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Unit Commitment Based On Frequency Regulating Reserve Constraint Using Dynamic Programming

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Abstract- **In dynamic programming-based power scheduling algorithms, thousands of hourly economic dispatches must be performed to consider every possible unit combination over all the stages of the optimization interval. The UC problem is formulated to minimize the total generation cost, while the load demand, reserve requirements, and unit constraints are satisfied. Among the UC constraints, an adequate provision of reserve is important to ensure the security of the power system and essential to bring the system back to acceptable level following the loss of a sizable online unit within seconds. If the unit commitment problem is constrained to observe a minimum system spinning reserve, frequency reserve constrained and an economic dispatch of a combination of units does not comply with this requirement, necessary and sufficient conditions have been established to guarantee that the dispatch of these units will meet the constraint. In this paper, we present necessary and sufficient conditions for the feasibility of unit combinations that can be checked off-line.**

Keywords: Frequency-regulating reserve, load-frequency sensitivity index, dynamic programming, and unit commitment.

NOMENCLATURE

The following are the list of symbols used throughout the paper.

C_i	the production cost of unit i
p_i^t	MW output of thermal unit at time step
y_i^t	Startup state of thermal unit at time step (binary)
z_i^t	Shutdown state of thermal unit at time step (binary)
$y_{c,i,j}^t$	Startup state of th configuration of combined-cycle unit at time step (binary).
$z_{c,i,j}^t$	Shutdown state of jth configuration of combined- cycle unit at time step (binary).
SSR	System spinning reserve
MSSR	Minimum system spinning reserve
X	number of states to each period
N	number of paths
F_{COST}(K,I)	least total cost to arrive at state (K,I)
P_{COST}(K,I)	production cost for state (K,I)

1. INTRODUCTION

Unit commitment is one of the decision-making levels in the hierarchy of power system operations management. The UC problem is generally categorized as a large-scale and highly nonlinear problem and is very difficult to solve in an accurate and efficient manner. The objective is to determine the set of generating units, among those owned by a utility that should be connected to the power grid on an hourly basis to supply the demand at minimum operating cost over the scheduling horizon. In this paper we present the off-line conditions that a unit combination must satisfy to not only meet the minimum system spinning reserve constraint, but also the power balance constraint, the unit capacity limits, and all the other pertinent constraints .If these conditions are not fulfilled by a unit combination, that combination can be discarded as unfeasible by the scheduling algorithm, thereby reducing drastically the number of decisions to be considered in the solution space. Among several system constraints, the reserve is a crucial requirement for maintaining system frequency within the normal limits without any load shedding when the system experiences a contingency. In [10], the thermal unit commitment problem has been traditionally solved in centralized power systems to determine when to start up or shut down thermal generating units and how to dispatch online generators to meet system demand and spinning reserve requirements while satisfying generation constraints (production limits, ramping limits, and minimum up and down times) over a specific short-term time span, so that the overall operation cost is minimized.

The definitions and classifications of reserves for electric utilities may be different, however, these reserves are typically classified according to the response time and they are deployed into primary, secondary, and tertiary reserves as mentioned in [8]. It is important for an isolated power system to avoid load shedding by providing sufficient frequency regulating reserve constraint following the loss of any online generation unit. For several decades, this large-scale, mixed-integer, combinatorial, and nonlinear programming problem has been an active research topic because of potential savings in operation costs. As a consequence, several solution techniques have been proposed such as heuristics, mixed-integer linear programming (MILP), Lagrangian relaxation, simulated annealing, and evolution-inspired approaches. Among the aforementioned methodologies, Lagrangian relaxation is the most widely used approach because of its capability of solving large-scale problems. The main disadvantage of this method is that, due to the no convexities of the unit commitment problem, heuristic procedures are needed to find feasible solutions, which may be suboptimal as defined in [10].

In this paper we present the Dynamic Programming algorithm for the conditions that a unit combination must satisfy to not only meet the minimum system spinning reserve constraint, but also the power balance constraint, the unit capacity limits, and all the other pertinent constraints as well. These conditions are shown to be necessary. We further show that these conditions turn out to be both necessary and sufficient when the spinning reserve constraint is to be met by re-dispatch. Clearly then, when these conditions are not fulfilled by a unit combination, that combination can be discarded as unfeasible by the scheduling algorithm, thereby reducing drastically the number of decisions to be considered in the solution space. The net result is a very efficient commitment algorithm as illustrated by examples. Furthermore, these feasibility conditions are independent of the problem formulation and thus can easily be implemented in other unit commitment algorithms. The advantages of proposed system are easy to implement, easy to maintain, we can develop many sub solutions, exhibits overlapping and easy to reuse.

