario). Main load and generation centers are also indicated with circles.

Colombian power system is more developed in the Central-South areas. On the other side, the most important areas are concentrated in the Central-East regions of Venezuela. It is important to point out that although the systems are tied through a single 150 km, 230 kV transmission line, the interconnection between strong areas (dashed traces in Fig. 1) is through a series of single and double circuit transmission lines. Table I presents characteristics of these transmission links.

Table I
Characteristics of Main Interconnecting Lines

Lines	km	kV
San Carlos-Sabanalarga	520	500
Sabanalarga-Cuestecitas	360	230
Cuestecitas-Cuatricentenario	150	230
Cuatricentenario- Tablazo	60	230
Tablazo-Arenosa	480	400

According to planning studies, the interconnection would allow a power transfer of 100 MW from Venezuela to Colombia. This limit could be increased to 150 MW with shunt compensation in Cuestecitas (Colombia).

III. OPERATING PROBLEMS

Preliminary studies of the interconnection showed the possibility of undamped low frequency power flow oscillations on the tie line, which were confirmed in the initial trials to operate the interconnection. A 0.2 Hz power flow oscillation with increasing amplitude was recorded, in these tests line protection was quickly activated (10-15 seconds) tripping the tie line. It is important to stress that this 0.2 Hz oscillation mode had not been detected in the past, and appeared as a result of the weak interconnection between these systems.

Transient stability time-domain simulations revealed sustained oscillations under several contingencies in the Colombian system. Particular cases were generation outages in San Carlos power plant, and topology changes in transmission lines between San Carlos and the interconnection point. Studies also showed that power system stabilizers located in San Carlos generating units, which were tuned for local oscillations, had the ability to provide positive damping for low frequency tie line oscillations. This emphasized the need to perform a detailed analysis where oscillations modes of the interconnected system were characterized and generators with high participation in troublesome oscillation modes could be identified. Additionally, new PSS's settings could also be determined to obtain the required damping.

IV. DETAILED SMALL SIGNAL STABILITY STUDY

During the study, the following steps were performed:

(a) Determination of accurate models for AVR's and PSS's.
(b) Characterization of oscillation modes.
(c) Determination of damping ratios.
(d) Sensitivity analysis and PSS's sitting.
(e) Verification of damping ratios using time-domain simulations.
(f) Verification of transient stability studies including new PSS's parameters.

In step (a) models were obtained for every generating unit in the interconnected system. Steps (b) to (f) were performed at the National Control Center (CENACE) of Comisión Federal de Electricidad de México (CFE), in Monterrey N.L., México. For this study the interactive power system simulator (SISP) developed by the research and development department of CENACE was used. SISP modules used in the study were the frequency-domain dynamic stability package (DINAMI), the time-domain transient stability program (ESTABI), and the load flow module (FLUJOS). Appendix I presents a brief description of DINAMI-SISP.

A. Models for AVR's and PSS's

For every generating unit it was necessary to obtain, by means of tests, a mathematical model, operating values and limits of parameters. In some cases equivalent models were used to fit the models available in the simulation packages.

B. Characterization of oscillation modes

A detailed linear analysis of the system was carried out using the dynamic stability software (DINAMI). The objective was to determine critical oscillation modes and the participation of generators involved in each mode. The results of the characterization were verified stimulating individual oscillation modes using the time-domain transient stability program. A detailed representation of the interconnected system was used for these simulations.

Main activities carried out in this step were the following:

- Determination of oscillation frequencies through a frequency-domain linear analysis of the interconnected system. Generators in the system were modeled by a classical model. The network was represented in detail.
- Identification of generating units with high participation in the low frequency oscillation modes.
- Reproduction of main oscillation modes in time-domain simulations.

In the characterization of oscillation modes, these were classified as local, regional and inter-area. Inter-area modes involved a large number of generating plants in both countries, and due to the longitudinal structure, corresponding power flow oscillations were observed in the interconnection line. Table II presents important power plants involved in the inter-area oscillation modes.

Frequencies of inter-area oscillation modes were in a range between 0.22 Hz and 1.49 Hz. Several of these modes involved the interaction among units in the North of Colombia and generators in the North-West regions of Venezuela. These modes could be considered as regional, but as they were observed in the interconnection line, were included in the inter-area modes.

Study results showed a large number of units participating in low frequency oscillation modes. This caused that individual participation of units in a inter-area mode had a low value, making the identification of important plants in these oscillation modes difficult.

To verify the small signal analysis performed and to clarify the participation of generating units, oscillation modes were reproduced through time-domain simulations. This process allowed to observe and check the oscillations in generating units with an important participation in each mode. It also helped to determine the transmission lines where these oscillations had a major effect.

