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# A Newly Built Power Flow Program in PSCAD/ EMTDC for Electric Power System Studies

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***Abstract*—The power flow computation consists of imposing specified power and voltage input conditions to a power network and producing the complete voltage information at all the system buses. The calculation is required for both the steady state analysis and the dynamic performance evaluation of power systems. It is also used to initialize other computer-aided power system software. This paper presents a novel production grade power flow program that performs the power flow computations of modern electric power systems efficiently and accurately. The new program is capable of providing the power flow information of independent subsystems simultaneously. It has a powerful feature of changing the power levels of generators and loads locally or globally in power systems. The paper also describes the under going integration and initialization of the well-known system simulation software PSCAD/EMTDC with the power flow program.**

***Index Terms*—Power flow program in PSCAD/EMTDC.**

## I. INTRODUCTION

THE power flow computation is fundamentally important to power system design and analysis [1], [2]. Based on the assumed load demands and generation levels, the computation provides the valuable information on the overall voltage profile, power flows in branches, line currents, line losses, and other related steady-state variables. It is performed in system planning, operational planning, and operational controls. Since a modern electric power system has a tremendous number of different components, performing its power flow computation can be challenging due to the large size and the high complexity of the system. Searching for better power flow calculation methods started with the Ward and Hale's approach in 1956 [1]. The computer-aided solutions to power system problems are receiving increasing attention. In power system studies the computer solution is the best means of providing quick and economical results of high accuracy. Better economy in the power flow calculation must, therefore, rely primarily on high speed and economical computers as well as accurate and efficient computer-aided software. When solving power flow problems, the admittance matrix of a considered system is formed, the constraints of the network are specified and suitable solution methods are used to obtain the specified system quantities. The Newton-Raphson's iterative method equipped with the memory and speed optimization techniques has become one of the most recognized power flow computational methods due to its better convergence characteristics [3]. The Fast PQ-Decoupled method is the other very attractive power flow solution technique because of it reliability and efficiency.

In order to have an accurate, efficient, and user-friendly power flow program, a suitable solution method must be chosen, optimized programming codes are required, and integrating the program with a graphical user interface is in demand.

This paper presents a powerful newly developed power flow program for power system design and studies in Manitoba HVDC Research Centre. To have a high solution speed, the efficient programming techniques and the powerful convergence improvement methods have been applied in the program's development. Integrating it with PSCAD/EMTDC is being undertaken and will greatly promote its popularity.

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## II. GENERAL PROGRAM DESCRIPTION

The power flow program is capable of performing the power flow calculation of power systems consisting of many different components, such as generators, passive branches, transformers, ac transmission lines and cables, dc links, loads, switched shunts, and unified power flow controllers (UPFCs). The input data format of the software is the same as that used in PSS/E such that data conversion is not required. To further promote its flexibility, it also accepts the raw data with the GE input data format. The program has been developed mainly with the Newton-Raphson's method and the Fast PQ-Decoupled technique because of their high solution speeds and accuracy, and the abilities of handling the system voltage and power flow controls. The efficiency optimizing techniques have been implemented in the program to further improve its solution speed. To assist reaching the solution of an ill-conditioned power system, the convergence improvement techniques have been included in the software development.

The power flow program includes the control functions of system components, such as the on-load tap changers of transformers, phase shifters, synchronous machines, switched shunts, and UPFCs, These devices are used to control either the specified bus voltages or the power flow through certain branches. For a power system having isolated subsystems, the program provides the information on the power flow of each subsystem simultaneously. Furthermore, the program has the capability of changing the power levels of generation and consumption locally or globally. It calculates the voltages at buses, the power and power losses through branches. The values of switched shunts, the turns ratios of transformers,

and the phase angles of phase shifters are established in the solution process. The program also produces the system information of each area, such as generation, power consumption, power losses, and area power exchanges [4].

The power flow program will be integrated with PSCAD/EMTDC such that power flow studies can be conducted graphically and more easily. EMTDC, which is an EMTP type power system simulation engine, will also be initialized by the power flow program.

## III. PROGRAM OPERATION

In order to generate the power flow solution of a power system, the input raw data of the network must be prepared. Generating a raw data file involves labeling buses and branches, assigning bus-types, calculating system parameters, assigning powers to loads, setting bus voltages, and forming different data sections based on the system's configuration and parameters.