Dynamic programming is considered an effective solution technique in power systems, not only because scheduling is naturally a sequential decision process, but also because formulation of the unit commitment problem results in a non-linear, non-convex, time dependent, and mix-integer problem. At each stage, economic dispatch is performed on every feasible unit combination to calculate its generation at equal fuel incremental costs. The optimal schedule is obtained by tracing the path linking the successive decisions that rendered the least total cumulative cost. Since transitional costs are time dependent, forward dynamic programming must be used. Because of its combinatorial nature, dynamic programming suffers from exponential increase of dimensionality which can prevent its applications in large-scale systems. Furthermore, these feasibility conditions are independent of the problem formulation and thus can easily be implemented in other unit commitment algorithms.

2. PROBLEM FORMULATION

The following section gives brief information about the problem formulation. The unit commitment problem formulation can be formulated by Objective Function and system Constraints. The objective function includes the operation cost of thermal units, combined-cycle units, the cost of power purchase, and the compensation cost of violating the number of limit associated with unit start-up and shutdown. The system constraints include power balance, unit capacity constraints and reserve constraints, in addition to this frequency regulating reserve constraint is also considered.

2.1. Objective Function

The objective function to be minimized in the UC problem includes the operation cost of thermal units, hybrid-cycle units, the power purchase cost, and the compensation cost of violating the number of limit associated with independent power producers, unit start up and shutdown. The objective function terms are represented in piecewise linear form which is given in equation (1):

$$\begin{aligned} F = {} & \sum_{t\in T}\sum_{i\in N}\left[f_i(p_i^t) + \left(y_i^t \times C_{u,i}\right) + \left(z_i^t \times C_{d,i}\right)\right] \\ & + \sum_{t\in T}\sum_{i\in N_c}\sum_{j=1}^{N_{T,i}}\left[cf_i\,(p_{c,i}^t) + (y_{c,i,j}^t \right. \\ & \left. \times CC_{u,i,j}) + (z_{c,i,j}^t \times CC_{d,i,j})\right] \\ & + \sum_{t\in T}\sum_{i\in N_p}\left(p_{ph,i} \times u_{ip,i}^t + \tilde{p}_{ip,i}^t\right) \\ & \times C_{ph,i} \\ & + \sum_{i\in N_p}\left(T_{yz,i} - N_{ss,i}\right) \times C_{m,i} \qquad (1) \end{aligned}$$

Where f_i and cf_i are fuel cost functions for the thermal and combined-cycle units, $C_{u,i}$,$C_{d,i}$,$CC_{u,i,j}$,$CC_{d,i,j}$ are unit start up and shutdown cost. $C_{ph,i}$,$C_{m,i}$ are the IPP power purchase and compensation costs. $P_{ph,i}$ is the minimum power purchase of IPP unit. $N_{ss,i}$ is the maximum number of startups/shutdowns of IPP unit. T is the set of scheduled time steps. N,N_c and N_p are the sets of thermal, combined-cycle, and IPP units. $N_{T,i}$ is the configuration number of the combined-cycle unit.

2.2. System Constraints

The optimization problem in unit commitment problem is subjected to the following constraints.

A. Power Balance Constraint

The sum of all unit power generation and purchase must meet the load demand at each time step and is given by (2)

$$\sum_{i\in N} p_i^t + \sum_{i\in N_c} p_{c,i}^t + \sum_{i\in N_p} p_{ip,i}^t + \sum_{k\in K_c}\sum_{i\in N_{p,k}} p_{s,i,k}^t = D^t, \forall t \in T \qquad (2)$$

Where K_r is the set of reservoirs. $N_{p,k}$ is the set of pumped storage units associated with reservoir.

B. Unit capacity constraints

The capacity constraints for each generating unit with its maximum and minimum limits are given in equation (3)

$$P_{i,MIN} \le p_{ik} \le P_{i,MAX} \ \ [MW] \ \forall\ i, \forall\ k \qquad (3)$$

C. Spinning Reserve Constraint

The spinning reserve constraint is represented using the maximum spinning reserve limit of the generating units which is given in (4)

$$SSR(j_k) \ge MSSR \ \ [MW] \ \ \forall\ k, \forall\ j \qquad (4)$$

Where

$$SSR(j_k) = \sum_{i\epsilon I_{ON}} \min(P_{i,MAX} - p_{i,k}, MSRi)$$

MSRi is the maximum spinning reserve for unit i, MSSR is the minimum system spinning reserve.

