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NEEDS AND IMPROVEMENTS IN POWER FLOW ANALYSIS

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Summary

This paper describes a power flow program which has been utilized by Brazilian utilities over the last 20 years, and is now being re-engineered to accommodate the full Newton-Raphson modeling of FACTS devices, LTC transformers, HVDC links, voltage stability analysis, remote voltage control and secondary voltage control. An augmented system of equations is required to represent a device control action and its corresponding control variable. Results on practical test systems are introduced to demonstrate the numerical robustness of the proposed approach.

Keywords: Power Flow, Newton Raphson, FACTS, HVDC, Voltage Stability, Graphical User Interface.

Introduction

The power flow program is the most frequently used tool in both operation and expansion planning studies of electrical power systems. It is used to determine: *(i)* Equipment rating; *(ii)* Electrical equipment loading and system losses; (*iii*) Bus voltage magnitudes and angles; (*iv*) Reactive power support requirements to maintain voltages within limits for a given scenario and a contingency list. The network configuration, the bus P-Q load and MW generation must be specified for each case study.

The increasing complexity of power systems, introduced by new large-scale AC and HVDC interconnections and by the application of FACTS devices in such systems, has imposed new challenges to power system engineers and software developers alike.

ANAREDE, the power flow production grade code from CEPEL, has been improved in order to meet the new operating requirements of the Brazilian power system. It has also been made able to perform steady-state voltage stability studies. This program allows full Newton solutions for systems containing the following equipment and controls:

- *i)* ULTC transformer tap control;
- *ii)* Remote voltage control through generation reactive power support;
- *iii)* HVDC link controls;
- *iv)* TCSC (Thyristor Controlled Series Capacitor) to either control active power flow or line current;
- *v)* SVC (Static Var Compensation) to provide reactive power support for voltage control;
- *vi)* Induction motor loads;
- *vii)* Generator reactive capability curve;
- *viii)* Automatic capacitor switching.

The control action of each device is represented by a set of equations which are linearized to produce the augmented system of equations that are assembled together with the conventional power flow equations to

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be ordered, factorized and solved by the Newton method using sparsity techniques [1,2,3]. The improved modeling of power flow controls and solution method yielded a more robust and faster convergence. Several artifices, such as introduction of dummy synchronous condenser on weak parts of the system, or the adoption of constant impedance load model, had to be used in studies utilizing the previous version to overcome control induced convergence problems.

Mathematical Modeling

The above mentioned augmented system of equations has the following form:

$$\begin{bmatrix} \Delta \mathbf{P} \\ \Delta \mathbf{Q} \\ \hline \Delta f \end{bmatrix} = \left[\begin{array}{cc|c} \frac{\partial \mathbf{P}}{\partial \theta} & \frac{\partial \mathbf{P}}{\partial V} & \frac{\partial \mathbf{P}}{\partial x} \\ \frac{\partial \mathbf{Q}}{\partial \theta} & \frac{\partial \mathbf{Q}}{\partial V} & \frac{\partial \mathbf{Q}}{\partial x} \\ \hline \frac{\partial f}{\partial \theta} & \frac{\partial f}{\partial V} & \frac{\partial f}{\partial x} \end{array}\right] \cdot \begin{bmatrix} \Delta \theta \\ \Delta \mathbf{V} \\ \hline \Delta x \end{bmatrix} \qquad (1)$$

Where f is the control mismatch function and x is the control variable.

Numerous new developments of the ANAREDE software are described below.

Representation of ULTC transformer tap control

A new variable a is defined to represent the tap value. The partial derivatives of the injected active and reactive power equations at the transformer terminal buses must then consider the tap variation. In this case the control equation *f(x)* must ensure that the controlled voltage matches the specified voltage. In addition, this implementation has the following features:

i) The controlled bus can be either local or remote;

ii) For transformer units connected in parallel, additional equations must ensure that all taps have the same value to avoid reactive power loop flows through the transformers.

iii) The tap control equations are made active after a couple of iterations, when the reactive power mismatches have reduced. This avoids unexpected tap saturation during the iterative process.

iv) An efficient back-off scheme has been designed to overcome the tap limit problems.

v) Discrete tap option is also available.