After inputting and processing the data of the power system, the program constructs the system admittance matrix [Y]. The complex power at the i-th bus in the power system is given by

$$P_i + jQ_i = V_i \sum_{j=1}^{N} Y_{ij} V_j^* \tag{1}$$

where $P_i$ and $Q_i$ are the real and reactive power entered into the i-th bus, respectively; $V_i$ and $V_j$ are the voltages at the i-th bus and the j-th bus, respectively; $Y_{ij}$ is the admittance of the branch between the i-th bus and the j-th bus. N is the number of buses related to the i-th bus.

The real and reactive power mismatches at the i-th bus are given by

$$\Delta P_i = P_{is} - V_i \sum_{j=1}^{N} V_j \left( G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij} \right) \tag{2}$$

$$\Delta Q_i = Q_{is} - V_i \sum_{j=1}^{N} V_j \left( G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij} \right) \tag{3}$$

where $P_{is}$ and $Q_{is}$ are the desired real and reactive power flowing into the i-th bus; $G_{ij}$ and $B_{ij}$ are the conductance and susceptance of the branch between the i-th bus and the j-th bus; $\theta_{ij}$ is the phase angle between the i-th bus and the j-th bus.

Equations (2) and (3) are then solved for the bus voltage amplitudes and angles by the Newton-Raphson's iterative method or the Fast PQ-Decoupled technique. Other desired system quantities are also computed in the network solution.

### A. Newton-Raphson's Iterative Method

Equations (2) and (3) can be solved with the damped-Newton-Raphson's iterative solution method for the desired system quantities as follows:

(1). The voltage of 1.0 + j0.0 p.u. is assigned to all the buses, resulting in a flat start. Or the buses are assigned with the respective known bus voltages.

(2). The Gauss-Seidel solution method is then applied for the first two iterations to obtain the better initial values of the variables for the Newton-Raphson solution method.

(3). The Jacobian matrix is formed and the power-mismatched matrix equation is solved for the variable corrections.

(4). If the calculated system variable changes are within the specified tolerances, other required system quantities are computed based on the system variables and parameters. Otherwise the procedure is repeated, starting with step 3. The whole process is repeated until all system variable corrections become smaller than the predetermined precision limits.

In the power flow program some of the control variables are automatically manipulated to assist convergence to the solution that satisfies the important specifications as follows:

(1). Transformers are adjusted such that voltage-controlled buses maintain their voltages or the real power through branches within the acceptable limits [5].

(2). If the reactive power of a generator exceeds the specified limits, its reactive power is set to the nearest limit and its terminal bus becomes a load bus.

(3). If the calculated real power at the slack bus exceeds the limits, the generation difference is distributed among the remaining units. The adjustment is repeated until the slack bus generation is within the specified limits.

(4). If the slack bus reactive power generation exceeds the limits, the slack bus may be assigned to a different generator bus, or the slack bus voltage can be changed appropriately without violating its voltage limits, or the reactive generation can be made by switching appropriate capacitor or inductor banks.

(5). If voltage and (or) reactive power limit violations persist despite all of the above actions, the capacitor and inductor switching is made in order to guarantee the feasibility of the final solution.

Fig. 1 shows the simplified flow chart of the solution process using the Newton-Raphson's solution method.

### B. Fast PQ-Decoupled Method

Equations (2) and (3) can be rewritten as [6]

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & N \\ J & L \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta V / V \end{bmatrix} \tag{4}$$

where

$$H_{ij} = \frac{\partial \Delta P_i}{\partial \theta_j};\ H_{ii} = \frac{\partial \Delta P_i}{\partial \theta_i};\ N_{ij} = \frac{\partial \Delta P_i}{\partial V_j} V_j;$$

$$N_{ii} = \frac{\partial \Delta P_i}{\partial V_i} V_i;\ J_{ij} = \frac{\partial \Delta Q_i}{\partial \theta_j};\ J_{ii} = \frac{\partial \Delta Q_i}{\partial \theta_i};$$

$$L_{ij} = \frac{\partial \Delta Q_i}{\partial V_j} V_j;\ L_{ii} = \frac{\partial \Delta Q_i}{\partial V_i} V_i.$$

Since the phase angle between two buses is not large and the mutual susceptance is much smaller than the self susceptance at a bus, the following relations are held:

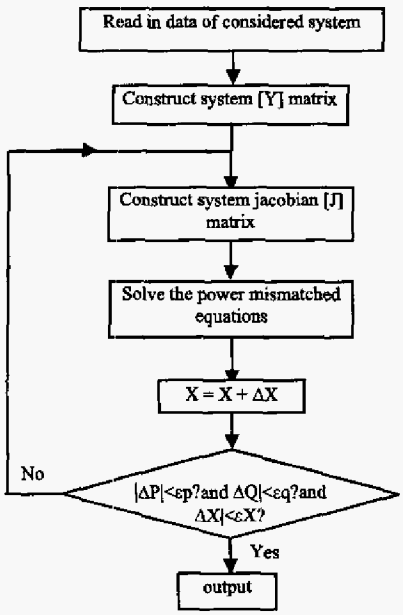


Fig. 1. Simplified flow chart of Newton-Raphson's iterative method.

$$\begin{aligned} \cos\theta_{ij} &\approx 1 \\ G_{ij}\sin\theta_{ij} &<< B_{ij} \\ Q_i &<< B_{ii}V_i^2 \end{aligned} \tag{5}$$

Therefore, (4) becomes

$$[\Delta P] = [H][\Delta\theta] \tag{6}$$

$$[\Delta Q] = [L][\Delta V / V] \tag{7}$$

where

$$H_{ii} = V_i^2 B_{ii};\ L_{ii} = V_i^2 B_{ii};\ H_{ij} = V_i V_j B_{ij};\ L_{ij} = V_i V_j B_{ij}.$$

Equations (6) and (7) can be further simplified as

$$\left[\frac{\Delta P}{V}\right] = [B^{/}][V\Delta\theta] \tag{8}$$

$$\left[\frac{\Delta Q}{V}\right] = [B^{//}][\Delta V] \tag{9}$$

where the elements of [B$^{/}$] are the negative reciprocals of the line reactances and the entries in [B$^{//}$] are the imaginary parts of the respective elements of the system admittance matrix [Y].

The dimensions of [B$^{/}$] and [B$^{//}$] are different. [B$^{/}$] has a dimension of n with n being the total bus number. The swing bus is included in [B$^{/}$] and its self admittance is set to a negative value with a very large amplitude. In constructing [B$^{/}$], the components with small effects on the real power, such as shunts and transformer turns ratios, are neglected. On the other hand, [B$^{//}$] has the dimension of lower than n. If the bus types of some buses are changed, [B$^{//}$] will be adjusted. In forming [B$^{//}$], the components with negligible effects on the reactive power, for instance the resistances of the branches, are removed. It is worth noting that although [B$^{/}$] and [B$^{//}$] have been simplified in the Fast PQ-Decoupled approach, the power mismatches are computed according to (2) and (3).

The Fast PQ-Decoupled solution method can be used to compute the power flow of a power system by solving (8) and (9) as follows:

(1). The voltage of 1.0 + j0.0 p.u. is assigned to all the buses, resulting in a flat start. Or the buses are assigned with the respective known bus voltages.

(2). The Jacobian matrices [B$^{/}$] and [B$^{//}$] are constructed.

(3). Equation (8) is solved for the variable corrections.

(4). If the calculated system variable changes are within the specified tolerances, other required system quantities are computed based on the system variables and parameters. Otherwise, (9) is solved for the system variable corrections. Please note that if some buses have changed their bus types, [B$^{//}$] must be adjusted before solving (9). If the calculated system variables are within the specified tolerances, other required system quantities are computed .Otherwise repeat step 3. The whole process is repeated until all system variable corrections become smaller than the predetermined precision limits. The program iteration process is shown in Fig. 2.

The system adjustment functions of regulated transformers, phase shifters, shunts, inter-area power exchanges, and UPFCs are implemented between the solution iterations to reserve the advantages of the high efficiency of the Fast PQ-Decoupled method [5], [6], [7].

A transformer tap changing is implemented as

$$T_m^{t+1} - T_m^t \approx A_m\left(V_i - V_i^{spec}\right) \tag{10}$$

where $T_m^{t+1}$ and $T_m^t$ are the turns ratios of the m-th transformer in iteration t + 1 and iteration t; $A_m$ is the scalar; $V_i$ and $V_i^{spec}$ are the voltage at the iteration t + 1 and the specified voltage at the i-th bus. The turns ratio of the transformer is obtained by solving (10).