The state transfer or recursion function required to solve this optimization problem using dynamic programming is given by

$$\mathrm{C_{COST}(j_K)} = \min\left(C_{COST}(j_{k-1})\right) + T_{COST}(j_{k-1}, j_k) + P_{COST}(j_k) \qquad (5)$$

$$\forall \mathrm{j_{k-1}} \in \mathrm{J_{k-1,}j_k} \in \mathrm{J_k}, \mathrm{k} \in \mathrm{K}$$

Where C_{COST} is the cumulative cost associated with every state j_k, for all states j_{k-1}, subject to all the problem constraints. For instance, for a time horizon of M stages and N generating units, there are a total of (2N-1) M possible unit combinations that the dynamic programming algorithm must consider during the scheduling period. The exponential increase in the number of combinations can quickly result in huge computational time and memory requirements.

The transitional cost associated with the start-up and shut-down of each unit i in unit combination j_k relative to unit combination at previous stage j_{k-1} is given in equation (6)

$$\mathrm{P_{COST}(j_k)} = \sum_{i=1}^{N} \mathrm{C_i(p_{ik})d_{ik}} \qquad (6)$$

Then the optimization function of the unit commitment problem can be stated in (7)

$$\arg\min \mathrm{Z(J)} = \sum_{k=1}^{K} \mathrm{P_{COST}(j_k)} + \mathrm{T_{COST}}\left(\mathrm{j_{k-1},j_k}\right) \forall \mathrm{j_k} \in \mathrm{J_k}, \forall \mathrm{J_k} \in \mathrm{J} \qquad (7)$$

The optimization of the dynamic programming is given by

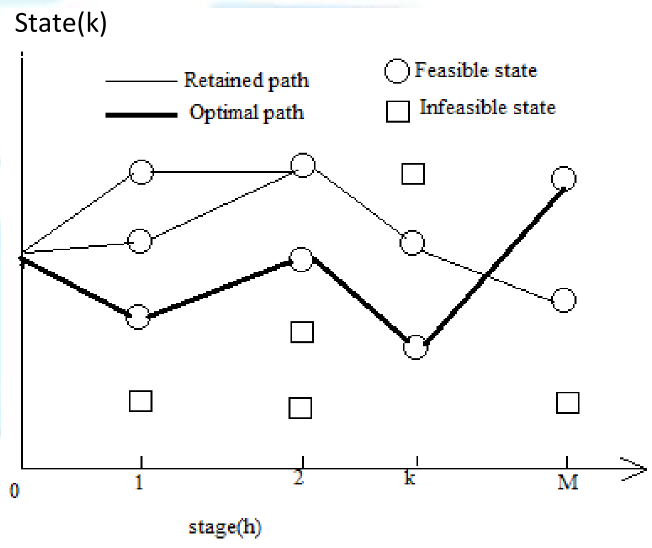

Fig 2.1 Dynamic programming optimization

The algorithm for the dynamic programming is given by

Step 1: start the program
Step 2: initialise the value of k=1
Step 3: calculate $F_{COST}(K,I)$ = MIN $[P_{COST}(K,I) + S_{COST}(K-1,L:K,I)]$ and repeat this for all states I in period K

Step 4: K=K+1
Step 5: calculate {L}="N" feasible state in interval k-1
Step 6: calculate F_{COST} = MIN [P_{COST}(K,I) +S_{COST}(K-1,L:K,I)+F_{COST}(K-1,L)] and repeat this for all states I in period K
Step 7: save N lowest cost strategies
Step 8: if K=M, last hour then go to step 9 else go to step 3
Step 9: trace optimal schedule
Step 10: stop