C. Damping ratio

The next step was to calculate the damping ratio of critical oscillation modes with detailed models of generators and excitation systems. The calculations showed that the oscillation mode with the lowest frequency (0.22 Hz) presented a negative damping ratio (-0.006), which indicated potential sustained power flow oscillations.

Extensive sensitivity tests were performed to determine the effect of excitation system gain on damping ratio, it was found that an increment in damping could be obtained through a gain reduction in some excitation systems. This analysis was performed starting with all the excitation systems active. After that, excitation system gains (K_A) were modified one by one, specially in units with high participation in the 0.22 Hz oscillation mode. The largest sensitivity to K_A values was observed in San Carlos power plant. A 25 % reduction in gain changed the damping ratio to 0.007.

Table II
Participation of Generating Plants in Inter-area Modes

Mode Hz	Power Plants	
	Venezuela	Colombia
0.222	Guri B	San Carlos-Chivor-Paraiso-Guaca-Betania Guatape, Cartagena
0.52	Agatón	Guajira
0.837	Urdaneta Ramón Laguna-Guri B	Guajira-Chivor
0.93	Urdaneta	Betania
0.964	Guri B-Urdaneta	Betania-Barranquilla Cartagena-San Carlos Chivor
1.17	Urdaneta	Tasajero-Betania Chivor-Cartagena
1.22	Urdaneta	Alto Anchicaya-Chivor
1.40	Urdaneta- Ramón Laguna-Concepción Planta Centro	Guajira
1.46	Urdaneta Ramón Laguna	Guajira
1.49	Guri A-Planta Centro	Guajira

With suitable changes in exciter gains throughout the system, damping ratios had a small improvement in all the low frequency oscillation modes. For the 0.22 Hz oscillation mode, damping ratio changed to 0.033, which was still considered a low value.

In the study, the analysis was concentrated on the damping that could be obtained through excitation control via power system stabilizers. Considering the structure and capacity of the power systems interconnected, and the weakness of the interconnection, it was considered that a damping ratio greater than 10 % would be required under different operating conditions, considering outages in generating units and PSS's out of services. With this damping a 0.22 Hz tie line power oscillations could be controlled or eliminated in 15 to 20 seconds.

It was interesting to observe in the analysis, that when excitation system gain of generating units in the north of Colombia was reduced, the damping ratio for the 0.22 Hz oscillation mode was also reduced. This behavior can be explained by the operating condition of the system and the type and location of excitation systems [7,9]. In this case, the north area has some local thermal generation but depends heavily in energy imported from the south. Additionally, all the generating units are equipped with slow excitation systems.

D. PSS's SITTING

Using the dynamic stability program (DINAMI), for every oscillation mode of interest, participation factors and residues of transfer functions were calculated for all the generating units [1,2]. Participation factors were ordered according to their value to identify important generating units in each mode.

Based on the rankings obtained from the participation factors previously calculated, an *ideal* stabilizer was simulated in every unit in order to evaluate the effectiveness of the stabilizing control on individual machines. The *ideal* stabilizing action was approximated by a direct proportionality (gain) between machine speed (ω_i) and the machine flux (E'qi) [8]. The effectiveness of stabilizing signals was determined by assigning non-zero values of gain to the machines one at the time, and determining the resulting change in system eigenvalues (damping sensitivity). The initial objective was to determine if an acceptable damping ratio could be obtained with the stabilizers available in the system and, if necessary, determine the need of new stabilization equipment.

Study results showed that with the PSS's installed in generating units in Colombia, some located in units with high participation in the critical oscillation mode, it was possible to change the damping ratio to desired levels. Table III summarizes the results obtained for the 0.22 Hz oscillation mode.

Table III
Damping sensitivity to an ideal PSS

PSS Available	Damping ratio σ/ω
No PSS	-0.006
San Carlos (one unit)	0.002
San Carlos (seven units)	0.085
Guaca (three units)	0.041
Paraiso (three units)	0.033
Betania (two units)	0.021
San Carlos-Paraiso	0.129
San Carlos-Guaca	0.137
Guaca-Paraiso-Betania	0.121
San Carlos-Paraiso-Guaca	0.188
San Carlos-Paraiso-Guaca-Betania	0.219

PSS stabilizing signals in San Carlos generating units showed the largest sensitivity on the damping ratio. This result was in agreement with participations factors and residues