The linearized constraint equation for a phase shifter is given by

$$\begin{aligned} P_{ij}^{spec} - P_{ij} \approx\ & P_{ij}^{spec} - P_{ij}\left(V_{io}, V_{jo}, \theta_{io}, \theta_{jo}, \phi_{ijo}\right) \\ & - \frac{\partial P_{ij}}{\partial V_i}\Delta V_i - \frac{\partial P_{ij}}{\partial V_j}\Delta V_j \\ & - \frac{\partial P_{ij}}{\partial \theta_i}\Delta\theta_i - \frac{\partial P_{ij}}{\partial \theta_j}\Delta\theta_j - \frac{\partial P_{ij}}{\partial \phi_{ij}}\Delta\phi_{ij} \end{aligned} \tag{11}$$

where $P_{ij}^{spec}$ is the required real power flow of the line i-j; $\Phi_{ij}$ is the phase angle of the phase shifter; $\Delta\Phi_{ij}$ is the increment of the phase shift angle.

After each iteration one can calculate the change in phase shift angle required to meet the constraint condition of controlling the line power $P_{ij}$ as

$$\Delta\phi_{ij} \approx \frac{1}{\partial P_{ij} / \partial \phi_{ij}} \Big[ P_{ij}^{spec} - P_{ij}\left(V_{io}, V_{jo}, \theta_{io}, \theta_{jo}, \phi_{ijo}\right) - \frac{\partial P_{ij}}{\partial V_i}\Delta V_i - \frac{\partial P_{ij}}{\partial V_j}\Delta V_j - \frac{\partial P_{ij}}{\partial \theta_i}\Delta\theta_i - \frac{\partial P_{ij}}{\partial \theta_j}\Delta\theta_j \Big] \quad (12)$$

In the power flow solution process, the generator Q-limit violations are checked. The buses having Q-limit violation are changed to PQ type and the MVAR outputs are held at the limiting values. The buses remain PQ type during the rest of the iterations can be changed back to PV type buses at the original voltage magnitude without the violation.

Area controls are used to regulate the interchange of real power between the specified areas of a power system by adjusting the scheduled real power generation at certain area swing generators. In the program the total real power generation of an area is first obtained. Then the generation of the area's swing bus is adjusted by the difference between the specified tie line power and the actual tie line flow. This power generation is modified between iterations.

UPFCs are also included in the power flow computation between iterations based on the bus voltage levels and the power flow along the branches controlled by the UPFCs.

## IV. IMPORTANT PROGRAM FEATURES

The power flow program not only can perform the similar functions of the power flow software commonly used in utilities, bus also has important features that make it a powerful tool in power flow computations.

The program can change the real and reactive power levels of the generators and loads of a considered power system globally. It is also able to set the power levels of these components by zones and areas. These important features ensure that the user can conveniently adjust the network's power generation and consumption in the power flow study, resulting in a quicker and better evaluation of the power flow of the system.

The program can be used to conduct the contingence studies, such as the disconnection of transmission lines, generators, and loads. The program is able to perform the load flow computation either directly using the raw data file or the schematic of a considered system constructed by PSCAD. The power flow solution can be obtained with the Newton-Raphson's iterative method or the Fast PQ-Decoupled technique. When computing power flows directly from the raw data file, the program accommodates both the PSSE and GE data formats. Furthermore, the program can perform the power flow computations of all the independent subsystems in a power system simultaneously and produce the power flow information on each subsystem. This feature enables the user to insight the operation of each subsystem in the power flow analysis.