The flowchart for the dynamic programming is given by

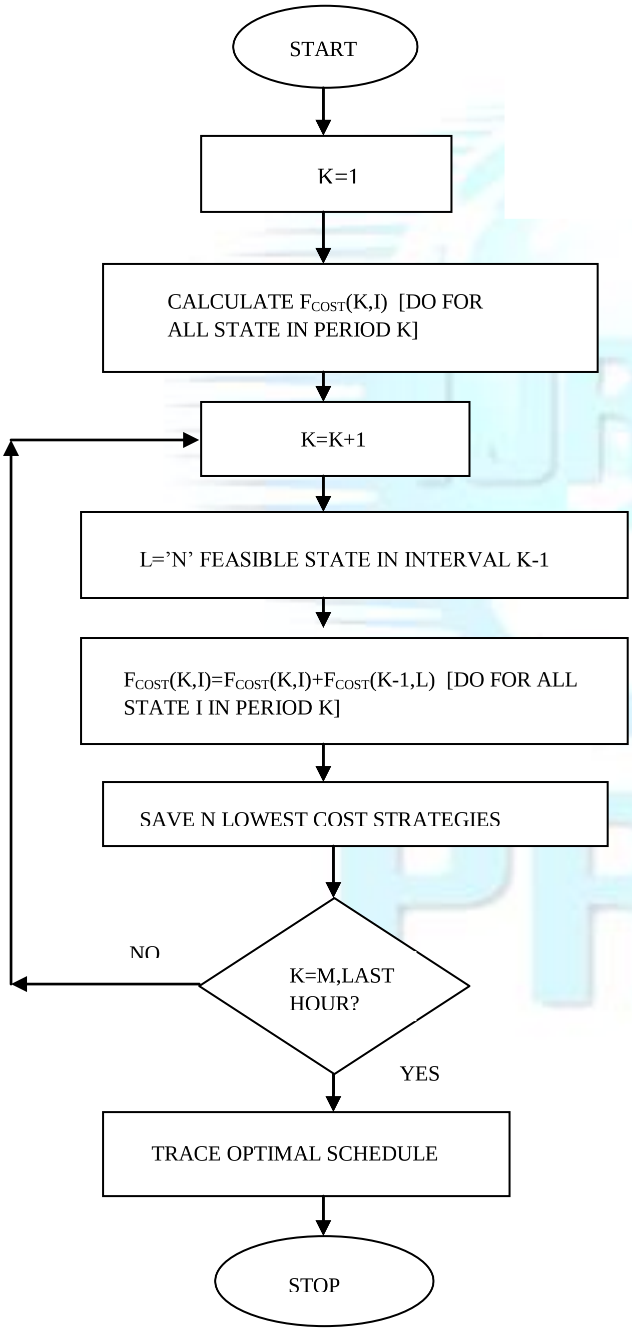

Fig (2.2) flowchart for dynamic programming

3. FEASIBILITY CONDITIONS

If constraints given are not met by a unit combination at a stage in the solution of the commitment problem, that unit combination is declared unfeasible and is no longer retained in the solution process. The fulfilment of these constraints may be tested after the economic dispatch of each unit combination is performed. Since economic dispatch is another optimization problem embedded in the unit commitment algorithm, and since for N units there are 2N-1 possible combinations at every stage k, then thousands of dispatches over the entire time horizon would need to be performed in the solution process just to discover that a great many of them were not feasible. Therefore, such a posterior test is very inefficient in terms of computer memory and time. Furthermore, an unfeasible unit combination, which meets constraints, may be rendered feasible by the re-dispatch of the units involved in that combination whenever certain feasibility conditions are satisfied. But these conditions can only be tested after a dispatch has been performed. A priori test for feasibility is performed off-line. That is, a test which eliminates those unit combinations that are guaranteed to be unfeasible before the start of the unit commitment algorithm, and thus before any dispatches are performed.

A unit combination whose on-line units form the set I_{ON} is said to be feasible when the solution of the economic dispatch problem satisfies constraints.

When a unit combination j_k contributes with a spinning reserve SSR(j_k) at stage k, the system spinning reserve margin is given by (8)

$$\Delta = MSSR - SSR(j_k) \qquad (8)$$

If $\Delta \leq 0$ the constraint is satisfied and re-dispatch is not needed. Conversely, if $\Delta > 0$, the constraint is violated and re-dispatch is required.

If a set I_{ON} is unfeasible by violating condition, it can still be rendered feasible by re-dispatch if and only if conditions are satisfied actually establish the bounds of the feasibility region in the system spinning reserve SSR(j_k) versus PD_k plane, which may be represented graphically as shown in Figure 2. The horizontal line bounding this region corresponds to the equation (9)

$$SSR(j_k) = SMSR = \sum_{i \epsilon I_{ON}} MSR_i \qquad (9)$$

The sloping line represents the reduction in system spinning reserve attainable by I_{ON} units as the load PD_k increased from the breakpoint defined as given in (10)

$$PB = \sum_{i \epsilon I_{ON}} P_{i,MAX} - \sum_{i \epsilon I_{ON}} MSR_i \qquad (10)$$

The highest possible load that these units can meet which is given in equation (11)

$$\mathrm{PH} = \sum_{i\epsilon I_{ON}} P_{i,MAX} - \mathrm{MSSR} \qquad (11)$$

which is the right side boundary of the feasibility region.

