Real-Time Implementation of Optimal Reactive Power Flow

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Abstract: **The application of optimal reactive power flow (ORPF) to the New Brunswick (NB) Power system is presented. The potential benefits and the real-time implementation problems of ORPF are discussed. Some important issues on real-time implementation of ORPF such as frequency of running, the number of activated control variables, and the order of adjustment of different controls are discussed.**

The application of ORPF on the NB Power network has shown two major benefits: 1) an improvement in the voltage profile and voltage stability, and 2) a savings in active power loss. The improvement in voltage profile can cause less violations and a more stable system from the voltage point of view. A reduction in active power loss gained from ORPF can save a significant amount of money. The total ideal saving for the year 1995 predicted in the study was in excess of $900,000, however, only ten to thirty percent of this amount is realistically obtainable due to operational and other constraints. These savings can be gained simultaneously with the improvement of the voltage profiles.

Keywords: optimal reactive power flow, power loss minimization, optimization methods

1 Introduction

Optimal power flow (OPF) problem is one of the major issues in operation of power systems [1]-[10]. This problem can be divided into two subproblems, MW and Mvar dispatch. In many cases, the optimal reactive power flow (ORPF) problem is considered independently [2], and in some others it is combined with MW dispatch [3]. However, in most real-time applications, ORPF has run independent of MW dispatch. The main objectives of ORPF address three important aspects: a) to keep the voltage profiles in an acceptable range [4], b) to minimize the total transmission energy loss [5], and c) to avoid excessive adjustment of transformer tap settings and discrete var sources switching [2, 5].

The control variables for this study constitute of the vars/voltages of generators, the tap ratios of transformers, reactive power generation of var sources, etc. The constraints include the var/voltage limits of generators, the voltage limits of load buses, tap ratio limits, var source limits, power flow balance at buses, security constraints, etc.

In most applications of ORPF, the power loss in the transmission network is minimized on the basis of a single snapshot of the network. For tracking on-line load changes, and keeping the network in optimal condition over time, the ORPF should be executed continuously, or at least very often. However, due to application and implementation difficulties, ORPF is run less frequently. Reasons for this include keeping operator workload within acceptable limits and avoiding excessive equipment switching (transformer taps, capacitor banks, etc.). An appropriate cycling time for ORPF implementation is addressed in this paper. The participation of different controls in each run of ORPF, and the order of optimal adjustments are also considered. Finally, the potential benefits of real-time implementation of ORPF are discussed. The study has shown two major benefits for NB Power network: 1) the improvement in the voltage profile and voltage stability, and 2) the savings in active power loss.

In Section 2, the real-time implementation issues of ORPF; in Section 3, the frequency of execution of ORPF, and in Section 4 the order of optimal adjustments of control variables are addressed. The simulation results are presented in Section 5. The concluding remarks are discussed in Section 6.

2 Real-Time Implementation of ORPF for NB Power Network

The NB Power ORPF package is running on a VAX computer at the Energy Control Center (ECC). The package can be used for on-line applications. This package can be utilized in connection with other application programs such as State Estimater (SE). For on-line execution of ORPF, the SE output should prepare appropriate input data for the ORPF program.

The connection between on-line data and the SE and ORPF programs is shown in Fig. 1. By getting a real-time snapshot of the NB Power network, the on-line data from SCADA is transferred to the SE program. The State Estimater program uses the network data to calculate the necessary input data for the ORPF program. By running ORPF, the optimal operating condition of the network including the new adjustments of control variables, voltage profile, power loss, etc. is obtained. By implementing the optimal settings on the network, the system moves to the optimal operating condition.

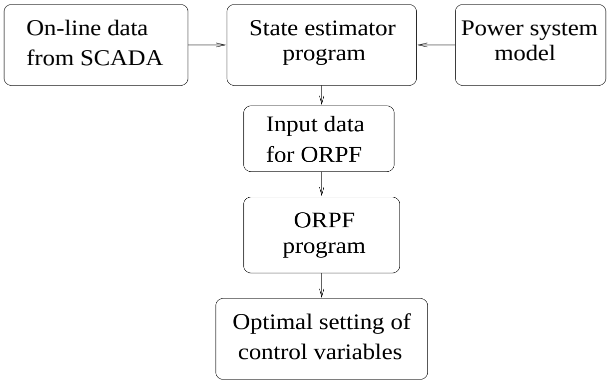

Figure 1: The connection between SCADA, SE, and ORPF programs

Some major issues in the real-time implementation of ORPF are the frequency of control adjustments, the participation of different controls in each run of ORPF, and the order of optimal adjustments. These topics are considered very carefully in Section 3 and Section 4, respectively.