Remote voltage control through generation reactive power support

This implementation required a control equation *f(x)* similar to the ULTC implementation. A P bus type at the generation is assumed to remotely control the voltage at a PQV bus. In this implementation the reactive power injection equation for the controlled bus is replaced by the control equation. The following features are available in this implementation:

i) For generating units connected in parallel additional equations must ensure that the total reactive power supplied is distributed among all units according to a given participation factor.

ii) The reactive power limits are handled in the conventional form [4].

HVDC link model

The HVDC link comprises two converters: the rectifier which consumes active power from an AC bus, and the inverter which delivers active power to another AC bus. The converter equations transform the AC voltage and current into DC voltage and current and vice-versa. The converters are linked to the AC buses by transformers. There is a DC network, or more specifically a DC line, which transmits the power from the rectifier to the inverter. There are AC and DC filters which reduce the harmonic components of the AC current and DC voltage. The converters have smoothing reactors which smooth the wave shape of the DC current.

A simplified schematic diagram showing a typical HVDC link is shown in Figure 1:

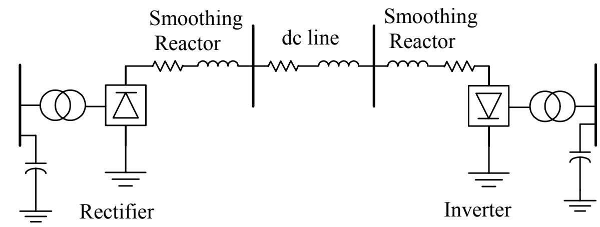

Figure 1. HVDC Link

The power flow model for the HVDC link neglects the harmonic effects. From the AC side, the HVDC converter can be considered as an injected power and from the DC network it is considered as a DC voltage source, as shown in Figure 2.

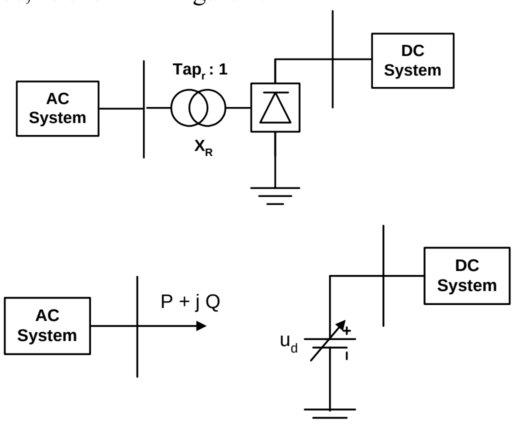

Figure 2. Converter Model for the Power Flow Program

The converters and transformers have closed-loop control systems. The firing angles of the thyristor bridges are changed, in order to vary the DC voltage of the converters [5]. The tap changer control varies the AC voltage at the converter bridge.

The most usual control strategy of a HVDC link is described:

- The rectifier firing control system keeps the DC current or power at a reference value.
- The inverter firing control system keeps the extinction angle at a minimum value.
- The tap changer control system of the rectifier transformers keeps the firing angle at a desired value.
- The tap changer control system of the inverter transformers keeps the DC voltage of the inverter at a desired value.

After defining the control strategy, the program user should specify the values for the DC current or power of the rectifier, the extinction angle of the inverter, the firing angle of the rectifier and the DC voltage of the inverter. The program then calculates the tap values of the transformers at the two ends, to achieve the specified operating conditions.

However, if the rectifier tap reaches a limit, the tap changer action is blocked and the rectifier firing angle, that was previously fixed, begins to vary. Similarly, if the inverter firing angle reaches a limit, the tap value is kept fixed at this limit and the DC voltage rectifier which was specified, begins to vary.

There is also a minimum limit for the firing angle. If the AC voltage of the rectifier is very low, the tap will reach the minimum limit and the firing angle is reduced. If the minimum firing angle limit is reached, the DC current or power is reduced. However, the control system of the inverter side is switched to control the current or power, when the current is reduced to a value lower then the current margin (typically 10% of the nominal DC current). In this case the extinction angle of the inverter rises. This control mode is called reduced voltage operation of the HVDC link.