The left side boundary is given by (12)

$$\mathrm{PL} = \sum_{i\epsilon I_{ON}} P_{i,MIN} \qquad (12)$$

which represents the lowest load that must be delivered.

3. LOAD FREQUENCY SENSITIVITY INDEX

The LFSI at time step T, labelled by η^t can be calculated by using the recorded system frequency during actual contingencies.

The system frequency variation during a contingency is highly related to the system load characteristics and is difficult to measure. For simplification, the LFSI is used to assess the load behaviour following the loss of an online unit. A brief interpretation of the proposed LFSI is described below in equation (13)

$$\eta^t = \frac{\partial P_G^t}{\partial f_s} \approx \frac{\Delta P_G^t}{\Delta f_s} \qquad (13)$$

Where ΔP_G^t is the amount of MW generation loss (in percentage of the system load at time step) and Δfs is the system frequency drop following the loss of an online unit. The calculation of LFSI highly depends on the system load characteristics and the operation mode of pumped-storage units. For instance, when the MW generation loss of an online unit occurred during the light load period, the system frequency deviation is typically larger than that during heavy load period. The operation modes of pumped-storage units also affect the severity of frequency deviation during the contingency. In addition, the trend of the load variation with time, dD^t/dt, affects the magnitude of LFSI. To quickly recover the system frequency drop, the system usually needs more FRR to satisfy the increasing load if the loss of an online unit occurs; on the other hand, it needs less FRR during the load decreasing period, since the natural drop of the load tends to ease the electric power shortage. The mean and standard deviation of the frequency for pumping load and without pumping load as mentioned in [10] is as follows:

1) With pumping load: The pumped-storage units are typically operated in pumping mode during the light load period; if the loss of an online unit occurs, the MW generation loss can be quickly replaced by shedding off the pumping load. The system frequency deviation is relatively smaller than that without pumping load at the same MW generation loss. Therefore, the LFSI is larger and the required FFR is less than that without pumping load, regardless of the load variation trend. For both load variation trends, the LFSI is set to be μ+σ.

2) Without pumping load: When the loss of a generating unit occurs not in the light load period, the percentage of MW generation loss to the total system load is smaller than that occurs in the other time period. The required FRR for the increasing load case must cover both the MW generation loss and the incremental system load; it is more than that of the decreasing case. Therefore, the LFSI for the increasing load case is set to be μ-σ to supply more FRR. For the case of decreasing load, the LFSI is set to be μ.

	With pumping load	Without pumping load
dD^t/dt	μ+σ	μ
dD^t/dt	μ+σ	μ-σ

Table I determinative criteria of LFSI

3.1 FREQUENCY REGULATING RESERVE CONSTRAINT

Primary frequency regulation is triggered by frequency deviations that arise as a consequence of imbalances between generation and demand. One source of these mismatches is the inherent demand randomness, which, being generally small and relatively slows, can be corrected by secondary regulation or AGC. Under such conditions, primary regulation is also active, helping keep frequency within bounds, but not in a very conspicuous fashion. In contrast, after a large imbalance between demand and generation, such as those caused by the loss of a generating unit, primary frequency regulation is vital in limiting system frequency excursions and maintaining a balance between generation and demand. More specifically, after the loss of a generating unit, the system frequency drops from its reference level as the kinetic energy of the rotating masses decreases.

The definitions and classifications of reserves for electric utilities may be different, however, these reserves are typically classified according to the response time and they are deployed into primary, secondary, and tertiary reserves. The FRR is used to maintain system frequency within the normal limits and the response time is sufficiently fast to bring the system frequency back to the allowed range if the loss of the largest online unit occurs. The spinning reserve is to supply energy within 10 min after the beginning of the contingency and sustains at least 30 min to provide protection. The operating reserve is the reserve capacity not synchronized to the system and can be used to inject energy into the grid within 30min and to sustain at least 60 min, when a disturbance occurs to the already connected generating units. It is important for an isolated power system to avoid load shedding by providing sufficient FRR following the loss of any online generation unit.

