Optimal Reactive Power Dispatch in Real-Time

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Abstract: *The real-time application of optimal reactive power dispatch (ORPD) to the New Brunswick (NB) Power network is presented. The potential benefits of ORPD are discussed, and some important issues in real-time implementation of ORPD are also outlined, such as frequency of execution, the number of activated control variables, and the order of adjustment of different controls.*

The application of ORPD 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 result in fewer violations and a more stable system from the voltage point of view. A reduction in active power loss gained from ORPD 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 dispatch, power loss minimization, optimization methods

1 Introduction

Optimal power dispatch (OPD) is one of the major control issues in the 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 dispatch (ORPD) problem is considered independently [2], and in some others it is combined with MW dispatch [3]. However, in most real-time applications, ORPD has run independent of MW dispatch. The main objectives of ORPD 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 include the vars and voltages of the generators, the transformer tap ratios, and reactive power generation of var sources (switched shunts). 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 ORPD, 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 ORPD should be executed continuously, or at least very often. However, due to application and implementation difficulties, ORPD 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 ORPD implementation is addressed in this paper. The participation of different controls in each run of ORPD, and the order of optimal adjustments are also considered. Finally, the potential benefits of real-time implementation of ORPD 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.

Sections 2, 3, and 4 address real-time implementation issues, the frequency of ORPD execution, and the order of adjustment of control variables, respectively. In Section 5, the conditions of the cost benefit study are discussed, and simulation results are presented in Section 6. Concluding remarks are provided in Section 7.

2 Real-Time Implementation of ORPD for NB Power Network

The NB Power ORPD 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 Estimator (SE). For on-line execution of ORPD, the SE output should prepare appropriate input data for the ORPD program.

The connection between on-line data and the SE and ORPD 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 Estimator program uses the network data to calculate the necessary input data for the ORPD program. By running ORPD, 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 control settings on the network, the system moves to the optimal operating condition.

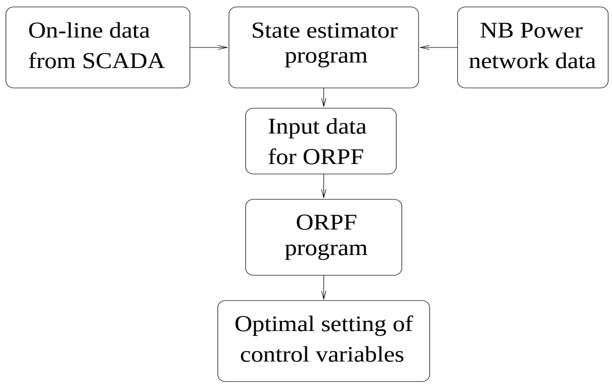

Figure 1: The connection between SCADA, SE, and ORPD programs

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

3 Frequency of Running ORPD

An important aspect in running the ORPD 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.

The daily load profile should be considered for finding the appropriate frequency of running ORPD. The daily load profile of one day in January between 1am and 10am is shown in Fig. 2. During times which the load changes rapidly, ORPD should be executed with a higher frequency. For example, between 5am to 8am the load has the highest rate of change, and ORPD should be run more often. However, during 2am to 4am the load is almost flat and one ORPD run could be enough. To be more specific, in Fig. 2 two time intervals between 1am to 5am and 5am to 7am are defined. Each interval is divided into several periods. The interval t_1 between 1am to 5am is divided into 3 periods of 1- and 2-hour duration; due to small load changes in these periods, one ORPD run per period is sufficient. During t_2, 4 periods of 30-minute duration are selected so that one ORPD run per period is again adequate for following the more rapid load changes.

Another strategy for running ORPD requires even less

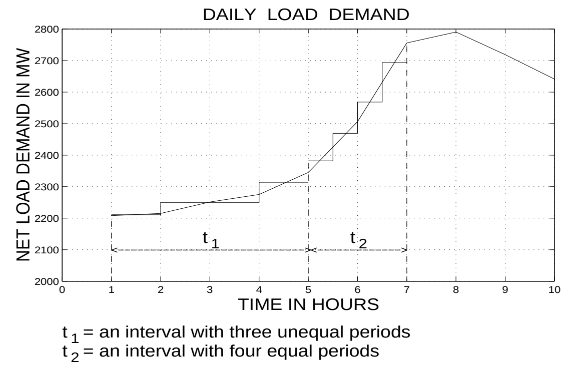

Figure 2: The selection of intervals and periods

control activity. In this second approach, discrete and continuous controls are changed at different frequencies. The discrete controls can be adjusted only at the beginning of intervals, while the continuous controls can be adjusted 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). This scheme reduces the operator workload and the depreciation of equipment. Strategy decisions along these lines can be made as Company policy or left to the operator's discretion. The best way of finding the frequency of running ORPD is by studying the load profile of each day separately. For giving some general considerations, an average daily load demand for month of January is calculated, and studied in the next section.