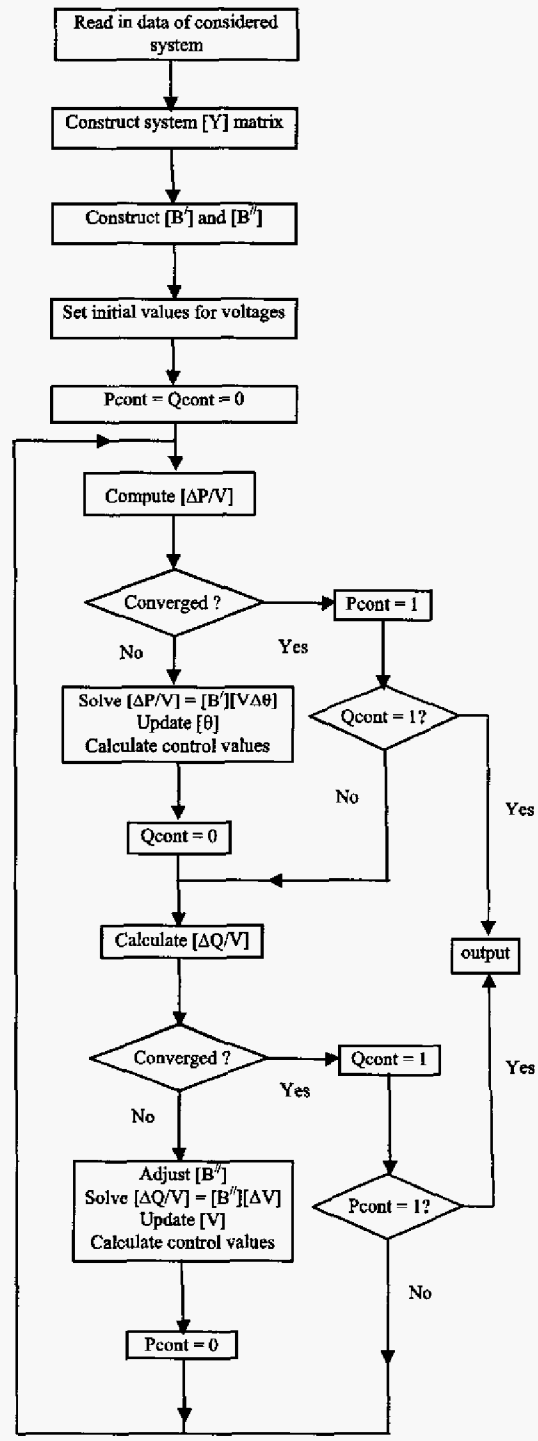


Fig. 2. Simplified flow chart of Fast PQ-Decoupled method.

## V. CONVERGENCE IMPROVEMENT

To improve the convergence of the solution in a power flow computation, a damped Newton-Raphson method [8], a better initial estimation technique, and the data adjustment method have been applied in the program. The Newton-Raphson's iterative method has the quadratic convergence characteristics; however, this property may not exist when dealing with ill-conditioned power systems. With $x^t$ and $\Delta x^t$ being a variable value and the variable correction in iteration t, the damped Newton-Raphson method applies a damping multiplier $\lambda_{min}$ to obtain a better approximation as

$$x^{t+1} \approx x^t + \lambda^t_{\min} \Delta x^t \tag{13}$$

The multiplier in the above equation is obtained by solving the following equation:

$$\partial h(\lambda) / \partial \lambda = 0 \tag{14}$$

where

$$f(x) = \sqrt{\sum_{i=1}^{n} \left| g_i(x^t) - g_i(x^{t-1}) \right|^2} \; ;$$

$$d_j = f\left(x^t + \lambda_j \Delta x^t\right);$$

$$h(\lambda) = d_2 - \frac{d_1 - d_3}{2(\Delta\lambda)} \lambda + \frac{d_1 - 2d_2 + d_3}{2(\Delta\lambda)^2} \lambda^2 \; ;$$

$g_i(x^t)$ is a power function and n is an integer.

The Gauss-Seidel solution method has been used to the system solution for the first two iterations to generate the system solution such that the Newton-Raphson method can start with better initial guesses to accelerate the system solution process. When dealing with ill-conditioned power systems, the program adjusts the respective system data according to the information on the suspected buses and devices to improve the convergence condition of the system solution such that the closest solution can be obtained.

Sometimes, zero impedance branches can cause convergence burden. In order to overcome this convergence barrier, zero impedance branch combination strategies have been implemented in the program to improve the convergence of system solutions.

## VI. PROGRAM STRUCTURE

The program has a data input processing unit, a system solution processing unit, and a result output unit. The physical structure of a considered power system is fully utilized to improve the use of computer memory and to optimize the solution efficiency.

In order to have a high-speed power flow program, some speed optimizing techniques have been applied in its development. When inputting the data from an input raw data file or generating the output file, looping structures have been minimized in the program. Checking constraints has also been minimized and more compacted and economical data structures have been used in the solution process.

Since forming the Jacobian matrix of the power-mismatched equation in the solution process with the Newton-Raphson method is truly a computational burden, accelerating the matrix generation is essential in the solution speed. An optimized routine for generating the Jacobian matrix has been implemented in the program to improve its efficiency.

To reserve the advantage of the Fast PQ-Decoupled method, system controls have been implemented between solution iterations, reducing the dimension of jacobian matrices and the necessity of adjusting matrix $[B^{//}]$.

