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Badrul H. Chowdhury
Missouri University of Science and Technology, bchow@mst.edu

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A RULE-BASED DYNAMIC ECONOMIC DISPATCH FOR POWER SYSTEMS

Badrul H. Chowdhury

Electrical Engineering Department, University of Wyoming
Laramie, WY 82071

ABSTRACT

Among the major economy security functions in power systems operation, economic dispatch ranks among the highest. The development and implementation of a new approach to economic dispatch is presented. A dynamic rule-based dispatch algorithm is introduced which aids the decision making process in a control center. With more and more utilities interested in non-conventional generation sources like, photovoltaic and wind generation systems, this algorithm can prove to be very helpful to the dispatcher.

INTRODUCTION

Among the major economy security function in power systems operation, economic dispatch (ED) ranks among the highest. It is defined as the process of allocating generation levels to the generating units in the mix, so that the system load may be supplied most economically under several recognized constraints imposed by the requirement of reliable service and equipment limitations. One of the earliest methods adopted for economic dispatch was the "base load" procedure [1], whereby limits are successively loaded to their lowest heat rate point beginning with the most efficient unit. The idea was that the next increment in the load should be picked up by the unit with the lowest incremental cost. Losses were added later in the formulation and solution of the dispatch problem. The classic coordination equations were discovered in 1951. These results form the backbone of today's economy operation methodology. This paper presents the development and implementation of a new approach to ED -- a dynamic rule-based (RB) dispatch algorithm.

Background

Through the years, economic dispatch has evolved from the conventional implementations which use the integro-proportional controls derived from servo-mechanism theory to modern proposals employing optimal power flow techniques. An excellent work by the IEEE Working Group 71-2 on operating economics provides a three part series on existing literature on economy-security functions, published between the years 1959 and 1972 [2] and between the years 1973 and 1979 [3]. Judging from the literature, a number of sub-areas may be identified within economic dispatch among which the most important ones are:

- Application of improved methodologies to economic dispatch.
- Automatic generation control.
- Security-constrained dispatch.
- Optimal dispatch.
- Dynamic dispatch.
- Economic dispatch with non-conventional sources.

The new techniques reported in the literature range from improved mathematical techniques to more efficient problem formulation. Among the mathematical techniques, some of the more important ones are the following:

i) Transportation method,
ii) Successive minimum cost flow technique,
iii) Reduced Hessian-based technique,
iv) Modern mathematical optimization methods such as sequential, quadratic, linear, non-linear, integer and dynamic programming techniques,
v) Constraint relaxation techniques,
vi) Network approach.

Dommel and Tinney [4] were among the first to work with optimal power flow equations. Their method uses Lagrangian multipliers to append the equality constraints to the objective function, which includes penalties for functional inequality constraint violations. More recently Lee, et al. [5] describe the application of the Minty algorithm to economic dispatch. The authors use the Fulkerson minimum cost flow method formulated in a linear form. This algorithm, reportedly gives comparable results to those obtained from the method using penalty factors [4] and is faster than the latter. Some algorithms making use of low storage techniques are discussed by Bottero, et al. [6] and Roy, et al. [7].

The Optimal Load Flow (OLF) problem has always been an extensively researched topic. Contaxis, et al. [8] decompose the OLF problem into real and reactive subproblems and the two subproblems are solved alternately by a transformation into quadratic programming problems through the use of Generalized Generation Distribution Factors. Romano, et al. [9] propose an economic dispatch algorithm suitable for on-

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line application. The method exploits the advantages associated with the decomposition and decoupling scheme, and is reported to be fast. Viviani, et al. [10] incorporate the effects of uncertain parameters into optimal power dispatch by employing the multivariate Gram-Charlier series as a means of modeling the probability density function characterizing the uncertain parameters. Talukdar, et al. [11] apply a dimension reduction procedure to the Han-Powell algorithm for solving optimal power dispatch problems. Techniques such as, network dissection and parallel processing are used for the objective.

Recently, increasingly more research is being conducted in the area of integrating non-conventional sources of generation into the operation of the power system. Zaininger, et al. [12] present results of a dynamic study of minute-to-minute ramping, frequency excursions and short-term transient stability of a power system containing wind power generations. The authors determine the allowable combined wind turbine (WT) cluster change corresponding to a 0.1 Hz and 0.4 Hz frequency excursion. Similar study is also presented by Curtice, et al. [13] and Simburger, et al. [14].