When the AC system at the inverter side is lightly loaded, the HVDC link can operate in a control mode called *High Mvar Consumption*. In this case the AC voltage, which is generally high, makes the inverter tap to reach the maximum limit. In the normal mode of operation, the DC voltage would then begin to vary. However, in this special mode of operation, the inverter control keeps the DC voltage constant by increasing the extinction angle, and consequently the inverter reactive consumption. The inverter works rather like a big reactor, absorbing the excess of reactive power in the lightly loaded system.

The HVDC link model is integrated into the Jacobian matrix allowing full Newton-Raphson solution. The control mode logic changes are considered by automatically changing the equations when the several control variables reach their limits. There is also a back-off strategy for the control mode logic.

The power flow program also allows the modeling of multi-terminal systems and the Capacitor Commutated Converters (CCC) [6,7]. The CCC has series capacitors between the converter bridges and the transformers showing better dynamic and steady state performances. In this case, the equations describing the behavior of the converter are more complex [7].

The Garabi project, which interconnects the 50 Hz Argentinean 500 kV system to the 60 Hz Brazilian 525 kV system since May 2000 is a back-to-back CCC scheme. The power flow studies of this project were carried out using the ANAREDE program [7].

TCSC model implementation

The TCSC is a FACTS control device that is able to regulate either the active power flow or the current magnitude through a transmission line by varying its series reactance using thyristor technology. The control equation $f(x)$ can either be line current or line active power flow and its corresponding control variable is the TCSC variable susceptance.

SVC model implementation

The SVC is a shunt type FACTS device [5] meant to control the voltage at a given bus. In transmission systems it is usually connected to a lower voltage bus through a step-down transformer to regulate the high voltage bus. In the SVC control equation $f(x)$, the SVC reactive power supplied can be written as a function of the voltage to be controlled. The SVC control variable is the reactive power supplied.

Representation of induction motors

An induction motor is represented by the addition of a network dummy bus connected to the induction motor bus through the corresponding blocked rotor short-circuit reactance branch. In addition, a shunt reactance, which is roughly equal to the motor magnetizing reactance, is connected to the dummy bus. This dummy bus is of the PQ type with reactive power injection equal to zero and active power equal to the mechanical power plus the rotor losses. During the power flow iterative process the motor slip is monitored in order to take one of the following decisions:

i) Continue the iterative process considering the motor model as it stands (slip between zero and one);

ii) If the motor slip becomes equal to one the user can either switch the actual model to blocked rotor model, or switch off the induction motor.

Generator reactive capability curve

The reactive power limits are a function of the maximum rotor and stator currents and the under-excitation condition limit [5]. The active power and the terminal bus voltage are taken into account to determine the reactive power limits [8]. Additionally, the initial reactive limits must be calculated before starting the iterative process.

Automatic capacitor/reactor switching

The automatic shunt capacitor/reactor switching facility is implemented to keep the system voltage profiles within specified limits whenever there is availability of reactive shunt compensation. The implementation requires an additional power flow run whenever there is a bus voltage outside limits and the automatically switched shunt compensators are available.

Secondary voltage control

Secondary voltage control schemes coordinate the action of several reactive power sources to control the voltage at a given pilot bus. The control equations define the participation factors among the several reactive power sources, which regulate the pilot bus voltage. A simplified secondary voltage control scheme is modeled in ANAREDE, as described in [9].

Steady State Voltage Stability Analysis

The steady state voltage stability analysis comprises:

i) The continuation power flow based on the tangent vector method [10];

ii) Modal analysis for sensitivity calculations [11].

The continuation power flow produces the *P x V* curve for load increase on a chosen set of system buses. The corresponding generation that take up load must also be defined by specifying their participation factors. In addition, the power factor for the load increase may be also specified.