## VII. PROGRAM INTEGRATION WITH PSCAD/EMTDC

Integrating the power flow program with PSCAD/EMTDC enables the user to conduct a power flow study of a power system schematically and easily. He may perform the load flow computation of a power network either with the input raw data file of the system or with the schematic system case built with PSCAD/EMTDC.

In order to integrate the power flow program with PSCAD/EMTDC, an interface linking these programs is in demand. In the integration, PSCAD is the command program and both EMTDC and the power flow program are the called-on programs. In order to fulfill a task, PSCAD calls either the power flow program or EMTDC or both these programs.

The power flow program is used to initialize EMTDC, making the transient simulation studies much easier. In the initialization of EMTDC, the useful data used to invoke the power flow program are extracted from the schematic diagram of an EMTDC case. The power flow program then generates the necessary data that finally are used to initialize the system for transient studies with EMTDC. Both the integration and the initialization of EMTDC with the power flow program are being undertaken.

## VIII. PROGRAM TESTS

In order to verify the power flow program, a number of tests on different electric power systems have been conducted. However, only 32 test systems, which have different structures ranging from a 6-bus system to a 25160-bus system summarized in Table I, are considered here. Some of these systems are among the selected power systems in China, South Korea, Australia, the United States, and Canada. The tests were focused on the program's accuracy and efficiency. The results obtained with the load flow program are compared with those obtained with PSS/E 29.

In most of the tests, the power flow computation of a power system took less than 10 iterations to reach a solution using either the Newton-Raphson's iterative method or the Fast PQ-Decoupled technique. In some tests, the Newton-Raphsson's iterative method could provide the power flow solution of the test networks without any help from the Gauss-Seidel method. The test results have proved that the load flow program is capable of handling the power flow computations of different power systems with high accuracy and at high solution speeds.

TABLE I
DATA OF THE TEST SYSTEMS

| test no. | bus num. | branch num. | shunt num. | transf. num. | gen. num. | dc-link num. | upfc num. |
|---|---|---|---|---|---|---|---|
| 1 | 6 | 4 | | | 2 | | |
| 2 | 8 | 5 | | | 2 | | |
| 3 | 9 | 6 | | 1 | 3 | | 1 |
| 4 | 10 | 6 | | | 3 | | |
| 5 | 14 | 17 | | | 5 | | |
| 6 | 20 | 25 | | | 6 | | |
| 7 | 20 | 26 | | 7 | 6 | | |
| 8 | 20 | 23 | | 2 | 6 | | |
| 9 | 22 | 36 | | 3 | 6 | | |
| 10 | 30 | 41 | | | 6 | | |
| 11 | 109 | 146 | 9 | 18 | 26 | 4 | |
| 12 | 118 | 186 | | | 54 | | |
| 13 | 127 | 154 | | | 9 | | |
| 14 | 160 | 319 | 44 | 37 | 41 | | |
| 15 | 173 | 205 | | | 42 | | |
| 16 | 278 | 444 | 4 | 49 | 42 | | |
| 17 | 298 | 459 | | 49 | 69 | 1 | |
| 18 | 505 | 704 | | | 52 | | |
| 19 | 1704 | 800 | 60 | 563 | 177 | | |
| 20 | 1147 | 1377 | | 92 | 49 | | |
| 21 | 1219 | 808 | 204 | 284 | 30 | 4 | |
| 22 | 1495 | 1925 | | | 157 | | |
| 23 | 1727 | 1928 | | 578 | 177 | | |
| 24 | 2152 | 3791 | | 15 | 424 | | |
| 25 | 2161 | 2767 | 28 | 371 | 427 | | |
| 26 | 2634 | 3338 | | | 246 | | |
| 27 | 3125 | 8807 | 17 | 641 | 791 | 7 | |
| 28 | 12239 | 10586 | 398 | 1025 | 1673 | | |
| 29 | 12451 | 15561 | | | 1987 | 5 | |
| 30 | 13256 | 16290 | 438 | 1656 | 1954 | 5 | |
| 31 | 18476 | 29352 | 975 | 1949 | 1814 | 9 | |
| 32 | 25160 | 24948 | | | 2437 | | 1 |

## IX. CONCLUSIONS

The paper has presented the new and powerful production grade power flow program developed in Manitoba HVDC Research Centre. It has many excellent features and is capable of performing the power flow computations of different power systems. The program provides accurate power flow computational results of power systems at high solution speeds.


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