PROPOSED RULE-BASED SYSTEM APPROACH

Dispatchers (operators) have to make decisions regularly when they operate and control the power system. Even in the absence of unusual and emergency situations, many of the decisions are non-trivial in their nature. Therefore, a successful operation depends on the ability of the dispatcher to interpret information and to execute proper control orders. Today, the work of the system operator is eased in many ways, for example, a computerized control system can improve the interpretation of the vast amount of data which are transmitted and collected in control centers. Application functions of various types also contribute to helping the dispatcher in the decision making process, but the requirement is that he must have the expertise or experience to use them.

An economic dispatch program is run at every 3-10 minute interval. The dispatcher has to work from the hourly committed dispatch units and use standard procedures to allocate generation levels, maintain the right amount of regulating capacity, maintain the system frequency, maintain the area control error (ACE) at zero, bring up fast-start units like peaking hydro or gas turbines in case of emergencies, etc. Inclusion of renewable technologies, like solar or wind generations in the mix, adds more problems to the dispatch scheme because of the intermittent nature of the technologies.

It is conceivable to represent the knowledge of the dispatcher as a rule-based computer algorithm. The decision-making process of the dispatcher renders itself perfectly to sets of if-then rule structures for use by a rule-based system. This RB approach to economic dispatch becomes almost a necessity, when the dispatch algorithm has to deal with intermittent generations.

A rule base will be defined as an intelligent combination of procedures that uses knowledge and inference techniques of the human expert to solve problems in an algorithmic manner. In narrow problem domains, the rule base can provide high performance, equalling or even exceeding that of human individual experts. In the proposed dynamic economic dispatch incorporating PV, a rule base is introduced to operate either by itself or in tandem with a conventional economic dispatch algorithm. The functions of the two are coordinated by another algorithm which supervises the flow of information and records them. This functional relationship between the three computer program modules are shown in Figure 1.

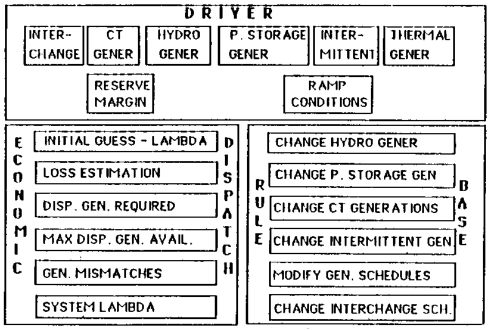

Figure 1. Functions of the three program module.

The operations of the economic dispatch and the rule base are coordinated by the module called DRIVER. The module makes sure that there is enough reserve margin as required by the system. It computes the contributions from all non-committable sources (like, CT, hydro, etc.), computes artificial minimum and maximum limits dictated by response rates of thermal units and passes the information to the ECONOMIC-DISPATCH module. The DRIVER then, receives back information on the mismatches between the possible dispatchable generation under the constraints, and that required by the system. This is then passed on to the RULE-BASE module which makes the necessary decisions to correct the situation. The RB at this stage communicates directly with the ED module. At this time, it is worthwhile to examine the nature of the problems faced by the generation sources when the rate of change of the net load exceeds that of the system generation.

In a generation system which consists of a combination of conventional and non-conventional generation sources, the net load is equivalent to the actual load demand, less the total generation from these non-conventional sources. Considering a full complement of non-conventional generation sources, the fundamental constraint of load allocation becomes:

"At any time t, expected power generation required from the thermal generators must equal expected load at time t plus the losses at time t minus the sum of generation from non-conventional sources minus the interchange OR

$$G_t-G_{t-1} = (D_t-D_{t-1}) + (L_t-L_{t-1}) - ((C_t-C_{t-1}) + (H_t-H_{t-1}) + (IM_t-IM_{t-1}) + (PSH_t-PSH_{t-1})) - (IC_t-IC_{t-1}) \quad (1)$$

where

G_t = the total thermal generation at time t
D_t = the total demand at time t
L_t = the total transmission losses at time t
C_t = the total combustion turbine generation at time t
H_t = the total hydro generation at time t
PSH_t = the total pumped-storage hydro generation at time t
IM_t = the total intermittent generation at time t
IC_t = the total interconnected power flow at time t

Normally, differences in losses and other load-generation mismatches in the absence of non-conventional sources like the intermittent generators and hydro units, are easily picked up by cycling (load following) units and the system maintains a matched load condition. An exception to this case occurs when either the load unexpectedly changes more drastically than anticipated within a specified period or one or more of the generators experiences an unexpected outage. Alternative to the special case is the presence of a number of non-conventional generation choices, particularly intermittent sources like photovoltaic plants and wind generating plants. Large minute-to-minute variations in these intermittent generations can cause the thermal plants to reach their response limits before load matching constraint is met. Also, hydrothermal unit generations depend on the flow of water and is therefore also a source of random input into the system generation. Thus, in general, two conditions might arise:

1. Thermal generation increase not possible in the dispatch interval.

This situation may arise because of a sudden net increase in load because of a drop in the output from non-conventional sources, causing the thermal generators to attempt to make up the loss. Using the up-ramp response constraint of each cycling thermal unit, the total system response capability (regulating capacity) in the "up" direction should be greater than or equal to the change in generation required of the units. Mathematically,

$$\frac{1}{100} \sum_i \Delta T \, \gamma_{ri} P_{it-1} \geq \Delta G_t \quad (2)$$

where

ΔT = dispatch interval
P_{it-1} = MW output of unit i at interval t-1
γ_{ri} = response rate of unit i in the raise direction (%/min).

Violation of equation (1) implies corrective action has to be taken to reach optimality.

2. Thermal generation decrease not possible in the dispatch interval.

This situation is brought about when there is a sudden increase of the net load because of an unexpected increase in the output from non-conventional sources. The thermal generators are expected to back-off part of their generations (unload) in order to accommodate the additional power generations from the non-conventional sources. Once again, the response rate of the thermal generators plays an important role, this time in the "lower" direction. According to the down-response rate of each unit, the total system response capacity in the lower direction should be greater than or equal to the change in generations required from the generators. Mathematically,

$$\frac{1}{100} \sum_i \Delta T \, \gamma_{li} P_{it-1} \geq \Delta G_t \quad (3)$$

where

γ_{li} = response rate of unit i in the lower direction (%/min).

Violation of equation (3), once again implies corrective action has to be taken by the dispatcher.

Such corrective actions are channeled into "rules" or "if-then" logic structures and incorporated in a rule base. The rule-base then assists the dispatcher in making decisions regarding system operation.

Rules in the Rule Base

Problems in operation require immediate corrective actions so that the system may be brought back to an optimal state. The following set of rules are considered for the rule-base:

RULE-SET 1. If the thermal units are unable to pick up the increased net demand of the system, and if the intermittent generation sources were operating below their rated capacity in the preceding interval of the dispatch, then increase the intermittent generation.

RULE-SET 2. If the thermal units are unable to pick up the increased net demand of the system, and if RULE-SET 1 is not satisfied, then increase the hydrothermal generation.

RULE-SET 3. If the thermal units are unable to pick up the increased net demand of the system, and if RULE-SET 2 is not satisfied, then increase pumped-storage hydro-generation.

RULE-SET 4. If the thermal units are unable to pick up the increased net demand of the system and if RULE-SET 3 is not satisfied, then increase total combustion turbine generation.

RULE-SET 5. If the thermal units are unable to pick up the increased net demand of the system, and RULE-SET 4 is not satisfied, then start-up unscheduled hydro unit(s).

RULE-SET 6. If the thermal units are unable to pick up the increased net demand of the system, and if RULE-SET 5 is not satisfied, then start-up unscheduled pumped storage unit(s).

RULE-SET 7. If the thermal units are unable to pick up the increased net demand of the system, and if RULE-SET 6 is not satisfied, then start-up unscheduled CT unit(s).

RULE-SET 8. If the thermal units are unable to pick up the increased net demand of the system, and if RULE-SET 7 is not satisfied, then buy unscheduled interconnected power.

RULE-SET 9. If the thermal units are unable to unload the extra generation because of a decrease in net system demand, then decrease CT generation.

RULE-SET 10. If the thermal units are unable to unload the extra generation because of a decrease in net system demand and if RULE-SET 9 is not satisfied, then decrease pumped storage hydro generation.

RULE-SET 11. If the thermal units are unable to unload the extra generation because of a decrease in net system demand the if RULE-SET 10 is not satisfied, then decrease hydro generation.

RULE-SET 12. If the thermal units are unable to unload the extra generation because of a decrease in net system demand and if RULE-SET 11 is not satisfied, then shut down scheduled CT unit(s).

RULE-SET 13. If the thermal units are unable to unload the extra generation because of a decrease in net system demand and if RULE-SET 12 is not satisfied, then shut down scheduled pumped storage hydro unit(s).

RULE-SET 14. If the thermal units are unable to unload the extra generation because of a decrease in net system demand and if RULE-SET 13 is not satisfied, then shut down scheduled hydro unit(s).

RULE-SET 15. If the thermal units are unable to unload the extra generation because of a decrease in net system demand and if RULE-SET 14 is not satisfied, then decrease tie-line interchange flow.