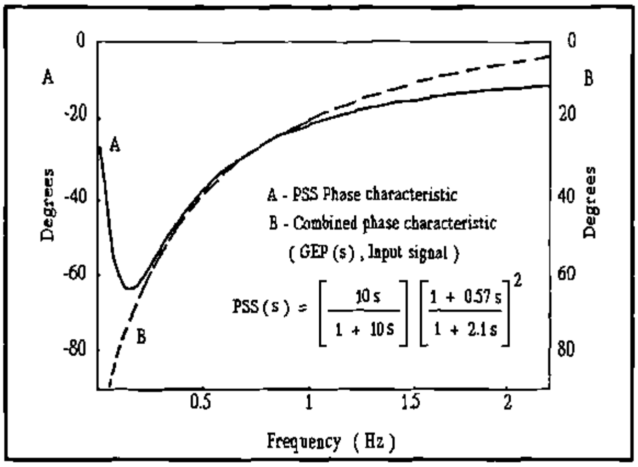

Fig.2 San Carlos Phase Characteristic.

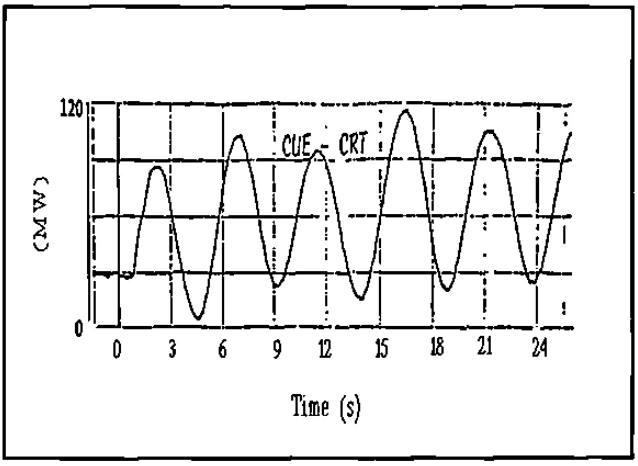

Fig.3 Tie line power flow before PSS tuning.

previously calculated. Therefore, San Carlos was initially selected as the best location to use stabilizing signals. The damping objective for the 0.22 Hz oscillation mode was reached when PSS's in other plants (Paraiso, Guaca, Betania), also with high participation factors, were used in combination with PSS's in San Carlos. Similar analysis were performed for other oscillation modes.

E. SELECTION OF PARAMETERS

In the tuning process it was necessary to evaluate the phase lag produced by generators, excitation systems and the power system (GEP(s)) [3]. The phase characteristic of the transfer function between excitation system input and generator electrical torque, combined with the phase of the stabilizer input signal, was used to determine the phase characteristic to be compensated. The compensation was performed for a desired range of frequencies that included the local mode of units and troublesome low frequency oscillation modes.

Fig.2 shows PSS transfer function and corresponding phase characteristic selected for San Carlos generating units. Phase compensation was evaluated through torque-angle analysis [4], the input signal available to power system stabilizers was electrical power. Phase compensation at 0.22 Hz minimized the effect of negative contributions due to synchronizing torque components and uncertainties in machine and system modelling. Power system stabilizer gains were adjusted to values that result in high damping ratio for the critical oscillation mode (0.22 Hz) without compromising the stability of other modes.

The tuning process was verified through multiple time-domain simulations, analyzing the response under different operating conditions. A similar procedure was followed for the tuning of stabilizers in other power plants (Paraiso, Guaca, Betania).

V. SAN CARLOS PSS FIELD SETTING

Once the study was completed, the implementation phase in San Carlos power plant included the following steps:

- Determination of PSS diagrams based on frequency response tests.
- Tuning of washout time constant through simulation and field tests.
- Checking the damping ratio for local oscillation modes.
- Performing tests with constant mechanical power to simulate a PSS with accelerating power as input signal.
- Performing tests with the tie line in service to verify the change in damping on tie line power flow oscillations.
- Design of PSS operating strategies.

VI. OPERATING SOLUTIONS ADOPTED

Power system stabilizers in San Carlos generating units were initially tuned considering a slow change in mechanical power. However, this plant had an important participation in automatic generation control and system frequency regulation. Stabilizers with electrical power as input signal must utilize some form of compensation for mechanical power changes [5]. At that time, with PSS's hardware available, it was not possible to adequately combine, in a generating unit, frequency regulation and damping functions. Therefore, in the test performed, four San Carlos units were equipped with damping signals and the rest of them were assigned to frequency regulation functions. In the future, consideration will be given to designs that approximate mechanical power variations through filtered signals [6].