The criterion of determining the FRR is difficult, since it varies from system to system. In the traditional UC problem the required amount of spinning reserve is usually provided according to the capacity of the largest online unit or a fixed percentage of the system load and such constraint may fail to specifically account for the dynamic characteristics of generator response and the load behaviour. In the system frequency constraint was considered and an iterative procedure was implemented to adjust the reserve levels until the frequency constraint was satisfied; however, this algorithm could diverge during the solution process because unit MW schedules might be changed and did not satisfy the reserve requirement.

The load- frequency sensitivity index (LFSI) was used to assess the frequency drop following the loss of the largest online unit. Then, the amount of hourly FRR was determined based on the known unit MW schedules. However, this method still had to recalculate the reserve levels until the frequency constraint was met by an iterative procedure. The LFSI and unit MW schedules are determined simultaneously. Then, the required FRR at each time step without violating the minimum system frequency is obtained. In the UC problem, both cost functions and unit/system constraints are modelled based on integer and linear approximations. For instance, models the non-differentiable and non-convex unit operating/start-up cost functions in stairwise and piecewise manners with inclusion of binary variables; the number of linear blocks in the nonlinear cost curves can be adjusted depending on the required accuracy of the model.

3.2 ADAPTIVE LFSI

The optimal unit MW schedules and the calculated LFSI are determined at each time step after the UC problem is solved. The equation (13) gives the expression of the proposed adaptive LFSI is shown below

$$\eta^t = \mu^t + [\mathrm{PMPS}^t + (\mathrm{PMPS}^t - 1).\,\mathrm{LV}^t].\,\sigma^t \qquad (13)$$

Where PMPS^t and LV^t are the pumped load index (binary variable) and the load variation index (binary parameter) at time step t. LV^t is pre-determined according to the load forecast information of the UC problem. If $dD^t/dt \geq 0$, then $\mathrm{LV}^t=1$. Otherwise, $\mathrm{LV}^t=0$. PMPS^t is defined in (14)

$$\mathrm{PMPS}^t=\begin{cases} 1, & \text{system including pumping load} \\ 0, & \text{otherwise} \end{cases} \qquad (14)$$

In an isolated power system, the FRR acts as a crucial reserve to be supplied within a very short margin time following a contingency. The margin time is defined as the time required bringing the system frequency back to meet the operation standard and is in the order of seconds.

4. RESULTS

MATLAB is a high-level language and interactive environment for numerical computation, visualization, and programming. Using MATLAB, you can analyze data, develop algorithms, and create models and applications. The frequency obtained from this method is about 49.2Hz, using the frequency regulating reserve constraint. The finding of frequency regulating reserve constraint method is different for different for various generating units. If any changes occur in the generating output, the system conditions will get change, so that the system should be maintained in normal operating conditions. The simulation output for the dynamic programming using MATLAB software is shown below:

Hr	Demand	Tot. Gen	Min MW	Max MW	Prod Cost	F-Cost
0	-	-	135	550	0	0
1	450	450	135	550	9208	9208
2	530	530	135	550	10648	19857
3	600	600	155	610	12450	32307
4	540	540	135	550	10828	43135
5	400	400	135	550	8308	51444
6	280	280	135	550	6192	57635
7	290	290	135	550	6366	64002
8	500	500	135	550	10108	74110

Table II: OUTPUT FOR HOURLY DEMANDS

The start up cost for these generating units is assumed as zero, which is the thermal constraints are not considered. The observations after the running of the unit commitment problem are if primary reserve is not scarce, cheaper units are dispatched at higher pre contingency generation values closer to their maximum generation. The loss of a single generating unit is less severe in a system where there are more units available, therefore keeping the frequency deviations and the required primary reserve at lower levels. Higher cost for primary reserve can significantly change the schedule of both energy and primary reserve. Stricter limits in the maximum allowed frequency deviation call for the scheduling of more units and strongly influence the generation and primary reserve dispatch. Optimizing with only tertiary reserve is usually computationally faster than with primary and tertiary reserves. Generally, the schedule obtained with only tertiary reserve is insecure with respect to frequency deviations.

5. CONCLUSION

In this paper, we have derived the mathematical formulation for the unit commitment problem in power systems using dynamic programming techniques. Two conditions were presented, which can be checked offline to eliminate unit combinations that are guaranteed a priori to be infeasible combinations since they are both necessary for a successful solution. Furthermore, we have presented a theorem with necessary and sufficient conditions for unit feasibility that require re dispatch to meet the system spinning reserve requirement. The minimum FRR limit and the unit MW schedules can be determined simultaneously when solving the UC problem and the optimal MW schedule is achieved. Simulation results based on the proposed method yield less cost of unit MW generation while the system security is maintained.

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