RULE-SET 16. If the thermal units are unable to unload the extra generation because of a decrease in net system demand and if RULE-SET 15 is not satisfied, then decrease total intermittent generation.

The set of rules 1 through 8 are valid for the situation when there is a significant reduction in the non-conventional generations causing the thermal generators to attempt to pick up generation. Response limitations of thermal units therefore require other measures to be taken. Rule-set 1 receives the highest priority as logical reasoning dictates that intermittent generations ought to be optimally utilized. Therefore, it will be the purpose of the RB to supervise the presence of maximum possible generations from intermittent sources which is the most favorable scenario from the production costs point of view.

Rule-set 2 through 4 are similar although concerning different unit types. Rule-set 5 through 8 are apparently violations of the optimal solution given by the unit commitment program. There is nothing so alarming about this violation. The only concern under this action, that of departure from optimality, is quite unwarranted, because the system is already in a sub-optimal state considering the fact that the thermal units are not able to follow the economic trajectory. The only legitimate concern under this situation should be that starting up unscheduled units may violate some constraints, e.g., minimum up-time or minimum down-time requirements. The rules to be established are therefore quired to examine these constraints before starting unscheduled units. As for start-up time itself, the units to be considered by the RB for start-up are fast-start units, like peaking hydro, pumped storage hydro and combustion turbines, which need little warm-up time. Figure 2 shows the logic for rule-set 5. For avoiding repetition of similar characteristics, other rule-sets are not shown. The logic for these sets of rules is centered on locating the optimal capacity unit which matches the generation increment requirement INC_AMOUNT. If that is not possible, multiple units are searched for, whose combined capacity adds up to the variable INC_AMOUNT. A sub-program called PRIORITY locates these units and "pushes" these units into a "stack", with the highest priority unit residing at the top of the stack. A sequential "pop" operation then brings out these units from the "stack".

CONCLUSIONS

The paper introduces a new operation tool for economic dispatch. It deals with the development and implementation of a new approach -- a dynamic rule-based dispatch algorithm which takes into account the major problems faced by the dispatch operator during a dispatch interval and channels

```
Comment Check to see if a hydro plant is present in the generation mix.
If (NUM_HYDRO = 0) then
    begin
    Comment No hydro plant is present. Therefore, set flag to false
            and go to rule 6.
    FLAG2 := false;
    end
else
    begin
    Comment Hydro plant is present in the mix. Search for units which are down.
            If found, locate the unit with a capacity which matches the MW amount
            of increase required by the system.
    UNIT_FOUND := 0;
    NUM_LOOP := 1;
    N := NUM_HYDRO;
    While (N > 0) do
        begin
        If (UP_HYD_STATUS(NUM_LOOP) = 1) then
          begin
          Comment The hydro unit is up. Check the next one.
          NUM_LOOP := NUM_LOOP + 1;
          N := N - 1;
          end
        else
          begin
          Comment Check for up-time and down-time constraint violations.
          call UNIT_VIOLATE (NUM_LOOP, VIO_FLAG);
          If (VIO_FLAG = true) then
            begin
            Comment Constraint violated. Check next unit.
            NUM_LOOP := NUM_LOOP + 1
            N := N - 1;
            end
          else
            begin
            UNIT_FOUND := UNIT_FOUND + 1;
            CONTRIB (UNIT_FOUND) := MAX_CAP (NUM_LOOP);
            NUM_LOOP := NUM_LOOP + 1;
            N := N - 1;
            end
          endif
          end
        endif
        end
    end
endif
If (UNIT_FOUND = 0) then
    FLAG2 := false;
else
    begin
    Comment Prioritize the hydro units selected.
    call PRIORITY (CONTRIB, INC_AMOUNT, UNIT_ORDER)
    Comment The order of the selected hydro units according to descending order
            of capacity is stacked in the UNIT_ORDER stack. This stack is popped
            sequentially to schedule the units.
    TOTAL_CAP := 0;
    While (TOT_CAP < > INC_AMOUNT) do
        begin
        UNIT := pop (UNIT_ORDER);
        TOTAL_CAP := TOTAL_CAP + MAX_CAP (UNIT)
        Comment Upgrade status of the unit to "up" mode.
        STATUS (UNIT) := 1;
        end
    end
endif
```

Figure 2. Rule-Set Number 5.

those into a data base for use by a rule-based system. The algorithm is very fast and can be used effectively in interconnected systems. It can also handle renewable technologies and is therefore very useful for major utilities contemplating on adding a significant amount of these new generation sources to their existing mix.

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