VII. AGREEMENT BETWEEN THEORETICAL AND FIELD RESULTS

Fig. 3 shows a recording of tie line power flow before the

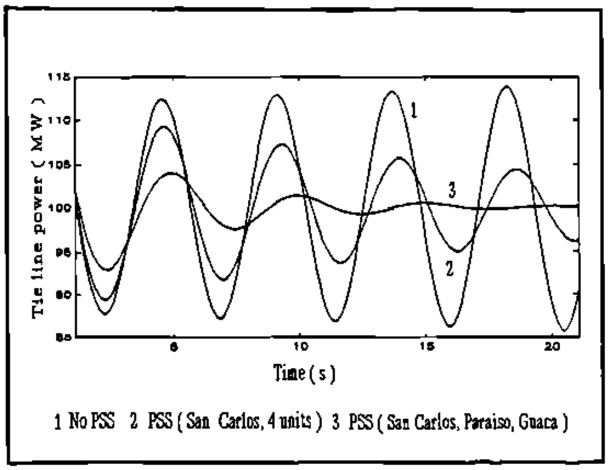

Fig.4 Time-domain simulation for the power flow on the interconnection line.

tuning of power system stabilizers. Clearly, the power flow oscillation is sustained with no apparent damping, measured oscillation frequency is practically the same value calculated in the study (0.22Hz).

One of the tests performed was the synchronization of both systems (Colombia-Venezuela) with four out of eight generating units in San Carlos with PSS's tuned for the low frequency inter-area mode. Figs. 4 and 5 show simulation results and a field recording obtained for the power flow in the interconnection line. Fig. 4 includes three cases, where the damping effect of additional PSS's in other power plants is observed. In the case with no PSS a sustained oscillation is obtained. Again, these results confirm the validity of the study and the effectiveness of the adjustments implemented to increase tie line damping.

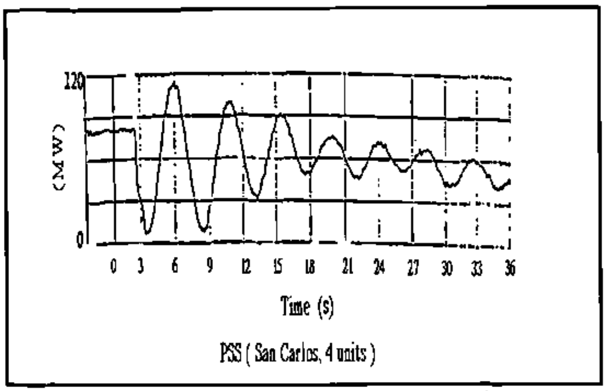

Fig. 5 Tie line power flow with PSS's adjusted.

Table IV shows the sensitivity of the damping ratio to power flow on the tie line. The calculation showed that oscillation frequency and damping ratio were not substantially affected by tie line operating condition. This is probably due to the low power flow in the interconnection (±100 MW) compared to the size of the systems interconnected. In Table IV four units in San Carlos were considered with stabilizing signals.

Table IV
Sensitivity to the tie line power flow

tie line power flow (MW)	low frequency mode (Hz)	damping ratio σ/ω
100	0.210	0.167
50	0.216	0.152
0	0.220	0.142
-50	0.222	0.134
-100	0.222	0.128

VIII. CONCLUSIONS

- Due to a weak interconnection between power systems (Colombia-Venezuela) a critical power flow oscillation made impossible to operate the interconnection. Studies revealed that a 0.22 Hz undamped oscillation was the cause of the problem. In this mode units in East-Central regions of Venezuela swing against generators in Central-South areas of Colombia.
- Characterization of modes was very important to enhance the understanding of system dynamic behavior. Stimulation of particular oscillations and the observation of effects throughout the system helped to define stabilizing strategies and to design field tests.
- Through excitation system gain control is was not possible to increase damping substantially. For the 0.22 Hz mode the most important effect came from a gain reduction in San Carlos Power Plant.
- For the critical oscillation mode, the largest sensitivities to increase damping through PSS's were associated to San Carlos, Chivor, Paraíso and Guaca generating units.
- A considerable improvement in damping ratio was obtained through the design and implementation of PSS's in the Colombian power system.
- Study results were validated by time-domain simulations and field recordings that confirmed the effectiveness of the stabilizing actions proposed and implemented.

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Appendix I.

Frequency-domain dynamic stability package
DINAMI-SISP

DINAMI-SISP module contains two main options; the first option is a program that forms the overall state matrix, and the second is an implementation of the original AESOPS algorithm [10]. In the first case, a standard EISPACK subroutine is used to perform the full eigensolution. DINAMI have identical modelling facilities as the transient stability module (ESTABI). Additionally, it includes the following special features for small signal stability studies;

- Participation Factor Calculation [11]
- Frequency Response Plots
- Transfer Function Residues [2]
- Controlability and Observability Factors