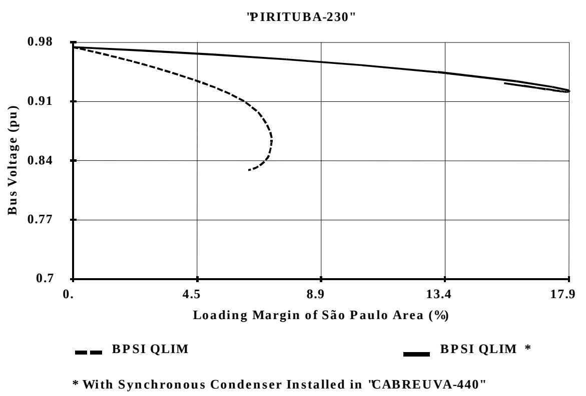

Figure 3. Voltage profile of "PIRITUBA-230"

Modal analysis was shown to be a very important tool to identify network areas with voltage stability problems and to determine the most adequate reactive power support strategy. The modal analysis is based on the calculation of the eigenvalues and the corresponding eigenvectors of the power flow Jacobian matrix at the given operating point. Modal analysis is most effectively used for system reinforcement studies or improved control measures when made at the point of collapse (maximum loadability point) or near it [12].

The continuation power flow was used to determine the loading margins of the São Paulo Area (major industrial center), starting from a given base case [12]. Figure 3 compares the loading margin of the original system with that attained after the installation of a synchronous condenser in the bus "CABREUVA-440". The choice of this bus was based on information provided by modal analysis at the maximum loadability point.

Contingency Analysis

The existing tools for contingency analysis in the actual program comprises:

i) LU factors update;

ii) Compensation methods;

iii) Refactorization method (Newton-Raphson iteration);

iv) Continuation power flow considering the circuit impedance as a continuation parameter.

Indeed, the last two models are numerically more robust and appropriate to run contingency analysis on the Brazilian interconnected power system, under heavy load conditions.

Sensitivity Analysis

The sensitivity analysis function is based on the sensitivities that can be extracted from the linearized system of equations at a given operating point. The following sensitivity models are available:

i) Bus voltage sensitivities regarding active or reactive power injection and PV bus voltage changes;

ii) Generator reactive power sensitivities regarding active or reactive power injection and PV bus voltage;

iii) Line power flow sensitivities regarding active or reactive power injection and line impedance variation.

Graphical User Interface

CEPEL started developing a graphical user interface (GUI) for ANAREDE many years ago. The strategy adopted, at that time, was to isolate the FORTRAN code from the GUI code so that the code could either be compiled together with the GUI code or not. The GUI developed allows easy drawing and manipulation of one-line diagrams. There is a complete set of filters that help the user to focus the analysis on a specific area of the network or to locate bus voltage or circuit flow violations. The GUI and the solution routines are linked together in a single executable so that variable updating does not depend on intermediate files. Originally developed for the X Window environment, this GUI has been migrated to the Windows environment and is being continuously developed.

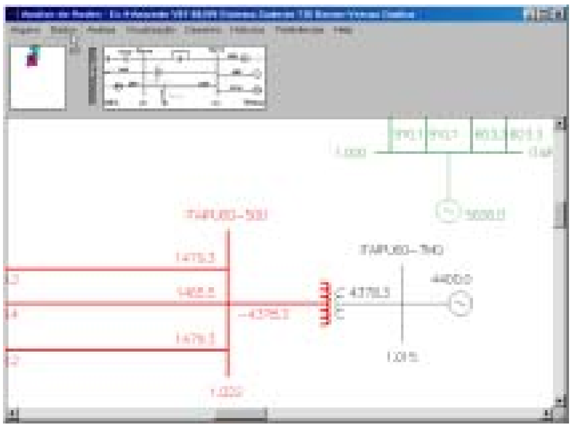

Figure 4. GUI main window

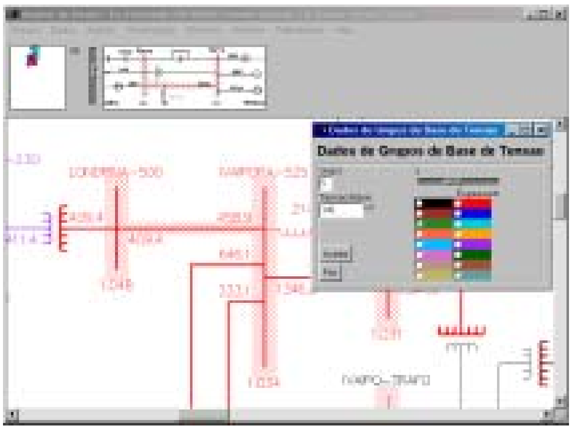

Figure 5. Bus overvoltage and circuit overload located with the aid of violation filters. User defined color code based on nominal voltage.