3 Frequency of Running ORPF

An important aspect in running the ORPF program is the frequency of its execution. This frequency can be varied from several minutes up to several hours. The frequency depends on some important factors, such as load profile variation, constraint violations, importance of power loss reduction and/or maintaining an appropriate voltage profile, and finally the philosophy dictated by the utility company. It is also possible that different control variables be adjusted at different frequencies.

For finding the appropriate frequency of running ORPF, the daily load profile should be considered. The daily load profile of one day in January between 1am and 10am is shown in Fig. 2. During the instants which the load changes rapidly, the ORPF should be executed with a higher frequency. For example, between 5am to 8am the load has the highest rate of change, and ORPF should be run more often. However, during 2am to 4am the load is almost flat and one ORPF run could be enough.

In Fig. 2, two time intervals between 1am to 5am and 5am to 7am are selected. Each interval is divided into several periods. The interval between 1am to 5am is divided into 3 periods. Due to small load changes in these periods, for each period one ORPF run is enough. During 5am to 7am, due to rapid load changes 4 periods are selected. Similarly, for each period one ORPF run is enough.

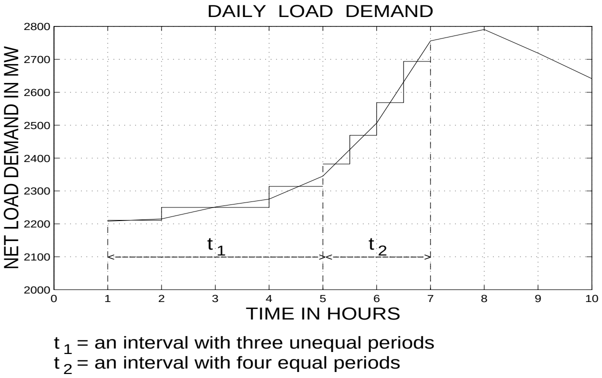

Figure 2: The selection of intervals and periods

Another method for running ORPF with less control action is also possible. In the second approach, the discrete and continuous controls can be set with different frequencies. The discrete controls can be adjusted only at the beginning of intervals, while the continuous controls can be set at the beginning of intervals and periods. In this method, discrete and continuous controls are adjusted at 1am and 5pm, while the continuous controls are also adjusted at 2am, 4am, 5:30am, 6am and 6:30am (Fig. 2). Strategy decision along these lines could be made as Company policy or left to the operator's discretion. The best way of finding the frequency of running ORPF is by studying the load profile of each day separately.

As a general rule, for high rate of load changes, ORPF should be run more often, and for flat load periods, ORPF should be executed less frequently. The appropriate cycle time can vary somehow between 15 minutes up to four hours. In cases where the cycle time is less than an hour, the procedure of separating the control variables into discrete and continuous sets as mentioned above can be followed.

4 The Number and Order of Control Adjustments

One of the important issues in the real-time execution of ORPF program is the number and order of control adjustments. The control variables can be divided into two main categories: 1) discrete controls (tap ratios, capacitor and reactor banks), and 2) continuous controls (generator var sources). Generally, the var adjustment of generators does not include any costs, however, the switching action of discrete controls can cause wear and shorten the life of the corresponding equipment.

The number of control adjustments in each run is important for three reasons:

1. The amount of adjustments must not cause excessive operator workload.
2. The control adjustments should be possible executable in a reasonable amount of time.
3. The discrete controls should not switched too frequently.

For these reasons, the number of control adjustments and the participation of different control types in each run of the ORPF program has been studied. Generally, all the generator vars may be adjusted after each run of ORPF, and they are adjusted to the optimal values in the extent which is possible. The discrete controls are adjusted with a different policy, and are considered below.

NB Power network has around 50 LTC transformers. Transformer taps are accounted as discrete controls. These controls, as mentioned in Section 3, may not be adjusted on all of the ORPF runs. If the cycling time of ORPF is too short (15/30 minutes), the operator may not have enough time to adjust all the controls. In these cases, the ORPF program can be executed by only using the continuous controls. The other discrete controls are switched shunts with the total number of 35 including capacitor and reactor banks. These controls may or may not participate in optimization, with a similar policy to tap ratios.

After finding the optimal solution, the difficult task is to execute the adjustments recommended by the program. The adjustment of control variables can be performed with different strategies, such as:

1. Adjustment by the order of control variable type; e.g., first adjust switched shunts, then generators and finally transformer taps.
2. Adjustment by the order of area and substation; e.g., pick up one area, and do the adjustments in that area by selecting one substation at a time.
3. A combination of item 1 and 2.