As a general rule, for high rate of load changes, ORPD should be run more often, and for flat load periods, ORPD should be executed less frequently. The cycle time which is proposed in the following section varies 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 and in Section 3.1 can be followed.

3.1 Frequency of Running ORPD in Month of January

The profile for average daily load in January shown in Fig. 3 is considered in this section. The load level during 1am to 6am is almost flat with of an approximate value of 1700 MW. This small variation of load does not necessitate more than one ORPD run. Thus, by running ORPD program around 1am no later adjustment is necessary, unless some unexpected load changes happen.

The morning load pick up and evening drop off has a similar rate of load changes. From 6am to 9am load has a substantial increase from 1700 to 2100 MW, and from 10pm to 1am the load has a big drop of 300 MW. To keep the system in a nearly optimal state during these intervals, more frequent runs of ORPD are necessary. A cycle of 15 to 20 minutes can keep the system close to optimal conditions during these intervals. It is also possible that the discrete and continuous control variables be adjusted with different frequencies during each interval. The discrete variables can be set with a cycle of one to one and a half hour, while the continuous variables can be adjusted with a cycle of 15 minutes.

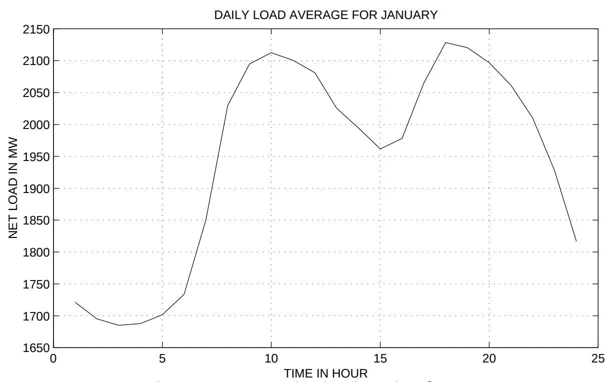

Figure 3: The average daily load of January 1995

From 9am up to 12pm, the load has a value around 2100 MW. In this situation, two runs of ORPD at 9am and 11:30am should keep the system in optimal condition. In these cases, if the forecast load has an almost flat value, it is better to avoid any changes of control variables, because some small fluctuation in the actual load may cause recurrent adjustments of control variables.

Between 12pm and 1:30pm, 4pm and 6pm, 8pm and 10pm; there is a load change of 100 MW. A cycle of 30 minutes is an appropriate value for running ORPD in these intervals due to small load changes. From 1:30pm up to 4pm, the load does not change substantially, and it only has a fluctuation less than 50 MW. One run of ORPD would be enough for keeping the system in optimal condition. Between 6pm and 8pm there is only a small reduction of 30 to 40 MW. With this small amount of load change only one run of ORPD would suffice.

4 The Number and Order of Control Adjustments

One of the important issues in the real-time execution of ORPD 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 ORPD program has been studied. Generally, all the generator vars may be adjusted after each run of ORPD, and they will be 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 3.1, may not be adjusted on all of the ORPD runs. If the cycling time of ORPD is too short (15/30 minutes), the operator may not have enough time to adjust all the controls. In these cases, the ORPD 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 are observed. If all the switched shunts are adjusted without any bus voltage violation, adjustments continue by skipping to step 3. If any bus voltage violation occurs, the switched shunt adjustments are stopped, and the procedure in step 2 is followed.

Step 2 - After finding the closest transformers and/or generators to the violated bus voltage, their recommended ORPD adjustments are 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 corrective action 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 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 voltage violations, the control action can be performed partially.

The effects of real-time implementation of ORPD 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 sections.

5 Study Period

The effects of on-line ORPD for the NB Power network has been studied for the load conditions of a 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. Each load level has a duration of one hour. For totally accurate study of the yearly average savings, all these cases should be studied. As is apparent, the simulation of all the loading levels is very time consuming and tedious. By using statistical sampling methods, a representative set of cases can be studied yielding accurate results. The representative loading conditions are selected by using the statistical analysis of the yearly load profile as given in the next section. For each case, by running the ORPD program the saving in power loss can be found, and the results are generalized for the whole year. This saving can be easily transformed to energy saving, and then dollar saving can be obtained by multiplying by the price of electric energy ($/MWH).

5.1 The Selection of Representative Loading Conditions

The representative loading conditions are selected on the basis of a step diagram related to class-interval of 25 MW (see Appendix A). The procedure for finding these points is shown in Figure 4, and explained below:

1. The ordinate axis between zero and the maximum load duration time are divided into N equal sections ($N = 10$). By drawing horizontal line at these points, totally eleven points on the step diagram will be found.
2. The points which are found on the step diagram are projected on the abscissa axis. Eleven equivalent points will be found on this axis. Two of these points are related to minimum and maximum loads, and the other points pertain to the light to heavy load conditions. These points constitute the representative loading conditions, and will be used for power loss minimization purposes.