Convergence Results

The test system utilized was the South-Southeastern Brazilian system under light, medium and heavy load conditions. The main characteristics of these system conditions are shown in Table 1.

Table 1: Test Systems

Test System Conditions	Light	Medium	Heavy
Buses	1768	1772	1772
Circuits	2527	2532	2530
PV Buses	165	168	177
Transformers (*ULTC*)	334	326	317
Remote Voltage Control	10	10	9
Load (MW)	**22.814**	**33.784**	**38.533**

The next four figures compare the convergence characteristics of the old and new versions of the ANAREDE Program. The control options which are active in these power flow solutions are:

i) Remote voltage control through reactive power support from generators;

ii) Reactive power generation limits;

iii) Bus voltage control by LTC action.

The solid lines correspond to the results of the new version. The dashed lines correspond to those of the old version.

The convergence characteristics under lightly load conditions and with no reactive power generation limits are shown in Figure 6. Figure 7 shows the results when the reactive power generation limits are modeled.

Note from Figures 6 and 7 that the results from the old version appear to be practically converged at the 5th iteration. However, the mismatches are seen to become much higher and oscillatory after the 6th iteration. These convergence problems appeared when the equations for the power system controls were included into the solution process at the 6th iteration.

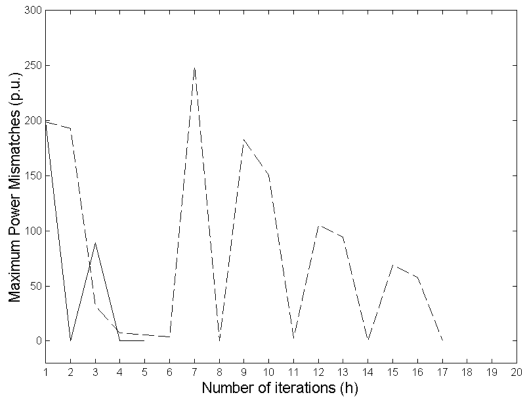

Figure 6. Test system under light load conditions

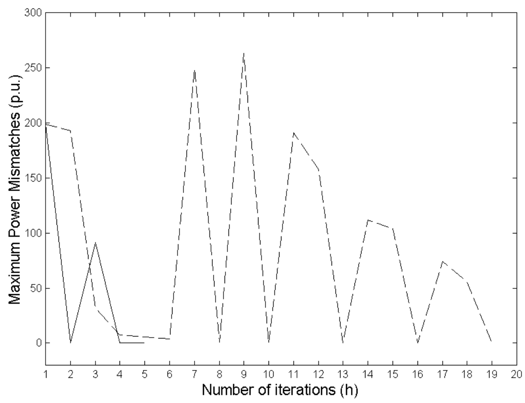

Figure 7. Test system under light load conditions with reactive power generation limits

Figures 8 and 9 show the convergence characteristics under medium and heavy load conditions, and in both cases, the generators do not violate their reactive power generation limits. Note, from Figure 8, that the old program version diverges under heavy loading conditions, when incorporating all the above mentioned controls.