The third method seems to perform most efficiently. A detailed procedure for doing the adjustment according to this method is described below:

step 1 - The adjustment of control variables starts with the switched shunts. They are adjusted one by one if no violations observed. If all the switched shunts are adjusted without any bus voltage violation, the adjustments continues by skipping to step 3. In case of any bus voltage violation, the switched shunt adjustments are stopped, and the procedure in step 2 will be followed.

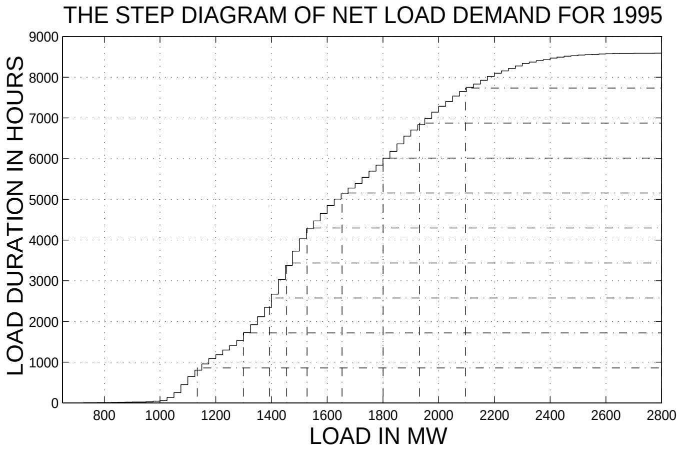

Figure 3: The procedure for finding the representative loading conditions from step diagram

Step 2 - After finding the closest transformers and/or generators to the violated bus voltage, their recommended adjustment by the program will be performed. In most cases, after one or two adjustments the bus voltage violation will be removed, and the order of adjustment continues by returning to step 1.

Step 3 - In this step, all the generator vars are adjusted. If no bus voltage violations are observed, the generators are moved to the optimal values one by one. If any bus voltage violation is predicted during the adjustment of one control, some correcting actions should be devised. The problem can be solved by the procedure explained in step 4, or by limiting the movement of the related control.

Step 4 - The closest transformers to the violated bus voltages are found. The tap ratios of these transformers are moved to the optimal values recommended by the program to remove the probable violations. After removing the violations, the remaining adjustments of step 3 continue.

Step 5 - In this step, all the switched shunts and generators are previously adjusted, and only the tap ratios should be adjusted. In this stage, all the transformer tap ratios are moved to the optimal values recommended by the program if no violation occurs. In case of probable voltage violations, the control action can be performed partially.

The effects of real-time implementation of ORPF on the NB Power network including the changes on voltage profile, the total dollar saving during a one-year interval are discussed in the following section.

5 Study Results

The effects of on-line ORPF on the NB Power network have been studied for the load conditions of a

Table 1: The representative loading conditions which found from Figure 3.

Case No.	1	2	3	4	5	6	7	8	9	10	11
Load Level (in MW)	675	1134	1299	1393	1454	1528	1653	1801	1932	2096	2800

whole year. The load data is related to the hourly net load history of the year 1995. These data include 8760 (365*24) load points. As is apparent, the simulation of all the loading levels is very time consuming and tedious. For this reason, by using statistical analysis, a representative set of loading conditions are selected. The representative set of loads can be studied yielding accurate results.

The representative loading conditions are chosen by using the step diagram. The procedure for finding these points is shown in Figure 3. The loading levels found from this method are given in Table 1. Note that each level is approximately representative of 9% of the load distribution. The average in power loss saving for all these cases gives an acceptable value for the average yearly saving in power loss.

5.1 ORPF Studies for the Selected Representative Loading Conditions

In this section, the representative loading conditions are used for ORPF benefit study purposes. Network data for each loading condition are obtained by getting a real-time snapshot from the NB Power system.

Two types of analysis can be done on the basis of these ORPF runs: the improvement in the voltage profile of NB Power network, and the reduction in power loss. The improvement in voltage profile can be obtained by comparing the bus voltage violations of the actual operating condition with those of the optimal state. For each load level, by subtracting the power loss of the actual and optimal conditions, the saving can be found. The arithmetic mean of these savings gives an acceptable value for the yearly average saving of the power loss for the NB Power network.