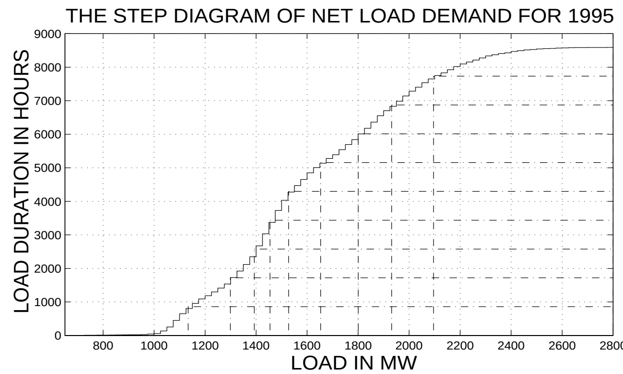

Figure 4: The procedure for finding the representative loading conditions from step diagram

The loading levels found from the above 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.

6 Study Results

6.1 ORPD Studies for the Selected Representative Loading Conditions

In this section, the loading conditions which are selected in Section 5 are used for ORPD benefit study purposes. Network data for each loading condition are obtained by getting a snapshot from the real-time situation of the NB Power system. The procedure for power loss minimization for each load level is as follows:

1. A loading condition which is close enough to a representative loading condition (Table 1) is obtained by getting a snapshot in real-time.
2. The power loss and the load flow data for the operating condition are saved for later comparison.
3. The ORPD program is executed. The output of the program gives the optimal operating condition including the power loss, the voltage profile of buses, the settings of different control variables, and probable constraints violations.

Two types of analysis can be done on the basis of these ORPD 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 saving values will give an acceptable value for the yearly average saving in the power loss of NB Power network.

Table 1: The representative loading conditions which found from Figure 4 for $N = 10$.

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

6.2 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 ORPD 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, via the procedure mentioned in the previous section, is minimized. The power loss for each load level before and after running the ORPD 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 5. The power loss in MW and in percentage of total load versus the related load level are shown in Figures 5-a and 5-b, respectively. The saving in power loss in MW and in percentage of power loss are depicted in Figures 5-c and 5-d, respectively.

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

Case No.	total net load	P_L before ORPD	P_L after ORPD	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:

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

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

$$4.52 \times 8760 \times 25 \approx \$\ 990,000$$

Another impact of on-line ORPD 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 ORPD 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 ORPD program. In general, these violations will be removed after running the ORPD program. In several cases, the bus voltage violations up to ten buses were observed in real-time snapshot, and were removed by running the ORPD program. Another issue in the comparison of bus voltages before and after running ORPD program is the voltage level of the buses. The change of all bus voltages due to ORPD can be presented by their average value. In one studied case, the average value of voltage profile of the network is increased by 2.2% after running the ORPD program.

7 Conclusion

Some of the important issues and the potential benefits of the real-time implementation of ORPD for the NB Power network have been demonstrated. Some basic considerations for the selection of ORPD 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 ORPD 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 ORPD 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

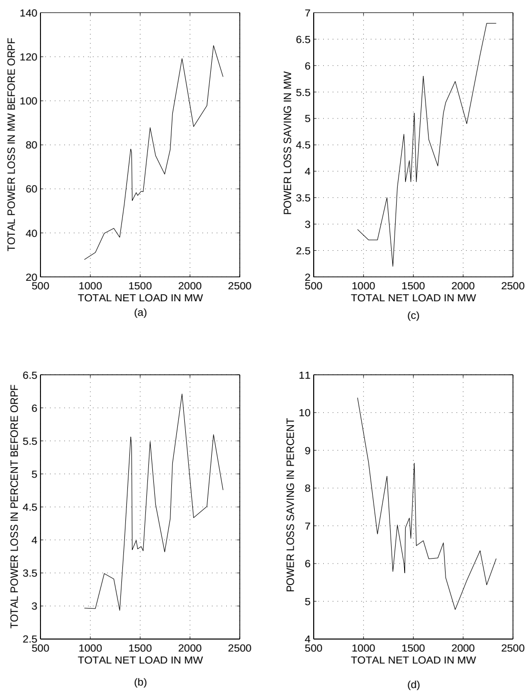

Figure 5: The power loss and its saving for loading conditions obtained from snapshots

acknowledge that real power loss savings achievable by a practical implementation of ORPD may be less than the idealized results presented here. Operational and other constraints might reduce the savings substantially.

8 Acknowledgment

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A Basic Definitions for Statistical Study

Load Data Frequency Distribution – The load data frequency distribution specifies the duration of each load level in hours. These distributions can be represented in tabular or graphical form.
Class-interval – For any type of statistical study, it is meaningful to classify the load range into several classes. Each class covers a specific range of loading conditions. The difference between the upper and the lower load levels of each class is called the *class-interval*. The duration time of each class is equal to the total number of loading conditions which lie in that class.
Histogram – A graph which represents the class-intervals on the x-axis and the duration of each class on the y-axis is called *histogram*.
Step diagram – The duration of load levels which are at or less than a given value, rather than the duration of each specific load level is presented by step diagram (see Figure 4). Step diagrams are directly constructed from histograms.