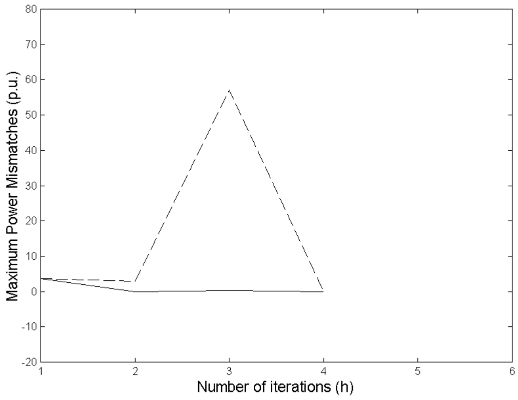

Figure 8. Test system under medium load conditions

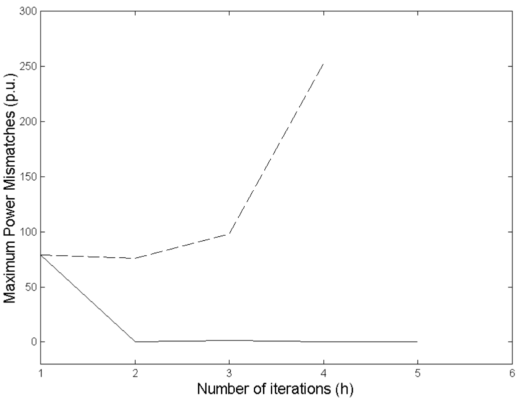

Figure 9. Test system under heavy load conditions

Future work

Integration of the power flow program with the optimal power flow program for enhanced voltage stability analysis incorporating a load shedding tool and a reactive power allocation tool to ensure power flow solvability [13].

The existing tie-line power control will be included in the augmented system Jacobian. In addition, this implementation will have a better modeling of the AGC action.

Governor response power flow will provide the network solution after a disturbance, considering a time frame around 20s [5].

References

[1] **W.F. Tinney** and **J. W. Walker**, "Direct Solutions of Sparse Network Equations by Optimally Ordered Triangular Factorizations", *Proceedings of IEEE*, November 1967, 55:1801-1809.

[2] **D. J. Gotham** and **G. T. Heydt**, "Power Flow Control and Power Flow Studies for Systems with FACTS Devices", *IEEE Transactions on Power Systems*, 13, No. 1:60-65, February 1998.

[3] **C. R. Fuerte-Esquivel** and **E. Acha**, "A Newton-Type Algorithm for the Control of Power Flow in Electrical Power Networks", *IEEE Transactions on Power Systems*, 12, No.4:1474-1480, November 1997.

[4] **A. J. Monticelli**, *Power System Load Flow*, Editora Edgard Bluncher Ltda, 1983. (in Portuguese)

[5] **P. Kundur**, *Power System Control and Stability,* EPRI-Power System Engineering Series, McGraw-Hill Inc, 1994.

[6] **V. M. da Costa**, **N. Martins** and **J. L. R. Pereira**, "Representation of user defined Controls in the Power Flow Problem", *Proceedings of VI SEPOPE,* Salvador, BA, Brazil, May 1998. (in Portuguese)

[7] **S. Gomes Jr.**, **N. Martins**, **R. Ljungqvist**, **T. Jonsson**, **H. J. C. P. Pinto**, **R. D. Rangel** and **A. R. C. D. Carvalho**, "Modeling ABB's HVDC/CCC into the CEPEL Simulation Package", *Proceedings of VI SEPOPE,* Salvador, BA, Brazil, May 1998.

[8] **P. A. Lof**, **G. Anderson**, and **D. J. Hill**, "Voltage Dependent Reactive Power Limits for Stability Studies", *IEEE Transactions on Power Systems*, 10, No. 1:220-228, February 1995.

[9] **H. J. C. P. Pinto**, **N. Martins**, **J. L. R. Pereira**, **V. M. da Costa and J. A. P. Filho,** "Steady State Secondary Voltage Control using the Newton-Raphson Method", *Submitted to XIII-CBA-Florianopolis-SC*, September 2000. (in Portuguese)

[10] **V. Ajjarapu, C. Christy,** "The Application of a Locally Parameterized Continuation Technique to the Study of Steady State Voltage Stability", *Proceedings of the 21st Annual North American Power Symposium,* Rolla, Missouri, October 1989.

[11] **B. Gao, G. K. Morison** and **P. Kundur,** "Voltage Stability Evaluation Using Modal Analysis", *IEEE Transactions on Power Systems,* 7, No. 4:1529-1542, November 1992.

[12] **J.C.R. Ferraz, N. Martins, H. J. C. P. Pinto** and **D. Falcão,** "Continuation Power Flow and Modal Analysis for Assessing and Enhancing Voltage Stability in Large Scale Power System", *Proceedings of the VII SEPOPE*, Curitiba, PR, May 2000.

[13] **S. Granville, J.C.O. Mello and A.C.G. Melo**, "Application of Interior Point Methods to Power Flow Unsolvability", *IEEE Transactions on Power Systems*, 11, No. 2, pp. 1096-1103, May 1996.