5.2 Calculation of the Yearly Average Saving for the NB Power Network

The loading conditions found from snapshots are studied for power loss minimization purposes. The results of ORPF studies for these load levels are shown in Table 2. The actual loading conditions, which are used for simulation studies, are given in the second column of Table 2. The power loss for these loading conditions is minimized. The power loss for each load level before and after running the ORPF program are given in the third and fourth columns of Table 2, respectively. The power loss saving for each loading condition is given in the fifth column of Table 2. For better visualization of these simulation results, some of the data are also shown in Figure 4. The power loss in MW and in percentage of total load versus the related load level are shown in Figures 4-a and 4-b, respectively. The saving in power loss in MW and in percentage of power loss are depicted in Figures 4-c and 4-d, respectively.

Table 2: The study results of ORPF program for the representative loading conditions, all the values of P_L are given in MW

Case No.	total net load	P_L before ORPF	P_L after ORPF	P_L saving
1	940.	27.9	25.0	2.9
2	1140.	39.8	37.1	2.7
3	1340.	52.7	49.0	3.7
4	1405.	78.1	73.4	4.7
5	1460.	58.3	54.1	4.2
6	1530.	58.7	54.9	3.8
7	1655.	75.1	70.5	4.6
8	1825.	94.2	88.9	5.3
9	1920.	119.2	113.5	5.7
10	2036.	88.3	83.0	5.3
11	2332.	110.9	104.1	6.8

The yearly average saving of power loss is equal to the arithmetic mean of power loss savings given in Table 2. This average value will be equal to:

$$P_{avr}^{yearly} \approx 4.52 \quad \mathrm{MW}$$

The yearly average dollar saving can be calculated by the multiplication of yearly energy loss saving in MWH by \$25/MWH as:

$$4.52 * 8760 * 25 \approx \$\ 990,000.$$

Another impact of on-line ORPF on the NB Power network is its effect on voltage profile. The voltage profile can be considered as the bus voltage violations and/or the average level of bus voltages in the network. In most cases, the ORPF program comes to a solution within the bus voltage limits. The bus voltage profile obtained from the snapshot shows all the bus voltage violations before running the ORPF program. In several cases, the bus voltage violations up to ten buses were observed in real-time snapshot, and were removed by running the ORPF program.

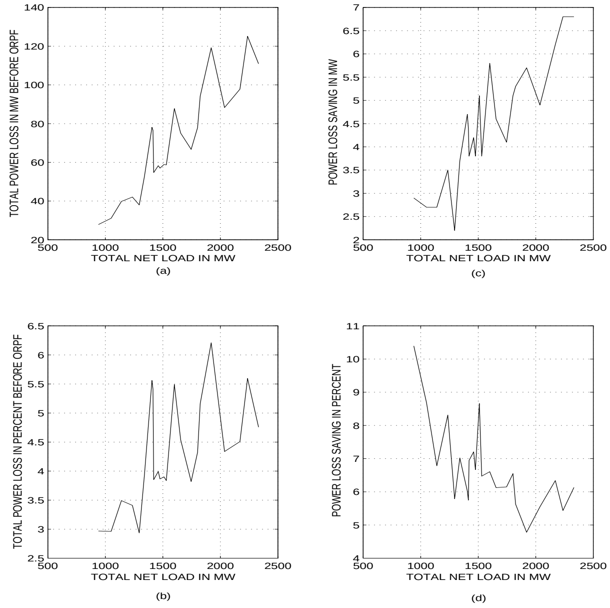

Figure 4: The power loss and its saving for loading conditions obtained from snapshots

6 Conclusion

Some of the important issues and the potential benefits of the real-time implementation of ORPF for the NB Power network have been demonstrated. Some basic considerations for the selection of ORPF cycling time, the activated control variables, and the order of optimal adjustment of controls are addressed. For cost benefit calculation, the loading conditions of the whole year of 1995 were studied. By using statistical analysis, several representative loading conditions were selected. The ORPF program was executed for all these loading levels. The study results of these representative loading conditions can be generalized to the whole year with good accuracy.

From the study and implementation results, two main points are justified: 1) a significant savings in active power loss can be achieved, and 2) the voltage profiles and stability of the NB power network can be improved. The total ideal saving for year 1995 predicted in study was in excess of $ 900,000. These savings can be gained simultaneously with the improvement of the voltage profiles. In other words, by running the ORPF program and adjusting the network accordingly, not only will the power loss be decreased, but bus voltage violations will also be removed. This leads to a more economical operating condition, and at the same time to a more secure system from the voltage point of view. Finally, we would like to acknowledge that real power loss savings achievable by a practical implementation of ORPF may be less than the idealized results presented here. Operational and other constraints might reduce the savings substantially.

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